P_0 at t^* can be estimated from Fig. 4(a) II for mixture blowdown:

$$P_0 = 450 \text{ psia} \tag{62}$$

(ii) Mass fraction remaining in the system after blowdown can be obtained from Fig. 4(a) IV for mixture blowdown at $P_0 = 450$ psia:

$$M^* = 0.13 \tag{63}$$

Using equations (34), (59), and (63), steam/water mass remaining is

$$M = M_i M^* = (9250)(0.13) = 1200 \text{ lb}_m \tag{64}$$

(iii) Maximum pressure rate to insure vapor blowdown is -5 psi/sec from expression (53). Assuming no irreversible pressure loss when flow chokes in the nozzle, Fig. 4(a) III gives the following estimate for initial dP_0/dt^* from the $\bar{f}(L/D) = 0$ curve:

$$\left(\frac{dP_0}{dt^*}\right)_i \approx -(10)10^6 \text{ psi/sq ft-sec/lb}_m \tag{65}$$

Required nozzle-flow area A_N can be found from equation (58), (59), and (65):

$$A_N = \frac{\left(\frac{dP_0}{dt}\right)_i}{\left(\frac{dP_0}{dt^*}\right)_i} M_i = \frac{(-5)(9250)}{(-10)10^6} = 0.0046 \text{ sq ft} \tag{66}$$

β, the required nozzle diameter ratio is therefore

$$\beta = \left(\frac{A_N}{A}\right)^{1/2} = \left(\frac{0.0046(64)}{\pi}\right)^{1/2} = 0.30 \tag{67}$$

DISCUSSION

Hans K. Fauske[2]

This paper presents the first general formulation of the blowdown problem giving maximum or critical flow rate in terms of vessel stagnation properties and pipe flow resistance. Previous papers discussing this subject have primarily concentrated on the characterization of the fluid behavior at the point of choking, giving the maximum discharge rate in terms of exit quality and critical pressure. For the containment designer, having available only information regarding upstream conditions and flow geometry, Mr. Moody's paper should prove extremely useful.

However, the following comments seem in order. The analysis by Mr. Moody for calculating maximum flow rates is based on an energy model assuming (1) annular and minimum kinetic energy flow leading to $k = \left(\frac{v_g}{v_f}\right)^{1/3}$, and (2) thermodynamic equilibrium. Recent experiments at Argonne [23, 24][3] using air-water mixtures indicate that the velocity ratios existing at critical flow conditions are considerably less than the cube root of the density ratio, and also exhibit a fairly strong quality dependence. The large deviation between experiment and analysis must be contributed to the assumption of annular and minimum kinetic energy flow. Visual observation of critical flow in a lucite channel indicated bubbly and highly dispersed flow regimes. In view of the steep pressure gradients prevailing at the point of choking, it is suggested that the measured velocity ratios result primarily from local slip rather than nonuniform phase distribution; i.e., a homogeneous slip flow is more likely to occur at the point of choking than annular.

In addition, comparisons between the abovementioned air-water data [23] and existing critical steam-water data, suggest that a steamwater mixture acts like a two-component system at the point of choking. This is equivalent to saying that there is no phase change or that a one-component mixture does not execute an equilibrium cycle during the passage of the small pressure disturbance. These findings are in general agreement with recent measurements of the speed of sound in two-phase mixtures [25].

In view of the foregoing remarks, it seems likely that the good predictions obtained by Moody's energy model would result primarily from the high values of velocity ratios employed in the model compensating for nonequilibrium effects at the point of choking. Similar observations can be made about previously published models, including the one by this discusser.

Additional References

23 H. K. Fauske, "Two-Phase Two- and One-Component Critical Flow," Symposium on Two-Phase Flow, Exeter, England, June 21–23, 1965.

24 H. K. Fauske, "An Evaluation of Existing Models for Calculating Maximum Escape Rates of Reactor Coolant," presented during a Panel Discussion on, "Loss of Coolant in Nuclear Reactors," Eighth National Heat Transfer Conference, Los Angeles, Calif., August, 1965.

