NON-PROPRIETARY VERSION

REVIEW OF HYDRODYNAMIC LOADS ON EMERGENCY CORE COOLING SUCTION STRAINERS

by

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CONTENTS

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Purpose

The purpose of this report is specified by NRC as: *"To review the appropriate Topical reports and any other relevant data on hydrodynamic loads on submerged structures provided by NRC." "This detailed review may involve the assessment of the validity of the correction factors used for the Keulegan-Carpenter numbers developed by others, and participation at meetings and/or conference calls in support of the Division of Systems Safety and Analysis of NRC."* NRC has further stated that *"The ultimate purpose of these reviews, analyses, and meetings is to provide sound technical advice to NRC on unsteady flow about specific types of strainers and, in particular, on the prevailing Keulegan-Carpenter numbers and acceleration drag so that NRC can perform its regulatory duties in the light of the expert opinion and complete its review of the strainers under their consideration."*

NRC has condensed the foregoing into two tasks: (1) To *"provide an expert opinion of typical values of the Keulegan-Carpenter number, K, and the acceleration drag coefficient, C_m, for structures similar to the GE stacked disk strainers under the conditions expected following a loss-of-coolant accident (LOCA) and safety/relief valve (SRV) discharge,"* and (2) To *"provide an expert opinion of the validity of the correction factor for the Keulegan-Carpenter number developed by Bliss and Franzoni (Attachment 4 of GE's August 8, 1999 letter to the NRC)."*

Preliminary Remarks

This report contains references to NRC, GE and the consultants of GE and NRC. It must be clearly understood that in these citations the undersigned does not refer to the entire NRC, GE or many consultants they may have had on other issues. Obviously, we refer here only to those departments or sections of GE and NRC and their consultants who were directly involved with the subject matter specified by NRC. Henceforth, the undersigned will be referred to as TS.

Several important facts must be emphasized: (a) TS is neither an employee of nor a consultant to NRC; (b) TS did not solicit the review performed herein, (c) This work is performed as part of an inter-agency agreement between two Government institutions in one of which TS serves as a Government employee; (d) It is not the purpose of TS to prove that the GE's stacked strainers are safe or unsafe; (e) The purpose of TS is to serve as a **referee** (as, e.g., reviewing a technical paper or report critically and scientifically), and nothing else (TS has some experience in reviews of this type. He reviewed over 3,000 papers for hundredths of journals during the past 40 years); (f) This report is based on the review of the material provided by NRC (about 3000 pages of voluminous material which contains very little factual information). Some of it is proprietary and TS is sworn, as a Government employee, to uphold and respect the integrity and the proprietary nature of the papers, figures, tables, reports, and any other information so identified by NRC, GE, and their consultants. Otherwise, TS has not introduced into this report any classified or proprietary information; and, finally, (g) the statements made herein by TS are strictly of his own and do not under any conceivable circumstances reflect the opinions of the Government or the Government Institution with which he is associated.

BACKGROUND INFORMATION

1. Governing parameters for a porous body subjected to sinusoidally-oscillating flow in a liquid

Consider a porous body of mass M_a (in air) and displaced volume (of its solid parts) V_s (= M_a/ρ_w) in a fluid of density ρ_w and viscosity ν_w. Assume that it is **subjected to a sinusoidal motion** with an amplitude A and single frequency f *(dictated by LOCA&SRVD events).* It should be noted that the frequency of the **imposed** fluid motion has nothing to do with the "in-water natural frequency f_n", (the first mode) of the body. If f and f_n are equal or close enough in direction and magnitude, the body may undergo self-excited oscillations, depending on its damping. [redacted]

The parameters governing the motion, (i.e., defining the force experienced by the body or the force-transfer coefficients), in general, are

A	Amplitude of **flow** oscillation
C_a	Added mass coefficient in general
C_{ao}	Added mass coefficient referred to V_o, (see Eqs. 9 & 11)
C_D	Drag coefficient
C_m	Inertia coefficient, (see Eq. 10)
D	Characteristics diameter of the body
d_h	Diameter of the hole (assumed to be uniform)
F	Force acting on the body
f	Frequency of flow oscillation
f_n	Natural frequency of the **body** in water

K_D $= 2\pi A/D$, Keulegan-Carpenter number

LOCA Loss of Coolant Accident

L_h Length of the hole (uniform)

Orientation of the body: Assumed to be fixed

P_{or} Porosity (assumed to be uniform)

Re_D $= U_m D/\nu$, Reynolds number

SRVD Safety-Relief-Valve Discharge

Shape of the body: Assumed to be a rigid perforated shell (no **large** deformations, as e.g., in the case of a bubble during its motion)

U_n Normal component of velocity at a hole

U_m Ambient velocity

V_o Volume bounded by the external surface (as if there were no holes), i.e., $V_o = V_s + V_w$

V_s Displaced volume of the Solid Material (e.g., steel of the Body)

V_w Volume of liquid inside the body and the holes

β_D $= Re_D / K_D = fD^2/\nu_w$ (**frequency parameter**, based on D)

ν_w Viscosity of water

ρ_w Density of water

ω $2\pi f$

Then the normalized force is given by

$$F \,/\left[0.5\rho_w D^2 (\omega A)^2\right] = F\{\, \boldsymbol{P_{or}},\, \boldsymbol{d_h/D},\, \boldsymbol{d_h/L_h},\, \boldsymbol{f/f_n},\, \boldsymbol{V_s/V_o},\, K_D\,(= 2\pi A/D),$$

$$Re_D\,(= \omega A D/\nu_w),\ or,\ \beta_D\,(= Re_D/K_D)\} \tag{1}$$

For a given type of body (e.g., the Duane Arnold strainer), P_{or} , d_h/D , d_h/L_h, V_s/V_o are fixed, and f/f_n is such that the strainer is not likely to be subjected to hydroelastic oscillations at synchronization. Expressing the normalized force F in terms of the remaining parameters governing the motion and the so-called Morison equation, one has

$$\boldsymbol{C}\text{ (drag or added-mass coeff.)} = F(K_D\,,\,\beta_D) \qquad (2)$$

Other suitable combinations of the foregoing parameters are possible. The shape and orientation of the body are assumed to be invariant for a given type of strainer. Otherwise, different sets of force coefficients must be obtained for each orientation and wall proximity conditions.

Equation (2) emphasizes the well-known fact that **pluck or hammer tests must be conducted at the appropriate Keulegan-Carpenter number K_D, dictated by the amplitude of flow oscillations created by LOCA/SRVD, (from the top to the bottom of the strainer) and at the proper flow oscillation frequencies f of LOCA/SRVD**, *not at the natural frequency f_n of the strainer and not at irrelevant Keulegan-Carpenter numbers (often varying from the top to the bottom of the strainer).* These facts are particularly important for perforated bodies because their behavior at relatively small Keulegan-Carpenter numbers and large frequency parameters (β_D) is almost opposite to that of non-perforated bodies. The reasons for this will become increasingly clear as this report proceeds.

The velocity seen by a typical hole on a strainer subjected to LOCA and/or SRVD is proportional to fA and not to f_nA. The dynamics of the flow through the holes plays a major role on the values of the drag and inertia coefficients (to be discussed more later). ***Pluck tests conducted at frequencies f_n are inconsequential and immaterial to the correct determination of the drag and inertia forces acting on a strainer. It has to be emphasized once and***

for all that to understand the phenomena under consideration one has to model correctly both the structure and the fluid motion. Thus, the answer to the question: *"how much displacement is sufficient in a pluck test to determine hydrodynamic mass"* is: Large enough to simulate the flow conditions about the actual strainer at proper frequency f and amplitude A in a suppression pool in accordance with the similarity laws (including the wall-proximity effects) described herein.

Equation (1) may also be used for model tests, should that be desirable. The condition of the surfaces between the holes on a strainer is assumed to be relatively smooth (i.e., not covered by sand or any other metallic deterioration). Otherwise, a model must simulate all the physical characteristics of the actual strainer, i.e., the model should have geometric, kinematic, and dynamic similarity to the actual strainer in the suppression pool. Obviously, incorrectly performed experiments cannot be corrected with approximate calculations based on steady flow assumptions.

It is clear from the foregoing that the porosity P_{or}, the Keulegan-Carpenter K_D, and the 'frequency parameter' β_D play very important roles in the values of the drag and inertia coefficients. The information gleaned from the non-porous bodies cannot be generalized to porous bodies, particularly the dependence of the force-transfer coefficients on K_D (for a given β_D). Normally, the inertia coefficient of a body (say, a non-perforated cylinder) in cross flow reaches a value of 2 (inviscid case) or 2.1 (for the viscous case) for K_D less than about 3 and begins to decrease as K_D $(= U_m/fD)$ increases beyond about 3. For a perforated body, however, the inverse is nearly true. A porous body at smaller Keulegan-Carpenter numbers is no longer in the "inertia dominated" regime, as in the case of solid bodies, because the fluid easily negotiates the holes. Thus, the added-mass (or the inertia coefficient) is in general smaller and its value for a given K_D depends on the value of β_D $(= Re_D/K_D)$. There is sufficient published (Sinha and Moorthy, 1999; Schlichting, 1979) as well as unpublished information to show that the rate of diffusion of vorticity, the thickness of the boundary layer, and the time-dependent wall shear are strongly affected by both K_D and β_D. In other words, data obtained at grossly different K_D and β_D values cannot be used for strainer analysis or comparison purposes. These facts have not been fully recognized in the indiscriminate use of the small-perforated sphere data.

2. Added mass and inertia coefficients for a porous body subjected to sinusoidally-oscillating body- or fluid-motion in a liquid

Let there be a perforated body comprised of a mass M_a (in air) and displaced volume V_s in a fluid of density ρ_w otherwise at rest.

