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**THE METHOD OF CHARACTERISTICS FOR
ANALYSIS OF PRESSURE TRANSIENTS
RESULTING FROM SODIUM-WATER REACTION
IN HYDRAULIC NETWORKS**

Yong Woo Shin

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BASE TECHNOLOGY

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ARGONNE NATIONAL LABORATORY, ARGONNE, ILLINOIS

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NOMENCLATURE

a	sonic speed	x	coordinate measured along pipe length
A	cross-sectional area of a pipe	Δx	internodal distance in a pipe branch
C^+, C^-	positive, negative characteristics	<u>Greek Letters</u>	
D	pipe inside diameter	ϵ	exponent appearing in the time-dependent rupture model
e	pipe-wall thickness	θ	ratio, $\Delta t / \Delta x$
E	Young's modulus	ρ	density
f	Darcy-Weisbach friction coefficient	$\vec{\lambda}; \lambda_1, \lambda_2$	vector normal to characteristic; its t component, x component
h	enthalpy	τ	time constant appearing in time-dependent rupture model
K	pressure loss coefficient	<u>Subscripts</u>	
m	mass of leak water	A	refers to an interpolation between nodes j and j - 1
$\dot{m}_0$	leak-water flow rate under choked flow condition	B	refers to an interpolation between nodes j and j + 1
p	absolute pressure	c	critical
r	rupture radius	i	refers to ith branch
r_0	initial rupture radius	j	refers to jth node in any branch
$r_{\max}$	maximum rupture radius	s	refers to constant entropy
s	entropy	∞	refers to surge tank or reservoir condition
t	time		
Δt	time step		
u	fluid velocity		
V	volume of reaction-product zone		

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ABSTRACT

The governing partial differential equations for one-dimensional, unsteady flows are reduced to a set of ordinary differential equations by the method of characteristics. The governing equations include the complete Navier-Stokes equation in which the viscous term is written in terms of the Darcy-Weisbach friction factor. By appropriate matching of the boundary conditions at the pipe junctions, the flow conditions following the sodium-water reaction can be determined for the entire network. The resulting characteristic and compatibility equations are written in finite differences. A computer program was written to solve the finite-difference equations together with various junction conditions in which a stepwise numerical-integration technique was used. The program uses the sodium-water-reaction dynamics model as developed by Zaker and Salmon for characterizing the source pressure.

The computer code was applied to calculate the pressure-pulse propagation in the EBR-II secondary sodium network for an assumed water leak rate of $1 \text{ lb}_m/\text{sec}$ at one end of the superheater. The same problem also was solved by the linear inviscid-analysis method of the converted NAHAMMER code. The comparison of the two results for zero initial velocity showed good agreement, indicating that the nonlinear and viscous effects are negligibly small. Nevertheless, an increased difference was observed between the two results as the magnitude of the velocity was increased.

I. INTRODUCTION

The possibility of water coming into contact with sodium as a result of local structural failure cannot be ruled out in designing sodium-water heat exchangers. The union of sodium and water results in an exothermic chemical reaction, usually producing high pressures. The pressure level attained depends on the nature and the rate at which the reaction proceeds, and the

constraint characteristics of the surrounding fluid. The assessment of the reaction-produced pressure and of its subsequent propagation throughout the connected pipe network is essential to design engineers to adequately account for such pressure loading on the structure in the design or, as an alternative, to provide for suitable relief devices. With the aid of the analysis method, if available, one can even select a particular piping arrangement yielding the most favorable network response, namely, the minimum pressure loading on the structure.

Zaker and Salmon¹ developed a sodium-water-reaction model to characterize the reaction-zone pressure, assuming an instantaneous chemical reaction. They further wrote a computer code for studying the coupled events of the sodium-water reaction and the subsequent pressure transient through the network. The arithmetic method used in the pressure-transient analysis is simple in formulation. Disadvantages with the method are that a-priori knowledge of pressure-wave propagation is an essential requirement and only simple boundary conditions can be accommodated. Chen et al.² developed the NAHAMMER code in connection with the pressure-pulse propagation analysis emanating from molten-fuel-coolant interaction. The method of characteristics was used for the simplified linear differential equations in which the nonlinear convective term and the viscous effect were neglected. The superposition technique was employed in the computational procedure for minimum coding effort. Recently, the NAHAMMER code was converted to a sodium-water-reaction analysis code³ by replacing the fuel-coolant interaction with the sodium-water-reaction model of Zaker and Salmon.

Both the converted NAHAMMER code and the Zaker-Salmon code neglect the fluid viscosity and the nonlinear nature of wave propagation. When viscosity is neglected, the wave strength remains unchanged while the wave travels in any pipe branch, and can only change when confronted with the boundary (the pipe junction).

The assumption of inviscidness can lead to unrealistically high estimates of pressures, especially at locations far from the source point. Because of the nondissipative nature, the validity of the analysis is restricted to the short time transient. The pressure level associated with sodium-water reaction will yield a relatively low material velocity in comparison to the sonic velocity in liquid sodium. Nevertheless, when the system to be analyzed has already high steady-state velocities, the nonlinearity can no longer be neglected.

This report describes the one-dimensional method of characteristics as applied to a hydraulic network consisting of a series of pipes joined by various connectors. Complete governing equations are considered that include the convective and viscous terms. A computer program is written to solve numerically the finite-difference equations of the reduced ordinary differential equations. It incorporates the Zaker-Salmon model of the sodium-water

reaction, and the code accounts for analysis of the sodium-water reaction and the subsequent network response for the entire excursion from the rapid initial transient to the final blowdown.

Numerical calculations were performed for the secondary sodium network of the EBR-II. Noticeable effects of friction and nonlinearity were observed when high steady-state system velocities were considered. The system velocity had a twofold effect: It influenced the source pressure through the coupling of the reaction dynamics and the ensuing network response, and it affected the manner in which the waves traveled through the network.

II. ANALYTICAL DEVELOPMENT

A. Hydrodynamics Equations

Although sodium is often assumed incompressible, sodium (as other liquids) has a bulk modulus of elasticity much less than that of solids. In fact, the small compressibility of liquids is of primary importance for problems involving rapidly varying unsteady motion or large changes in pressure. A rapid application of force to a point in fluid can, depending on the rate, lead to a transient state of motion in which pressure can differ greatly from point to point. Conversely, if the force is applied in a time period comparable to the transit time of compression waves, the fluid reacts like an incompressible substance. In the final set of equations, density is treated as a constant when it appears explicitly although all its derivatives are retained.

The basic equations for a compressible, one-dimensional, unsteady viscous flow are:

Continuity

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho u) = 0; \quad (1)$$

Momentum

$$\rho \left(\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} \right) + \frac{\partial p}{\partial x} + \frac{f \rho u |u|}{2D} = 0; \quad (2)$$

Energy

$$\rho \left(\frac{\partial h}{\partial t} + u \frac{\partial h}{\partial x} \right) - \frac{\partial p}{\partial t} - u \frac{\partial p}{\partial x} = 0; \quad (3)$$

State

$$h = h(p, \rho); \quad (4)$$

where f is the Darcy-Weisbach friction coefficient, and D is the inside pipe diameter. The viscous term in the momentum equation represents the frictional retardation force acting on the pipe wall in which the absolute-value sign is used to show its direction opposite to the flow. The viscous-dissipation term is neglected in the energy equation. The set of the above four equations could be solved for the four unknowns. For convenience, however, terms involving enthalpy and density are eliminated from the system of equations.

Substituting Eq. 4 into Eq. 3 gives

$$\rho \left[\frac{\partial h}{\partial p} \frac{\partial p}{\partial t} + \frac{\partial h}{\partial \rho} \frac{\partial \rho}{\partial t} + u \left(\frac{\partial h}{\partial p} \frac{\partial p}{\partial x} + \frac{\partial h}{\partial \rho} \frac{\partial \rho}{\partial x} \right) \right] - \frac{\partial p}{\partial t} - u \frac{\partial p}{\partial x} = 0,$$

and rearranging yields

$$a^2 \left(\frac{\partial \rho}{\partial t} + u \frac{\partial \rho}{\partial x} \right) - \frac{\partial p}{\partial t} - u \frac{\partial p}{\partial x} = 0, \quad (5)$$

where

$$a = \sqrt{-\rho \frac{\partial h}{\partial \rho} \left(\rho \frac{\partial h}{\partial p} - 1 \right)^{-1}}$$

is a thermodynamic-state variable identified to be the sonic speed upon utilizing the following isentropic processes of state change and fluid flow:

$$a^2 = \left(\frac{\partial p}{\partial \rho} \right)_s; \quad (6)$$

$$\frac{\partial s}{\partial t} + u \frac{\partial s}{\partial x} = 0. \quad (7)$$

Terms involving density in Eq. 5 are eliminated by using Eq. 1 to give

$$\rho a^2 \frac{\partial u}{\partial x} + \frac{\partial p}{\partial t} + u \frac{\partial p}{\partial x} = 0. \quad (8)$$

The new set of equations (Eqs. 2 and 8) is used for a simultaneous solution for unknowns u and p , where density ρ and sonic speed a are approximated as constants. These equations are of the hyperbolic type, for which the method of characteristics is used as the solution procedure.

B. The Method of Characteristics

The new set of equations as derived in Sec. A is rewritten here as

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + \frac{1}{\rho} \frac{\partial p}{\partial x} + \frac{fu|u|}{2D} = 0 \quad (2')$$

and

$$\rho a^2 \frac{\partial u}{\partial x} + \frac{\partial p}{\partial t} + u \frac{\partial p}{\partial x} = 0. \quad (8)$$

These first-order partial differential equations are quasi-linear hyperbolic equations, which possess real characteristics. For such equations, in particular, in two independent variables, the method of characteristics is an informative and convenient solution procedure.

