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ANALYTICAL MODEL FOR ESTIMATING DRAG FORCES ON RIGID SUBMERGED STRUCTURES CAUSED BY CONDENSATION OSCILLATIONS AND CHUGGING

MARK III CONTAINMENTS

L. E. LASHER

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L. E. Lasher

Reviewed: H E Townsend

H. E. Townsend, Manager
Containment Methods

Approved: H E Townsend ACTIN FOR A E ROGERS

A. E. Rogers, Manager
Containment Technology

Approved: J. Jacobson 8/10/79

J. Jacobson, Manager
Reactor and Containment Design

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

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ABSTRACT

This report presents analytical models to calculate the condensation- and chugging-caused forces experienced by rigid structural members. The analytical formulation is provided to give the acceleration drag amplitudes resulting from the flow that is induced by the condensation and chugging processes. The basic flow-field method applies to the condensation oscillation phase. Chugging loads for the horizontal-vent Mark III system are transmitted acoustically and, therefore, are modeled differently. For the chugging loads a procedure is provided to calculate the force transferred by a reflecting pressure wave.

1. INTRODUCTION

The pressure-suppression concept of containment utilizes the phenomenon of steam condensing into a large pool of water. The condensation process begins after the vent is cleared of water and the drywell air has been carried over into the suppression chamber. Experiments have revealed that there are two distinct condensation regimes that occur during a blowdown. The initial phase of condensation, called condensation oscillation, has a high to medium mass flux. The second phase begins when the mass flux drops below a certain minimum value and is denoted as chugging. Chugging is characterized by a low and intermittent mass flux that manifests itself as a series of pulses that repeat in a more or less regular fashion.

For computing loads on submerged structures, the condensation process has been broken into these two regimes: a quasi-steady oscillatory condensation state and a chugging state.

The basic flow model utilized in this report derives from the work in Reference 1, where the flow field is assumed to be locally uniform and unsteady. This environment produces a standard (velocity-squared) drag plus an acceleration (pressure-gradient) drag. It is assumed that the condensation processes induce a bulk pool motion that results in a drag force.

Preliminary considerations indicate that the condensation loads on submerged structures are primarily the consequence of acceleration drag. This drag results from the pressure gradient associated with the local fluid acceleration caused by the condensation oscillations. For most structures the standard velocity drag adds an insignificant contribution. This is not surprising since the velocities during condensation are small at all locations except immediately adjacent to the vent exit; this conclusion was based on the results of a computer code that models the condensation processes by a fluid source. The velocity falls off approximately as the inverse square of the distance from the source, thus being greatly attenuated even at the location of nearby structures. The standard drag, in addition, is proportional to the square of the velocity making the force attenuate as the inverse fourth power of distance removed from the source, resulting in small standard drag loads for structures not immediately adjacent to the vent exit. The methods of Reference 1 can be used to calculate the standard drag for structures situated closer to the vent exit.

The predictions given by this model are based on the data obtained from the General Electric (GE) Pressure Suppression Test Facility (PSTF) tests.[2,3,4]

The condensation oscillation process is portrayed by a source located at the vent exit.

The chugging process is portrayed by a wave propagation through the pool water. The origin point of this wave is located at the bubble collapse site, some distance above the uppermost vent. No chugging is observed for any horizontal vent other than the top one.

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 contains Appendices A and B, which include detailed derivations and formulations of the methods summarized in the first section.

2. MAJOR ASSUMPTIONS

Calculation of the acceleration drag force is based upon the assumption of a locally uniform flow field. Assumptions relating to the model given in Reference 1 also apply to this model.

The submerged structures are assumed to be rigid.

Condensation oscillation is modeled by means of point sources located at the vent exit.

The strength of the source for condensation oscillation is determined from measured wall pressure values in the tests performed in Reference 2.

Chugging is modeled as an acoustic-wave propagation. The short duration of the pressure pulses measured at the wall and the delay times observed at nearby pressure taps indicated the presence of acoustic wave phenomena.

The pulse strength and duration of the acoustic wave are assumed to be the same as the most severe case measured in Reference 2.