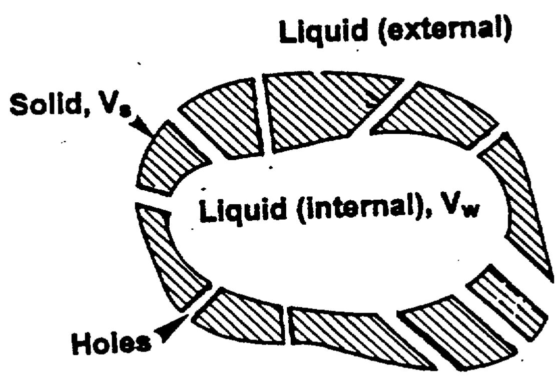

Fig. 1 A representative 3-D perforated body.

Let us define:

V_w = Volume of liquid inside the body and the holes,

V_o = Volume bounded by the external surface of the body (as if there were no holes), i.e., $V_o = V_s + V_w$.

Let this *body accelerate* in a given direction with a uniform acceleration a_x. The total mass accelerated is then given by

$$\sum M = M_a + \alpha \rho_w V_w + \beta \rho_w V_o \tag{3}$$

in which the second term on the right-hand side represents the contribution to the added mass of the motion of the fluid inside the body (holes may be considered as part of the inside or the outside domain). Since the entire internal fluid does not contribute to the added mass (due to the perforations of the body), an unknown fraction α of it is taken where α is smaller than 1. The third term represents the contribution to the added mass of the motion of fluid outside the body. It is assumed, without any approximations (see later), that the contribution to the added mass of fluid motion through the holes (porous wall) is included either in the second term or in the third term or shared between the second and third terms. It will be clear shortly that the experiments can determine only the sum of the last two terms. It is impossible to determine α and β independently (analytically, numerically, or experimentally). However, this is not an impediment to the determination of the total added-mass and inertia coefficients for design purposes.

For a **properly conducted** pluck test in air (at frequencies near *f* and amplitudes *A* of the *sinusoidal fluid motion* to be eventually imposed on a strainer by LOCA/SRVD), one has (in a vacuum)

$$f_a = \frac{1}{2\pi}\sqrt{\frac{k}{M_a}} \tag{4}$$

and for a properly conducted pluck test in water, one has

$$f_a = \frac{1}{2\pi}\sqrt{\frac{k}{M_a + \Delta M}} \tag{5}$$

where

$$\Delta \mathrm{M} = \mathrm{M_H} = \alpha \rho_\omega V_\omega + \beta \rho_\omega V_O \tag{6}$$

Using Eqs. (4) and (5), one has

$$\Delta M = \alpha \rho_w V_w + \beta \rho_w V_o = \frac{k}{(2\pi f_a)^2}\left[\left(\frac{f_a}{f_w}\right)^2 - 1\right] \tag{7}$$

This equation may be normalized by a reference mass. There is no special reason as to why any mass cannot be a reference mass, as long as it is used consistently in all calculations. The use of a *conventional* reference mass such as the mass of fluid within V_o (e.g. density of water times the volume of a sphere or cylinder) or the imaginary fluid mass in a cylinder enclosing a flat plate is more appropriate. The magnitude of the added mass can then be thought of as a fraction of the mass of water displaced by the enclosed volume. This gives one some idea as to how much does the in-vacuum mass of the body increase due to the character of the body and its motion (e.g., perforations, direction of motion, the type of motion, or the combinations thereof). Such information often serves as a first and rough means of judging the accuracy of the experiments. In the case of perforated bodies, common sense suggests that "density of water times the total volume V_o enclosed by the "skin" of the body, i.e., $\rho_w V_o$ be used as the reference mass.

Let us now assume that the reference mass is given by $\rho_w V_r$ where V_r is the reference volume. Then Eq. (7) may be written as,

$$C_{ar} = \frac{\Delta M}{r_w V_r} = \alpha \frac{V_w}{V_r} + \beta \frac{V_o}{V_r} = \frac{k}{(2\pi f_a)^2}\frac{1}{\rho_w V_r}\left[\left(\frac{f_a}{f_w}\right)^2 - 1\right] \tag{8}$$

where C_{ar} is the added mass coefficient in terms of the reference mass $\rho_w V_r$. If the added mass coefficient is expressed in terms of the volume V_o of the body (volume of the external skin or shell of a strainer) times the density of water, then one has

$$C_{ao} = \frac{\Delta M}{\rho_w V_o} = \alpha \frac{V_w}{V_o} + \beta = \frac{k}{(2\pi f_a)^2} \frac{1}{\rho_w V_o}\left[\left(\frac{f_a}{f_w}\right)^2 - 1\right] \tag{9}$$

Clearly, the added mass coefficient can be calculated due to all fluid motions within and exterior to the body (including the holes) *but the individual components of the added mass (due to the internal flow, flow through the perforations, and the flow external to the body) cannot be separated.* If the body is not perforated, then $V_o = V_s$ and $V_w = 0$. In this case, only the external fluid motion gives rise to added mass and the Eq. (9) reduces to $C_{ao} = \beta$. For a non-porous circular cylinder $\beta = 1$. For a porous cylinder, the added mass coefficient reduces to that given by Eq. (9) where α and β cannot be determined independently, as noted above.

If the body is at rest (as in the case of a strainer) and the fluid is in motion (as in the case of SRVD and LOCA), then the acceleration, as in the case of all accelerations, gives rise to a buoyant force to the SOLID parts of the body in the direction of the fluid acceleration. For example, in the case of gravitational acceleration the buoyant force acting on a body totally immersed in water is $B = \rho_w V_s\, g$, {recall that V_s is the actual volume of the solid material (minus all the holes, of course)}. For an acceleration a_x in lieu of 'g', the buoyant force is $B = \rho_w V_s\, a_x$. Then and only then one can speak of an inertia coefficient C_{mo} which combines the added mass and the contribution of the buoyant force, i.e.,

$$C_{mo} = C_{ao} + \frac{\rho_w V_s a_x}{\rho_w V_o a_x} = C_{ao} + \frac{V_s}{V_o} \tag{10}$$

or,

$$C_{mo} = C_{ao} + \frac{V_s}{V_o} \tag{11}$$

In the case of a non-perforated (fully-enclosed) cylinder (regardless of its contents), $V_s = V_o$ and $C_{ao} = 1$, as noted above, and $C_{mo} = 2$.

The definitions of "added mass" and "inertia coefficient" have been used for 50 years or more. However, the Power industry has chosen to use other (often more confusing) definitions, starting in early 70's. The researchers working for GE on LOCA and SRVD scenarios introduced expressions such as "standard drag coefficient," "acceleration drag," "acceleration drag load," "acceleration drag volume," etc. Clearly, there is nothing "standard" about the drag coefficient. "Drag" is used mostly to define the velocity-square-dependent force acting on a body (in Morison's force decomposition) whether the velocity is constant or time-dependent. Acceleration gives rise to an inertial force, not to a "drag." "Acceleration drag load" is another superfluous definition. "Acceleration drag volume, ADV" is a dimensional quantity (volume) and does not allow one to compare the ADVs of various bodies, even if they are geometrically similar. It is because of this reason that a few words will be said about the acceleration drag volume (ADV). It is defined as,

$$ADV(V_{cir}) = \frac{M_H}{\rho_w} + V_s \tag{12}$$

where V_{cir} is the "circumscribed volume of the strainer," M_H is our added mass ΔM [see, Eq. (6)] and V_s is the volume of the "steel in the strainer." In terms of our more universal notation, $ADV(V_{cir})$ reduces to

$$ADV(V_{cir}) = \frac{\Delta M}{\rho_w} + V_s = V_o C_{ao} + V_s = V_o C_{mo} \tag{13}$$

or

$$C_{ao} = \frac{M_H}{V_o \rho_w} \quad and \quad C_{mo} = \frac{ADV(V_{cir})}{V_o} \tag{14}$$

The simplicity and the physical meaning of the universal definitions are clearly evident from the foregoing expressions. In any case, the inertial force acting on the body in the direction of the uniform acceleration is given by

$$F = \rho_w [ADV(V_{cir})] \frac{dU}{dt} \tag{15}$$

or

$$F = \rho_w C_{mo} V_o \frac{dU}{dt} \tag{16}$$

Some additional approximations, limitations, and difficulties encountered in the analysis and experiments will now be pointed out.

In a suppression pool, the bubble fluctuation gives rise to time-dependent loads on the walls of the pool and on the structures in the pool. These loads are **primarily inertial** and the velocity-square dependent drag forces are relatively small. Furthermore, the largest forces occur during the initial stages of the accident, not during the continuous discharge of the flow through the strainer. The uniqueness of the flow discussed herein comes from the fact that the bubble-induced displacements are quite small relative to the size of the submerged body (small Keulegan-Carpenter numbers) but the inertial forces (measured in terms of $a_x D/U^2$ or in terms of β_D) could indeed be very large. The determination of the loading would have been much easier had the body been non-perforated and the flow been uniform. Unfortunately, the bubble-generated flow is not uniform and has *radially expanding* local and convective acceleration components. Thus, the distribution of the acceleration and velocity on a given strainer may be very complex due to the shape, orientation, and torus-proximity or strainer-strainer-torus proximity effects on the flow. In other words, the magnitude of fluid displacement at each hole on a perforated disk and central cone is different and thus the Keulegan-Carpenter is different, i.e., The direction and magnitude of the velocity, acceleration, and displacement at each and every hole is unique. This is in addition to the well-known limitations of the Morison equation. Clearly, it does not make any difference whether the Keulegan-Carpenter number is defined in terms of the hole size (assumed to be uniform) or the strainer diameter. ***The Keulegan-Carpenter number is nowhere the same in a radially-expanding time-dependent flow about a perforated, geometrically complex, and arbitrarily-oriented bluff body in the proximity of a torus.*** Thus, to reduce the radially expanding and oscillating flow about a strainer to that of a uniformly accelerating flow along the strainer (possibly quantified at a single point at the centroid of the strainer) requires some courage, some faith in the so-called expert opinions, and reasonable safety factors. As far as the force calculations are concerned, there is, and perhaps there will always be, some gray area between the reality and the achievables with the current technology. It is clear that the presence of perforations increases the complexity of the problem by an order of magnitude: As Sir Geoffrey Ingram Taylor (a great fluid dynamist of our times) put it ***"Though the fundamental laws of the mechanics of the simplest fluids, which possess Newtonian viscosity, are known and understood, to apply them to give a complete description of any industrially significant process is often far beyond our power."*** In other words: Caveat emptor!

