NEDO-21472
Class I
78NED253
April 1978

ANALYTICAL MODEL FOR LIQUID JET PROPERTIES FOR PREDICTING FORCES ON RIGID SUBMERGED STRUCTURES

Approved: H. H. KLEPFER, MANAGER
Technology and Development

Prepared by: F. J. Moody

Revised by: L. E. Lasher
L. C. Chow

BOILING WATER REACTOR PROJECTS DEPARTMENT • GENERAL ELECTRIC COMPANY
SAN JOSE, CALIFORNIA 95125

GENERAL ELECTRIC

8006120038

NOTICE

This document contains proprietary information of General Electric Company and is furnished in confidence solely for the purpose or purposes stated in the transmittal letter. No other use, direct or indirect, of the document or the information it contains is authorized. The recipient shall not publish or otherwise disclose this document or the information therein to others without prior written consent of the General Electric Company, and shall return the document at the request of the General Electric Company.

Neither the General Electric Company nor any of the contributors to this document makes any warranty or representation (express or implied) with respect to the accuracy, completeness, or usefulness of the information contained in this document, or that the use of such information may not infringe privately owned rights; nor do they assume any responsibility for liability or damage of any kind which may result from the use of any of the information contained in this document.

Proprietary information of the General Electric Company is indicated by "bars" drawn in the margin of the text of this report, and by the words "Company Proprietary" in illustration and table titles.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

NOTATION

A	Structure area projection normal to flow, lying inside the jet boundary
$A(x,t)$	Jet area
A_D	Discharge area
A_I	Intercepted jet area
C_D	Standard drag coefficient
F	Jet force acting upon structure
g_c	Acceleration of gravity constant
K	Momentum exchange factor
ℓ, ℓ_p	Jet penetration length
t	Time
V	Jet velocity
V_D	Discharge velocity
x	Distance measured from point of discharge
ρ	Water Density
P_∞	Local Hydrastatic Pressure

ABSTRACT

The unsteady discharge of a water jet into a suppression pool, caused by either a postulated loss-of-coolant accident (LOCA) or a safety relief valve (SRV) actuation, will create forces on structures in its path. This study provides a method for calculating submerged jet velocity and cross sectional area arriving at a given structure in terms of the jet discharge properties. Procedures are limited for use with ramshead, downcomer, or weir-vent type discharges.

1. INTRODUCTION

A LOCA or SRV actuation causes the discharge of a water column into the pressure suppression pool; the resulting drag or impingement forces on submerged structures must be evaluated for design assessment. A procedure for estimating the unsteady submerged jet velocity and shape is provided in this report. The jet velocity is used for determining either standard (velocity squared) drag forces and/or direct impingement forces. The shape of the jet is also important in determining which structures are intercepted by the discharge. The jet penetration length (ℓ, ℓ_p) can also be used to indicate the location of the SRV ramshead bubble.

Steady submerged jets have been treated in a number of textbooks showing growth of the turbulent region. This turbulence is accompanied by a spreading of the jet profile and diminishing of the jet forward velocity. However, some simple experiments and other observations of water clearing from pipes strongly suggest that spreading is relatively minor during early stages of jet discharge. Consequently, a steady jet model may not yield realistic profiles and velocity fields for determining the forces of unsteady jets. The observed jet shapes are predicted by solving the one-dimensional unsteady flow equations of mass and momentum. This type of procedure conforms with established engineering methods of modeling fluid mechanics problems.

This study provides a method for estimating unsteady jet properties to be used for determining forces on submerged structures. The major assumptions employed in this study will be verified in a confirmatory test program.

This report is organized into two sections. The first section summarizes the information required to implement the analytical model methodology. The second section of the report is labeled as an appendix; it includes detailed derivations and formulations of the methods summarized in the first section. A companion applications memorandum for loads on submerged structures makes reference to information in both portions of the report.

2. MAJOR ASSUMPTIONS

1. The water jet is analyzed as an unsteady jet with no divergence other than that determined from the one-dimensional mass and momentum equations. The fluid particle velocities within the jet are assumed to remain unattenuated from the initial discharge value.

   This differs from steady-state models which predict a constant angle of divergence for turbulent jets.

2a. When a structure is engulfed in the jet path, the force on the structure can be calculated using a standard velocity-squared drag equation.

2b. If a structure partially or fully intercepts the jet, a momentum balance is used to find the proportionality factor between the drag and the velocity squared.