In the general theory of the method of characteristics^{4,5} in two independent variables, there exists an axis called the characteristic direction, normal to which the solution cannot be extended (refer to Fig. 1). Along the

characteristics, the derivatives are no longer arbitrary, but related through equations called the compatibility relations, which are now ordinary differential equations. This requires that a linear combination of Eqs. 2' and 8 be free of the component of gradients $\vec{\nabla}u$ and $\vec{\nabla}p$, in the direction $\vec{\lambda}$ normal to the characteristics. A linear combination of Eqs. 2' and 8,

$$\alpha_1 \left(\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + \frac{1}{\rho} \frac{\partial p}{\partial x} + \frac{fu|u|}{2D} \right) + \alpha_2 \left(\rho a^2 \frac{\partial u}{\partial x} + \frac{\partial p}{\partial t} + u \frac{\partial p}{\partial x} \right) = 0, \quad (9)$$

when rearranged, yields

$$\alpha_1 \frac{\partial u}{\partial t} + (\alpha_1 u + \alpha_2 \rho a^2) \frac{\partial u}{\partial x} + \alpha_2 \frac{\partial p}{\partial t} + \left(\alpha_2 u + \frac{\alpha_1}{\rho} \right) \frac{\partial p}{\partial x} + \alpha_1 \frac{fu|u|}{2D} = 0, \quad (10)$$

where α_1 and α_2 are some constants to be determined later. Equation 10 will have no gradient components parallel to $\vec{\lambda}$ if

$$\lambda_1 \alpha_1 + \lambda_2 (\alpha_1 u + \alpha_2 \rho a^2) = 0$$

and

$$\lambda_1 \alpha_2 + \lambda_2 \left(\alpha_2 u + \frac{\alpha_1}{\rho} \right) = 0,$$

which, upon rearranging, gives

$$\left. \begin{aligned} (\lambda_1 + \lambda_2 u) \alpha_1 + \lambda_2 \rho a^2 \alpha_2 &= 0 \\ \frac{\lambda_2}{\rho} \alpha_1 + (\lambda_1 + \lambda_2 u) \alpha_2 &= 0 \end{aligned} \right\} \quad (11)$$

Fig. 1
A Characteristic Curve and Its Normal $\vec{\lambda}$ at Point P in x-t Plane

Equations 11 are homogeneous in α_1 and α_2 , and, for their nontrivial solution, the coefficient determinant, called the characteristic determinant, must vanish; that is,

$$\begin{vmatrix} \lambda_1 + \lambda_2 u & \lambda_2 \rho a^2 \\ \frac{\lambda_2}{\rho} & \lambda_1 + \lambda_2 u \end{vmatrix} = 0, \quad (12)$$

or, expanding,

$$\frac{\lambda_1}{\lambda_2} + u = \mp a. \quad (13)$$

With reference to Fig. 1, the following geometrical relationship in x - t plane holds:

$$\frac{\lambda_1}{\lambda_2} = -\frac{dx}{dt}. \quad (14)$$

Equations 13 and 14 determine the characteristic relations,

$$\frac{dx}{dt} = u \pm a. \quad (15)$$

Now the remaining task is to find the compatibility relations that contain the components of the gradients $\vec{\nabla}u$ and $\vec{\nabla}p$ only in directions along the characteristic curves defined by Eq. 15. This is accomplished by inserting Eq. 13 into Eq. 11 to obtain

$$\alpha_2 = \pm \frac{1}{\rho a} \alpha_1 \quad (16)$$

and substituting Eq. 16 into Eq. 10, which yields

$$\frac{\partial u}{\partial t} + (u \pm a) \frac{\partial u}{\partial x} \pm \frac{1}{\rho a} \left[\frac{\partial p}{\partial t} + (u \pm a) \frac{\partial p}{\partial x} \right] + \frac{fu|u|}{2D} = 0, \quad (17)$$

where the order of the sign $\pm$ corresponds to that of the characteristic relations, Eq. 15. Combining Eq. 17 with Eq. 15 gives

$$\frac{\partial u}{\partial t} + \frac{\partial u}{\partial x} \frac{dx}{dt} \pm \frac{1}{\rho a} \left(\frac{\partial p}{\partial t} + \frac{\partial p}{\partial x} \frac{dx}{dt} \right) + \frac{fu|u|}{2D} = 0,$$

and choosing t as the parameter along the characteristics finally yields

$$\frac{du}{dt} \pm \frac{1}{\rho a} \frac{dp}{dt} + \frac{fu|u|}{2D} = 0. \quad (18)$$

In summary, instead of solving the partial differential Eqs. 2 and 8, the ordinary differential Eqs. 18 are used, and the solution is extended from the given initial curve along the characteristics defined in Eq. 15. The set of reduced equations are rewritten as

$$\frac{du}{dt} + \frac{1}{\rho a} \frac{dp}{dt} + \frac{fu|u|}{2D} = 0, \quad (19)$$

along the positive characteristic C^+ ,

$$dx = (u + a) dt, \quad (20)$$

and

$$\frac{du}{dt} - \frac{1}{\rho a} \frac{dp}{dt} + \frac{fu|u|}{2D} = 0 \quad (21)$$

along the negative characteristic C^- ,

$$dx = (u - a) dt. \quad (22)$$

C. Finite-difference Approximation

A typical step-integration procedure consists of extending the solution to a neighboring point P (see Fig. 2) from the horizontal strip $\overline{RS}$ on which the solution is known. A repetition of the procedure from the initial condition given at $t = 0$ yields the desired approximate numerical solution. For uniform spacing ($\Delta x = \text{const}$), the time step

$$\Delta t \leq \frac{\Delta x}{a + |u|} \quad (23)$$

is chosen so that the domain of dependence of the differential system is contained within the domain of dependence of the approximating difference system. As shown in Fig. 2, points A and B, at which the two characteristics intercept the initial curve, always fall between points R and S. Thus the Courant-Friedrichs-Lewy⁶ criterion for convergence and stability of the finite-difference scheme is satisfied. Points A and B are obtained by a linear interpolation between points R and Q, and Q and S, respectively. Using the approximate characteristic relations

$$\left. \begin{aligned} x_P - x_A &= (u + a) \Delta t \\ x_P - x_B &= (u - a) \Delta t \end{aligned} \right\}, \quad (24)$$

and

Fig. 2

Diagram Showing the Finite-difference Network and Local Characteristics Passing through Point P near Initial Curve

linear interpolations yield

$$\left. \begin{aligned} u_A &= \frac{u_Q - a\theta(u_Q - u_R)}{1 + \theta(u_Q - u_R)}, \\ u_B &= \frac{u_Q + a\theta(u_S - u_Q)}{1 + \theta(u_S - u_Q)}, \\ p_A &= p_Q - \theta(a + u_A)(p_Q - p_R), \\ p_B &= p_Q + \theta(a - u_B)(p_S - p_Q), \end{aligned} \right\} \quad (25)$$

and

where

$$\theta = \frac{\Delta t}{\Delta x} \quad (26)$$

and the subscripts A, B, P, Q, R, and S refer to the points in Fig. 2.

For stepwise numerical integration, the x-t plane is divided into a finite number of discrete nodes using uniform spacing in x and a fixed time step. Each pipe branch in the system network is segmented into n discrete nodes. The compatibility relations, Eqs. 19 and 21, are written in finite differences for jth node of ith pipe at time $t + \Delta t$ along the two characteristics passing through the nodal point:

$$u_{i,j}^{t+\Delta t} - u_{i,A}^t + \frac{1}{\rho a_i} (p_{i,j}^{t+\Delta t} - p_{i,A}^t) + \frac{f_{i,A}^t u_{i,A}^t |u_{i,A}^t| \Delta t}{2D_i} = 0$$

and

$$u_{i,j}^{t+\Delta t} - u_{i,B}^t - \frac{1}{\rho a_i} (p_{i,j}^{t+\Delta t} - p_{i,B}^t) + \frac{f_{i,B}^t u_{i,B}^t |u_{i,B}^t| \Delta t}{2D_i} = 0,$$

which, upon explicitly solving for the unknowns $u_{i,j}^{t+\Delta t}$ and $p_{i,j}^{t+\Delta t}$, results in

$$\begin{aligned} u_{i,j}^{t+\Delta t} &= \frac{1}{2} \left[\left(u_{i,A}^t + u_{i,B}^t \right) + \frac{1}{\rho a_i} \left(p_{i,A}^t - p_{i,B}^t \right) \right. \\ &\quad \left. - \frac{\Delta t}{2D_i} \left(f_{i,A}^t u_{i,A}^t |u_{i,A}^t| + f_{i,B}^t u_{i,B}^t |u_{i,B}^t| \right) \right] \end{aligned} \quad (27)$$

and

$$p_{i,j}^{t+\Delta t} = \frac{1}{2} \left[\left(p_{i,A}^t + p_{i,A}^t \right) + \frac{1}{\rho a_i} \left(u_{i,A}^t - u_{i,B}^t \right) - \frac{\rho a_i \Delta t}{2D_i} \left(f_{i,A}^t u_{i,A}^t \left| u_{i,A}^t \right| - f_{i,B}^t u_{i,B}^t \left| u_{i,B}^t \right| \right) \right]. \quad (28)$$

In arriving at the above finite-difference equations, the velocity in the viscous term was approximated locally as constant. Nevertheless, when a large change in velocity is encountered during the stepwise calculation, an iterative scheme can be employed so that an average value between points A and P is used.

D. Boundary Conditions

As part of the systems network analysis, the boundary conditions describing the wave interactions at various pipe junctions are given here. The type of junctions covered in this study are (1) sudden expansion or contraction, (2) tee junction (joining three up to six branches), (3) closed end, (4) surge tank or reservoir, (5) far end, (6) dummy junction, (7) acoustic-impedance discontinuity, and (8) rupture disk.

1. Sudden Expansion or Contraction

Consider two pipe branches, i and $i + 1$, with cross-sectional areas A_i and A_{i+1} joined in that order in the increasing x direction. At the junction, the continuity, energy, and compatibility relations must be satisfied:

Continuity

$$u_{i,n}^{t+\Delta t} A_i = u_{i+1,1}^{t+\Delta t} A_{i+1};$$

Energy

$$\frac{1}{2} \rho \left(u_{i,n}^{t+\Delta t} \right)^2 + p_{i,n} = \frac{1}{2} \rho \left(u_{i+1,1}^{t+\Delta t} \right)^2 + p_{i+1,1} + \frac{1}{2} K \rho \left(u_{i,n}^{t+\Delta t} \right)^2;$$

Compatibility

Along C^+ in i th branch,

$$u_{i,n}^{t+\Delta t} - u_{i,A}^t + \frac{1}{\rho a_i} \left(p_{i,n}^{t+\Delta t} - p_{i,n}^t \right) + \frac{f_{i,A}^t u_{i,A}^t \left| u_{i,A}^t \right| \Delta t}{2D_i} = 0;$$

Along C^- in $(i+1)$ th branch,

$$u_{i+1,1}^{t+\Delta t} - u_{i+1,B}^t - \frac{1}{\rho a_{i+1}} (p_{i+1,1}^{t+\Delta t} - p_{i+1,B}^t) + \frac{f_{i+1,B}^t u_{i+1,B}^t |u_{i+1,B}^t| \Delta t}{2D_{i+1}} = 0,$$

where K is the loss coefficient.

