10/4/77
250 TTIS

UCID- 17580

Lawrence Livermore Laboratory

UNSTEADY JET-SLUG DYNAMICS

Sang-Wook Kang

September 9, 1977

MASTER

This is an informal report intended primarily for internal or limited external distribution. The opinions and conclusions stated are those of the author and may or may not be those of the laboratory.

Prepared for U.S. Energy Research & Development Administration under contract No. W-7405-Eng-48.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

UNSTEADY JET-SLUG DYNAMICS

Sang-Wook Kang
H-Division/Physics Department

ABSTRACT

The present analysis treats the transient load characteristics at the wet-well bottom during the vent-clearing event under loss-of-coolant accident conditions. A conceptual model is introduced wherein the liquid-jet inertia and the net momentum-efflux are the two dominant physical factors. The derived load-history equations were found to be functions of the vent-clearing characteristics and of the jet-decay mode in the liquid pool. The theoretical results obtained by a physical modelling of these phenomena appear to agree reasonably well with the available data from UCLA and from LLL 1/5-scale experiments.

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

INTRODUCTION

We wish to develop an approximate theoretical analysis capable of predicting the load history of the pressure-suppression system of boiling-water reactors following a loss-of-coolant accident. The response of the system to the accident may involve first the air/vapor rushing down the vent(s) submerged in a wet well, the mixture forming bubbles in the pool after clearing the vent tube, perhaps causing condensation/evaporation of the system (including "chugging"), the swelling of the liquid pool, which may result in impacting on the ringheader, etc. Experiments performed under simulated conditions appear to suggest that one of the critical impacts on the structure takes place during the period surrounding the vent-clearing event.

This paper is concerned with the theoretical treatment of the transient load characteristics at the pool bottom during the initial moments following LOCA, up to the time the liquid column in the vent downcomer clears the tube submerged in the wet well.

A control-volume integral approach will be utilized in the present analysis. This global-characteristics method has been found to afford mathematical tractability and delineation of dominant physical parameters without undue sacrifice in accuracy in related problems such as steady-flow jets (Ref. 1-2), as well as other fluid-dynamic problems (Refs. 3-6).

We shall derive relevant load-history equations for an incompressible liquid flowing through the control volume using the governing conservation principles. It will turn out later (see Equation (5)) that the equations thus derived show two physical factors that dominate the jet-slug dynamics, viz., (1) the jet-inertia effect, which enhances the load; and (2) the net momentum-efflux effect, which lightens the reaction force--and the pressure force--at the bottom of the wet well.

The derived load-history equation requires, for quantitative calculation, the vent-clearing characteristic and the mode of jet-decay in the control volume. The vent-clearing history has already been investigated and been reported in an earlier Memorandum (Ref. 7). A model is introduced into the present analysis to describe the jet-decay characteristic in the control volume. In particular, the assumed "similarity" functions (as given in Equations (8) and (9)) produce two parameters whose magnitudes determine the jet-flow behavior. It will turn out (see Figure 4) that only one of these parameters clearly dominates--at least quantitatively--the flow phenomena and an approximation based on this finding will be used in the load-history calculation.

In what follows, the steps described so far will be cast in mathematical forms, together with discussions in greater detail.

ANALYSIS

The control volume selected for investigation of the unsteady jet-slug dynamics is shown schematically in Figure 1.

The governing global-conservation equations for the control volume in axisymmetric, cylindrical coordinate system are (see Chapters 4, 6 in Ref. 6 for basic equation forms):

Axial Momentum:

$$\frac{d}{dt} \left[\int_L^H \int_A \rho U dA dZ \right] + \int_S \rho U w dS - \int_A \rho V_L^2 dA = (p_L - p_w) A + \int_L^H \rho g A dZ \quad (1)$$

continuity:

$$\frac{d}{dt} \left[\int_L^H \int_A \rho dA dZ \right] + \int_S \rho w dS - \int_A \rho V_L dA = 0 \quad (2)$$

where the symbols denote their usual meaning and most of these are described in Figure 1. The term p_L is the static pressure at the end of the vent downcomer pipe at $Z=L$, and p_w stands for the wall pressure at the bottom of the wet well. The term dA is the incremental cross-sectional area and is equal to $2\pi r dr$, while dS signifies the surface area along Z and is equal to $2\pi R dZ$.