3. General comments on unsteady flow about perforated bodies

The forces acting on perforated or porous **plates and screens in steady flow** are adequately theorized, experimented, and verified [Baines and Peterson, 1951), Carrothers and Baines (1975), Graham (1976), Laws and Livesey (1978)].

The commonly accepted definition for the pressure drop across a hole, based on the equations of energy and momentum, is given by (see, e.g., Baines and Peterson, 1951)

$$\Delta p = \frac{(1-P_{or})}{2C_q P_{or}^2}\rho U_n \,|U_n| \tag{17}$$

where U_n is the normal velocity component at the plate (or at the hole) and C_q is the discharge coefficient of the hole (its value depends on the opening geometry, inclination of the velocity vector, and the Reynolds number). It is clear from Eq. (17) that this is a *quadratic discharge law* and holds true when the hole **Reynolds number is sufficiently large** (larger than about 200, as in the case of strainers, as will be seen later). In cases where the velocity is nearly zero (but not necessarily the acceleration), the pressure drop Δp is proportional to velocity *(linear discharge law)* and is given by the so-called Darcy's law (see,e.g., any elementary fluid mechanics book). For oscillating flows at low Reynolds numbers *(Re_D)*, the recommended resistance law is a sum of the quadratic and linear terms. It will be shown later that Re_D for a strainer is over 300,000 and Re_d is over 1,000. These Reynolds numbers require the use of a *quadratic discharge law.*

A **perforated body** is a rigid hollow shell whose bounding surface is pierced by a distribution of small apertures which allow the near-free passage of fluid. In general, the essential characteristics of flow through a perforation depends on the parameters given by Eq. (1), i.e.,

$$F \,/\, [0.5\rho_w D^2 (\omega A)^2] = F\{\, \boldsymbol{P_{or}},\, \boldsymbol{d_h/D},\, \boldsymbol{d_h/L_h},\, \boldsymbol{f/f_n},\, \boldsymbol{V_s/V_o},\, K_D\,(=2\pi A/D),$$
$$Re_D\,(=\omega AD/\nu_w),\ or,\ \beta_D\,(=Re_D/K_D)\} \qquad (1\text{-R})$$

The porosity, hole size, and *D* determine the relative spacing of the perforations. There are very few experiments and analyses that deal with flow about **shells or bodies** with perforated walls. This is in part due to the highly specialized use of such bodies and partly due to the difficulty of analysis and measurements. It is a well-known fact that the determination of the steady drag force or the dynamic response of a solid (non-perforated) body is a fairly complex problem even though the flow goes only *about* the body. In the case of a perforated body (e.g., a sphere or cylinder) the flow goes partly through the body and partly around the body. Thus, the pressure distribution and, ultimately, the force acting on the body depend on the enormously complex nature of the phenomenon.

For perforated bodies, the effect of flow unsteadiness in general and the added mass in particular have not been subjected to extensive theoretical, numerical, and experimental work. The existing works deal only with highly specialized cases and include the effect of perforations rather indirectly (Howe, 1979). The unsteady flow results show that the added mass depends on both the frequency and the amplitude of oscillation of the flow or the body. There can be no doubt that perforations have a profound effect on the added mass and damping of the body. In general, perforations reduce the added mass since the body becomes partly transparent to the fluid motion.

The most striking differences between a non-perforated and perforated body manifest themselves in time-dependent flows. For a solid body (say, a non-perforated circular cylinder), the added mass (or the inertia coefficient) **does not** depend on β_D for K_D smaller than about 3 (i.e., in the region where the flow does not yet separate). In this region the inertial force is large, drag force is relatively small, and one refers to it as the "inertia dominated regime" for obvious reasons (see, e.g., Sarpkaya & Isaacson, 1981). Thus, one can carry pluck or hammer tests at very small amplitudes **and at any reasonable frequency** ***(not necessarily at the frequency of the flow oscillation)*** *simply because the inertia coefficient does not depend on* β_D. For larger K_D, both the drag and inertia forces become significant and dependent on K_D and β_D and one can no longer carry out pluck tests at arbitrary amplitudes and frequencies. ***Then the amplitudes must be equal to those dictated by the prevailing*** K_D ***values and the frequency of oscillations must be equal to that of the imposed flow if one wants to extract the correct drag and inertia coefficients even for a non-perforated body.***

For a perforated body, the region of very small K_D values is not the inertia-dominated region (it is the drag-dominated region!). **The reason the inertial force happens to be large even at very small** K_D **values** (in spite of relatively small inertia coefficients) **relative to the drag force** (in spite of relatively large drag coefficients) is a phenomenon peculiar only to the suppression pool dynamics: ***Very large initial accelerations and relatively small velocities*** [redacted] To complicate the matters further, the wake of the perforated body (on both sides of the body) is affected by the flow through the body as well as about the body. The flow through the holes causes large amounts of energy dissipation. For example, for a Reynolds number (based on the hole diameter), varying sinusoidally, from zero to 300, the discharge coefficient of the orifice varies from zero to 0.72 (see, e.g., Tuve and Sprenkle, 1933; and Coder, 1974) during any half cycle. In other words, the flow at small K values strongly depends on both K_D and β_D. That is why one cannot perform pluck or hammer tests at arbitrary amplitudes and frequencies. As noted previously, the proper values of the added mass and drag coefficients for a perforated body at relatively small K_D values can be determined accurately only if the body is subjected to the oscillations dictated by K_D and the frequency parameter β_D, i.e., with an amplitude A and the frequency f of the oscillation of the external flow imposed by LOCA/SRVD. Obviously, it is of no special importance whether K_D is based on D or any other diameter. For all that matters, *the Keulegan-Carpenter number* may be based on the hole diameter, the strainer diameter, or even the pipe diameter, as long as the experiments are carried out at the amplitude A and frequency f and plotted with respect to a consistently used Keulegan-Carpenter number.

None of the pluck or hammer tests performed by GE or by its contractors were carried out at the correct amplitudes and frequencies of flow oscillation LOCA/SRVD). Neither the subsequent corrections for perforations through the use of steady flow equations (e.g., momentum), nor the application of the free-streamline theory based on the Schwarz-Christoffel transformations, nor the correction for the free-surface-proximity effects, nor the use of concentric cylinders (for the correction of the lateral confinement effects of an independently vibrating outer container) change the facts deduced from a scientific understanding of the prevailing flow about a very complex body. The pluck and hammer tests described in the reports and documents would have been appropriate if the strainer were a non-perforated body and if the oscillations were carried out at the amplitude of oscillation of the SRVD/LOCA flow, not at the infinitesimal amplitudes of oscillation of the body at its natural frequency. Thus, the hammer or pluck tests so far performed by GE and/or their contractors are irrelevant and immaterial to the assessment of the safety issues raised by NRC in connection with the GE strainers and will not be discussed here further.

4. Howe's (1979) inviscid flow analysis of oscillatory flow about a perforated spherical shell

Howe's analysis is discussed here primarily because it has been linked, rather unfortunately, to the small-scale viscous-flow experiments carried out by TS with a perforated spherical shell and to the analysis of Drs. Bliss & Franzoni. These will be described in more detail later. Suffice it to note that there are other inviscid-flow analyses of oscillatory flow about perforated plates, disks, and cylinders. These will not be discussed in any detail here primarily because they are no more relevant to the strainer issue than the spherical shell.

Howe (1979) carried out an inviscid-flow analysis of oscillatory flow about and through the perforated surface of a rigid spherical shell and found that the added mass is given by

$$\Delta M = \frac{\frac{3}{2}M_o}{\left[1+\frac{3}{\pi}\frac{A_{hole}}{A_{tot}}\frac{R_{sph}}{R_{hole}}\right]} \tag{18}$$

in which ΔM is the added mass, $M_W = \rho_w V_w$, is the mass of water inside the sphere $[(4/3)\pi R_{sph}^3]$, A_{hole}, the total area of the perforations ($A_{hole} = N\pi R_{hole}^2$), N, the total number of holes, A_{tot}, the total area of a solid sphere ($4\pi R_{sph}^2$), $A_{hole}/A_{tot} = P_{or}$ = porosity, R_{sph}, the radius of the sphere, and R_{hole} (= $d/2$), the radius of a single circular hole. Note that $(3/2)M_o$ represents the added mass in the absence of perforations (including the interior fluid), because the analysis accounts for the so-called Froude-Krylov force (buoyant force) due to the pressure gradient to accelerate the flow about the sphere.