A simultaneous solution of the above four equations for the four unknowns at the junction is

$$u_{i,n}^{t+\Delta t} = \beta \pm \sqrt{\beta^2 - \gamma}; \begin{cases} + \text{ is used if } \delta < 0 \\ - \text{ is used if } \delta > 0 \end{cases} \quad (29a)$$

$$u_{i+1,1}^{t+\Delta t} = \frac{A_i}{A_{i+1}} u_{i,n}^{t+\Delta t}; \quad (29b)$$

$$p_{i,n}^{t+\Delta t} = p_{i,A}^t - \rho a_i \left(u_{i,n}^{t+\Delta t} - u_{i,A}^t \right) - \frac{f_{i,A}^t \rho a_i u_{i,A}^t |u_{i,A}^t| \Delta t}{2D_i}; \quad (29c)$$

$$p_{i+1,1}^{t+\Delta t} = p_{i+1,B}^t + \rho a_{i+1} \left(u_{i+1,1}^{t+\Delta t} - u_{i+1,B}^t \right) + \frac{f_{i+1,B}^t \rho a_{i+1} u_{i+1,B}^t |u_{i+1,B}^t| \Delta t}{2D_{i+1}}; \quad (29d)$$

where

$$\beta = \frac{1}{\delta} \left(a_i + a_{i+1} \frac{A_i}{A_{i+1}} \right),$$

$$\gamma = \frac{2}{\delta} \left[a_i u_{i,A}^t + a_{i+1} u_{i+1,A}^t + \frac{1}{\rho} \left(p_{i,A}^t - p_{i+1,B}^t \right) - \frac{\Delta t}{2} \left(\frac{f_{i,A}^t a_i u_{i,A}^t |u_{i,A}^t|}{D_i} + \frac{f_{i+1,B}^t a_{i+1} u_{i+1,B}^t |u_{i+1,B}^t|}{D_{i+1}} \right) \right],$$

and

$$\delta = 1 - \left(\frac{A_i}{A_{i+1}} \right)^2 - K.$$

For the sudden-expansion⁷ case, the loss coefficient K is

$$K = \left(1 - \frac{A_i}{A_{i+1}}\right)^2 \quad \text{for } u_{i,n}^t > 0$$

and

$$K = \left(1 - \frac{A_i}{A_{i+1}}\right)^2 \quad \text{for } u_{i,n}^t < 0; \quad (30a)$$

and for the sudden-contraction⁸ case,

$$K = 0.45 \left(\frac{A_i}{A_{i+1}}\right) \left(\frac{A_i}{A_{i+1}} - 1\right) \quad \text{for } u_{i,n}^t > 0$$

and

$$K = -0.45 \left(1 - \frac{A_i}{A_{i+1}}\right) \quad \text{for } u_{i,n}^t < 0. \quad (30b)$$

2. Tee Junction

Consider a tee junction that joins $\ell + m$ branches at a junction where ℓ branches are connected to the junction at their end nodes whereas the remaining m branches are connected at their first nodes. With neglected pressure loss and kinetic-energy change, the following conditions must be satisfied:

Continuity

$$\sum_{j=1}^{\ell} A_j u_{j,n}^{t+\Delta t} = \sum_{k=1}^m A_k u_{k,l}^{t+\Delta t};$$

Equality of pressure condition

$$p_{1,n}^{t+\Delta t} = p_{2,n}^{t+\Delta t} = \dots = p_{\ell,n}^{t+\Delta t} = p_{1,l}^{t+\Delta t} = p_{2,l}^{t+\Delta t} = \dots = p_{m,l}^{t+\Delta t};$$

Compatibility

Along C^+ in ℓ branches

$$u_{j,n}^{t+\Delta t} - u_{j,A}^t + \frac{1}{\rho a_j} (p_{j,n}^{t+\Delta t} - p_{j,A}^t) + \frac{f_{j,A}^t u_{j,A}^t |u_{j,A}^t| \Delta t}{2D_j} = 0,$$

$$j = 1, 2, \dots, \ell;$$

Along C^- in m branches

$$u_{k,1}^{t+\Delta t} - u_{k,B}^t - \frac{1}{\rho a_k} (p_{k,1}^{t+\Delta t} - p_{k,B}^t) + \frac{f_{k,B}^t u_{k,B}^t |u_{k,B}^t| \Delta t}{2D_k} = 0,$$

$$k = 1, \dots, m.$$

The solutions of the above equations are

$$\begin{aligned} p_{j,n}^{t+\Delta t} = p_{k,1}^{t+\Delta t} = & \frac{1}{\sum_{j=1}^{\ell} c_j + \sum_{k=1}^m c_k} \left(\sum_{j=1}^{\ell} A_j u_{j,A}^t - \sum_{k=1}^m A_k u_{k,B}^t + \sum_{j=1}^{\ell} c_j p_{j,A}^t \right. \\ & \left. + \sum_{k=1}^m c_k p_{k,B}^t - \sum_{j=1}^{\ell} b_j f_{j,A}^t u_{j,A}^t |u_{j,A}^t| \Delta t + \sum_{k=1}^m b_k f_{k,B}^t u_{k,B}^t |u_{k,B}^t| \Delta t \right), \\ & j = 1, \dots, \ell \text{ and } k = 1, \dots, m; \end{aligned} \quad (31a)$$

$$u_{j,n}^{t+\Delta t} = u_{j,A}^t - \frac{1}{\rho a_j} (p_{j,n}^{t+\Delta t} - p_{j,A}^t) - \frac{f_{j,A}^t u_{j,A}^t |u_{j,A}^t| \Delta t}{2D_j}, \quad j = 1, \dots, \ell; \quad (31b)$$

$$\begin{aligned} u_{k,1}^{t+\Delta t} = u_{k,B}^t + \frac{1}{\rho a_k} (p_{k,1}^{t+\Delta t} - p_{k,B}^t) - \frac{f_{k,B}^t u_{k,B}^t |u_{k,B}^t| \Delta t}{2D_k}, \\ k = 1, \dots, m; \end{aligned} \quad (31c)$$

where

$$c_j = \frac{A_j}{\rho a_j}, \quad c_k = \frac{A_k}{\rho a_k},$$

$$b_j = \frac{A_j}{2D_j}, \quad b_k = \frac{A_k}{2D_k},$$

and the subscripts j and k refer to branches that are connected to the junction.

3. Closed End

The zero-velocity condition at the junction and the compatibility relation along the characteristic directed toward the junction determine the flow conditions at the closed end. For the last node of the i th branch that is closed,

$$u_{i,n}^{t+\Delta t} = 0; \quad (32a)$$

$$p_{i,n}^{t+\Delta t} = p_{i,A}^t + \rho a_i \left(u_{i,A}^t - \frac{f_{i,A}^t u_{i,A}^t |u_{i,A}^t| \Delta t}{2D_i} \right). \quad (32b)$$

For the first node that is closed,

$$u_{i,1}^{t+\Delta t} = 0; \quad (32c)$$

$$p_{i,1}^{t+\Delta t} = p_{i,B}^t - \rho a_i \left(u_{i,B}^t - \frac{f_{i,B}^t u_{i,B}^t |u_{i,B}^t| \Delta t}{2D_i} \right). \quad (32d)$$

4. Surge Tank or Reservoir

Pressure is maintained constant in the surge tank or reservoir. This condition and the compatibility relation along the characteristic directed to the junction determine the flow condition. For the last node connected to the surge tank,

$$u_{i,n}^{t+\Delta t} = u_{i,A}^t + \frac{1}{\rho a_i} (p_{i,A}^t - p_\infty) - \frac{f_{i,A}^t u_{i,A}^t |u_{i,A}^t| \Delta t}{2D_i}; \quad (33a)$$

$$p_{i,n}^{t+\Delta t} = p_\infty. \quad (33b)$$

For the first node connected to the tank,

$$u_{i,1}^{t+\Delta t} = u_{i,B}^t + \frac{1}{\rho a_i} (p_\infty - p_{i,B}^t) - \frac{f_{i,B}^t u_{i,B}^t |u_{i,B}^t| \Delta t}{2D_i}; \quad (33c)$$

$$p_{i,1}^{t+\Delta t} = p_\infty, \quad (33d)$$

where p_∞ is the gas pressure in the surge tank or reservoir.

5. Far End

The far-end condition is used when a large and complicated system network is to be simplified. The condition provides for means of discarding part of the network, leaving no effects on the remaining part of the system. The flow conditions at the junction are obtained using the simple wave analysis as in Chen et al.,² so that no reflected waves are admitted to the system from the far end. For the last node connected to a far end,

$$u_{i,n}^{t+\Delta t} = u_i^0 + \frac{1}{2} \left[u_{i,A}^t - u_i^0 + \frac{1}{\rho a_i} (p_{i,A}^t - p_i^0) \right]; \quad (34a)$$

$$p_{i,n}^{t+\Delta t} = p_i^0 + \frac{1}{2} \left[\rho a_i (u_{i,A}^t - u_i^0) + p_{i,A}^t - p_i^0 \right]. \quad (34b)$$

For the first node connected to a far end,

$$u_{i,1}^{t+\Delta t} = u_i^0 + \frac{1}{2} \left[u_{i,B}^t - u_i^0 - \frac{1}{\rho a_i} (p_{i,B}^t - p_i^0) \right]; \quad (34c)$$

$$p_{i,1}^{t+\Delta t} = p_i^0 + \frac{1}{2} \left[-\rho a_i (u_{i,B}^t - u_i^0) + p_{i,B}^t - p_i^0 \right], \quad (34d)$$

where u_i^0 and p_i^0 are steady-state system velocity and pressure, respectively, in the i th branch.

6. Dummy Junction and Acoustic-impedance Discontinuity

A dummy junction is useful when the network contains a pipe branch extremely long compared to other sections and it is desirable to treat it as two or more branches. The acoustic-impedance discontinuity resulting from the sudden change in sonic speed is treated at the same time. The conditions to be satisfied at the junction connecting the i th and $(i+1)$ th branches are:

Continuity

$$u_{i,n}^{t+\Delta t} = u_{i+1,1}^{t+\Delta t};$$

Energy

$$p_{i,n}^{t+\Delta t} = p_{i+1,1}^{t+\Delta t};$$

Along C^+ in i th pipe

$$u_{i,n}^{t+\Delta t} - u_{i,A}^t + \frac{1}{\rho a_i} (p_{i,n}^{t+\Delta t} - p_{i,A}^t) + \frac{f_{i,A}^t u_{i,A}^t |u_{i,n}^t| \Delta t}{2D_i} = 0;$$

Along C^- in $(i+1)$ th pipe

$$u_{i+1,1}^{t+\Delta t} - u_{i+1,B}^t - \frac{1}{\rho a_{i+1}} (p_{i+1,1}^{t+\Delta t} - p_{i+1,B}^t) + \frac{f_{i+1,B}^t u_{i+1,B}^t |u_{i+1,B}^t| \Delta t}{2D_{i+1}} = 0.$$

Thus the flow conditions are

$$u_{i,n}^{t+\Delta t} = u_{i+1,1}^{t+\Delta t} = \frac{1}{2} \left[u_{i,A}^t + u_{i+1,B}^t + \frac{1}{\rho} \left(\frac{p_{i,A}^t}{a_i} - \frac{p_{i+1,B}^t}{a_{i+1}} \right) - \frac{\Delta t}{2} \left(\frac{f_{i,A}^t u_{i,A}^t |u_{i,A}^t|}{D_i} + \frac{f_{i+1,B}^t u_{i+1,B}^t |u_{i+1,B}^t|}{D_{i+1}} \right) \right] \quad (35a)$$

and

$$p_{i,n}^{t+\Delta t} = p_{i+1,1}^{t+\Delta t} = \frac{\rho a_i a_{i+1}}{a_i + a_{i+1}} \left[u_{i,A}^t - u_{i+1,B}^t + \frac{1}{\rho} \left(\frac{p_{i,A}^t}{a_i} + \frac{p_{i+1,B}^t}{a_{i+1}} \right) - \frac{\Delta t}{2} \left(\frac{f_{i,A}^t u_{i,A}^t |u_{i,A}^t|}{D_i} - \frac{f_{i+1,B}^t u_{i+1,B}^t |u_{i+1,B}^t|}{D_{i+1}} \right) \right]. \quad (35b)$$

7. Rupture Disk

The rupture disk is a pressure-relief device that acts as a closed end until it is exposed to a critical pressure p_c . At the instant the junction pressure reaches the critical pressure, the disk breaks, and subsequently the junction behaves as the reservoir condition described in Sec. 4 above.