3. SUMMARY

3.1 DRAG ON SUBMERGED STRUCTURES

The methods used here follow very closely those used to predict drag forces caused by a loss-of-coolant accident (LOCA) and safety relief air discharges.[1]

The acceleration drag, F_A, is given by

$$F_A = \frac{\rho \dot{U} V_A}{g_c} \tag{3-1}$$

where

ρ = pool water density

$\dot{U}$ = equivalent uniform flow acceleration

and

V_A = acceleration drag volume[1]

The acceleration flow field is calculated by

$$\dot{U} = \dot{S} \frac{1}{r_{eff}^2} , \tag{3-2}$$

where

$$\frac{1}{r_{eff}^2} = \sqrt{X^2 + Y^2 + Z^2} \tag{3-3}$$

and

$$X = \sum_{k=-\infty}^{\infty} \sum_{j=-\infty}^{\infty} \sum_{i=-\infty}^{\infty} \frac{(-1)^j (x-x_i)}{{r_{ijk}}^3}$$

$$Y = \sum_{k=-\infty}^{\infty} \sum_{j=-\infty}^{\infty} \sum_{i=-\infty}^{\infty} \frac{(-1)^j (y-y_j)}{{r_{ijk}}^3}$$

$$Z = \sum_{k=-\infty}^{\infty} \sum_{j=-\infty}^{\infty} \sum_{i=-\infty}^{\infty} \frac{(-1)^j (z-z_k)}{{r_{ijk}}^3}$$

The source strength, $\dot{S}$, is related to the wall pressure by

$$\dot{S} = \frac{P_{wall}}{\rho \; f(r)} \tag{3-4}$$

where

$$f(r) = \sum_{k=-\infty}^{\infty} \sum_{j=-\infty}^{\infty} \sum_{i=-\infty}^{\infty} \frac{(-1)^j}{r_{ijk}}$$

The definitions of the symbols are given in the Nomenclature in Section 4. The derivations of Equations (3-2) through (3-4) are given in the Appendices.

3.2 CONDENSATION OSCILLATION

A determination is made at the outset about the number of vents that are to be considered in the load computation for condensation oscillation. Using the vent nearest to the submerged structure as a reference value, the relative magnitudes of $1/r_{eff}^2$ [Equation (3-3)] for all the nearby vents are calculated. The magnitude of $1/r_{eff}^2$ measures the attenuation with distance of the acceleration field. For the case of an infinite pool, $r_{eff} = r$, the actual distance between the point of interest and the source. In order to account for the finite pool effects of the various boundaries on the acceleration field, the method of images is incorporated. A discussion of the procedure used to obtain r_{eff} in a finite pool is given in Appendix A. As determined by this calculation, consider only those vents for which $1/r_{eff}^2$ is greater than a certain fraction, f, of $1/r_{eff}^2$ for the nearest vent. The fraction, f, is chosen small enough so that the total error produced by disregarding the contributions from the neglected vents is acceptably low. In making the above calculation a single vent is assumed to influence the whole suppression pool so that the dimension D used in the method of images represents the mean circumferential dimension of the whole pool.

The source-strength magnitudes associated with each vent are next assigned. For the oscillatory condensation phase the maximum value of source strength derived from experimental data of Reference 2 is taken. Equation (3-4) relates the source strength to the measured wall pressures.

The acceleration field resulting from the combination of vents is then obtained by using vector addition of the fields induced by the individual vents in the whole pool.

The pressure time history and frequency content of the equivalent sources are based upon containment wall pressure data.[2]

3.3 CHUGGING

Test results given[2] and flow visualizations[3] indicate that the pressures measured at the wall are a result of the bubble collapse at or near the pool side of the drywell wall. The short duration of this pulse ($\sim$2 ms) suggests that the loading due to chugging in Mark III should be analyzed as acoustic-wave propagation rather than bulk-pool motion. The importance of acoustic effects can be estimated for an unsteady flow by comparing the acoustic propagation time to the problem disturbance time. Following Reference 1, the acoustic propagation time is defined as the time required for an acoustic wave to travel a characteristic distance L at sonic speed c, namely L/c. If the problem disturbance time is t_∞, then the condition $t_\infty \leq L/c$ means acoustic effects must be accounted for. Conversely, if $t_\infty > L/c$ then the disturbance propagation and reflection throughout the liquid is sufficiently fast that acoustic effects are negligible perturbations on a bulk flow field. For the Mark III containment, L is taken as the distance from the vent exit to the containment wall, i.e., $L \sim 20$ ft, with $c \sim 4000$ fps, $L/c \sim 5$ ms and $t_\infty \sim 2$ ms so that acoustic effects should be considered. In the condensation-oscillation phase, t_∞ is the period of oscillation, i.e., $t_\infty \sim 100$ ms thereby making acoustic effects unimportant.