25 N. I. Semenov and S. I. Kosterin, "Results of Studying the Speed of Sound in Moving Gas-Liquid Systems," *Teploenergetika*, vol. 11, no. 6, 1964, p. 46.

A. N. Nahavandi[4]

The author is to be commended for his contribution to the theory of two-phase critical flow and transient blowdown. The distinctive feature of the present paper, as compared to earlier steady state and transient blowdown studies [26, 27, 28, 29][5] is the presentation of graphs for the prediction of (1) the maximum steam/water pipe flow rate in terms of upstream stagnation properties and pipe resistance, and (2) the transient blowdowns for 1000 and 2000 psia saturated-water reservoir for a wide range of fL/D. In contrast with previous analyses, these graphs provide the designer with a convenient tool to estimate the maximum steam/water flow rates from constant-area adiabatic pipes, as well as the time-dependent pressure, mass, and energy fractions for a steam/water system in a reservoir discharging through a pipe.

In the course of his presentation, the author raises several important, yet unresolved questions, involved in the transient blowdown analysis. One of these unresolved problems is the fluid state distribution in the discharge pipe and the reservoir. Intuitively, it seems logical to assume that large leaks are characterized by a homogenized-mixture blowdown while small leaks cause stratification of the steam and water phases. Nevertheless, there is a great need for either a rigorous analytical formulation for the determination of the fluid state in reservoir and pipe or for an experimentally verified correlation to describe the steam bubble behavior in the reservoir and the discharge pipe. In the absence of such developments, it is generally difficult, if not impossible, to accurately predict the fraction of steam bubbles rising to the vessel steam-water interface and those entering the discharge pipe. In this manner, the accurate prediction of two-phase vessel blowdown hinges heavily upon the developments of models to determine the fluid state spatial distribution in the pipe and reservoir.

Other problems associated with the blowdown analysis are the methods for the calculation of slip ratio and the wall shear along the fluid flow path. A number of correlations have been proposed by various authors for these two variables. These correlations, however, are not generally in agreement and their application results in a considerable variation in the estimated flow dis-

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[5] Numbers in brackets designate Additional References at end of this discussion.

charge quantities and blowdown characteristics. Even the experimental verification of the final results is not a decisive proof of the correctness of the slip ratio and wall shear correlations, since in certain instances their inaccuracies may be subtractive. In view of these difficulties, it is believed that fundamental investigations are still needed to develop more accurate and experimentally verified correlations for slip ratio and wall shear in two-phase flow as well as in the approach region to critical flow.

The author's present analysis can be improved in the following areas:

1 In the blowdown transient analysis, the author employs a time-dependent analysis for the determination of reservoir properties. However, the pipe flow equations are treated in a quasi-steady-state fashion. For momentum equation in the discharge pipe, it is essential to include the inertia term as follows:

$$\frac{A}{g_c}\frac{dG}{dt} + \frac{1}{g_c}\frac{d\Omega}{dl} + A\frac{dP}{dl} + \tau_w P_w = 0$$

Ignoring the inertia term imposes instantaneous changes in the fluid velocity, thus introducing inaccuracies at least in the initial stage of the blowdown.

2 In the blowdown transient analysis, the problem of fluid transport through the reservoir and the discharge pipe has not received adequate attention. The author assumes that the state of fluid, as computed for the reservoir, prevails in the discharge pipe. This restrictive assumption, together with the neglect of inertia term in momentum equation, gives rise to the disagreement between the theory and experiment for the experimentally observed sharp initial dip in pressure shown in Fig. 6(*b*). Although the mathematical formulation of the fluid transport without appropriate correlations for the steam bubble behavior would be rather inaccurate, sectionalization of the reservoir and the pipe into spatial elements and the application of continuity and energy equations to fluid flow in each element will provide an adequate transport model, at least for the case of homogenized-mixture blowdown.