Equation (18) may be re-written as,

$$\frac{\Delta M}{M_o} = \frac{\frac{3}{2}}{\left[1 + \frac{3}{4\pi}\left(N\frac{R_{hole}}{R_{sph}}\right)\right]} \tag{18-R}$$

where N is the number of holes, as noted above. It is clear from Eqs. (18) and (18R) that when the dissipative effects (turbulence) are discounted, the presence of surface apertures always reduces the magnitude of the added mass, and therefore the inertial force experienced by the shell in accelerating motion. It is also apparent that for a given porosity ($P_{or} = A_{hole}/A_{tot}$), the inertial mass is diminished further as the aperture radius R_{hole} is decreased, i.e., as the total number of perforations, N increases. Ultimately, the sphere becomes effectively transparent to the incident fluctuating flow. It must be emphasized that Howe's inviscid flow analysis is valid only for $K_D = 0^+$ and β_D = infinity, i.e., it does not apply to any other K_D. In real flows, the viscous effects become important at all K_D and β_D values. This points out to one of the most difficult issues in the determination of the effect of porosity on perforated shells. For extremely small amplitudes, the inertial force (due to added mass) becomes extremely sensitive to the amplitude of the oscillation and to the magnitude of the rather elusive viscous effects (time-dependent shear, flow separation at the circumferences of the holes, vortex shedding, and turbulent energy dissipation). This is why the "strainer" problem has not so far been sufficiently understood, let alone resolved.

5. Wills' (1975) report on perforated Ball Fluid Velocity Sensor

This report, written four years prior to Howe's analysis, is one of the first descriptions of the use of a perforated sphere as a device to measure ocean wave velocities from fixed platforms in the range of Keulegan-Carpenter numbers from about 4 to 30. The hope was that if the inertia coefficient remained independent of the Keulegan-Carpenter number in the range stated, the measure of the instantaneous force acting on the perforated ball, the use of a constant inertia coefficient, and the use of Morison's equation would enable one to determine the magnitude (and the direction with strain gages in two perpendicular planes) of the velocity of waves over a long time period. It was never the intention of either Wills or TS to deal with K_D values smaller than about 4 or to expect high accuracy from a small ball at relatively low velocities, as noted in Wills' letter appended to the report. The data for $K_D < 4$ exhibited large scatter and only the averaged values were shown knowing that ocean structures and waves lead to Keulegan-Carpenter numbers much larger than 4 (the region of $K_D < 4$ for a perforated sphere was of no practical or scientific interest either to Wills or to TS). It is for these reasons that the data for $K_D < 4$ were never published in any report or paper. Wills' report (and the attached figure and letter) were cited only once in a proprietary report submitted to another industry as part of a small contract *to conduct a literature search and to provide a list (with hard copies) of as many papers and reports directly or indirectly related to flow about perforated bodies.* It was never anticipated that any body would ever want to use it 25 years later for the assessment of large cylindrical strainers. The prophecy of the use of such invalidated, unverified, and unpublished data for totally unanticipated and unintended purposes (in the parameter domain far below those appropriate to a non-spherical strainer) would have sounded preposterous.

The data attached to Wills' report have never been used by TS for the assessment of any strainer (or any other object) in any paper, report, or contract. NRC has become aware of its existence through the proprietary report provided to them by the organization for which the report was prepared. Apparently, and most unfortunately, the copies of the report were provided to Prof. A. A. Sonin and GE for their use in the assessment of the GE strainers.

The following facts are provided (posthumously) for clarification. The prototype sphere is made of polypropylene with a diameter of 70 mm and a wall thickness of 1 mm. It is perforated by N = 92 holes of d = 7 mm diameter, almost equally spaced. A sphere of identical diameter but with 91 holes of $\boldsymbol{d}$ **= 6** mm was subjected oscillating flow experiments in May 1975 by TS at the request of Wills (as shown in Wills' report) to determine the drag and inertia coefficients. As noted above, the accuracy of the data for K_D smaller than 4 cannot be ascertained. In other words, the data for $K_D < 4$ are not dependable enough to make a case for the rapid rise of the inertia coefficient in a narrow range of K_D values. It is for the same reason that it would be equally meaningless to attempt to define an "appropriate" K_D value which will support or refute the idea that the inertia coefficient for a GE strainer is larger **or** smaller than some disputed value on the basis of a perforated ball (about 15 times smaller than a GE strainer in the range of entirely different K_D and β_D values).

Unfortunately, Wills' report and the figure attached to it received wide distribution and inappropriate attention for all the wrong reasons. It is now apparent that neither NRC, nor GE, nor their consultants made any effort to ask for the details of the experiments (e.g., an uncertainty analysis) and to question the parameter range *(Re_D, β_D)* of the experiments or to undertake/suggest additional experiments with much larger perforated spherical shells [redacted] in the lower range of K_D values and higher range of β_D values).

The sphere experiments were carried out in an oscillating flow tunnel which had a period of $T = 5.325$ s (i.e., $f = 0.188$ Hz). Using its actual dimensions (D = 70 mm., d(hole) = 6 mm, it is easy to show that the maximum velocity is U_m = 0.01315 K_D, (m/s, where $K_D = U_m T/D$, as usual), and Re_D (Reynolds number = $U_m D/\nu$) =0.01315 K_D x0.07x10^6 = 920 K_D. The Reynolds number for a hole is $Re_d = U_m d/\nu = 0.01315\ K_D \times (0.006) \times 10^6 = 80\ K_D$. Note that kinematic viscosity ν of water is taken to be 10^{-6} m^2/s. Then, for K_D. = 0.1, i.e., with a velocity of 1.3 mm/s through the hole, one has $\boldsymbol{Re_d = 8}$. Obviously, this is an extremely small Reynolds number (nearly, in the Stokes regime) for a slow laminar flow. Even at K = 2, the velocity through the hole is only 2.6 cm/s.

According to a technical note of Dr. A. J. Bilanin (C.D.I. Technical Note 99-12), [redacted] **It must be emphatically stated that it is not the purpose of this report to accept or refute the validity of the magnitudes of f, K(strainer), and K(hole) values reported by Dr. Bilanin.** The sole purpose of the use of the velocities and accelerations derived from them is to show the inappropriateness of the use of the spherical shell data for the strainer case discussed by Dr. Bilanin.

The data tabulated below shows the gross dynamic (as well as kinematic and geometric) dissimilarities between the spherical shell and the Duane Arnold strainer. For larger velocities and accelerations, the dissimilarities become even larger.

For the perforated spherical shell:

$\beta(hole) = fD_h^2/\nu = 6.76$

Re (hole) = 6.76$K(hole)$ = 57.5 [redacted]

$\beta(sph) = fD^2/\nu = 920$

Re (sph) = 920$K(Sph)$ = 22 [redacted]

For the Duane Arnold strainer (DAS):

[redacted]

Obviously, the Reynolds numbers and β values of the two cases are incomparable and strongly discourage the use of the small sphere results (at meager Reynolds numbers and β values) in assessing the hydrodynamic loads on a strainer. Dr. A. A. Sonin's assessment of the inertia coefficients (Report to NRC by A. A. Sonin, dated January 19, 2000) on the basis of such unwarranted comparisons is not in keeping with the fundamental laws of modeling. The use of the small sphere results (in any region of K) is equally invalid in the approximate inviscid/viscous flow analysis of strainers. A perforated circular cylinder of proper size and porosity would have been far more preferable. These will be discussed in more detail later.

Returning once again to the issue of large Reynolds numbers and β values, the answer to the question raised by Dr. John Lynch (in his E-mail to TS on 09/01/98) *"The issue at hand is how much displacement is sufficient in a pluck test to determine hydrodynamic mass"* is, as previously noted above, "Large enough to simulate the flow conditions about the actual strainer at proper frequency f and amplitude A in a suppression pool in accordance with the similarity laws (including the wall-proximity effects) described herein." This requires a thorough analysis and accurate knowledge of the prevailing velocities and accelerations (their magnitudes and directions) along the length of the most representative strainers. It follows that the use of correct velocities, accelerations, inertia coefficients, and the structural details and material properties of the strainer will enable one to calculate the largest (flow-induced) stresses (at the suction piping at torus penetration). There are a number of other loads (e.g., dead weight, seismic loads, pressure and temperature under operating conditions, static torus displacements, pool swell, condensation oscillations, chugging, SRV torus motion loads, pre-chug torus motion loads, etc.) which must be taken into account in calculating the maximum stress. It appears that the application of known loads and measurement of strains on a strainer currently mounted in a suppression pool may be impractical for a number of reasons. However, this would have been the surest way to assess the margin of safety of a strainer: The determination of its load carrying capacity through (load versus strain) measurements and the calculation of the maximum stress due to all conceivable loads that might possibly act on the strainer.

COMMENTS ON VARIOUS REPORTS

(a) Literature search

No effort has been made by GE to seek and peruse the appropriate literature on flow about perforated bodies. Often recourse was made to well-known texts on fluid dynamics which contain nothing about the behavior of porous bodies in time-dependent flows. This hampered the development of proper methodology for the assessment of the strainers. Efforts were channeled towards finding approximate corrections or reduction factors for the effect of porosity and viscosity on the drag and inertia coefficients without the appreciation of the underlying phenomena. The early recognition of the impossibility of reliable theoretical or numerical analysis and the enlightened performance of a series of correct experiments at the right frequency and flow-oscillation amplitude would have achieved all that is desired by all concerned. These facts have been amply stressed in the foregoing sections.