   The theory assumes the water jet is a momentum-carrying slug of water producing a standard drag for a, above, and a transfer of momentum conservation for b, above. The jet does not impose an acceleration field in the bulk fluid, i.e., no pressure gradients are established in the surrounding fluid. The water in the jet is at constant pressure along its axis as well as in the transverse direction. The fluid outside the jet can be considered to have constant pressure.

3. The jet flow is assumed to be inviscid.

4. This assumption addresses the behavior of the jet as it passes into the pool and is considered to be a proprietary part of the model.

3. SUMMARY

Acce' rating unsteady water jets tend to have relatively small cross-sectional vari tion during forward travel when compared with steady jets.

Based on considerations of the so-called Helmholtz (waving-flag) instability and turbulent boundary layer characteristics, growth of the turbulent flow boundary outward from an unsteady jet appears to be extremely small.

An advancing jet was considered in the context of potential flow and the kinematical boundary condition for the interface between the discharging and surrounding liquid; the jet front tends to become "rounded" instead of "broadened."

If a liquid jet is discharged at constant acceleration, shear of the surrounding liquid is initially zero, but grows slowly so that the jet's forward motion is not strongly reduced. This implies that the jet can penetrate deeply into the surrounding liquid. Negligible shear was one basis of the jet model in this study, and this is an appropriate assumption for ramshead, downcomer or weir-vent jets.

The solutions for a jet with constant discharge velocity, constant discharge acceleration, and linearly increasing discharge accelerations are summarized in the proprietary version.

The standard drag force on a submerged structure is based on the jet velocity and area profile arriving at the structure. When the jet tail arrives at the structure, the drag force returns to zero. If a structure is fully submerged inside the jet boundary, a velocity-squared drag is experienced of the form

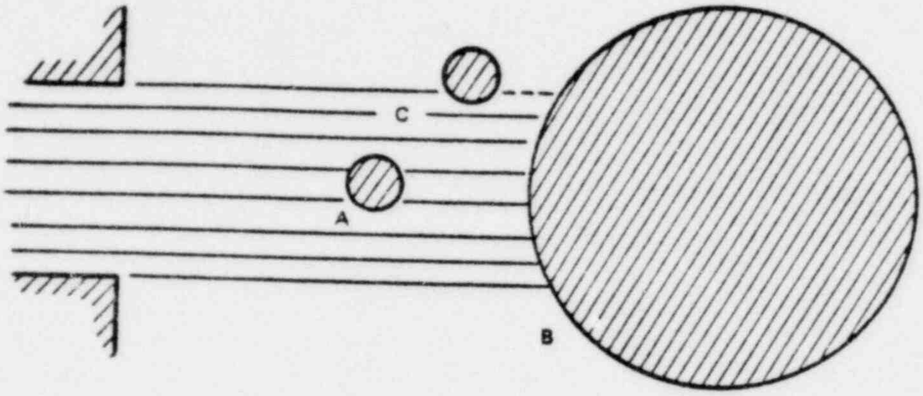
$$F = C_D A \frac{V^2}{2g_c} \rho \qquad (1)$$

where C_D is a standard drag coefficient for the geometry and A is the structure area projection normal to the direction of flow, lying inside the jet boundary (for structural cross-sections that are symmetric about an axis, with the axis normal to the jet flow). For structures oriented such that their axis of symmetry is skewed to the jet direction of flow, the flow should be divided into two velocity components, one normal to the axis and the other parallel to it. Equation (1) should still be used for the skewed case, but with V now being the normal component of the jet velocity.

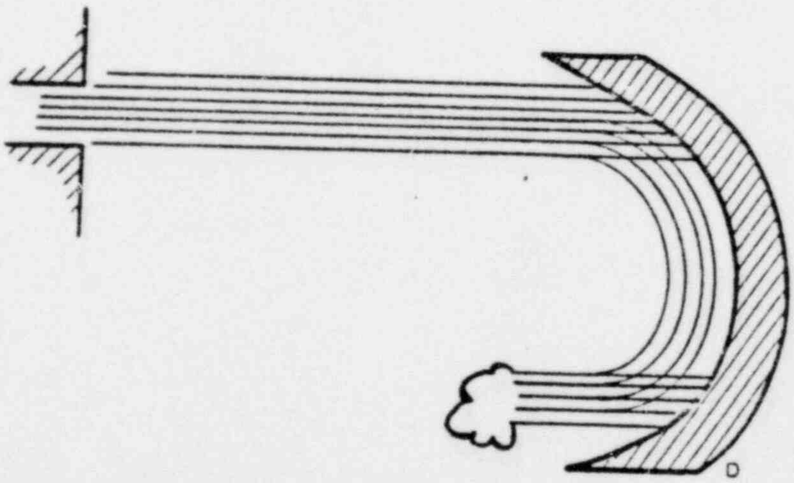
If a structure fully or partially intercepts the jet, an equation of the same form as Equation (1) is applicable:

$$F = KA_I \frac{V^2}{2g_c} \rho \qquad (2)$$

Equation (2) is derived for a simple stoppage of momentum, where A_I is equal to the intercepted jet area normal to the jet direction. The values for K range up to a maximum of K=4. For momentum stoppage with no reflection, K=2, and in the unlikely occurrence that the structure turns the jet back on itself, a maximum value of K=4 would be used. The following sketch illustrates some of the possible structure-jet interactions.



STRUCTURE A: FULLY SUBMERGED, USE C_D AND EQUATION (1)
B: FULLY INTERCEPTS JET, USE K AND EQUATION (2)
C: PARTIALLY INTERCEPTS JET, USE K AND EQUATION (2)



STRUCTURE D: TURNS JET BACK ON ITSELF,
USE K AND EQUATION (2)

Figure I. Sketch of Some Possible Structure/Jet Interactions

4. APPENDIX

SUBMERGED LIQUID JET PROPERTIES FOR PREDICTING FORCES ON SUBMERGED STRUCTURES

F. J. Moody

ABSTRACT

The velocity and cross-section properties of unsteady, submerged liquid jets are required for the prediction of drag and impingement forces on submerged structures. This study was undertaken to help understand important phenomena governing jet spreading during the start of jet discharge. Although turbulence plays an important role in the spreading of steady jet flows, its effects are relatively small in unsteady jet behavior. It was found that when liquid discharge begins, the resulting unsteady jet advances into stationary liquid as a uniform cylinder without significant spreading.

4.1 INTRODUCTION

A submerged liquid jet is capable of creating drag or impingement forces on structures that lie in its path. These forces are dependent on jet velocity, liquid density, and the fraction of jet area that is intercepted by a structure.

Steady, submerged jets have been considered by a number of workers (Schlichting, 1955; Landau & Lifshitz, 1959; and Rouse, 1959), but an appropriate analysis of unsteady submerged jets has not been found in the literature. It is expected that when submerged jet discharge begins, the turbulent shear boundary will tend to be thinner than that predicted by steady jet analyses because momentum transfer to surrounding liquid requires a finite time. Behavior of the jet frontal region as it advances into stationary liquid is not well known, nor are the effects of unsteady discharge on the jet profile fully understood. This study was undertaken to estimate properties of unsteady submerged jets, and to provide a simple jet model to be used in obtaining time- and space-dependent properties for reasonably conservative force predictions on submerged structures.

4.2 TURBULENT, STEADY JETS

A brief review of steady jet profiles and properties should be useful in assessing whether a time-dependent jet profile is necessary for estimating forces on submerged structures.

During submerged circular jet discharge of initial diameter D, shear at the jet-surrounding fluid boundary undergoes turbulent diffusion in both the outward and inward radial directions. When inward shear diffusion reaches the jet center some distance $x = x_o$ from discharge, the established jet velocity profile approximates a normal probability curve. The outer boundary of turbulent diffusion forms a cone whose side makes an angle of 12 to 15 degrees with the jet axis, its vertex lying on $x = 0$ (Landau & Lifshitz, 1959, p. 132). Landau also provides the useful information that two-dimensional jet flow into a suddenly expanded region results in an experimentally determined angle of diffusion into the jet of about 5 degrees. Interpreting this result for a circular jet, the inward turbulent shear diffusion is expected to be bounded by a cone with its base at the jet discharge and its vertex at x_o as shown in Figure 1, making an angle of about 5 degrees with the axis. The established jet velocity profile begins at x_o. Therefore, from geometric considerations, a steady submerged jet involves a region of forward moving fluid whose outer boundary profile is approximated by Figure 1 in which

$$\left.\begin{aligned} r_j &= \frac{D}{2} + 0.126\,x \;;\; x < x_o \\ r_j &= 0.213\,x \quad\;;\; x > x_o \end{aligned}\right\} \qquad \text{(A-1)}$$

where

$$x_o = 11.4\,\frac{D}{2} \qquad \text{(A-2)}$$

If U_D is jet velocity at the point of discharge, the steady centerline velocity is expressed by (Rouse, 1959, p. 384)

$$\left.\begin{aligned} u_{\mathcal{C}}/u_D &= 1.0 \quad\;;\; x < x_o \\ u_{\mathcal{C}}/u_D &= 5.7\,\frac{D}{x} \;;\; x > x_o \end{aligned}\right\} \qquad \text{(A-3)}$$