On the basis of a 1/r spherical wave attenuation, the location of the bubble center was calculated and found to be situated above the top vent from the 1/3 area scale data.[2]

The force on the submerged structure is obtained from the following equation:

$$\frac{F_C}{A} = \frac{2(\Delta P_o r_o)\sin\theta}{r} = 2\frac{\rho\dot{S}}{g_c}\quad\frac{\sin\theta}{r} \tag{3-5}$$

where $(\Delta P_o r_o) = \dfrac{\rho\dot{S}}{g_c}$ is the pulse strength of the wave in psi-ft; r is the distance in feet from the bubble center to the structure; θ is the angle between the propagation direction and the structure; A is the projected area of the structure and F_C/A is the chugging force per unit projected area in psi (cf, Figure 3-1).

The time history of the chugging is based upon PSTF test results.[2,4]

The number of vents considered for chugging is based on a calculation of geometric attenuation. Consider only those vents whose chugging attenuation is no less than a certain fraction, f, of the attenuation from the nearest vent. Add vectorially the loads of all vents considered, recalling that the only vents chugging are the top ones

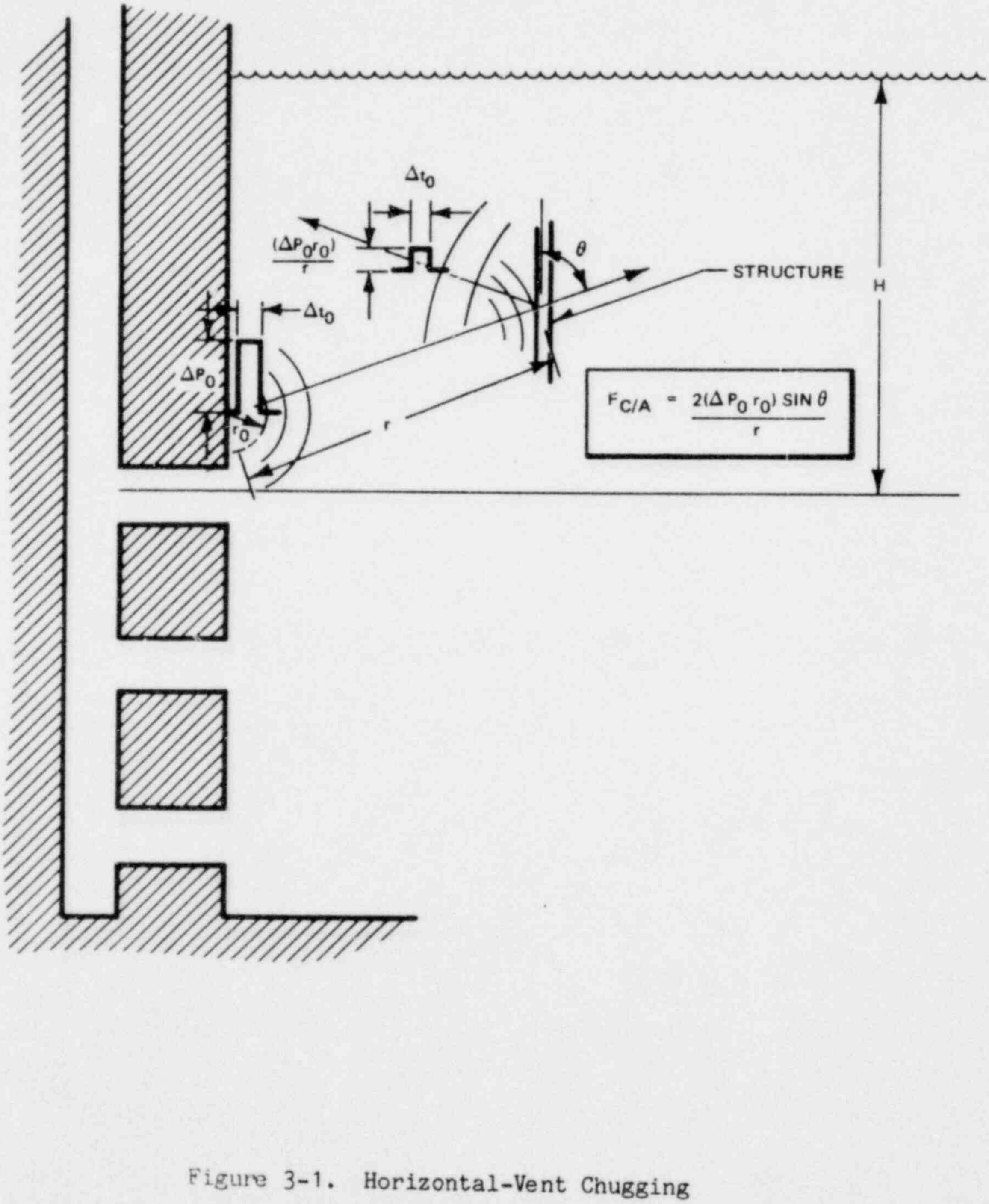

Figure 3-1. Horizontal-Vent Chugging

4. NOMENCLATURE

A	Projected area of structure
C	Sonic speed
D	Characteristic length of suppression pool
f	Distance - attenuation cutoff fraction
$f(r)$	Defined by Equation B-3
F_A,F_C	Acceleration drag force; chugging force
g_c	Gravitational constant
H	Characteristic depth of suppression pool
L	Characteristic width of suppression pool; characteristic distance
P	Wall pressure
$\Delta P_o r_o$	Acoustic wave pulse strength
r	Radial coordinate; distance from bubble center to structure
r_{eff}	Effective radial attenuation distance
$\dot{S}$	Source strength proportional to the rate or change of volume flow from source
t_∞	Problem disturbance time
$\dot{U}$	Equivalent uniform flow acceleration
V_A	Acceleration drag volume
x,y,z	Rectangular space coordinates
X,Y,Z	Variables entering in the determination of $1/r_{eff}^2$; functions of source location, structure location, and pool geometry