Physically, the first term on the left-hand-side of Eq. (1) corresponds to the axial-inertia forces, whereas the second and the third terms denote the momentum efflux from the control surface along Z and the momentum influx from the vent tube, respectively. Thus these two latter terms combined signify the net momentum efflux from the control volume.

Assume incompressibility of the liquid in the control volume. Assume also for simplicity that the velocity distribution of U is uniform in the radial direction, so that $U = U(Z,t)$ and $V_L = V_L(t)$, and that $w = w(Z,t)$. Equations (1) and (2) then become

$$\frac{d}{dt} \left(\int_L^H U dZ \right) + \frac{2}{R} \int_L^H U w dZ - V_L^2 = \frac{(p_L - p_w)}{\rho} + g(H-L) \quad (3)$$

and

$$V_L = \frac{2}{R} \int_L^H w dZ \quad (4)$$

Substituting $p_L = p_\infty + \rho g L$ and introducing terms Ω and K in Eq. (2), we obtain

$$\Omega(t) = \frac{d}{dt} \left(\int_L^H U dZ \right) - K V_L^2 \quad (5)$$

where

$$\Omega(t) \equiv -[p_w(t) - (p_\infty + \rho gH)]/\rho \quad (6)$$

and

$$K \equiv 1 - \frac{2}{RV_L^2} \int_L^H U w dZ \quad (7)$$

Physically, the term $\Omega(t)$ is the "pressure-response" function at the wall, the sign being negative based on the sign convention employed in the analysis and the action and reaction in the free-body diagram. The term K signifies the coefficient for the net momentum efflux from the control volume.

Now, inspection of Equation (5) yields the following observation: that quantitatively the magnitudes of the two competing terms on the right-hand-side of the equation depend greatly upon the function $U = U(Z,t)$ the jet-decay characteristics along Z , and upon the function $V_L = V_L(t)$, the liquid-jet velocity at the end of the vent tube. Thus it is imperative that these two functions be determined as accurately as possible in order to obtain quantitatively meaningful results. These two functions will therefore be discussed and formulated in the following sections.

$V_L = V_L(t)$:

This function, signifying the instantaneous magnitude of the liquid velocity at $Z = L$, has been derived as a part of the vent-clearing analysis reported earlier in Ref. 7. In it, it was observed that the closed-form solution obtained by assuming a constant mean driving overpressure seemed to agree well with the test data. Moreover, the agreement becomes even better if one introduces the equivalent tube-length concept, i.e. $L^* = L + R$ (say), which accounts for

the unsteady nature of the flow. This concept has the additional, physically reasonable result that the liquid velocity at the time of vent clearing is no longer infinite. It is noted in passing that Reference 8 also makes use of this additional-liquid-slug concept. Therefore, pending dissemination of a more accurate analysis in the literature, the results obtained in Reference 7 will be used here to express the velocity history of the liquid column in the vent tube.

$$U = U(Z, t):$$

This function describes the jet-decay characteristics in the control volume and is a rather complicated function even after we simplify it by assuming a uniform-distribution behavior in the radial direction. On the subject of free jets in steady flow--free jet in this case meaning that the obstacle is placed far from the tube exit plane, say, farther than nine diameter length, i.e. $(H-L)/D > 9$ --there are numerous analyses in the literature, some representative papers being References 9-14. However, few papers are available on the case where the distance between the obstacle and the tube exit is relatively close, one of these papers being Reference 15 by Tani and Komatsu. These authors experimentally studied the jet-impingement cases in which the ratio $(H-L)/D$ was as small as four, under steady-state flow conditions. They obtained the jet-decay behavior along the jet axis which may be characterized as some sort of a power function of the distance from the nozzle exit.