III. COMPUTER PROGRAM

The computer program NATRANSIENT is written in FORTRAN IV for the IBM S/360-195 computer for analysis of pressure-pulse propagation in liquid-sodium circuits where the pulses evolve as a result of chemical reaction of sodium and water. The Zaker-Salmon analysis¹ is used for calculating the source pressure. In their reaction model, briefly summarized in Appendix A, the rupture is assumed to open instantaneously to its maximum value. To provide means for examining the sensitivity of this assumption, NATRANSIENT includes a time-dependent rupture model,

$$\left. \begin{aligned} \frac{r}{r_{\max}} &= \frac{r_0}{r_{\max}} + \left(1 - \frac{r_0}{r_{\max}}\right) \left(\frac{t}{\tau}\right)^6 & \text{for } t \leq \tau; \\ \frac{r}{r_{\max}} &= 1 & \text{for } t > \tau; \\ \dot{m}_0 &= 18.9(\pi r^2) \text{ lb}_m/\text{sec.} \end{aligned} \right\} \quad (36)$$

The Colebrook-White correlation⁷ determines the Darcy-Weisbach friction coefficient for a given flow condition and pipe roughness in which an iterative scheme is used, since the correlation is an implicit expression. The thermophysical properties of liquid sodium are extracted from Golden and Tokar.⁹ The sonic velocities in each pipe branch are further modified¹⁰ to account for pipe dilatation:

$$a = a_0 \left(1 + \frac{\rho a_0^2 D c_1}{E e}\right)^{-1/2}, \quad (37a)$$

where a_0 denotes the sonic speed in a perfectly rigid pipe, e is the pipe-wall thickness, and c_1 is the Poisson-ratio-effect correction constant, which is one for the case with expansion joints throughout. A further reduction in the sonic speed due to the presence of a rigid inclusion is accounted for by replacing the Young's modulus E in Eq. 37a by the effective Young's modulus,

$$E_{\text{eff}} = \frac{A_{\text{Net}}}{A_{\text{Gross}}} E, \quad (37b)$$

where A_{Net} and A_{Gross} are the net and gross flow areas, respectively.

After every time-step calculation, the highest material velocity existing in the system is determined. To ensure numerical stability, a check is made to see if the maximum velocity satisfies the stability criterion, Eq. 3. The time step Δt is reduced, if necessary, for the next time-step calculation. All calculations are single-precision stepwise calculations advancing with time in which essentially no iterations are involved.

A. Description of Input Data

The following cards are required as input data to the program and are described in the order in which they appear in the input deck.

<u>Card No</u>	<u>FORTTRAN Name</u>	<u>Format</u>	<u>Description</u>
1		8I5	
	LEGNO		Total number of pipe branches.
	JUNNO		Total number of junctions
	NOT		Number of surge tank and reservoir
	NOPRIN		Frequency of printout If NOPRIN = 1, every step result is printed If NOPRIN = 2, the result of every second step is printed, etc
	KS		Parameter specifying details of printout Results of every KSth node in every branch are printed
	JJ		Branch number in which leak site is located.
	IC		If IC = 1, initial velocities and pressures in all branches are input individually If IC $\neq$ 1, initial velocities and pressures are set to UR and PR, respectively
	NP		If NP = 1, the friction factor f is set to 0. The result then corresponds to inviscid analysis. Set NP = 0 for normal run
2		6E12 5	
	DT		Time step, in seconds
	UR		Initial velocity If IC $\neq$ 1, initial velocities in all branches are set to UR
	PR		Initial pressure If IC $\neq$ 1, initial pressures in all branches are set to PR
	PCR		The critical pressure, in psi, at or above which rupture disks break
	TR		Temperature of the liquid sodium in the network
	XI		Initial time, in seconds, at which calculation starts
	XF		Final time, in seconds, at which calculation terminates
3		2I5	
	INDTR		An indicator signaling results of how many branches are to be printed If INDTR = 2, results of only two branches are printed If INDTR = 0 all results are printed
	NOTT		Number of rupture disks
4 (Multiple Cards)		16I5	
	INT(NQ)		The branch numbers of which results are to be printed NQ ranges from 1 to INDTR If INDTR = 0, skip this card Provide as many cards as necessary

<u>Card No</u>	<u>FORTTRAN Name</u>	<u>Format</u>	<u>Description</u>
5 (Multiple Cards)		213,6E12.5/,E12.5	Total LEGNO sets of cards Each set consists of two cards containing the following data in the order cited
	NI(L)		Junction number connected to the first node of Lth branch
	NN(L)		Junction number connected to the last node of Lth branch
	A(L)		Net cross-sectional area of Lth branch, in square inches
	LENGTH(L)		Length of Lth branch, in feet
	RF(L)		Roughness of Lth branch, in feet.
	H(L)		Thickness of Lth branch, in inches
	ES(L)		Young's modulus of Lth pipe material, in psi
	D(L)		Inside diameter of Lth branch, in inches
	PO(L)		Initial pressure in Lth branch, in psi This is used with option IC = 1
	UO(L)		Initial velocity in Lth branch, in ft/sec This is used with option IC = 1
			Argument L in above 10 arrays ranges from one to LEGNO
6		40I2	
	NJ(J)		Number indicating junction type for junction J, where J ranges from one to J 'NNO Junction type specifications are as follows 1 Sudden expansion or contraction. 3 Tee (joining three to six branches) 7 Closed end 8 Surge tank or reservoir 9 Far end. 6 Dummy junction 5 Acoustic-impedance discontinuity 10 Rupture disk
7		E12 5,I5	
	PT(I)		Gas pressure of surge tank or reservoir I, in psi
	IT(I)		Junction number to which surge tank I is attached I ranges from one to NOT. If NOT = 0, skip this card
8		E12.5,I5	
	PT(I)		Pressure of Ith reservoir to which rupture disks open, in psi
	IT(I)		Junction number to which Ith rupture disk is attached I ranges from one to NOTT If NOTT = 0, skip this card

<u>Card No.</u>	<u>FORTTRAN Name</u>	<u>Format</u>	<u>Description</u>
9		5E12.5	
	PI		System pressure used in source pressure calculation, in psi.
	WZD		Instantaneous leak rate, in lb _m /sec.
	PCT		Ratio of initial-to-final leak areas used for time-dependent rupture-rate study. PCT = 1.0 represents instantaneous leak.
	TAU		Time constant appearing in time-dependent rupture-rate model, Eq. 36, in seconds.
	EXP		Exponent appearing in time-dependent rupture-rate model, Eq. 36.

B. Program Limitations

The program has a number of limitations. Those that result from the dimension specification are:

<u>The number of</u>	<u>Cannot exceed</u>
(1) Branches	50
(2) Nodes in any one branch	120
(3) Junctions	50
(4) Surge tanks	10

Further limitations are:

(5) The program is a one-dimensional analysis method and, hence, does not take account of multidimensional effects of any section, such as the steam generator, which has a relatively small L/D ratio.

(6) The program cannot be applied to problems involving shock waves.

IV. NUMERICAL CALCULATIONS

A. Sample Problems

The secondary sodium circuit of the EBR-II was chosen as the sample problem. The network configuration and the dimensions of individual pipe branches are shown in Fig. 3. The network contains two superheaters, eight evaporators, and two rupture disks. For purposes of simplification, part of the system was removed and the rest was used for the calculation. The branch and the junction arrangements of the simplified network are shown in Fig. 4. Junctions 36 and 37 are the rupture disks, which are designed upon exposure to a pressure of 160 psia or higher. Junctions 38-42 are the far ends at which no wave reflections are allowed to take place.

Fig. 3. Simplified EBR-II Secondary Sodium Network

Fig. 4

Branch and Junction Numbering for Pressure-transient Analysis of EBR-II Secondary Sodium Network

A partial steam-tube rupture, corresponding to an instantaneous leak rate of $1 \text{ lb}_m/\text{sec}$, was considered to occur at the upper end of a superheater, branch 1 in Fig. 4. Two different initial conditions also were considered: (1) zero velocity everywhere and 60-psia system pressure, and (2) steady 23,000 gpm of total flow equally divided over parallel circuits. For the latter case, the initial pressures used in the calculation reflect the losses across sudden expansions and contractions, neglecting friction losses in the interior of pipe branches. Thus the pressure transients are mainly of the reaction-produced source pressure. Table I lists the branch and junction arrangement and the initial flow conditions for the two cases.

TABLE I. Initial Flow Conditions Used for Calculations and Arrangement of Branches and Junctions

Branch No.	Junction No. (type)		Case 1		Case 2	
	n = 1	n = N	Velocity, ft/sec	Pressure, psia	Velocity, ft/sec	Pressure, psia
1	43(6)	1(1)	0	60	19.364	92.307
2	1(1)	2(3)	0	60	75.165	51.523
3	2(3)	3(1)	0	60	0	51.523
4	3(1)	4(1)	0	60	0	51.523
5	4(1)	5(3)	0	60	0	51.523
6	2(3)	5(3)	0	60	75.165	51.523
7	5(3)	6(3)	0	60	33.409	51.523
8	6(3)	7(3)	0	60	33.409	51.523
9	7(3)	8(3)	0	60	66.818	51.523
10	21(1)	6(3)	0	60	0	51.523
11	20(3)	7(3)	0	60	75.165	51.523
12	20(3)	21(1)	0	60	0	51.523
13	19(1)	20(3)	0	60	75.165	51.523
14	18(1)	19(1)	0	60	19.364	92.307
15	17(3)	18(1)	0	60	75.156	80.000
16	16(1)	17(3)	0	60	0	80.000
17	15(3)	17(3)	0	60	75.156	80.000
18	14(1)	16(1)	0	60	0	80.000
19	15(3)	14(1)	0	60	0	80.000
20	13(3)	15(3)	0	60	33.409	80.000
21	12(3)	13(3)	0	60	66.818	80.000
22	12(3)	11(1)	0	60	0	80.000
23	13(3)	10(3)	0	60	75.165	80.000
24	11(1)	10(3)	0	60	0	80.000
25	10(3)	9(1)	0	60	75.165	80.000
26	42(9)	12(3)	0	60	66.818	80.000
27	8(3)	22(3)	0	60	48.110	51.523
28	8(3)	31(3)	0	60	48.110	51.523
29	22(3)	23(1)	0	60	18.791	51.523
30	23(1)	24(1)	0	60	4.8408	52.293
31	24(1)	25(1)	0	60	18.791	49.744
32	25(1)	26(3)	0	60	12.027	49.744
33	26(3)	38(9)	0	60	24.055	49.744
34	27(1)	26(3)	0	60	18.790	49.744
35	28(1)	27(1)	0	60	4.8408	52.293
36	29(3)	28(1)	0	60	18.791	51.523
37	22(3)	29(3)	0	60	36.082	51.523
38	29(3)	30(3)	0	60	24.055	51.523
39	30(3)	36(10)	0	60	0	51.523
40	30(3)	39(9)	0	60	24.055	51.523
41	31(3)	32(3)	0	60	36.082	51.523
42	32(3)	37(10)	0	60	0	51.523
43	32(3)	40(9)	0	60	36.082	51.523
44	33(1)	34(1)	0	60	4.8408	52.293
45	34(1)	35(1)	0	60	18.791	49.744
46	35(1)	41(9)	0	60	12.027	49.744
47	31(3)	33(1)	0	60	18.791	51.523
48	9(1)	43(6)	0	60	19.364	92.307

B. Results and Discussions

1. Comparison of NATRANSIENT and Converted NAHAMMER Results

First, calculations were made using both the NATRANSIENT and the converted NAHAMMER² for the same initial flow conditions as given in Case 1 of Table I. The NATRANSIENT result was obtained by deliberately negating the viscous effects. The inviscid result of the nonlinear analysis of NATRANSIENT and the linear converted NAHAMMER result are both plotted and compared in Fig. 5. In both calculations, the pressure plots at two selected points--the reaction-product zone and the lower end of a superheater--exhibit close agreement. This indicates that the nonlinear effects are negligibly small, since the local fluid velocities are much smaller than the local sonic speed. Slightly lower junction-9 pressure peaks were observed in the NATRANSIENT result, despite its slightly higher source pressures than the converted NAHAMMER result. This discrepancy is attributed to the interpolation procedure used in the NATRANSIENT code, since the interpolation procedure tends to smooth out the peaks. This discrepancy can be made small by taking a small time step. All calculations presented in this report were obtained using $\Delta t = 0.0001$ sec.