Equations (A-1) through (A-3) would be recommended for predicting steady jet properties to be used in calculating steady forces on submerged structures.

4.3 GROWTH RATE OF TURBULENT DIFFUSION BOUNDARY

Although a flat plate parallel to the direction of fluid flow probably damps fluid turbulence more than the interface of a submerged liquid jet, an estimate of the unsteady jet boundary layer growth rate is attempted from flat plate theory.

First, an unsteady laminar boundary layer growth rate can be estimated from a steady solution. For example, the Blasius solution for boundary layer thickness on a flat plate whose leading edge is at $x = 0$ is approximated by (Schlichting, 1955, p. 109):

$$\delta \approx 5 \sqrt{\frac{\nu x}{u_\infty}} \tag{A-4}$$

The classical unsteady problem of a suddenly accelerated infinite plane wall shows that the boundary layer at fixed x grows like

$$\delta \approx 4 \sqrt{\nu t} \tag{A-5}$$

Following a free stream fluid particle past a steady developed boundary layer by setting $x = u_\infty t$ in Equation (A-4), the growth rate at fixed x approximates Equation (A-5). Similarly, the steady turbulent boundary layer on a plate is given as

$$\delta = 0.37\, x \left(\frac{\nu}{u_\infty x}\right)^{1/5} \tag{A-6}$$

Following a free stream fluid particle by setting $x = u_\infty t$, an estimate of the growth rate at fixed x is

$$\delta = 0.37\, u_\infty^{3/5}\, \nu^{1/5}\, t^{4/5} \tag{A-7}$$

Because Equation (A-7) is for a flat plate, how well it predicts the boundary layer near a submerged jet is questionable. Comparing Equations (A-1) and (A-6) for the boundary of turbulence surrounding a jet and the boundary layer on a flat plate, shows that for water flows of moderate velocity, turbulence spreading of a steady submerged jet is roughly ten times that of a plate. At first, employment of Equation (A-7) appears inappropriate for time-dependent boundary layer growth on a plate to estimate turbulence spreading from a jet. However, there are a number of unreported observations including simple experiments which indicate that turbulence spreading of an unsteady submerged jet is quite slow, permitting a jet column to advance large distances without much spreading.

Such observations are in support of the so-called Helmholtz instability (Lamb, 1945, p. 374) which is very gradual and permits long, relatively uniform filament flows. Therefore, if the unsteady jet boundary is not unstable, turbulent diffusion into surrounding fluid resembles that from a plate until the turbulence boundary either grows to its steady shape or the jet itself becomes unstable. Equation (A-7) may then be more representative of jet turbulence growth than would ordinarily be expected. Therefore, if Equation (A-7) is interpreted for a submerged jet, u_∞ should be its discharge velocity, and time t should extend from the instant the jet front arrives at a given location x. Rough calculations indicate that the turbulence region about an unsteady jet grows slowly relative to jet penetration distance. Thus, a starting or unsteady jet would be thinner than steady established jet.

For cases in which turbulence and shear are of only small importance, investigation of submerged jets for the limiting case of frictionless liquid is desirable.

4.4 A SUBMERGED JET IN FRICTIONLESS LIQUID

The classical solution for inviscid, irrotational liquid discharge from the end of a pipe into a large [illegible] of identical liquid produces a streamline pattern like that shown in Figure 2-(a). However, this pattern is not usually observed in practice for sharp entrances. Instead, shear effects are active at the corners, causing boundary layer separation, which prevents jet fluid from turning sharply. The observed flow pattern appears more like that of Figure 2-(b). The jet frontal region does not seem to spread or flatten outward substantially. This observation is partially explained from potential flow and kinematical considerations.