As regards any analysis of unsteady jet flows relevant to the present problem, the author has no knowledge of ready references. Therefore, we propose the following model. Under the assumption of an incompressible liquid flow, the instantaneous transmission of the signal in the liquid being one of the consequences of this assumption, it seems reasonable to utilize the qualitative

results of the steady jet-decay analyses and thus to approximate the transient jet-flow characteristic by giving it a "similarity" power-function behavior, so that the jet-velocity distribution instantly adjusts to the changing values of V_L , the jet velocity at the tube exit. Thus we put

$$U(Z,t) = V_L(t) \left(\frac{H-Z}{H-L} \right)^M \quad (8)$$

Similarly, we put

$$w(Z,t) = \bar{W}(t) \left(\frac{Z-L}{H-L} \right)^\Delta \quad (9)$$

The power exponents M and Δ now will respectively describe the instantaneous modes of the axial jet decay and of the radial velocity along the Z -axis.

The functional behaviors of these two velocity distributions are shown in Figures 2 and 3 in terms of a dimensionless jet-axis distance ξ defined to be

$$\xi \equiv \left(\frac{Z-L}{H-L} \right) \quad (10)$$

It is not clear at this juncture what values of M and Δ are reasonable for confined unsteady jets. From physical viewpoint, it seems evident that the parameter M , characterizing as it does the jet-decay behavior along the jet axis, will depend to some extent on the distance between the tube exit and the obstacle (wall). For example, if this distance is infinitely large, the jet flow would simulate the free-jet phenomena; on the other hand, if this distance is very small, say one-diameter length away from the exit, the deflection of the flow due to the presence of the wall would be prominent. The distance effect studied by Tani (Ref. 15) for steady jets will be qualitatively incorporated into the present formulation.

It is also possible that the coefficient M may vary with time under unsteady jet-flow conditions. These factors are all combined in the present analysis into two parameters, M and Δ , based on the approximations introduced into the formulation. Refinement can clearly be made on the formulation; for example, by subdividing the control volume into two or more axial segments and introducing difference parameters M_i and Δ_i : however, this elaborate procedure is deemed premature at this stage of the analysis.

Load-history equation $\Omega = \Omega(t)$

Substitution of Equations (8) and (9) in the continuity equation (4) yields:

$$\bar{W}(t) = V_L(t) \left(\frac{\Delta+1}{2} \right) \left(\frac{R}{H-L} \right) \quad (11)$$

The above expression provides the relationship between the vent-exit velocity, $V_L(t)$, and the maximum radial velocity in the jet $\bar{W}(t)$.

Substitution of Equations (8) and (9) in the inertia term yields:

$$\frac{d}{dt} \left(\int_L^H U dZ \right) = \frac{(H-L)}{(M+1)} \frac{dV_L}{dt} \quad (12)$$

The net momentum-efflux coefficient, K , can be obtained from Equation (7) by utilizing Equation (11) for $\bar{W}$:

$$K \equiv 1 - \frac{2}{RV_L^2} \int_L^H U dZ = 1 - (\Delta+1) \int_0^1 (1-\xi)^M \xi^\Delta d\xi \quad (13)$$

The variation of K as a function of M and Δ is shown in Figure 4. It is seen that, for the value of Δ between zero and unity—a physically reasonable range—the trend of K is to increase in magnitude from zero at $M = 0$ to approximately unity at $M \sim 5$. It may also be seen that the effect of M is dominant compared to that of Δ on the magnitude of K . The functional behavior of K suggests the following analytic expression:

$$K \sim (M/5)^{1/3} \quad (14)$$

This function is shown in Figure 4 as a series of $\bullet$ -symbols. Considering the approximate nature of the present formulation, Equation (14) will be used in lieu of Equation (13) for the sake of expediency. However, if necessary—or if greater quantitative accuracy is desired—we can always revert to the use of the more exact equation (13).

Combining these equations, we obtain the load-history equation:

$$\Omega(t) = \frac{(H-L)}{(M+1)} \frac{dV_L}{dt} - \left(\frac{M}{5}\right)^{1/3} V_L^2(t) \quad (15)$$

The acceleration term, dV_L/dt , and the velocity term, V_L , are to be obtained from the vent-clearing analysis (Ref. 7), in which the equivalent tube-concept is introduced as previously mentioned.