Fig. 5

Pressure vs Time for Instantaneous Leak Rate $\dot{m}_0 = 1 \text{ lb}_m/\text{sec}$, Comparing Result of Present Analysis Method (NATRANSIENT with neglected viscous effect) with That of Converted NAHAMMER

Figure 6 compares a viscous result obtained with the NATRANSIENT code for the initial flows given for Case 2 in Table I with the converted NAHAMMER result for the same initial conditions. The plots show the combined effects of nonlinearity, viscosity, and coupling of the source-pressure generation and the network response on the pressure-time history. The inviscid analysis predicted higher source pressures (about 90 psi higher) and correspondingly higher pressure peaks of junction 9. There was no significant difference between calculated pressures at junction 26, a point located far from the leak site.

Fig. 6. Pressure vs Time for Instantaneous Leak Rate $\dot{m}_0 = 1 \text{ lb}_m/\text{sec}$, Showing Results of Present Nonlinear Viscous Analysis (NATTRANSIENT) in Comparison to Results of Linear Inviscid Analysis (converted NAHAMMER)

2. Viscous Effects on Pressure Transients

The velocity increment associated with the sodium-water reaction corresponding to a $1\text{-lb}_m/\text{sec}$ leak rate resulted in negligible viscous effects. As the fluid velocities are increased by considering high initial system velocities, the viscous effects are increasingly pronounced. To demonstrate the viscous effects on pressure transients, an arbitrarily high system flow rate of $23,000 \text{ gpm}$ was assumed. The velocities and pressures corresponding to this flow rate are given in Case 2 of Table I. This flow rate is approximately three times the operating flow rate of the EBR-II.¹¹

Figure 7 shows the results with and without the viscous effects obtained by the NATTRANSIENT code. In both instances, there was essentially no difference between pressures at junctions 1 and 9 until $t = 100 \text{ msec}$. From 100 msec , the viscous result indicated higher source pressure and correspondingly higher junction-9 pressure. This indicates that the viscosity provides an added constraint to the pressure-relieving mechanism of volume expansion of the reaction-product zone. Consequently, the viscous analysis predicts a slower rate of decrease in source pressure than the inviscid analysis. Figure 7 also shows the effect of viscosity on pressure at a point located far from the leak site, junction 26. In general, the viscous result showed lower pressures than the inviscid result. Also, the time scale is somewhat shifted; i.e., the inviscid result predicts the maximum pressure peak at an earlier time than the viscous result.

Fig. 7

Pressure vs Time for Instantaneous Leak Rate $\dot{m}_0 = 1 \text{ lb}_m/\text{sec}$, Showing Effects of Viscosity

APPENDIX A

Source Pressure Calculation by Zaker and Salmon Analysis

The one-dimensional model as developed by Zaker and Salmon¹ for the sodium-water reaction and for the product-zone growth characterizing the source pressure is reproduced here. An instantaneous reaction was assumed, and the break was assumed to occur at a junction connecting two or more pipe branches. Mass and energy balances taken for a control volume enclosing the product zone at the junction lead to the following ordinary differential equations in pressure p and product-zone volume V :

$$\frac{dV}{dt} = B \frac{dm}{dt} + \sum_{i=1}^n u_i A_i \quad (\text{A.1})$$

and

$$\frac{dp}{dt} = \left[(F - CBp) \frac{dm}{dt} - (1 + C) p \sum u_i A_i \right] / CV, \quad (\text{A.2})$$

where dm/dt is the leak rate, which depends on the steam-reservoir condition, the rupture area, and the back pressure in the reaction-product zone; B , C , and F are constants; and u_i and A_i are the fluid velocity and flow cross-sectional area, respectively, of the i th branch connected to the leak site. For the steam-reservoir state of 1325 psia and 580°F, the critical pressure at the break is calculated to be 790 psia, and for these conditions the leak rate is written

$$\left. \begin{aligned} \frac{dm}{dt} &= \dot{m}_0 && \text{for } p < 790 \text{ psia;} \\ \frac{dm}{dt} &= \dot{m}_0 \left[1 - \left(\frac{p - 790}{535} \right)^2 \right]^{1/2} && \text{for } 790 \leq p \leq 1325 \text{ psia;} \\ \frac{dm}{dt} &= 0 && \text{for } p > 1325 \text{ psia.} \end{aligned} \right\} \quad (\text{A.3})$$

The initial conditions considered are

$$\left. \begin{aligned} \frac{dp}{dt} &= 0, \\ V &= 0, \\ u_i &= \frac{p - p_1}{\rho a_i}, \end{aligned} \right\} \quad (\text{A.4})$$

and

where p_1 is the system fluid pressure existing before the leak starts, and a_i is the sonic velocity in the i th branch. The initial pressure thus is determined by Eq. A.2 to be

$$p = \frac{(F - CBp) \frac{dm}{dt}}{(1 + C) \sum u_i A_i} \quad (A.5)$$

The equations and initial conditions, Eqs. A.1-A.5, determine the source pressure p and volume V for given leak rate dm/dt and velocities u_i .

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C *****
C *
C *      PROGRAM SODIUM TRANSIENT
C *
C *      THE 'METHOD OF CHARACTERISTICS' IS USED FOR PRESSURE TRANSIENT
C *      ANALYSIS IN HYDRAULIC NETWORKS. ZAKER AND SALMON ANALYSIS
C *      CALCULATES SOURCE PRESSURE. THE PROGRAM CONSIDERS COMPLETE
C *      EQUATIONS INCLUDING NONLINEAR CONVECTIVE AND VISCOUS TERMS.
C *      YONG WOO SHIN : SEPTEMBER 1, 1973
C *****
C
C      MAIN PROGRAM
C      COMMON /R1/ N1(50),NN(50),N(50) /R5/ LEGNO,RHO,AMU,DT,PR,UR,NP
C      X/R2/ A(50),C(50),DZ(50),D(50),P(50,120,2),U(50,120,2),RF(50)
C
C      DIMENSION LENGTH(50),NJ(50),PMAX(50),PT(10),IT(10),H(50),ES(50),
C      XINT(50),TMAX(50),PO(50),UO(50)
C
C      DATA DL0/59.566/,DL1/-0.79504E-02/,DL2/-0.2872E-06/,DL3/ 0.60350
C      XE-10/,CL1/8285./,CL2/-2187./,CL3/ 2290./,JMAX/50/,JMIN/1/,LMAX/50/
C      2,LMIN/1/,PMAX,TMAX/100*0./,GC/32.173/,NIN,NOUT,I1,I2/5,6,1,2/,
C      3PT/10*0./,IT/10*0/
C ***** PARTIAL LISTING OF INPUT DATA *****
C * LEGNO - NO OF BRANCHES
C * JUNNO - NO OF JUNCTIONS
C * NOT - NO OF SURGE TANK AND RESERVOIR
C * NOPRIN - FREQUENCY OF PRINTOUT
C * KS - PARAMETER SPECIFYING DETAIL OF PRINTOUT
C * JJ - BRANCH IN WHICH LEAK SITE IS LOCATED
C * IC - IF IC = 1, INITIAL CONDITIONS ARE INPUT
C * INDIVIDUALLY
C * NP - IF IF NP = 1, INVISCID ANALYSIS
C * DT - TIME STEP IN SECOND
C * UR - INITIAL VELOCITY
C * PR - INITIAL PRESSURE
C * PCR - CRITICAL PRESSURE AT OR ABOVE WHICH RUPTURE
C * DISK BREAKS
C * TR - SYSTEM TEMPERATURE IN FAHRENHEIT
C * XI - INITIAL TIME AT WHICH CALCULATION STARTS
C * XF - FINAL TIME AT WHICH CALCULATION TERMINATES
C * INDTR - BRANCH NUMBERS OF WHICH RESULTS ARE PRINTED
C * IF INDTR = 0, ALL RESULTS ARE PRINTED
C * NOTT - NO OF RUPTURE DISKS
C *****
C      REAL LENGTH
C      NC=0
C**** READ INITIAL AND JUNCTION CONDITIONS OF EACH BRANCH *****
C      READ (NIN,1) LEGNO,JUNNO,NOT,NOPRIN,KS,JJ,IC,NP,DT,UR,PR,PCR,TR,
C      XXI,XF
C      READ(NIN,1210) INDTR,NOTT
C      IF (INDTR.GT.0) READ (NIN,1215) (INT(NQ),NQ=1,INDTR)
C      IF (LEGNO.GT.LMAX.OR.LEGNO.LT.LMIN) GO TO 401
C      IF (JUNNO.GT.JMAX.OR.JUNNO.LT.JMIN) GO TO 402
C      READ (NIN,2) (N1(L),NN(L),A(L),LENGTH(L),RF(L),H(L),ES(L),D(L),
C      XPO(L),UO(L),L=1,LEGNO)
C      READ (NIN,3) (NJ(J),J=1,JUNNO)
C**** READ CONDITIONS FOR SURGE TANK OR RESERVOIR *****
C      IF (NOT.GE.1) READ(NIN,5) (PT(I),IT(I),I=1,NOT)
C      NNTT=NOT+NOTT
C      NOT1=NOT+1
C**** READ CONDITIONS FOR RUPTURE DISK *****
C      IF (NOTT.GE.1) READ (NIN,5) (PT(I),IT(I),I=NOT1,NNTT)
C      TT=XI-DT
C**** CALCULATE DENSITY, VISCOSITY AND SONIC SPEED *****
C      RHO=DL0+DL1*TR+DL2*TR**2+DL3*TR**3