Although shear is active in the corner regions of Figure 2, for high Reynolds number flows associated with water the jet boundary divides interior and exterior regions which are relatively free of rotation, and therefore can be analyzed by potential flow methods. Figure 3 shows the jet at some stage after it has entered surrounding fluid. The kinematical boundary condition is obtained by first expressing the interface in the functional form,

$$y_s = y_s(r_s, t) \quad \text{(A-8)}$$

Although jet and surrounding fluid velocities generally will be different across any part of the interface, the normal velocity components must be equal. For the interface expressed by Equation (A-8), the normal unit vector at any instant is given by

$$\vec{n} = \frac{\vec{n}_y - \left(\frac{\partial y_s}{\partial r_s}\right)_t \vec{n}_r}{\sqrt{1 + \left(\frac{\partial y_s}{\partial r_s}\right)_t^2}} \tag{A-9}$$

Velocities of jet fluid (1) and surrounding fluid (2) adjacent to the interface at r_s, y_s are respectively

$$\vec{v}_1 = u_1 \vec{n}_r + v_1 \vec{n}_y \tag{A-10}$$

and

$$\vec{v}_2 = u_2 \vec{n}_r + \vec{v}_2 \vec{n}_y \tag{A-11}$$

Equality of the normal velocity components is obtained from

$$\vec{v}_1 \cdot \vec{n} = \vec{v}_2 \cdot \vec{n}$$

which results in the kinematical interface condition

$$\left(\frac{\partial y_s}{\partial r_s}\right)_t = \frac{v_2 - v_1}{u_2 - u_1} \tag{A-12}$$

Equation (A-12) expresses the interface slope at time t. If $(\partial y_s/\partial r_s)_t > 0$, jet fluid bulges outward, whereas if $(\partial y_s/\partial r_s)_t < 0$, the jet rounds inward. In order to determine $(\partial y_s/\partial r_s)_t$, velocity components u_1, v_1 and u_2, v_2 are required. However, a qualitative consideration, assisted by known steady potential flow results, may be adequate for determining the sign of $(\partial y_s/\partial r_s)_t$.

Suppose the jet enters as a cylindrical liquid plug, shown in Figure 4-(a). Inside the plug, $v_1 > 0$ and $u_1 = 0$. It can be reasoned that at A, surrounding liquid velocity is $v_2 = v_1$ and $u_2 = 0$, whereas on A-B, $v_2 = v_1$ and $u_2 > 0$. Thus, from Equation (A-12), the surface tends to remain flat on A-B. On B-C, $u_1 = u_2 = 0$ and $v_1 > v_2$, corresponding to an infinitely steep boundary. Ideally, a flat cylinder would penetrate with unchanged shape. Surprisingly, penetrating cylinders have been observed in movies of submerged water jet discharge.

Next, suppose that A-B-C in Figure 4-(b) is slightly rounded. Along the entire surface except precisely at A, $v_1 > v_2$ and except at C, $u_2 > u_1$. It follows from Equation (A-12) that $(\partial y_s/\partial r_s)_t < 0$, and the negative sloping interface is a valid configuration.

Finally, suppose that A-B-C in Figure 4-(c) is slightly bulged. Surface A-B would be valid from the previous case. On surface B-C, again, $v_1 > v_2$. However, near C, the surrounding liquid is stagnant whereas the jet liquid is not, implying that $u_1 > u_2$. Equation (A-12) verifies the possibility of a positive slope of B-C, and indicates that a bulged configuration also could be valid.

At this point, Equation (A-12) alone clearly is not sufficient to determine the actual jet frontal shape, but merely implies possible valid configurations. Returning to Figure 4-(a), localized shear would produce high drag at corner B, tending to round it, eventually joining it to a relatively uniform jet shaft to the point of discharge. Therefore, the profile of Figure 4-(b) may be the most probable. The frontal corner shear drag would also help explain a ring vortex which has been observed in films. The vortex, which itself is quite stable, may clear the way for the starting jet to advance as a uniform cylinder.

The foregoing discussion is an attempt to qualitatively explain the observed behavior of submerged starting jets. The remainder of this study is devoted to consideration of a jet whose frontal region has not broadened or slowed considerably due to dynamic coupling with the surrounding liquid.