(b) Inviscid-flow approximations (measurements)

Most of the theoretical efforts employed a series of inviscid flow approximations. It has not been fully appreciated that a GE strainer is a very complex body, immersed in a very complex 3-D time-dependent flow. The quantities such as "acceleration volume" and "hydrodynamic mass" were estimated and compared with experiments which were equally approximate (often irrelevant) to the strainer issue. For example, report by Dr. F. J. Moody (NEDC-32721P-Revision 1, February 1997) used an approximate inviscid flow analysis to state that [redacted]

There is no method to assess the impact of the approximations made on the suggested design values. In fact, it is stated in the same report that [redacted] Most interestingly, Dr. Moody used in his Example Force Pressure Calculations [redacted] It has been noted previously that Dr. Bilanin used a maximum acceleration of [redacted] in connection with his calculations of the Duane Arnold strainer. Clearly, the acceleration used by Dr. Moody is almost exactly 2.5 times larger than that used by Dr. Bilanin. It appears to TS on the basis of his nearly 30 years of involvement with loads on structures in pressure suppression pools (Mark I, Mark-II, and Mark-III) that the acceleration value used by Dr. Moody is in better agreement with that which would result from the initial bubble accelerations as large as [redacted]. As noted above, accurate knowledge of the prevailing velocities and accelerations (their magnitudes and directions) along the length of the most representative strainers (i.e., plant unique velocity and acceleration data) and the determination of the appropriate inertia coefficient (for the frequencies and flow amplitudes to be encountered) hold the key to the resolution of the strainer problem.

Only a few brief comments will be made here on pluck and hammer tests carried out by GE and its consultants for the reasons amply described and repeated in the foregoing. The existing tests described in the reports (provided to TS by NRC) are far from satisfactory and cannot provide correct inertia coefficients for the strainers under consideration.

Oscillating the top of the strainer with imperceptibly small amplitudes (or accelerations) while the base is held rigid is not a correct description of the flow about the strainer. Furthermore, carrying out experiments with the said accelerations (with a triangular distribution of minute magnitude) in a tank covered on top with a few inches of water has nothing to do with the acceleration magnitudes and distributions on the actual strainers. Clearly, if one plucks something or hits it on the head, one does get a damping response and an average frequency. But the answer provided by nature is not the answer to the intended question. The hammering of perforated cylinders or strainers in containers that are themselves vibrating in very shallow water in a shaky container and carrying out yet another "correction" analysis (e.g., GENE E22-00110-10, Rev. 0, Class III, August 1997), (assuming that the strainer is in a non-vibrating rigid container), are not in the best interests of quality assurance.

No amount of correction for the water elevation or container confinement or for the vibrations of the container can help to determine the correct inertia coefficient, particularly when such coefficients are highly dependent on fluid-oscillation frequency and fluid-oscillation amplitude i.e., LOCA and SRVD. Suffice it to note that **correct experiments** with **correct parameters** in **proper environments** must and can be conducted. The means and the ideas have been amply described herein. There is convincing evidence from the recent experiments and experiences of other organizations that such tests can be carried out to resolve all the outstanding issues. The proprietary nature of these works does not allow their further discussion here.

(c) Inviscid-flow approximations (Analyses)

Teske - Boschitsch Analysis

The analysis by Drs. Teske and Boschitsch (NEDC-32721P Revision 1, C.D.I. Technical Memorandum No. 97-03, Feb., 1997) has nothing to do with the issue on hand and the realities of the GE strainer. It is for a rigid body in an inviscid fluid, with no holes on the walls and no armature in the conical pipe. No further comments are necessary.

Bliss - Franzoni Analysis

The report by Drs. D. B. Bliss and Linda P. Franzoni (C.D.I. Report No. 99-09), (referred to hereafter as B&F) will now be discussed in some detail after a reminder from **Paul Adrian Maurice Dirac** that "A theory with mathematical beauty is more likely to be correct than an ugly one that fits some experimental data."

As noted earlier, Howe's inviscid flow analysis (1979) is an exact solution (with mathematical beauty) of the spherical–shell problem. It does not and cannot predict a dependence of the inertia coefficient on the Keulegan-Carpenter number. It is valid only for ($K_D = 0^+$, $\beta_D = \infty$). It is rather unfortunate that Howe's contribution of 1979 has escaped the attention of B&F.

A correct inviscid flow analysis of the spherical shell problem does necessarily and invariably reduce to that given by Howe [see the Eqs. (18) and (18-R) herein]. There, is at present, no analytical or numerical solution for a time-dependent VISCOUS flow about a perforated shell and one is not likely to come into existence in the foreseeable future.

It is rather surprising that B&F did not ask for the details of the experiments under which the spherical shell was tested. More will be said later about the new and more precise spherical shell data.

The B&F analysis begins to falter after Eq. (8). There is no need (in an inviscid flow analysis) to assume that the pressure differential across the porous surface is "proportional to the **velocity** through the surface," as in their Eq. (9). In fact, their subsequent approximations lead to a κ value (the "complex flow resistance coefficient") which renders the differential pressure highly nonlinear.

In their Eq. (10), they have thrown out the nonlinear part of the Bernoulli equation [i.e., $-(1/2)(\nabla\Phi)^2$] for no rhyme or reason, by simply stating that "The pressure is given by the linearized Bernoulli equation." **That** simply is not true.

It does not make any mathematical sense to use a linearized Bernoulli equation and then introduce highly questionable nonlinearities into κ, their "complex flow resistance coefficient," to render the differential pressure in Eq. (9) a function of "velocity-square-dependent" nonlinear term and a function of "acceleration-dependent" linear term. The nature of the approximation needs the introduction of the so-called Morison equation (here for a cylindrical object), given by,

$$F(t) = \frac{1}{2}\rho C_d LD\,|U|\,U + \rho C_m L\frac{\pi D^2}{4}\frac{dU}{dt} \tag{19}$$

in which $F(t)$ is the force acting on the body due to the unsteady flow $U(t)$ and L is the length of the cylinder. C_d and C_m are the "Fourier" averaged drag and inertia coefficients (for further details see, Sarpkaya & Isaacson, 1981).

Dividing Eq. (19) by LD, one has a pressure expression given by,

$$p(t) = \rho\left[\frac{1}{2}C_d\,|U| + C_m\frac{\pi}{4}\frac{D}{U}\frac{dU}{dt}\right]U \tag{20}$$

The terms inside the bracket represent the velocity and acceleration-dependent components of the coefficient κ. However, the conceptual similarity stops there. They engage in a series of steady-flow Bernoulli and momentum equations (22-27) to obtain "the equivalent flow resistance coefficient for nonlinear orifice flow." Since they do not know how to deal with the correct solution of the problem, they resort to averaging. First, the time-dependent flow about the sphere is averaged over a cycle, and if, this were not enough, it is then averaged over the surface of the sphere. By this time, there is no truth left in the approximate analysis. Then they conclude that their Eq. (37) gives the inertia coefficient.

Just to give an idea, to any fluid-mechanically as well as mathematically educated reader, we have cut and pasted their numerous expressions to give an idea as to how their Eqs. (17) and (36) will look like

[redacted] (21a)

and

[redacted] (21b)

Clearly, they are still coupled and terribly convoluted.

The use of the non-linearized or full Bernoulli equation (for inviscid flow) would have obviated the need for such unacceptable assumptions. The only correct "pressure differential across the porous surface" for an inviscid fluid is that used by Howe: The full Bernoulli equation [see Eq. (2.21) in Howe]. It must be emphasized once again that the inviscid flow analysis for this flow yields a solution only at ($K_D = 0^+$, $\beta = \infty$). Even though the assessment of the B&F analysis should stop here, comments will be made on the remainder of their analysis for those interested in other assumptions introduced by B&F.

Clearly, Eq. (16) of B&F should have been our Eq. (18) or (18-R), after Howe. The statement leading to Eq. (16) needs to be carefully scrutinized. B&F stated that "The net force on the sphere is found from integrating the pressure differential between the inside and the outside over the spherical surface." This is true exactly only for **an inviscid fluid** or approximately for separated flows at high Reynolds numbers. It is a well-known fact that (see, e.g., Schlichting's "Boundary-Layer Theory," 6th edition, p. 106) in slow oscillatory flows (as in the case of the perforated spherical shell), **"one third of the drag is due to the pressure distribution and that the remaining two thirds are due to the existence of shear."** Obviously, the issue is more complex for double digit Reynolds numbers (not too large, not too small for the perforated sphere). Nevertheless, the fact remains that an important part of the force at relatively small Reynolds numbers cannot be ignored. The analysis of Bliss and Franzoni does not even mention the time-dependent shear force on the skin of the spherical shell (on both the inside and outside surfaces). How could such an analysis which totally ignores the most important part of the force can possibly agree with any properly conducted experiment **"without the introduction of any empirical parameters or corrections, (from B&F, p.1)."**

What emerges from the foregoing is that an attempt has been made to simplify a very complex problem, assuming the fluid to be inviscid at times and viscous at other times. This may have been a consequence of their being provided the original spherical-shell data and their attempt to reproduce it. Unfortunately, the combination of the two does not leave any confidence in the analysis of B&F. One must hasten to add that there are acceptable ways to introduce the effects of viscosity (shear, flow separation, modification of the entire pressure distribution) and other nonlinear effects into an exact inviscid flow analysis, as done over centuries (during the golden days of hydraulics). That is not what is recommended here.

B&F's Eq. (17) attributes a new meaning to κ. It is now stated that "κ is the sum of a linear inertance and a nonlinear flow resistance" in spite of the fact that their Eq. (9) depicts a linear pressure drop. In other words, the linearity or the non-linearity of the pressure drop is dictated by whether the differential velocity is to the first power [as in Darcy's law, as in Eq. (9)] or by the square of the differential velocity as in Howe's analysis {his Eq. (2.21)}. It makes no sense to attribute "nonlinearity" to a resistance coefficient halfway through the analysis. B&F has already decided through the use of their Eq. (9) that the total pressure drop will be linear and that κ is only a resistance coefficient, not another velocity-dependent quantity [as in their Eq. (27)]. This is a rather strange twist in flow analysis where a coefficient is made a function of the local velocity. It can depend only on K_D and β [for a given body shape, and *NR(hole)/R(spr)*, see Howe's analysis]. It must also be noted that what was defined as "where κ is a complex resistance coefficient" (following Eq. (9)), became "... κ is the sum of a linear inertance and a nonlinear flow resistance" {(following Eq. (17)}. This is a misuse of the linear equation given by Eq.(17) where the velocity u is multiplied with a variable coefficient κ, comprised of an acceleration dependent added mass and a velocity-square dependent "nonlinear flow resistance." It is hard to find another example of this type in the annals of fluid mechanics.