$\dot{\phi}$	Acceleration potential
ρ	Liquid density

5. REFERENCES

1. F. J. Moody, L. C. Chow, and L. E. Lasher, **Analytical Model for Estimating Drag Forces on Rigid Submerged Structures Caused by LOCA and Safety Relief Valve Air Discharges**, September 1977 (NEDO-21471).

2. A. M. Varzaly, W. A. Grafton, H. Chang, and M. K. Mitchell, **Mark III 1/3 Scale Tests, Test Series 5807**, March 1977 (NEDO-21596).

3. A. M. Varzaly, **Mark III Small Scale Chugging Tests, Test Series 5013**, September 1977 (NEDO-21529).

4. A. M. Varzaly, W. A. Grafton, D. S. Seeley, **Mark III Confirmatory Test Program Full Scale Condensation and Stratification Phenomena Test Series 5707**, August 1978 (NEDE-21853-P).

APPENDIX A
METHOD OF IMAGES

Since friction effects are restricted to comparatively thin boundary layers, and acoustic effects of water can only moderate the drag forces because they themselves dissipate part of the energy, the flow of water inside a pressure suppression pool can be described by the irrotational flow equations (A-1) and (A-2).

$$\nabla^2\phi = 0 \tag{A-1}$$

$$\rho \frac{\partial\phi}{\partial t} + \rho \frac{(\nabla\phi)^2}{2} + P + \rho g z = C(t) \tag{A-2}$$

where ϕ is the velocity potential. At the free surface, the pressure is assumed to be static, therefore, C(t) can be chosen to be a constant.

Equation (A-2) can be simplified by splitting the fluid pressure P into a dynamic component and a static component:

$$P = P_{dyn} + P_{stat}$$

where

$$P_{stat} = -\rho g z + C$$

$$P_{dyn} = -\rho \frac{\partial\phi}{\partial t} - \rho \frac{(\nabla\phi)^2}{2} \tag{A-3}$$

In Equation (A-3), P_{dyn} is the pressure in reference to the local net static pressure. In the rest of the discussion, P stands for P_{dyn}.

A collapsing bubble is assumed to be represented by a spherical point source at the vent exit. For an infinite pool,

$$\dot{\phi} = - \frac{\dot{S}(t)}{r} \tag{A-4}$$

where S is the source strength, which is proportional to the rate of change of volume flow from the source.