Substituting appropriate terms in Equation (15) and effecting nondimensionalization of the variables for greater generality in application, we obtain:

$$\Phi(\tau) \sim \frac{\left(\frac{H}{L} - 1\right)}{(M+1) \left(1 + \frac{R}{L}\right)} \left[\frac{B(\tau) - \psi}{1 - \psi} \right] - B_m \left(\frac{M}{5}\right)^{1/3} \ln \left(\frac{1}{1-\psi}\right) \quad (16)$$

where

$$\phi \equiv \frac{\Omega}{gL^*} = \frac{p_w - (p_\infty + \rho gH)}{\rho gL^*}$$

$$B \equiv \frac{p_1 - p_\infty}{\rho gL^*} ; \quad B_M = \frac{p_m}{\rho gL^*}$$

$$\psi \equiv \frac{z}{L^*} ; \quad \tau \equiv \frac{t}{L^*} \sqrt{\frac{p_m}{\rho}} \sqrt{\frac{2}{\pi}}$$

and the approximate sign in place of the equality symbol is used because of expressing the velocity term V_L based on the approximate closed-form results of the vent-clearing analysis. Recognizing the introduction of some simplifying assumptions into the present analysis this procedure is believed to be reasonable.

Moreover, the load-history equation thus derived, i.e. Equation (16), turns out to be entirely tractable when combined with the vent-clearing result for ψ (Ref. 7), i.e.

$$\tau = \text{erf} (\mu) \tag{17}$$

where $\mu \equiv (-\ln(1-\psi))^{1/2}$ and τ has the meaning already defined in Equation (16).

Recapitulating, we have derived an expression for the load history which depends upon two competing physical phenomena, i.e., the inertia effect which enhances the load response, and the net momentum-efflux term which relieves the load response at the wet-well bottom.

DISCUSSION

Inspection of these two effects in Equation (16) provides the following general observation, viz., the inertia term depends on H/L , R/L , M and ψ , especially on M for a given configuration, while the momentum-efflux term is greatly affected by M . In view of the absence of any definitive value of M that one can apply to the present analysis based on a separate investigation at this juncture, and in view of the rather encompassing nature of the parameter M , we propose to determine this value (strictly applicable to the load-history study only) from comparing the experiment of UCLA with the present approximate theory. If the value of M thus obtained is a physically reasonable value, then application of the theory to other similar tests (such as LLL 1/5-scale tests) with the same M -value should yield reasonable comparisons. Following this reasoning, comparison was made between the UCLA test results (Ref. 16) and the present theory. The pressure history obtained by UCLA is shown in Figure 5. It is seen that in this particular experiment the vent clearing coincides with the maximum (or nearly maximum) pressures for both this driving overpressure and the load at the bottom of the cylinder. We wish to predict satisfactorily the load history, $p_w(t)$, with known $p_l(t)$. The vent-clearing theory predicts a somewhat speedier liquid column motion, by about 5 milliseconds. Considering the accuracy resolution involved, this amount of discrepancy is believed to be permissible. Thus, translating the vent-clearing time by 5 milliseconds, the present load-history theory was applied to the UCLA test conditions by using $M = 2$ and $M = 3$. This is shown in Figure 6. Based on comparison of the test result for p_w in Figure 5 with the theory for p_w in Figure 6, the most appropriate value of the parameter M seems to be:

$$M \approx 3$$

(18)

Physically, this value would signify a rather precipitous reduction in the axial velocity (assumed radially uniform) as the jet slug approaches stagnation condition at the wet-well bottom wall, resulting in an increased efflux of the maxx through the side surface, i.e., an enhanced jet deflection. Considering the relatively small distance between the jet exit from the tube and the obstacle (wall), and considering also the assumption of the incompressibility of the liquid, this value is tentatively taken to be a plausible value in the analysis of the unsteady jet-slug dynamics.