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      CR=CL1+CL2*(TR-210.)/CL3
      AMU=EXP(2.303*(1.0203+397.17/(TR+460.))-0.4925*ALOG10(TR+460.)))/
X3600.
C**** SONIC SPEED ACCOUNTING FOR PIPE EXPANSION *****
      DO 2002 L=1,LEGNO
      ESS=ES(L)*A(L)/(3.14159265*D(L)**2./4.)
2002 C(L)=CR/SQRT(1.+RHO*CR**2*D(L)/ESS/H(L)/(144.*GC))
C**** DETERMINE DZ(L) AND N(L) IN EACH BRANCH *****
203 DO 204 L=1,LEGNO
      ZM=LENGTH(L)/(C(L)*DT)/1.2
      NM=ZM
      IF (NM.EQ.0) NM=1
      N(L)=NM+1
      IF (N(L).GT.120) GO TO 205
204 DZ(L)=LENGTH(L)/NM
      GO TO 206
C**** RECALCULATE DT TO SATISFY N(L) .LT. 120 *****
205 DTT=2.*DT
      WRITE (NOUT,106) DT,DTT
      DT=DTT
      GO TO 203
C**** INITIAL VALUES OF UO, PO, U AND P *****
206 DO 207 L=1,LEGNO
C**** IF IC = 1, UO AND PO ARE GIVEN INDIVIDUALLY *****
      IF (IC.EQ.1) GO TO 202
      PO(L)=PR
      UO(L)=UR
202 DO 207 K=1,2
      DO 207 I=1,120
      P(L,I,K)=PO(L)
207 U(L,I,K)=UO(L)
      DO 50 L=1,LEGNO
      IF (N1(L).EQ.NN(JJ)) LLN=L
      IF (NN(L).EQ.N1(JJ)) LL1=L
50 CONTINUE
      NV1=N(LL1)
      NV2=1
      TD=XI-DT
C**** PRINT INITIAL CONDITIONS AND DESCRIPTION OF NETWORK ARRANGEMENT *****
      WRITE (NOUT,4)
      WRITE (NOUT,6) LEGNO,JUNNO,NOT,NOTT,JJ,IC,NP,INDTR,NOPRIN,KS
      WRITE (NOUT,1311) UR,PR,PCR,TR,RHO,AMU,DT,XI,XF
      IF (NOT.GE.1) WRITE (NOUT,1313)
      IF (NOT.GE.1) WRITE (NOUT,9) (I,PT(I),IT(I),I=1,NOT)
      IF (NOT.GE.1) WRITE (NOUT,1315)
      IF (NOTT.GE.1) WRITE (NOUT,1312)
      IF (NOTT.GE.1) WRITE (NOUT,1314) (I,PT(I),IT(I),I=NOT1,NNTT)
      WRITE (NOUT,7)
      DO 211 L=1,LEGNO
      LN1=N1(L)
      LNN=NN(L)
211 WRITE (NOUT,8) (L,LN1,NJ(LN1),LNN,NJ(LNN),N(L),DZ(L),LENGTH(L),
      XA(L))
      WRITE (NOUT,11)
      WRITE (NOUT,12) (L,D(L),H(L),ES(L),C(L),PO(L),UO(L),L=1,LEGNO)
C**** CONVERT INCHES TO FEET *****
      PCR=PCR*144.
      DO 215 L=1,LEGNO
      PO(L)=PO(L)*144.
      A(L)=A(L)/144.
      D(L)=D(L)/12.
      RF(L)=RF(L)/12.
      DO 215 K=1,2
      DO 215 I=1,120
215 P(L,I,K)=P(L,I,K)*144.
      DO 216 K=1,10
216 PT(K)=PT(K)*144.

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C**** DETERMINE MAXIMUM PRESSURE AND VELOCITY IN EACH BRANCH *****
FR1=1.0
FR2=1.2
IF (TT.LT.0.0) GO TO 250
220 UMX=0.
CUMX=0.
DO 213 L=1,LEGNO
NK=N(L)
PPX=PMAX(L)
DO 212 I=1,NK
UMX=AMAX1(UMX,ABS(U(L,I,2)))
212 PMAX(L)=AMAX1(PMAX(L),P(L,I,2))
IF (PMAX(L).GT.PPX) TMAX(L)=TT
CUP=1.+UMX/C(L)
213 CUMX=AMAX1(CUP,CUMX)
C**** REDETERMINE DT FOR NUMERICAL STABILITY *****
IF (CUMX.GE.FR1.AND.CUMX.LT.FR2) GO TO 226
FT1=FR2
FT2=FT1+0.2
IF (CUMX.GT.FT2) GO TO 222
DT=DT*FT1/FT2
FR1=FT1
FR2=FT2
WRITE (NOUT,1225) DT
GO TO 226
222 WRITE (NOUT,1230) CUMX
STOP
C**** PRINT PRESSURE AND VELOCITY AT SPECIFIED TIME STEP *****
225 IF (TT.LE.TD) GO TO 250
IF (TT.EQ.0.) WRITE (NOUT,13)
TD=TD+NOPRIN*DT
IF (TT.LE.0.0) TTT=TT
IF (TT.GT.0.0) TTT=TT+2.0E-9
WRITE (NOUT,16) TTT,NC
WRITE (NOUT,15)
DO 242 L=1,LEGNO
IF (INDTR.EQ.0) GO TO 1105
DO 1101 LL=1,INDTR
1101 IF (L.EQ.INT(LL)) GO TO 1105
GO TO 242
1105 WRITE (NOUT,17) L
NK=N(L)
DO 240 I=1,NK,KS
IF (I.GE.NK) GO TO 241
Z=(I-1)*DZ(L)
PPP=P(L,I,2)/144.
230 WRITE (NOUT,19) Z,PPP,U(L,I,2)
240 CONTINUE
241 Z=LENGTH(L)
I=NK
PPP=P(L,I,2)/144.
WRITE (NOUT,19) Z,PPP,U(L,I,2)
IF (L.EQ.JJ) WRITE (NOUT,265) PP
242 CONTINUE
250 TT=TT+DT
IF (TT.GT.XF) GO TO 999
DO 300 L=1,LEGNO
NK=N(L)
DO 300 I=1,NK
U(L,I,1)=U(L,I,2)
300 P(L,I,1)=P(L,I,2)
C**** INTERIOR NODE CALCULATION AT EACH TIME STEP *****
DO 309 L=1,LEGNO
NK=N(L)
NKM=NK-1
IF (L.EQ.JJ) GO TO 261
GO TO 270

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261 V1=-U(LL1,NV1,1)*12.
    V2=U(LLN,NV2,1)*12.
    A1=A(LL1)*144.
    A2=A(LLN)*144.
    CALL SOURCE (PP,TT,V1,V2,C(LL1),C(LLN),A1,A2)
    PPP=PP*144.
    GO TO 303
270 IF (NK.LE.2) GO TO 309
    DO 302 I=2,NKM
        CALL INTER (L,I,I1,UA,PA)
        CALL FACTOR (L,UA,FA)
        CALL INTER (L,I,I2,UB,PB)
        CALL FACTOR (L,UB,FB)
        U(L,I,2)=0.5*(UA+UB+GC*(PA-PB)/(RHO*C(L))-DT/(2.*D(L))*
X(UA*ABS(UA)*FA+UB*ABS(UB)*FB))
302 P(L,I,2)=0.5*(PA+PB+RHO*C(L)*(UA-UB)/GC-RHO*C(L)*DT/(2.*D(L)*GC)*
X(UA*ABS(UA)*FA-UB*ABS(UB)*FB))
    GO TO 309
303 NK=N(JJ)
    DO 306 I=1,NK
        U(L,I,2)=U(L,I,1)
        P(L,I,1)=PPP
306 P(L,I,2)=PPP
309 CONTINUE
C**** BOUNDARY NODE CALCULATION AT EACH TIME STEP *****
    DO 320 J=1,JUNNO
        JC=NJ(J)
        IF (JC.EQ.3) GO TO 313
        DO 310 L=1,LEGNO
            IF (N1(L).EQ.J) J1=L
            IF (NN(L).NE.J) GO TO 310
            JN=L
            I=N(L)
310 CONTINUE
            IF (JC.EQ.7.OR.JC.EQ.8.OR.JC.EQ.9.OR.JC.EQ.10) GO TO 315
            IF (JC.EQ.6) GO TO 314
C**** SUDDEN EXPANSION OR CONTRACTION *****
            IF (NN(JN).NE.N1(J1)) GO TO 404
            JNL=N(JN)
            CALL PIPES (J1,JN,I,JJ)
            GO TO 320
313 CALL TEE (J,JJ,IC)
            GO TO 320
C**** DUMMY JUNCTION *****
314 CALL DUMMY (J1,JN,I,JJ)
            GO TO 320
315 IF (NOT.EQ.0) GO TO 325
            DO 311 K=1,NOT
311 IF (IT(K).EQ.J) GO TO 325
325 DO 316 L=1,LEGNO
            IF (N1(L).EQ.J) GO TO 317
316 IF (NN(L).EQ.J) GO TO 318
            GO TO 320
317 IF (JC.EQ.7.OR.JC.EQ.9.OR.JC.EQ.10) GO TO 328
C**** SURGE TANK OR RESERVOIR *****
            P(L,1,2)=PT(K)
            CALL INTER (L,I1,I2,UB,PB)
            CALL FACTOR (L,UB,FB)
            U(L,1,2)=UB+GC*(PT(K)-PB)/(RHO*C(L))-FB*UB*ABS(UB)*DT/(2.*D(L))
            GO TO 320
318 IF (JC.EQ.7.OR.JC.EQ.9.OR.JC.EQ.10) GO TO 329
C**** SURGE TANK OR RESERVOIR *****
            P(L,I,2)=PT(K)
            CALL INTER (L,I,I1,UA,PA)
            CALL FACTOR (L,UA,FA)
            U(L,I,2)=UA-GC*(PT(K)-PA)/(RHO*C(L))-FA*UA*ABS(UA)*DT/(2.*D(L))
            GO TO 320