Even though not worthy of serious comment, Eq. (19) is an unnecessary approximation. The last term, $(4/\pi^2)$ times the sphere volume of radius *a*, is just a guess and yet it is introduced as ".. and the second term is the hydrodynamic mass of fluid on both sides of the hole." Why is all that hand-waving necessary if the inviscid flow analysis through the proper use of the Bernoulli equation is supposed to account for the truth, as in Howe's analysis.

The assumption of a "fully developed separated orifice flow", shown in their Fig. 3 is unacceptable. It must be noted again and again that *this is a time-dependent flow* with a frequency of about [redacted] and that the oscillating flow about a hole is not like a steady jet but like a series of O-rings, shedding on both sides of the hole, at various angles of inclination. Their steady jet assumption in laminar conditions is not compatible with the unsteady pressure drop across the holes. A flow oscillating through a hole (at relatively high frequencies, as in the case of strainers) does not ever behave like "fully developed separated orifice flows."

Additional assumptions lead to Eqs. (26) and (27). However, the transition from Eq. (26) to Eq. (27) is not mathematically sound either. If the pressure drops due to inertance and non-linear flow resistance was properly introduced into the Eq. (17), one cannot obtain Eq. (27). B&F wrote it down just to get a linear dependence on velocity in Eq. (27).

The foregoing should be more than enough to convince any fluid dynamist that the solution produced by B&F is not, to say the least, fluid mechanically and mathematically sound. It is rather unfortunate that they have repeatedly misstated the facts with the words "Without the introduction of any empirical parameters or corrections….." The fact of the matter is that everything they have introduced beyond Eq. (8) is empirical parameters and corrections. Their neglect of the very important shear force is unpardonable even in a very approximate analysis. B&F did not fully realize that the oscillating viscous flow about a perforated body cannot be solved either analytically or numerically. It is also doubtful that one can reproduce the spherical-shell data (described above) without retrofitting them to an approximate 'hydraulics" analysis.

Finally, to make the matters even more approximate B&F have delved into the world of velocity averaging in all equations beginning with Eq. (28). As noted earlier, such averaging has no meaning here for a number of reasons: (1) the flow "sees" a hole at an inclined angle depending on the position of the hole on the sphere, on the disks, and on the conical surface, as one moves around the bodies or disks, i.e., the velocity is not normal to the said surfaces and varies with the radial position of the holes. Thus, averaging of the velocity over the entire surface of the body does not make any sense.

As far as the strainer is concerned, B&F did not deal with the effects of armature (pressure and shear). They can be very effective in setting greater masses of fluid into acceleration within the body of the conical section and dramatically increase the inertia coefficient. Their prediction that [redacted] is nothing more than hand waving in view of all the numerous assumptions throughout their analysis. They wanted to tackle a very difficult problem (presently, unsolvable), failed even to obtain an exact inviscid-flow solution, and ended up with totally unacceptable confused thoughts, confused analysis of convoluted expressions.

4. Recent Experiments versus Bliss & Franzoni Predictions

During the past year, the original spherical ball provided by Wills has been subjected to extremely careful experiments with better instrumentation, particularly at very low K_D values, using oscillations in air and in water at frequencies as large as 6 Hz. As noted above, the earlier experiments (1975) were conducted at very low frequencies and the measurement of forces was rather difficult and subject to large scatter at relatively small K_D. values. The new data, together with those at higher K_D values, are shown in Fig. 2.

First, it must be emphasized that in this and in all other figures to follow, C_{ao} is the 'inertia coefficient', 'corrected for the buoyant force' (see Eqs. 9 and 11). Figure 2 does not resemble the old data reported in Wills, particularly at K_D values smaller than about 4. The coefficient C_{ao} does not fall below about 1.26 even for K_D values as small as 0.04. This is because of the profound effect of the unsteady shear on the added mass coefficient at high frequencies. Likewise, the drag coefficient continues to rise without any tendency to decrease.

To those interested in mathematics, the importance of viscosity and frequency enters into the added mass (of a rigid sphere) through a term like

$$\frac{9}{2}\left(\frac{\rho\pi D^3}{6}\right)\sqrt{\frac{2\mu}{\rho\omega D^2}}\,\frac{dU}{dt} \tag{22}$$

which can be very large at high frequencies (Sarpkaya & Isaacson, 1981). The issue is, of course much more complex for a perforated body where the holes help to create and diffuse vorticity and dissipate large amounts of energy. As emphatically noted by Howe (1979), "The essential nature of flow through a perforated surface depends on Reynolds number and Strouhal number based on the characteristic aperture diameter, on the spacing of the perforations, and on whether or not the incident flow is turbulent. Choking of the aperture flow may well occur at the extreme of low Reynolds number or in the presence of intense turbulent fluctuations." In short, the inviscid flow analysis yields only a singular point at C_{ao} = 0.5 for $K_D = 0^+$ (for details see Hall's solution and our Eq. 18-R). Such a result has no physical meaning for a perforated sphere in oscillatory viscous flows.

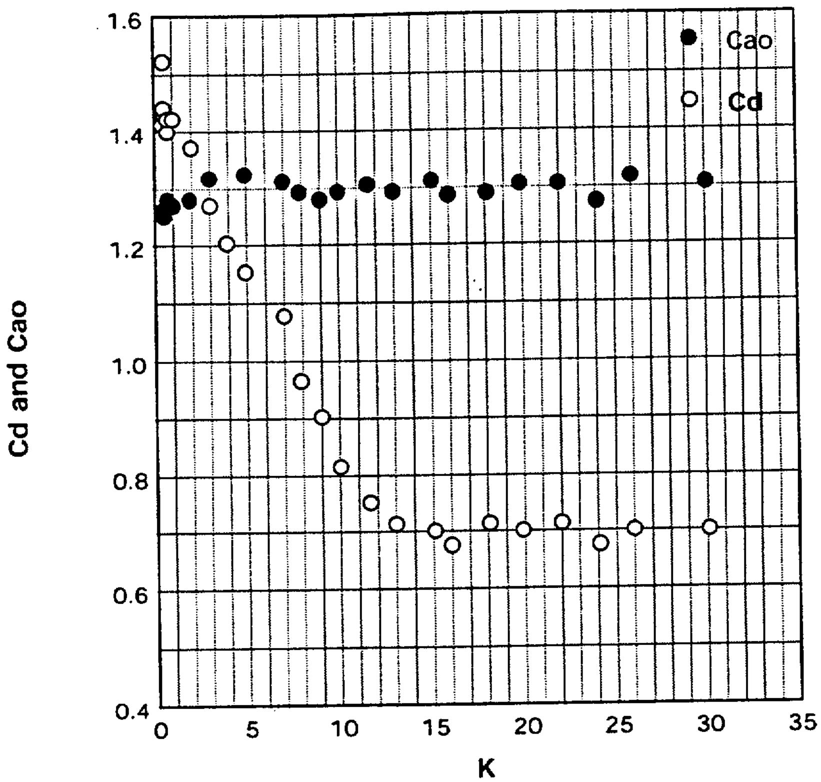

Figure 2 Drag coefficient and the buoyancy-corrected Inertia coefficient for a perforated sphere, originally used by Wills.

(a) Oscillating flow about perforated cylinders

It is because of TS's great interest in unsteady flow in general and in perforated bodies in particular that a series of experiments were undertaken by CDR Osgood (2000) during the period of 9/99 through 9/00, under the direction of TS. These experiments have not been sponsored by NRC and, as noted in the reference to Osgood, the results have been approved for public release and unlimited distribution. Circular cylinders of various sizes and perforations (30%, 28%, 23%, and 51%) were subjected to sinusoidally oscillating flow in a large U-shaped water tunnel (fD^2/ν = 6,400). The perforated skins were rolled from commercially available stainless steel, copper, or aluminum sheets. Particular attention was paid to the joints to make sure that the perforations were continuous and uninterrupted. The force transfer coefficients [drag and inertia (corrected for buoyant force)] were determined in the range of Keulegan-Carpenter numbers from about 0.1 to 40. The results have shown that the effect of the perforations is to decrease the inertia coefficient and to increase the drag coefficient. The limiting value of the inertia coefficient (as K_D approaches zero) strongly depends on the porosity of the cylinder. The displaced relative volume of each cylinder was $V_s/V_o = 0.035$.

A photograph of the cylinders tested is shown in Fig. 3. Note that all cylinders are equal length (L = 914 mm). There was a clearance of 0.2 mm between the tunnel walls and the ends of the cylinder. Tests with different hole size and spacing (for a given porosity) have shown that the drag and inertia coefficients did not strongly depend on the combinations of the hole size/hole spacing.

Representative data from Osgood's work are shown here in Figs. 4 and 5 for the porosities of 30% and 51% only. It is clear that the drag coefficients can reach very high values. It is also clear that C_{ao} strongly depends on the porosity. For a cylinder of 30% porosity, it is about 1.2 at K = 0.18. For a cylinder of 51% porosity, however, C_{ao} decreases to about 0.2 at K = 0.2. In order to fill the gap between the porosities of 30% and 51%, the on-going investigation was extended to several cylinders of 40% porosity. The results of these measurements are shown in Fig. 6. Clearly, C_{ao} has increased to about 0.3 at $K = 0.03$.