If the above value of M is reasonable, then the theory should predict with acceptable accuracy the load-history under other conditions. For this purpose, the test data taken at LLL (Ref. 17) were chosen. In particular, comparison was made between the Test 1.3.1 results and theory. Figures 7 and 8 give histories of the driving air pressure in the ringheader and at the bottom of the torus, respectively. The region of present interest is re-drawn in Figure 9.

Although the physical configurations for the test apparatus and the theory are not strictly the same, sufficient similarity was believed to exist to warrant comparisons between theory and experiment. The theoretical result based on $M = 3$ is shown in Figure 10, where the time scale was translated 5 milliseconds to adjust the vent-clearing history as previously mentioned.

Reasonable agreement is believed to exist between the experimental load history of LLL Test 1.3.1. (Figure 9) and the theoretical prediction (Figure 10).

Some remarks and exegesis on the analysis presented in this paper are in order. It goes without saying that any quantitative result reflects both the qualitative assumptions made (i.e., physical models) and the quantitative approximations: for example, the description of K in Eq. (14). The major simplifications introduced into the present study are: the incompressibility of the liquid,

the use of the closed-form results from the vent-clearing analysis, the choice of the parameter M to describe the unsteady jet-decay behavior, and the parameter K to characterize encompassingly the net momentum-efflux phenomena. Concerning the incompressibility-fluid assumption, it is noted that currently there are studies in progress which treat the liquid as compressible. Hopefully their results will shed insight into the adequacy--or inadequacy--of the incompressibility approximation. A more accurate vent-clearing history would be desirable to improve quantitative comparison with experiments; however, the vent history employed in the present analysis is believed to be sufficiently reliable, although any result which enhances the accuracy of course would be useful. A separate, unsteady jet study in confined configurations, practically non-existent in the literature to the author's knowledge, would enhance the possibility of determining the value of M more accurately. Theoretical and/or experimental investigation of the unsteady jet-flow phenomena will be a worthwhile project to undertake in the future. With regard to the expression of K in Equation (14), this procedure was taken strictly for convenience and, as stated previously, the more exact equation, Eq. (13), can be used if greater quantitative accuracy is desired. One final remark: in the theory it was assumed that the liquid pool extended to infinity in the radial direction, thus constituting a reservoir. On the other hand the experiments of UCLA and LLL were performed for a finite liquid pool. Concerning the side-wall effects on the jet flow, the test results of Reference 15 show that this side-wall effect would be significant only if the radial distance between the stagnation point and the side wall is less than about three-tube diameter length, i.e., $(\text{distance})/D < 3$. The configuration of UCLA is: $22.5 \text{ cm}/4.7 \text{ cm} \sim 4.8 > 3$, while that of LLL is: $\text{ca } 90 \text{ cm}/12.5 \text{ cm} \sim 7.2 > 3$.

Thus the side-wall effect is believed to be small--at least while the liquid column is still in the vent tube and clearing the downcomer--compared to other physical factors considered in the present analysis.

CLOSING REMARKS

In summary, an approximate preliminary theory for the load history up to vent clearing was developed based on a conceptual model of two competing physical parameters: the inertia effect and the net momentum-efflux phenomena. A dominant parameter M describing the jet-decay behavior was delineated from the theory. For the value $M \sim 3$, the theoretical predictions appear to agree reasonably well with the experimental data of UCLA and of LLL in terms of the load history at the bottom of the wet well under the loss-of-coolant accident conditions.

Quantitative refinements to the present, "zeroth-order" model theory can be effected, either by removing some of the assumptions made or by introducing more elaborate models into the present analysis. Future studies would envision these steps; however, the present approximate theory is believed to be sufficiently self-contained to warrant dissemination at this juncture.