3 The present analysis, on one hand, includes the pipe friction but neglects the pipe entrance losses by assuming idealized isentropic entrance. To make the study more consistent, pipe entrance losses could be incorporated in the analysis.

4 In the estimation of equivalent fL/D for experimental verification of the theory, this quantity is estimated from the initial pressure drop which is not generally available to the designer. However, the design engineer would be interested to know the agreement between the theory and the experiment for the case where the equivalent fL/D calculation were based on the summation of geometric loss coefficients for two-phase flow (as computed in reference [30]) plus fL/D components.

Additional References

26 T. A. Harris, "Analysis of the Coolant Expansion Due to a Loss-of-Coolant Accident in a Pressurized Water Nuclear Power Plant," *Nuclear Science and Engineering*, Journal of the American Nuclear Society, vol. 6, 1959, pp. 238–244.

27 A. N. Nahavandi, "A Digital Computer Analysis of Loss-of-Coolant Accident for a Multicircuit Core Nuclear Power Plant," *Nuclear Science and Engineering*, vol. 14, 1962, pp. 272–286.

28 S. G. Margolis and J. A. Redfield, "Analytical Model for Blowdown Experiments," *Transactions of the American Nuclear Society*, vol. 8, no. 1, Annual Meeting, June, 1965.

29 A. N. Nahavandi and R. F. von Hollen, "Two-phase Pressure Gradients in the Approach Region to Critical Flow," *Nuclear Science and Engineering*, vol. 22, 1965, pp. 463–469.

30 D. E. Fitzsimmons, "Two-Phase Pressure Drop in Piping Components," General Electric, Hanford Atomic Products Operation, Richland, Wash., HW-80970, Rev. 1, March, 1964.

Author's Closure

The discussions of H. Fauske and A. N. Navahandi are greatly appreciated.

Comments by both discussers should stimulate further research for a more complete understanding of two-phase flow phenomena.

Fauske concluded from recent tests that a steam/water slip ratio at critical flow is closer to unity rather than $(v_g/v_f)^{1/3}$ used in the present model. A slip ratio of $(v_g/v_f)^{1/3}$ corresponds to a *mathematical* extremum for the annular, equilibrium two-phase flow rate.

Fauske also mentioned that a steam/water mixture acts like a two-component gas/liquid system at critical flow, with suppressed phase change in either direction. It is well established that meta-stable states do exist in two-phase systems undergoing rapid pressure changes. There is a compensating feature, however, for the steam/water system. State equations for saturated steam/water show that isenthalpic or isentropic pressure changes with continuous phase equilibrium require relatively small quality change and hence small phase change, especially in the mid-quality range. Therefore it may be concluded that the phase equilibrium assumption for steam/water approaches the behavior of a two-component system. The same compensating feature is not expected for other fluids. The questions of actual slip ratio, flow pattern, and nonequilibrium effects at critical flow are open to further study.

Navahandi points out the need for further understanding of two-phase flow behavior in the approach region to critical flow. His suggested improvements in the present model should alert the potential user to its inherent idealizations and restrictions. Pipe flow inertia effects could be very important in determining reservoir internal stresses in the early stages of blowdown, especially when the reservoir contains regions of subcooled liquid. Difficulties also may arise from the present single-reservoir model if fluid mass in the discharge line is a large fraction of total mass. A model with multinode reservoirs would be more applicable to such cases.

It should be mentioned that the isentropic entrance assumed is simply a convenience in the present model. Entrance losses can be included as an equivalent (fL/D) component.

Geometric loss factors consistent with the model presented only can be represented as equivalent (fL/D), based on liquid in single phase flow. However, Navahandi's suggestion 4 that (fL/D) be based on two-phase pressure loss correlations would definitely improve agreement between theory and data in Fig. 5(*f*), which is predominated by a sharp entrance loss.