SHEAR ON THE PENETRATING JET

Shear of surrounding liquid on the penetrating jet would be quite high if the jet entered with initial velocity other than zero. This conclusion is supported by the shear associated with the sudden acceleration of a submerged plane wall parallel to its surface mentioned earlier. However, if the pla~~ all is linearly accelerated with velocity $u = kt$, the shear stress is given by

$$\tau_w = \frac{4k\rho}{g_c} \sqrt{\nu t} \qquad \text{(A-13)}$$

If Equation (A-13) is interpreted for an accelerating submerged liquid jet, it implies that shear which retards the forward motion grows like $\sqrt{t}$. For relatively short times and moderate acceleration, the shear force probably is small enough to neglect.

4.5 MODEL FOR UNSTEADY JET PROPERTIES

Figure 5 shows the submerged jet profile in surrounding liquid of equal density at some stage of its development. Based on the previous discussion, it is assumed that jet liquid forms an elongated column whose transverse dimension is small relative to its length. Therefore, radial velocity at any cross section also is small relative to the axial velocity so that pressure inside the jet is approximately P_∞. That part of the jet behind the frontal region is assumed to be primarily a region of one-dimensional flow with negligible friction on its boundary.

For one-dimensional unsteady flow of an incompressible liquid with time- and space-dependent cross section and forward velocity in a region of negligible pressure gradients, the mass and momentum principles are given by

$$\text{Mass} \qquad \frac{\partial A}{\partial t} + \frac{\partial (AV)}{\partial x} = 0 \qquad \text{(A-14)}$$

$$\text{Momentum} \qquad \frac{\partial V}{\partial t} + V \frac{\partial V}{\partial x} = 0 \qquad \text{(A-15)}$$

Because the jet originates from discharge area A_D, and the discharge velocity is presumed to be a known function of time $V_D(t)$, appropriate boundary conditions are given by

$$A(0,t) = A_D = \text{constant} \tag{A-16}$$

$$V(0,t) = V_D(t) \tag{A-17}$$

When the jet begins discharging from location x = 0, the initial conditions are

$$A(0,0) = A_D \tag{A-18}$$

$$V(0,0) = V_D(0) \tag{A-19}$$

If V is written in the functional form

$$V = V(x,t) \tag{A-20}$$

its differential is given by

$$dV = \left(\frac{\partial V}{\partial x}\right)_t dx + \left(\frac{\partial V}{\partial t}\right)_x dt \tag{A-21}$$

Moving with a jet fluid particle as it travels by setting

$$dx = V dt \tag{A-22}$$

in Equation (A-21), from Equation (A-15)

$$\frac{dV}{dt} = 0 \qquad \text{on the path } \frac{dx}{dt} = V \tag{A-23}$$

Based on the one-dimensional frictionless equations of this section, velocity and cross sectional characteristics are obtained for jets with a given discharge velocity and discharge acceleration.

4.6 CONCLUSIONS

The foregoing considerations show that a submerged liquid jet can penetrate long distances without significant spreading. Moreover, surrounding fluid shear grows slowly so that the retarding force does not strongly decelerate a starting jet. Kinematical considerations suggest that the jet front will tend toward roundness rather than broadening.

4.7 REFERENCES

Lamb, Sir Horace, 1932, *Hydrodynamics*, Dover.

Landau, L. D. & Lifshitz, E. M., 1959, *Fluid Mechanics*, Addison-Wesley

Rouse, H., 1959, *Advanced Mechanics of Fluids*, Wiley.

Schlichting, H., 1955, *Boundary Layer Theory*, New York: Pergamon.