REFERENCES

1. Abramovich, G. N., The Theory of Turbulent Jets, MIT Press (1963).
2. Rajaratnam, N., Turbulent Jets, Elsevier, Amsterdam-New York (1976).
3. Kreith, F., Principles of Heat Transfer, 2nd ed., International Textbook Co. (1965); pp. 297-305.
4. Kang, S.-W., "Nonequilibrium, Ionized, Hypersonic Flow over a Blunt Body at Low Reynolds Number", AIAA Journal, Vol. 8, No. 7, July 1970, pp. 1263-1270.
5. Schlichting, H., Boundary Layer Theory, Pergamon Press (1955); pp. 206-214.
6. Hansen, A. G., Fluid Mechanics, J. Wiley and Sons (1964); Chapters 4-6.
7. Kang, S.-W., "Vent-Clearing Phenomena--An Analytic Study", H-Division Memo (29 August 1977).
8. Koch, E. H., Frenkel, E., Slegers, L., and Weissshaupl, H.A., "Dynamic Loads on Pressure Suppression Containments" Proc. Second Int. Conf. on Structural Mechanics in Reactor Technology, Berlin (September, 1973), Vol. VI-Part B Supplement, J 1/5, pp. 1-14.
9. Witze, P.O., "A Study of Impinging, Axisymmetric Turbulent Flows: the Wall Jet, the Radial Jet, and Opposing Free Jets", Sandia Report (Livermore) SAND 74-8257 (Jan. 1975).
10. Ohja, S.K., and Gollakota, S., "Jet Impingement on a Curved Surface", AIAA Journal, Vol. 15, No. 4 (April 1977), pp. 453-454.
11. Poreh, M., and Cermak, J.E., "Flow Characteristics of a Circular Submerged Jet Impinging Normally on a Smooth Boundary", Proc. Sixth Midwestern Conference on Fluid Mechanics, (1959), pp. 198-212.
12. Wolfshtein, M., "Some Solutions of the Turbulent Impinging Jet", Journal of Basic Engineering (ASME), (Dec. 1970), pp. 915-922.
13. Yamaguchi, S., and Maki, T., "Jet Flames Stabilized by a Counter Air Stream", Bull. Japan Soc. Mech. Engrs., Vol. 14, No. 73 (1971), pp. 683-693.

14. Matsumoto, R., and Kimoto, K., "A Study of Opposing Jets in Air Stream and their Flame--1st Report, A Structure of Two Dimensional Opposing Jets in the State without Flames", Bull. Japan Soc. Mech. Engrs., Vol. 16, No. 95 (May 1973), pp. 838-850.
15. Tani, I., and Komatsu, Y., "Impingement of a Round Jet on a Flat Surface", Proc. Eleventh Int. Congress of Applied Mechanics, Munich (1964), Goertler, H., ed., pp. 672-676.
16. Catton, I., et al., "Suppression Pool Dynamics", Quarterly Progress Report, July 1, 1976-Sept. 30, 1976, NUREG-0264-1; also, C.K. Chan (private communication).
17. McCauley, E., et al., "Mark I 1/5-scale Boiling Water Reactor Pressure Suppression Experiment--Quick-look Report", UCID-17446-4 (June 3, 1977).

ACKNOWLEDGMENTS

The author wishes to acknowledge the invaluable assistance rendered by Mr. E. Gong in the programming and execution on the computer of the various equations involved in the present analysis.

The useful and stimulating discussions with Drs. B. Bowman, A. Buckingham, L. Edwards, W. McMaster and M. Ross are greatly appreciated.

Figure 1. Schematic Diagram of Unsteady Jet-Slug Dynamics

$$u(\xi, t) = V_L(t) (1 - \xi)^M$$

$$\xi \equiv \frac{Z-L}{H-L}$$

Figure 2. Axial-Jet Decay Modes

Figure 4. Variation of the Net Momentum-Efflux Coefficient (K)

Figure 5. Experimental Pressure
Histories during Vent Clearing
(100%)

Figure 6. Theoretical Pressure History (UCLA-configuration)

NRC TEST NO. 1.3.1

CHAN 31

Figure 7-A. Experimental Drywell
Pressure History (LLL Test 1.3.1.)

Figure 7-B. Experimental Ringheader
Pressure History (LLL Test 1.3.1.)

Figure 8. Experimental Wall-Pressure History (LLL Test 1.3.1.)

Figure 9. Experimental Wall-Pressure
History during Vent Clearing
(LLL Test 1.3.1.)

Figure 10. Theoretical Pressure History (ILL Test 1.3.1.)