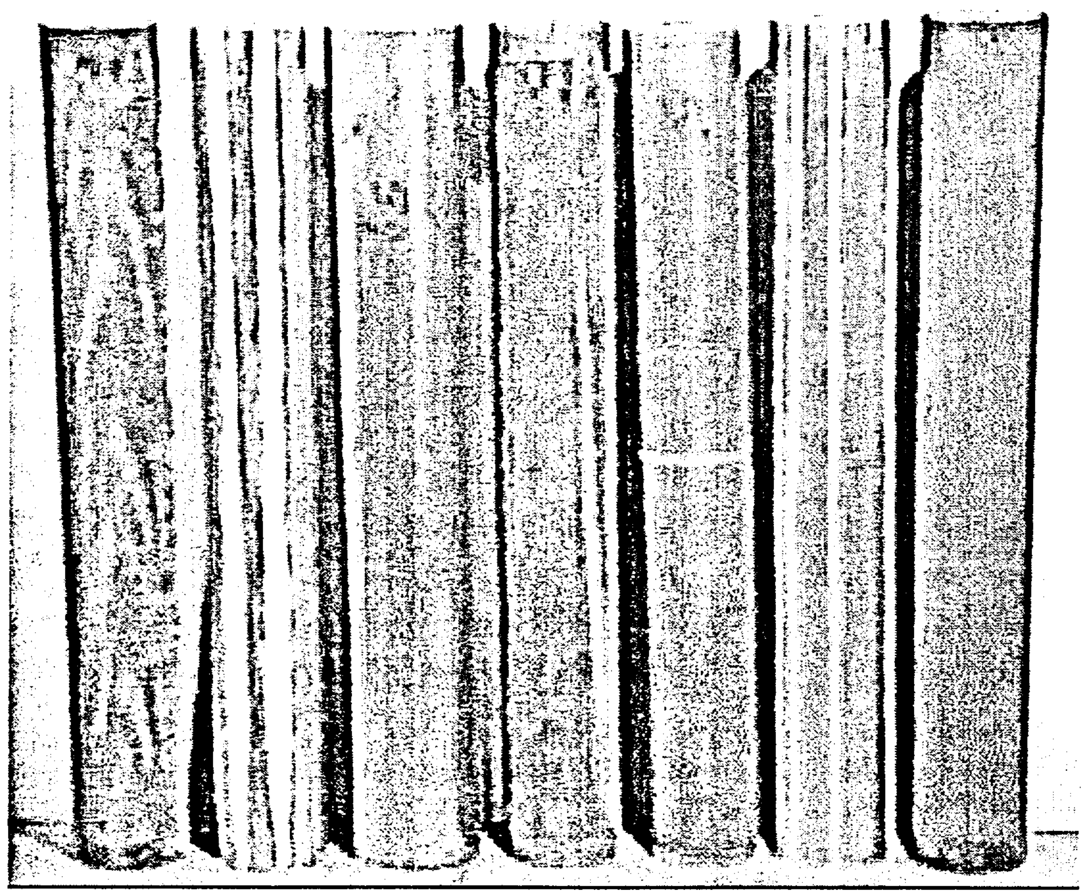

Figure 3. Various perforated cylinders subjected to oscillatory flow in a large U-shaped water tunnel.

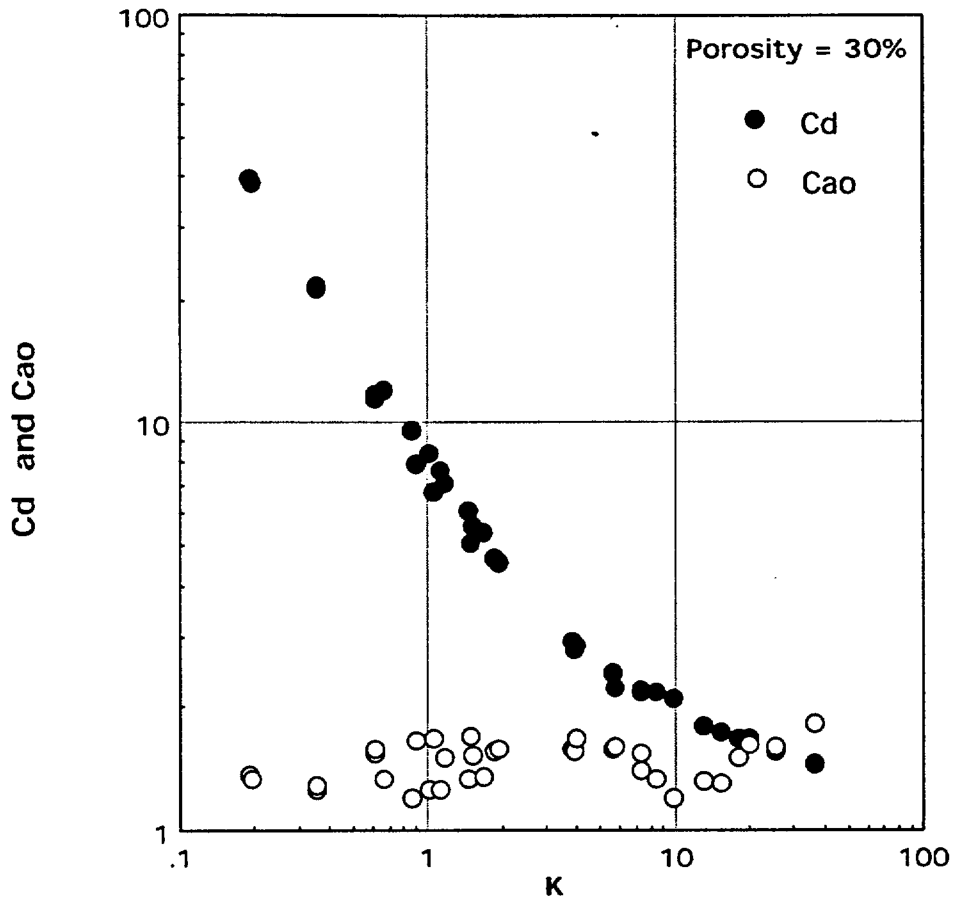

Figure 4. Drag and buoyancy-corrected inertia coefficients for a porous cylinder with a porosity of 30%.

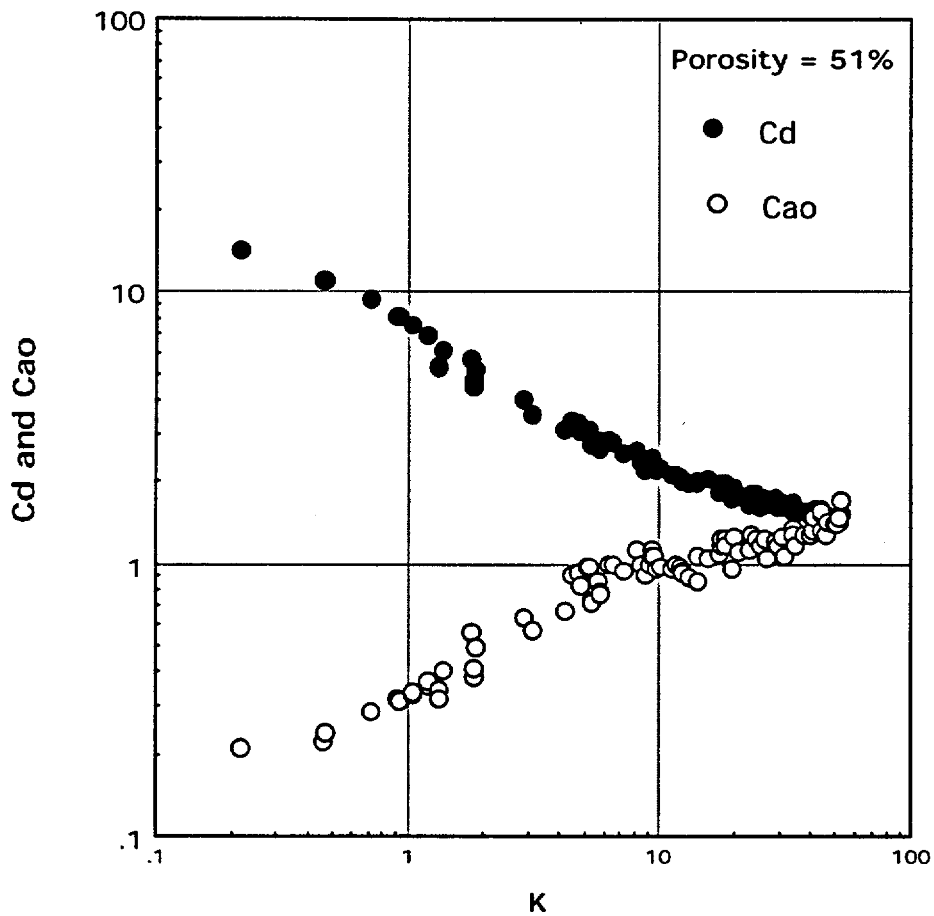

Figure 5. Drag and buoyancy-corrected inertia coefficients for a porous cylinder with a porosity of 51%.