The effect of pool boundaries is simulated by creating an array of virtual image sources and the effect of free surface is simulated by creating an array of virtual image sinks. Following Reference A-1, for a rectangular box with a free surface,

$$\dot{\Phi} = - \dot{S} \sum_{k=-\infty}^{\infty} \sum_{j=-\infty}^{\infty} \sum_{i=-\infty}^{\infty} \frac{(-1)^j}{r_{ijk}} \tag{A-5}$$

where

$$r^2{}_{ijk} = (x-x_i)^2 + (y-y_j)^2 + (z-z_k)^2$$

The position of a source or sink, (x_i, y_j, z_k) is

$$\begin{aligned} x_i &= 2iL \pm x_o \quad ; \quad i = 0, \pm 1, \pm 2, \ldots \\ y_j &= 2jh \pm y_o \quad ; \quad j + 0, \pm 1, \pm 2, \ldots \\ z_k &= 2kD \pm z_o \quad ; \quad K = 0, \pm 1, \pm 2, \ldots \end{aligned} \tag{A-6}$$

where L, D, and H are rectangular box dimensions shown in Figure A-1. The acceleration magnitude is

$$|\dot{V}| = |\dot{\nabla}\Phi| = \dot{S} \frac{1}{r_{eff}^2} \tag{A-7}$$

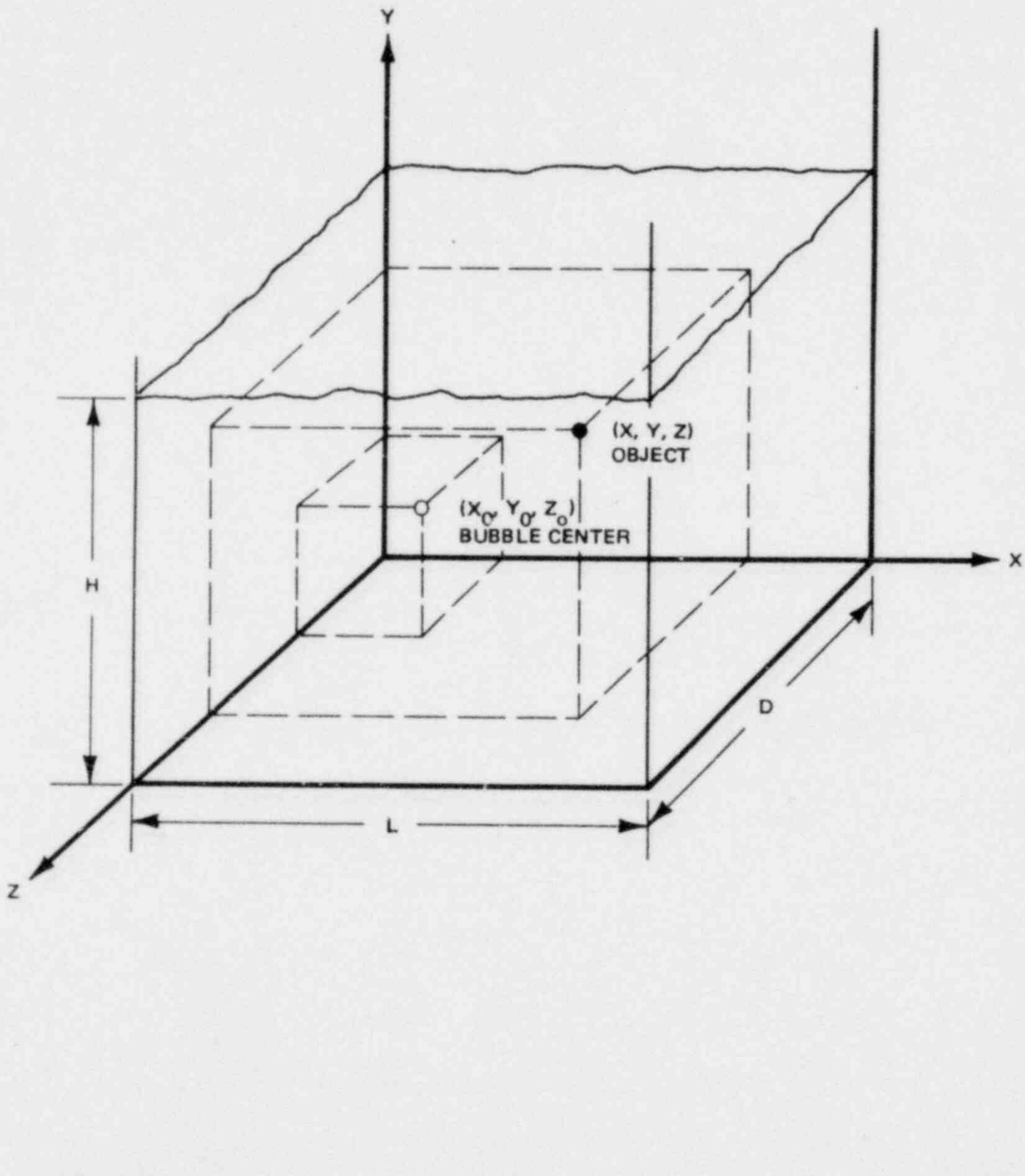

Figure A-1. Rectangular Box Formed by Four Vertical Walls, a Horizontal Floor, and a Free Surface where

$$\frac{1}{r_{eff}^2} = \sqrt{X^2 + Y^2 + Z^2} \tag{A-8}$$

and

$$X = \sum_{k=-\infty}^{\infty} \sum_{j=-\infty}^{\infty} \sum_{i=-\infty}^{\infty} \frac{(-1)^j (x-x_i)}{r_{ijk}^{\;3}}$$

$$Y = \sum_{k=-\infty}^{\infty} \sum_{j=-\infty}^{\infty} \sum_{i=-\infty}^{\infty} \frac{(-1)^j (y-y_j)}{r_{ijk}^{\;3}}$$

$$Z = \sum_{k=-\infty}^{\infty} \sum_{j=-\infty}^{\infty} \sum_{i=-\infty}^{\infty} \frac{(-1)^j (z-z_k)}{r_{ijk}^{\;3}}$$

The nondimensional form $1/\bar{r}_{eff}^2 = L^2/r_{eff}^2$.

The source strength, $\dot{S}$, is determined in Appendix B.

The unit vector designating the direction of the acceleration is given by