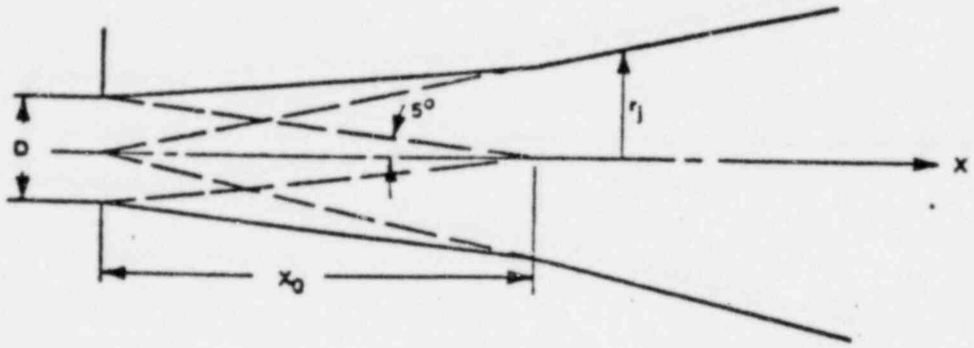


Figure 1. Steady Jet Profile

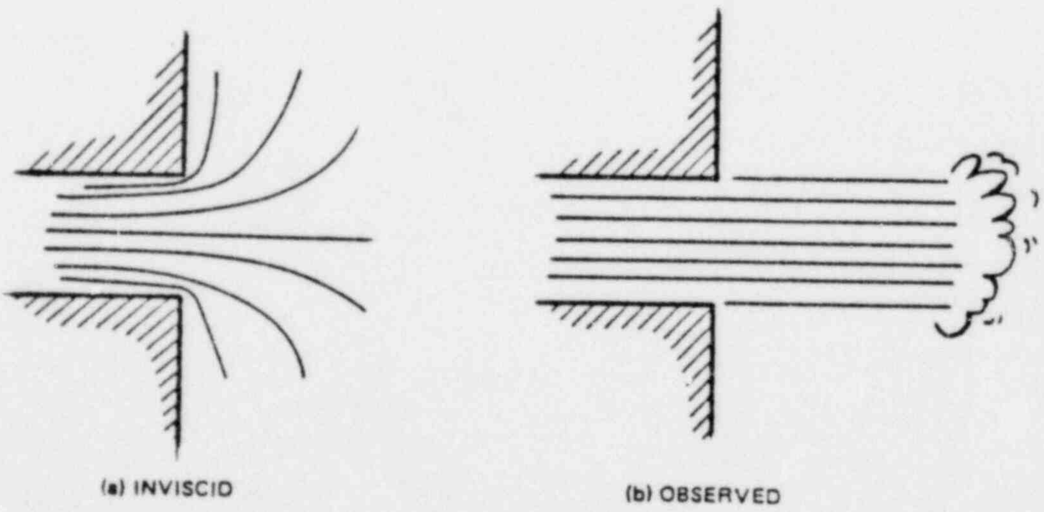


Figure 2. Limiting Jet Profiles

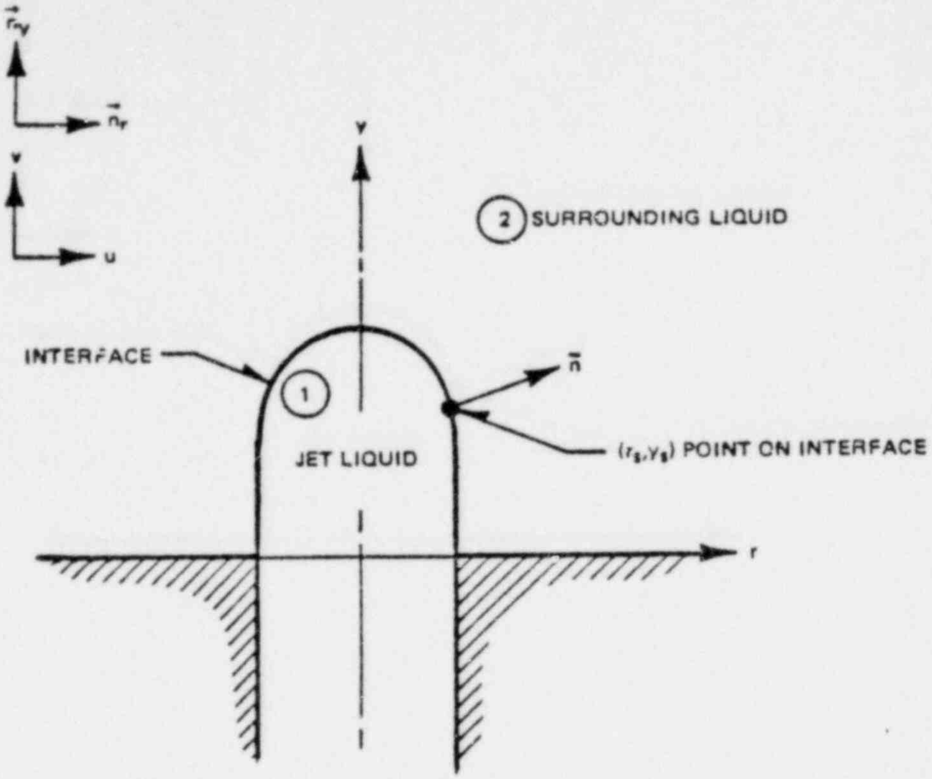


Figure 3. Entering Liquid Region

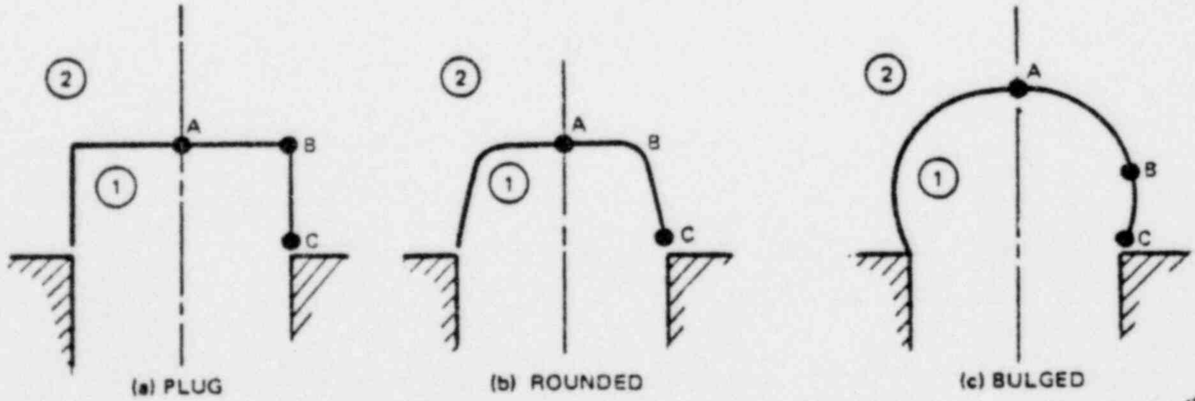


Figure 4. Jet Entry Profiles

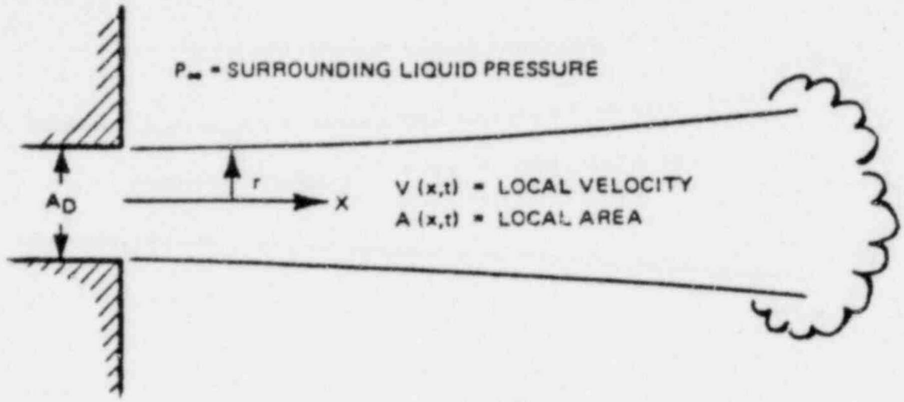


Figure 5. Unsteady Jet Model

NUCLEAR ENERGY DIVISION • GENERAL ELECTRIC COMPANY
SAN JOSE, CALIFORNIA 95125

GENERAL ELECTRIC

TECHNICAL INFORMATION SERIES

TITLE PAGE

AUTHOR	SUBJECT	NO.
F. J. Moody	Nuclear Sciences and Technology	78NED253
		DATE April 1978

TITLE	GE CLASS
Analytical Model for Liquid Jet Properties for Predicting Forces on Rigid Submerged Structures	I
	GOVT. CLASS
REPRODUCIBLE COPY FILED AT TECHNICAL PUBLICATIONS, R&UO, SAN JOSE, CALIFORNIA	NO. PAGES 27

SUMMARY

The unsteady discharge of a water jet into a suppression pool, caused by either a postulated loss-of-coolant accident (LOCA) or a safety relief valve (SRV) actuation. This study provides a method for calculating submerged jet velocity and cross-sectional area arriving at a given structure in terms of the jet discharge properties.

By cutting out this rectangle and folding on the center line, the above information can be fitted into a standard card file.

NED DOCUMENT NUMBER NEDO-21472

INFORMATION PREPARED FOR Nuclear Energy Projects Division

TESTS MADE BY Applied Mechanics

COUNTERSIGNED ______ SECTION ______

BUILDING AND ROOM NO. 940 LOCATION M/C 186