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328 IF(JC.EQ.9) GO TO 319
C**** CLOSED END *****
      CALL INTER (L,I1,I2,UB,PB)
      CALL FACTOR (L,UB,FB)
      U(L,1,2)=0.
      P(L,1,2)=PB+RHO*C(L)/GC*(-UB+FB*UB*ABS(UB)*DT/(2.*D(L)))
      GO TO 320
C**** FAR END *****
319 U(L,1,2)=UO(L)-((P(L,2,1)-PO(L))*GC/(RHO*C(L))-U(L,2,1)+UO(L))/2.
      P(L,1,2)=PO(L)+(P(L,2,1)-PO(L)-RHO*C(L)*(U(L,2,1)-UO(L))/GC)/2.
      GO TO 320
329 IF(JC.EQ.9) GO TO 322
C**** CLOSED END *****
      CALL INTER (L,I,I1,UA,PA)
      CALL FACTOR (L,UA,FA)
      U(L,I,2)=0.
      P(L,I,2)=PA+RHO*C(L)/GC*(UA-FA*UA*ABS(UA)*DT/(2.*D(L)))
      GO TO 320
C**** FAR END *****
322 U(L,I,2)=UO(L)+((P(L,I-1,1)-PO(L))*GC/(RHO*C(L))+U(L,I-1,1)-
      XUO(L))/2.
      P(L,I,2)=PO(L)+(P(L,I-1,1)-PO(L)+RHO*C(L)*(U(L,I-1,1)-UO(L))/GC)
      X/2.
320 CONTINUE
      IF(NOT.EQ.NOTT) GO TO 390
      DO 375 J=1,JUNNO
      IF (NJ(J).NE.10) GO TO 375
      DO 355 L=1,LEGNO
      IF (N1(L).EQ.J) GO TO 357
355 IF (NN(L).EQ.J) GO TO 358
357 IF (P(L,1,2).GE.PCR) NJ(J)=8
      IF (P(L,1,2).GE.PCR) NOT=NOT+1
      GO TO 375
358 NLL=N(L)
      IF (P(L,NLL,2).GE.PCR) NJ(J)=8
      IF (P(L,NLL,2).GE.PCR) NOT=NOT+1
375 CONTINUE
390 NC=NC+1
      GO TO 220
C**** DIAGNOSTIC MESSAGE PRINTS *****
401 WRITE (NOUT,101) LMIN,LMAX
      GO TO 999
402 WRITE (NOUT,102) JMIN,JMAX
      GO TO 999
404 WRITE (NOUT,108)
999 WRITE (NOUT,105)
      WRITE (NOUT,110)
      DO 998 L=1,LEGNO
      PMX=PMAX(L)/144.
998 PRINT 109,L,PMX,TMAX(L)
      STOP
C**** FORMAT STATEMENTS *****
1 FORMAT (8I5,/,6E12.5,/,E12.5)
2 FORMAT (2I3,6E12.5,/,2E12.5)
3 FORMAT(40I2)
4 FORMAT (1H1,/,30X,'----- INITIAL CONDITIONS AND DESCRIPTION OF
      XNETWORK ARRANGEMENT -----',///)
5 FORMAT (E12.5,I5)
6 FORMAT (5X,'LEGNO' =,I5,7X,'JUNNO' =,I5,7X,'NOT' =,I5,7X,
      X'NOTT' =,I5,7X,'JJ' =,I5,7X,/,5X,'IC' =,I5,7X,'NP' =,
      2I5,7X,'INDTR' =,I5,7X,'NOPRIN' =,I5,7X,'KS' =,I5,7X,///)
7 FORMAT (1H1,/,9X,'BRANCH',14X,'JUNCTION TYPE',14X,'NO',12X,
      X'INTERNODAL',12X,'LENGTH',15X,'AREA',/,11X,'NO',12X,'N' = 1',11X,
      2'N' = N',7X,'OF NODES',10X,'DISTANCE',14X,'FEET',14X,'SQR INCH',/)
8 FORMAT (9X,I4,9X,I4,'(I,I2,')',8X,I4,'(I,I2,')',8X,I4,7X,
      XE15.4,5X,E15.4,5X,E15.4)
9 FORMAT (36X,I5,5X,E12.5,6X,I5)

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11 FORMAT (1H1,/,11X,'BRANCH',12X,'DIAMETER',8X,'THICKNESS',6X,
X'YOUNGS MODULUS',5X,'SONIC SPEED',7X,'PRESSURE',9X,'VELOCITY',
2/,13X,'NO',16X,'INCH',13X,'INCH',14X,'PSI',12X,'FT/SEC',13X,
3'PSI',12X,'FT/SEC',/)
12 FORMAT (11X,I4,8X,E15.4,2X,E15.4,2X,E15.4,2X,E15.4,2X,E15.4,
X2X,E15.4)
13 FORMAT (1H1,/,40X,'----- RESULT OF PRESSURE TRANSIENT CALCULATI
XON -----',/)
15 FORMAT (47X,'DISTANCE, FT',12X,'PRESSURE, PSI',11X,
X'VELOCITY, FT/SEC')
16 FORMAT(/,9X,'TIME =' ,E15.5,' SEC',5X,'( NC =' ,I4,' STEPS )',/)
17 FORMAT (20X,'BRANCH NO =' , I5)
19 FORMAT (44X,E15.6,10X,E15.6,10X,E15.6)
101 FORMAT (/,10X,'ERROR IN NUMBER OF BRANCHES ----- LEGNO .LT.'
X,I5,' OR LEGNO .GT.',I5)
102 FORMAT (/,10X,'ERROR IN NUMBER OF JUNCTIONS ----- JUNNO .LT.',
XI5,'OR JUNNO .GT.',I5)
105 FORMAT (//,45X,'----- END OF CALCULATION -----')
106 FORMAT (' CASE OF N(J).GT.120 ..... RESET DT=' ,E12.5,' TO DT=' ,
XE12.5)
108 FORMAT (/,2X,' ERROR IN SUBROUTINE PIPES ..... NN.NE.N1' )
109 FORMAT (25X,'MAXIMUM PRESSURE IN BRANCH',I4,' = ' ,E12.5,
X' PSI OCCURRED AT ' ,E12.5,' SEC')
110 FORMAT (1H1,/,30X,'----- MAXIMUM PRESSURES IN EACH BRANCH DURIN
XG CALCULATION -----',///)
265 FORMAT (44X,'SOURCE PRESSURE IS',7X,E15.6)
1210 FORMAT (2I5)
1215 FORMAT (16I5)
1225 FORMAT (5X,/, '***** DT IS DECREASED TO ' ,E12.5,' *****',/)
1230 FORMAT (5X,/, '***** CUMX IS OUTSIDE RANGE .EQ.' ,E12.5,' *****',/)
1311 FORMAT (5X,'UR = ' ,E12.5,5X,'PR = ' , E12.5,5X,'PCR = ' ,E12.5,5X,
X'TR = ' ,E12.5,5X,'RHO = ' ,E12.5,5X,/,5X,'AMU = ' ,E12.5,5X,
X'DT = ' ,E12.5,5X,'XI = ' ,E12.5,5X,'XF = ' ,E12.5,///)
1312 FORMAT (43X,'--- RUPTURE DISKS ---',/,37X,'DISK NO',2X,
X'GAS PRESSURE',4X,'JUNCTION NO')
1313 FORMAT (38X,'--- SURGE TANKS AND RESERVOIRS ---',/,32X,
X'TANK NO',2X,'GAS PRESSURE',4X,'JUNCTION NO',/)
1314 FORMAT (36X,I5,5X,E12.5,6X,I5)
1315 FORMAT (///)
END

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SUBROUTINE INTER (L, LN, IN, UC, PC)
COMMON /R5/ LEGNO, RHO, AMU, DT, PR, UR, NP /R2/ A(50), C(50), DZ(50),
XD(50), P(50,120,2), U(50,120,2), RF(50)
C**** THIS SUBPROGRAM PERFORMS INTERPOLATION FOR PRESSURE AND VELOCITY*****
THTA=DT/DZ(L)
IF(IN.EQ.2) GO TO 10
UC=(U(L, LN, 1)-C(L)*THTA*(U(L, LN, 1)-U(L, LN-1, 1)))/(1.+THTA*
X(U(L, LN, 1)-U(L, LN-1, 1)))
PC=P(L, LN, 1)-THTA*(C(L)+UC)*(P(L, LN, 1)-P(L, LN-1, 1))
RETURN
10 UC=(U(L, LN, 1)+C(L)*THTA*(U(L, LN+1, 1)-U(L, LN, 1)))/(1.+THTA*
X(U(L, LN+1, 1)-U(L, LN, 1)))
PC=P(L, LN, 1)+THTA*(C(L)-UC)*(P(L, LN+1, 1)-P(L, LN, 1))
RETURN
END

SUBROUTINE DUMMY (J1, JN, I, JJ)
COMMON /R5/ LEGNO, RHO, AMU, DT, PR, UR, NP /R2/ A(50), C(50), DZ(50),
XD(50), P(50,120,2), U(50,120,2), RF(50)
DATA GC/32.173/, I1, I2/1, 2/
C**** THIS SUBPROGRAM DESCRIBES DUMMY JUNCTION AND ACOUSTIC IMPEDANCE *****
C**** DISCONTINUITY *****
CFF=RHO/(1./C(JN)+1./C(J1))

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      IF (JN.NE.JJ) GO TO 10
      UA=U(JJ,I,1)
      PA=P(JJ,I,1)
      GO TO 12
10  CALL INTER (JN,I,I1,UA,PA)
12  CALL FACTOR (JN,UA,FA)
      IF (J1.NE.JJ) GO TO 20
      UB=U(JJ,1,1)
      PB=P(JJ,1,1)
      GO TO 22
20  CALL INTER (J1,I1,I2,UB,PB)
22  CALL FACTOR (J1,UB,FB)
      P(JN,I,2)=((PA/C(JN)+PB/C(J1))/RHO+(UA-UB)/GC-FA*UA*ABS(UA)*DT/
X(2.*GC*D(JN))+FB*UB*ABS(UB)*DT/(2.*D(J1)*GC))*CFF
      P(J1,1,2)=P(JN,I,2)
      U(JN,I,2)=0.5*(UA+UB+(PA/C(JN)-PB/C(J1))*GC/RHO-DT/2.*(FA*UA*
XABS(UA)/D(JN)+FB*UB*ABS(UB)/D(J1)))
      U(J1,1,2)=U(JN,I,2)
      RETURN
      END

```

```

      SUBROUTINE PIPES (J1,JN,I,JJ)
      COMMON /R5/ LEGND,RHO,AMU,DT,PR,UR,NP /R2/ A(50),C(50),DZ(50),
XD(50),P(50,120,2),U(50,120,2),RF(50)
      DATA GC/32.173/,NOUT,I1,I2/6,1,2/
C**** THIS SUBPROGRAM DESCRIBES SUDDEN EXPANSION AND CONTRACTION *****
      REAL K
      R=A(JN)/A(J1)
      UU=U(JN,I,1)
C***** DUMMY JUNCTION CASE *****
      IF (R.FQ.1) GO TO 15
C***** EXPANSION CASE *****
      IF (R.LT.1.0.AND.UU.GE.0.) K=(1.-R)**2
      IF (R.GT.1.0.AND.UU.LT.0.) K=-(R-1.)**2
C***** CONTRACTION CASE *****
      IF (R.GT.1.0.AND.UU.GE.0.) K=.45*R*(R-1.)
      IF (R.LT.1.0.AND.UU.LT.0.) K=-.45*(1.-R)
      DD=1.-R**2-K
      IF (ABS(DD).LE.1.0E-5) WRITE(NOUT,25) DD
      IF (JN.NE.JJ) GO TO 5
      UA=U(JJ,I,1)
      PA=P(JJ,I,1)
      GO TO 7
5  CALL INTER (JN,I,I1,UA,PA)
7  CALL FACTOR (JN,UA,FA)
      IF (J1.NE.JJ) GO TO 10
      UB=U(JJ,1,1)
      PB=P(JJ,1,1)
      GO TO 12
10  CALL INTER (J1,I1,I2,UB,PB)
12  CALL FACTOR (J1,UB,FB)
      BB=(C(JN)+C(J1)*R)/DD
      CC=(2.*(C(JN)*UA+C(J1)*UB)+2.*GC*(PA-PB)/RHO-DT*(FA*C(JN)*UA*
XABS(UA)/D(JN)+FB*C(J1)*UB*ABS(UB)/D(J1)))/DD
      U(JN,I,2)=SQROOT(BB,CC,DD)
      U(J1,1,2)=U(JN,I,2)*R
      P(JN,I,2)=PA-RHO*C(JN)*(U(JN,I,2)-UA+FA*UA*ABS(UA)*DT/2./D(JN))/GC
      P(J1,1,2)=PB+RHO*C(J1)*(U(J1,1,2)-UB+FB*UB*ABS(UB)*DT/2./D(J1))/GC
      RETURN
15  WRITE(NOUT,20)
20  FORMAT(5X,'***** ERROR IN SPECIFICATION OF DIAMETER DISCONTINUITY
X*****')
25  FORMAT (5X,'***** ABS(DD) IS .LE. 1.E-5: DD .EQ.',E12.5,' *****')
      RETURN
      END

```