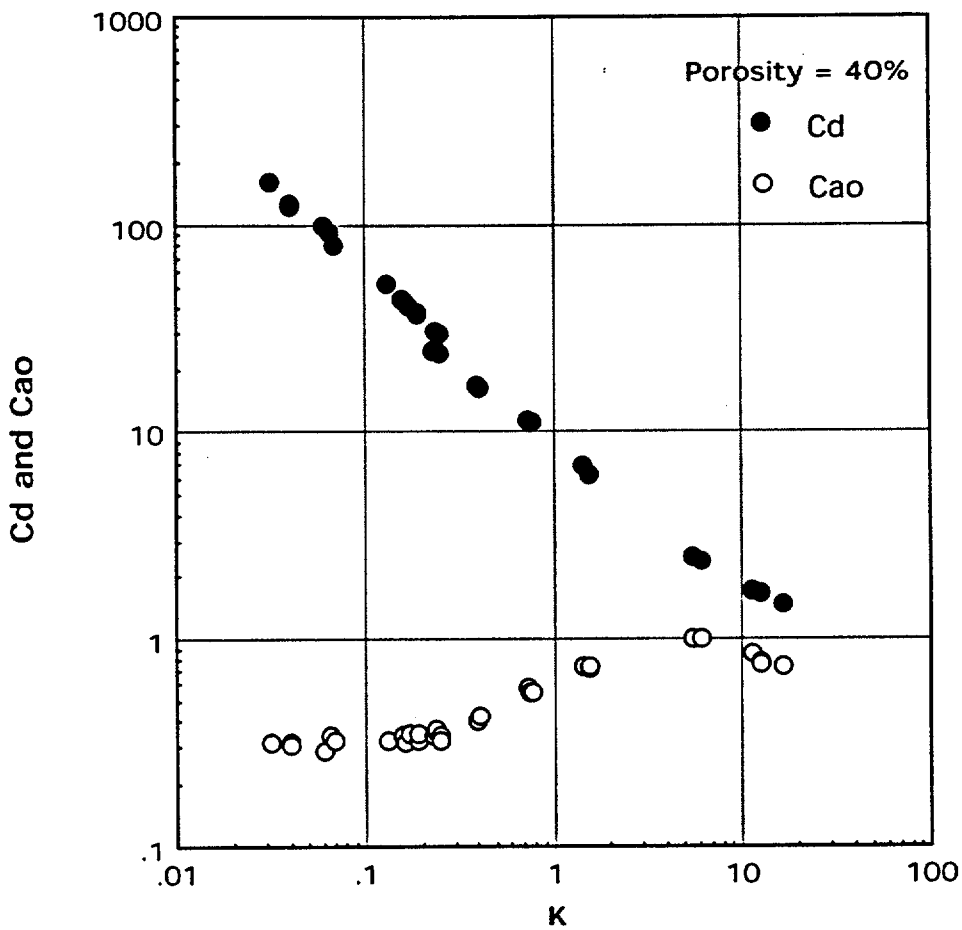

Figure 6. Drag and buoyancy-corrected inertia coefficients for a porous cylinder with a porosity of 40%.

In order to simplify the comparison of the said coefficients for three porosities, the data shown in Figs. 4, 5, and 6 are re-plotted in Fig. 7. It is evident that the inertia coefficient for the cylinder with 40% porosity is somewhat larger than that

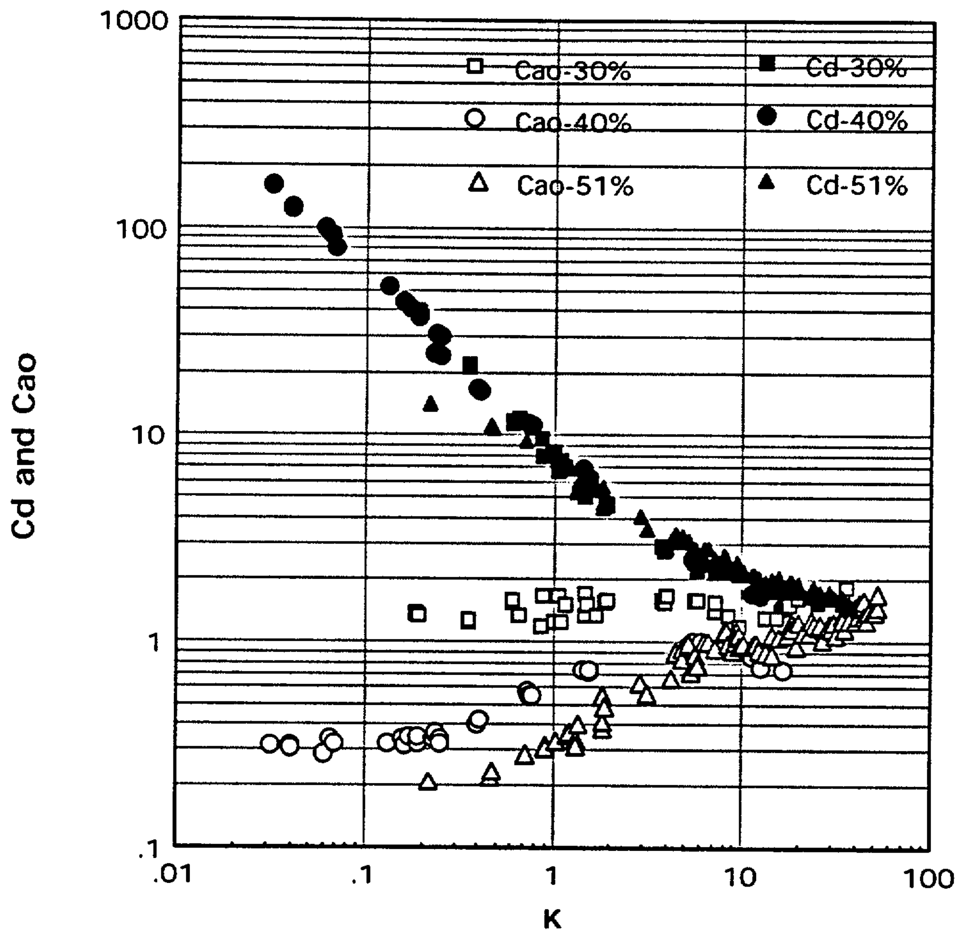

Figure 7. Drag and buoyancy-corrected inertia coefficients for porous cylinder of 30%, 40%, and 51%.

for the 51% porosity. This is not surprising. It is, in fact, a convincing demonstration of the facts surrounding the variation of the inertia coefficient and its dependence on porosity. We have every reason to believe that the inertia coefficient of a perforated cylinder with a porosity [redacted] for all values of the frequency parameter [redacted] The data shown in Fig. 7 present enormous mathematical and numerical challenges. It is our conjecture that GE strainers [redacted] cannot have C_{ao} values smaller than about [redacted] at proper Keulegan-Carpenter numbers and frequency parameters. A "correct" model experiment of the strainer will go long ways to prove the validity of one and all assertions.

(b) Need for additional experiments

There is urgent need to carry out additional experiments with perforated cylinders and strainer models (with armature) subjected to forced oscillations at specified amplitudes and frequencies. Such experiments can be performed at a reasonable cost for the benefit of all concerned and for publication in the open literature. The results will not only help to resolve some of the outstanding issues but will also provide sound data for those interested in correct analyses that meet the criteria enunciated by **Paul Adrian Maurice Dirac.**

7. Conclusions

(a) It appears that the issues discussed in many *Topical Reports* and papers on GE strainers (provided to TS) have arisen partly because of the attempts to carry the information gleaned from non-perforated bodies and steady flows to perforated bodies (in unsteady flows), and partly because of the use of old or "well-known" mechanical techniques to new and very complex problems without the benefit of the understanding of the underlying fluid dynamical phenomena.

There is no doubt that the perforations change the dynamics of the flow. Such a realization could have been easily achieved three or four years ago through a thorough literature search. Unfortunately, this has not been done by any of the participants (NRC, GE, and their consultants) of the issues discussed herein. Running to the library, walking to the computing center, and proceeding with caution to the laboratory could have saved a great deal of time, dollars, and agony.

(b) The B&F analysis offers nothing new, predicts nothing new, and leads to erroneous conclusions. It cannot be used in defense of the approximate "analyses" and equally approximate "experiments" of GE.

(b) One can find acceleration values as large as [redacted] (according to Mr. Lynch) and then K values as large as [redacted] (again according to Mr. Lynch). One is desperately looking for a *correctly calculated* acceleration and velocity distribution that everybody can agree upon as a starting point for the analyses and experiments. Yet, there are endless exchanges of (mostly trivial) questions and garbled responses, rather than simple facts. This may not be the first time that the need for an "honest experiment" has been replaced by 3000 pages of irrelevant material. The correct acceleration and velocity field about the strainer for various accident scenarios, complete drawings of the strainer, and the material properties must be made available to all parties for an intelligent assessment of the load carrying capacity of the GE strainers.

(d) Pluck or hammer tests must be conducted at the appropriate Keulegan-Carpenter number K_D, dictated by the amplitude of flow oscillations created by LOCA/SRVD, (from the top to the bottom of the strainer) and at the proper flow oscillation frequencies f of LOCA/SRVD, not at the natural frequency f_n of the strainer and not at irrelevant Keulegan-Carpenter numbers (often varying from the top to the bottom of the strainer). In model tests, the matching of the Keulegan-Carpenter numbers as well the frequency parameters is of prime importance.

(e) The proper values of the added mass and drag coefficients for a perforated body at relatively small K_D values can be determined accurately only if the body is subjected to the oscillations dictated by K_D and the frequency parameter β_D, i.e., with an amplitude A and the frequency f of the oscillation of the external flow imposed by LOCA/SRVD.

(f) It is our conjecture that GE strainers ([redacted]) cannot have C_{ao} values smaller than about [redacted] at proper Keulegan-Carpenter numbers and frequency parameters. A "correct" model experiment of the strainer will go long ways to prove the validity of one and all assertions.

It is sincerely hoped that this report has enlightened some dark corners in the world of unsteady flows in general and perforated bodies in particular. Every attempt has been made to remain impartial and to fully respect the ideas and opinions of others without sacrificing the truth as we know it and/or as we have acquired it. Much remains to be done in the years to come and it is sincerely hoped that correct decisions will prevail in the light of the collective knowledge, wisdom , and cooperation of all concerned.

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