$$\vec{n} = \frac{\nabla\dot{\phi}}{|\nabla\dot{\phi}|} = \frac{1}{\sqrt{X^2 + Y^2 + Z^2}} \left(X\vec{n}_x + Y\vec{n}_y + Z\vec{n}_z\right) \tag{A-9}$$

REFERENCES

A-1. F. J. Moody, L. C. Chow, and L. E. Lasher, **Analytical Model for Estimating Drag Forces on Rigid Submerged Structures Caused by LOCA and Safety Relief Valve Air Discharges**, September 1977 (NEDO-21471).

APPENDIX B

DETERMINATION OF SOURCE STRENGTHS

The source strengths, $\dot{S}$, are determined from the wall pressure measurements from PSTF 1/3-area scale tests.[B-1]

From Equation (A-5) in Appendix A, the acceleration potential, $\dot{\phi}$ is:

$$\dot{\Phi} = -\dot{S} \sum_{k=-\infty}^{\infty} \sum_{j=-\infty}^{\infty} \sum_{i=-\infty}^{\infty} \frac{(-1)^j}{r_{ijk}} \tag{B-1}$$

Assuming that, near the wall, the velocity term in Equation (A-3) is small, then

$$\begin{aligned} P_{wall} &= -\rho\dot{\phi} \\ &= \rho\dot{S} \sum_{k=-\infty}^{\infty} \sum_{j=-\infty}^{\infty} \sum_{i=-\infty}^{\infty} \frac{(-1)^j}{r_{ijk}} \end{aligned} \tag{B-2}$$

Hence, $\dot{S}$ can be determined after the geometric factor on the right of Equation (B-2) is known.

$$\dot{S} = \frac{P_{wall}}{\rho\ f(r)} \tag{B-3}$$

where

$$f(r) = \sum_{k=-\infty}^{\infty} \sum_{j=-\infty}^{\infty} \sum_{i=-\infty}^{\infty} \frac{(-1)^j}{r_{ijk}}$$

For the PSTF Mark III 1/3-area scale tests, pressure measurements were made on the containment wall at a 2-foot elevation from the basemat. The corresponding f (r) at the same location is found to be 1.68 feet^{-1} for Mark III.

REFERENCES

B-1. A. M. Varzaly, W. A. Grafton, H. Chang, and M. K. Mitchell, **Mark III 1/3 Scale Tests, Test Series 5807**, March 1977 (NEDO-21596).

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SUMMARY

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