```

FUNCTION SQROOT (BB,CC,DD)
DATA NOUT/6/
10 FORMAT (5X,'***** SQROOT HAS NEGATIVE ARGUMENT',E12.5,' *****')
IF (CC.EQ.0.0) GO TO 9
CARG=BB*BB-CC
IF (CARG.LT.0.) GO TO 15
IF (DD.GE.0.) SQROOT=BB-SQRT(CARG)
IF (DD.LT.0.) SQROOT=BB+SQRT(CARG)
RETURN
9 SQROOT=0.
RETURN
15 WRITE (NOUT,10) CARG
CARG=ABS(CARG)
IF (DD.GE.0.) SQROOT=BB-SQRT(CARG)
IF (DD.LT.0.) SQROOT=BB+SQRT(CARG)
RETURN
END

```

```

SUBROUTINE FACTOR (L,V,F)
COMMON /R5/ LEGNO,RHO,AMU,DT,PR,UR,NP /R2/ A(50),C(50),DZ(50),
XD(50),P(50,120,2),U(50,120,2),RF(50)
DATA NOUT/6/
C**** THIS SUBPROGRAM DETERMINES 'WEISBACH' FRICTION FACTOR USING *****
C**** 'COLEBROOK-WHITE' CORRELATION *****
N=0
F=0.
Q=ABS(V)
C**** IF NP=1, FRICTION IS NEGLECTED *****
IF (NP.EQ.1) RETURN
RR=RF(L)/D(L)
RE=RHO*Q*D(L)/AMU
IF (RE.LE.0.1) RETURN
IF (RE.GT.3000.) GO TO 5
C**** LAMINAR FLOW *****
F=64./RE
RETURN
5 IF(RR.GT.1.E-4) GO TO 10
C**** INITIAL ESTIMATE FOR SMOOTH PIPE BY 'BLASIUS' EQUATION *****
F=0.316/RF**.25
GO TO 25
C**** INITIAL ESTIMATE FOR ROUGH PIPE BY 'VON KARMAN' EQUATION *****
10 F=1./(-2.*ALOG10(RR)+1.14)**2
C**** F IS DETERMINED ITERATIVELY BY 'COLEBROOK-WHITE' CORRELATION *****
25 SF=SQRT(F)
GO TO 35
30 SF=FF
35 DD=1.14-2.*ALOG10(RR+9.35/(RE*SF))
FF=1./DD
IF ((ABS(FF-SF)/SF).LE.0.01) GO TO 50
IF (N.GE.50) GO TO 45
N=N+1
GO TO 30
45 WRITE (NOUT,100)
100 FORMAT (5X,'***** NO CONVERGENCE IS ACHIEVED *****')
50 F=FF**2
RETURN
END

```

```

SUBROUTINE TEE (JT,JJ,IC)
COMMON /R1/ N1(50),NN(50),N(50) /R5/ LEGNO,RHO,AMU,DT,PR,UR,NP
X/R2/ A(50),C(50),DZ(50),D(50),P(50,120,2),U(50,120,2),RF(50)
DATA GC/32.173/,I1,I2/1,2/
DIMENSION M1(6),MN(6),UA(6),UB(6),PA(6),PB(6)
C**** THIS SUBPROGRAM DESCRIBES TEE JUNCTION JOINING UP TO 6 BRANCHES *****
PC=PR*144.
NN1=0
NNN=0
CR=0.
CS=0.
UBS=0.
PBS=0.
FBS=0.
UAR=0.
PAR=0.
FAR=0.
DO 4 L=1,LEGNO
IF (N1(L).NE.JT) GO TO 1
NN1=NN1+1
M1(NN1)=L
1 IF (NN(L).NE.JT)GO TO 4
NNN=NNN+1
MN(NNN)=L
4 CONTINUE
NT=NN1+NNN
DO 10 I=1,NT
IF (I.GT.NN1) GO TO 5
L=M1(I)
IF (L.NE.JJ) GO TO 2
UB(I)=U(L,1,1)
PB(I)=P(L,1,I)
GO TO 3
2 CALL INTER (L,I1,I2,UB(I),PB(I))
3 DCS=A(L)/(RHO*C(L))*GC
UBS=UBS+A(L)*UB(I)
PBS=PBS+DCS*PB(I)
CS=CS+DCS
BS=A(L)/(2.*D(L))
CALL FACTOR (L,UB(I),FB)
FBS=FBS+FB*BS*UB(I)*ABS(UB(I))*DT
GO TO 10
5 M=I-NN1
L=MN(M)
NM=N(L)-1
IF (L.NE.JJ) GO TO 7
UA(M)=U(L,NM+1,1)
PA(M)=P(L,NM+1,1)
GO TO 8
7 CALL INTER (L,N(L),I1,UA(M),PA(M))
8 DCR=A(L)/(RHO*C(L))*GC
UAR=UAR+A(L)*UA(M)
PAR=PAR+DCR*PA(M)
CR=CR+DCR
BR=A(L)/(2.*D(L))
CALL FACTOR (L,UA(M),FA)
FAR=FAR+FA*BR*UA(M)*ABS(UA(M))*DT
10 CONTINUE
IF (IC.EQ.1) GO TO 13
C**** IF U=0 AND P=PR IN EVERY BRANCH, SET U=0 AND PJT=PR *****
DO 12 I=1,NT
IF (I.GT.NN1) GO TO 11
IF (UB(I).EQ.0.0.AND.PB(I).EQ.PC) GO TO 12
GO TO 13
11 M=I-NN1
IF (UA(M).EQ.0.0.AND.PA(M).EQ.PC) GO TO 12
GO TO 13

```

```

12 CONTINUE
   PJT=PC
   GO TO 14
13 PJT=(UAR-UBS+PAR+PBS-FAR+FBS)/(CR+CS)
14 DO 20 I=1,NT
   IF (I.GT.NN1) GO TO 15
   L=M1(I)
   CALL FACTOR (L,UB(I),FB)
   U(L,1,2)=UB(I)+(PJT-PB(I))*GC/(RHO*C(L))-FB*UB(I)*ABS(UB(I))*
XDT/(2.*D(L))
   P(L,1,2)=PJT
   GO TO 20
15 M=I-NN1
   L=MN(M)
   NL=N(L)
   CALL FACTOR (L,UA(M),FA)
   U(L,NL,2)=UA(M)-(PJT-PA(M))*GC/(RHO*C(L))-FA*UA(M)*ABS(UA(M))*
XDT/(2.*D(L))
   P(L,NL,2)=PJT
20 CONTINUE
   RETURN
   FND

```

```

SUBROUTINE SOURCE (P,T,V1,V2,C1,C2,A1,A2)
COMMON /R5/ LEGNO,RHO,AMU,DT,PR,UR,NP
DATA GC/32.173/
C**** THIS SUBPROGRAM CALCULATES SOURCE PRESSURE BY ZAKER-SALMON ANALYSIS *****
REAL MDOT
IF (T) 9,1,9
C**** READ INPUT DATA *****
1 READ (5,1000) P1,WZD,PCT,TAU,EXP
1000 FORMAT(5E12.5)
C ***** DESCRIPTION OF INPUT DATA *****
C * P1 - SYSTEM PRESSURE, PSI *
C * WZD - LEAK RATE, LB/SEC *
C * PCT - FRACTIONAL INITIAL RUPTURE RADIUS OF MAX RADIUS *
C * TAU - TIME CONSTANT APPEARING IN TIME-DEPENDENT RUPTURE MODEL *
C * EXP - EXPONENT APPEARING IN TIME-DEPENDENT RUPTURE MODEL *
C *****
RMAX=(WZD/(3.14159*18.9))**.5
RI=PCT*RMAX
WRITE(6,2000) P1,WZD,RI,TAU,EXP
2000 FORMAT (1H1,////,37X,'----- INPUT DATA FOR SOURCE PRESSURE CALCU
XLATION -----',////,47X,'SYSTEM PRESSURE P1 = ',E12.5,' PSI',/,
251X,'LEAK RATE MDOT = ',E12.5,' LB/SEC',/,45X,'INITIAL BREAK RADIUS
35 = ',E12.5,' INCH',/,48X,'TIME CONSTANT TAU = ',E12.5,' SEC',/,
449X,'EXPONENT EPSILON = ',E12.5)
C=12.3
B=23.*1728./9./RHO
E=5700.*12.*778.
PL=P1
PU=1325.
PT=P1+100.
RC1=RHO*C1/GC/1728.
RC2=RHO*C2/GC/1728.
K=0
RR=RI+(RMAX-RI)*(T/TAU)**EXP
WZD=3.14159*18.9*RR**2
7 CALL FOF(P,PT,WZD)
MDOT=FP
T1=E-C*B*PT
IF (T1) 4,4,15
15 CONTINUE
T2=(PT-P1)/RC1*A1+(PT-P1)/RC2*A2
FP=T1*FP/(1.+C)/T2

```

```

      IF (PT-FP) 2,3,4
2  PL=PT
   GOTO 5
4  PU=PT
5  ERR=(PU-PL)/PU
   IF (ERR-1.0E-6) 3,3,6
6  PT=(PL+PU)/2.
   K=K+1
   IF (K.EQ.200) GOTO 20
   GOTO 7
3  PB=PT-P1
   P=PT
   RETURN
20 WRITE (6,3000) PU,PL,PT
3000 FORMAT (' PU,PL,PT'/(3E15.5))
      CALL EXIT
9  IF (T.GT.TAU) GO TO 19
   RR=RI+(RMAX-RI)*(T/TAU)**EXP
   WZD=3.14159*18.9*RR**2
19 IF (T.GT.DT) GO TO 101
   VIN1=V1
   VIN2=V2
   PBDOT=0.0
   VEE=0.0
   VEEDOT=B*MDOT+VIN1*A1+VIN2*A2
101 IF (T.EQ.DT) GO TO 105
   CALL FOF (FP,P,WZD)
   VEEDOT=B*FP+V1*A1+V2*A2
   IF ((V1.EQ.VIN1).AND.(V2.EQ.VIN2)) GO TO 105
   PBDOT=((E-C*B*P)*FP-(1.+C)*P*(V1*A1+V2*A2))/C/VEE
105 PB=PB+PBDOT*DT
   P=PB+P1
   VEE=VEE+VEEDOT*DT
   RETURN
END

```

```

      SUBROUTINE FOF (FP,P,WZD)
C**** THIS SUBPROGRAM DETERMINES INSTANTANEOUS LEAK RATE *****
      FP=WD
      IF (P-790.) 1,1,2
1  RETURN
2  FP=0.
      IF (P-1325.) 3,1,1
3  FP=WD*SQRT(1.-((P-790.)/535.)**2)
   RETURN
END

```

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