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HYDRODYNAMIC INERTIAL MASS TESTING OF ECCS SUCTION STRAINERS

SUPPLEMENT 1 - FREE VIBRATION DATA ANALYSIS

Test Report No. TR-ECCS-GEN-05-NP

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C_m	hydrodynamic acceleration (inertial mass) drag coefficient
f_{SUP}	measured natural frequency of the support structure, Hz
f_{ST}	measured natural frequency of strainer test specimen, Hz
f_{CYL}	measured natural frequency of Reference Test Cylinder, Hz
W_{SUP}	total weight of support structure (hydrodynamic plus self-weight), lbs
$W_{ST.H2O}$	hydrodynamic weight of strainer test specimen, lbs
$W_{CYL.H2O}$	hydrodynamic weight of Reference Test Cylinder, lbs
V	displaced enclosed volume, (ft^3)
W_{ST}	strainer air weight, lbs
W_{CYL}	reference test cylinder air weight, lbs
$W_{ST.TOT}$	strainer total weight ($W_{ST} + W_{ST.H2O}$), lbs
$W_{CYL.TOT}$	reference test cylinder total weight ($W_{CYL} + W_{CYL.H2O}$), lbs
ρ	water mass density (1.9366 $lbf\text{-}s^2/ft^4$ @ 20°C)
$W_{SPC.TOT}$	effective specimen total weight ($W_{ST.TOT} + W_{SUP}$ or $W_{CYL.TOT} + W_{SUP}$), lbs

0 INTRODUCTION

This report is a supplement to Report No. TR-ECCS-GEN-01, "Hydrodynamic Inertial Mass Testing of ECCS Suction Strainers," (Reference 1) and provides a step-by-step discussion of the analysis of the data resulting from the free vibration (pluck) tests. Some of the analysis presented in this report was not discussed in TR-ECCS-GEN-01. It is presented here because it helps to clarify some of the insights and conclusions presented in that report.

Some information presented in this report duplicates information presented in TR-ECCS-GEN-01. It is repeated in this report to facilitate the use and understanding of the data and analysis without continual reference to TR-ECCS-GEN-01.

2.0 BACKGROUND

A test program was conducted by Duke Engineering & Services to investigate the behavior of large capacity stacked disk ECCS suction strainers subjected to accelerated separated fluid flow fields. The purpose of the test program was to generate the data required to develop empirically-based values for the hydrodynamic inertial mass coefficient, C_m, for use in qualification calculations related to installation of replacement ECCS suction strainers in BWR suppression pools.

3.0 TEST PROCEDURE AND DESCRIPTION OF TEST SPECIMENS

Reference 1 provides a complete description of the free vibration tests. The test procedure and test specimens are described again in this section to facilitate the use of this report.

3.1 Free Vibration Test Procedure

A load of approximately 200 lbs was applied to the test specimen using the hanging weight load calibration system shown in Figure 3.1. The load was then quick-released by cutting the line and the test specimen underwent submerged free oscillation. Response data (load on specimen and acceleration) was recorded by the data acquisition system during the test. The standard data acquisition rate for free vibration tests was 50 samples per second. Following each test, the data was processed and plotted as a history of the appropriate response for the test duration. The free vibration tests were repeated three (or four) times.

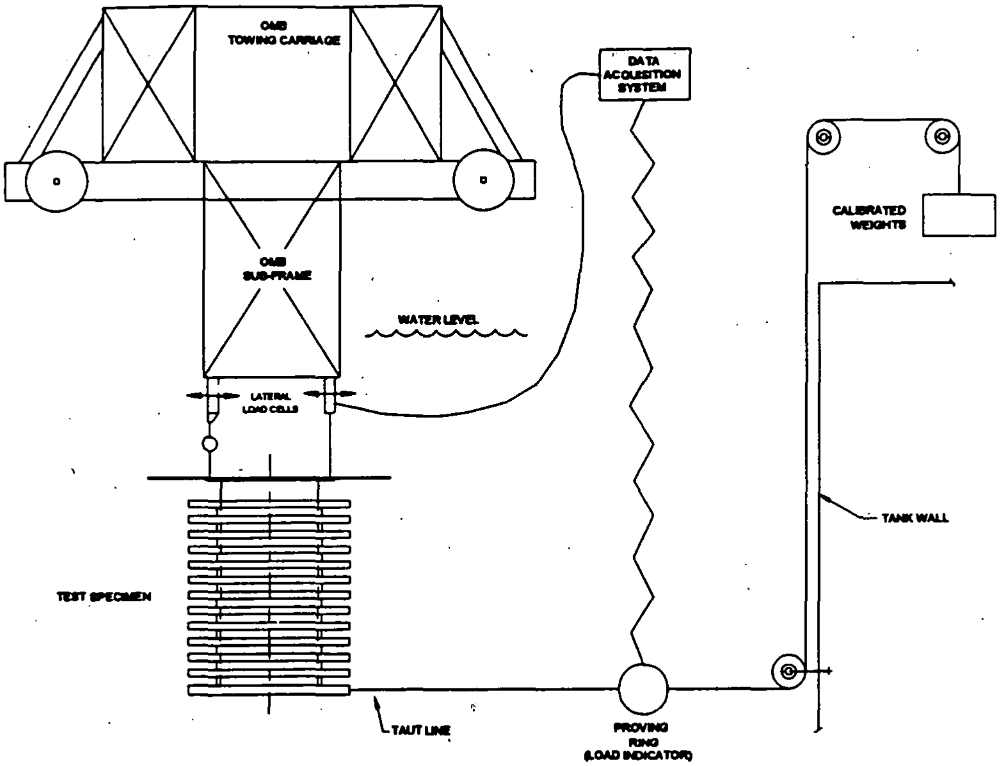


FIGURE 3.1

LAYOUT OF LOAD CALIBRATION SYSTEM

Separate series of tests were undertaken for the small Prototype No. Test-1 Strainer (100 Series) and the large Prototype No. 2 Strainer (500 Series). In addition, tests were performed for; the adapter/boundary assembly alone (i.e. without a test specimen attached) (200 Series); the reference smooth test cylinder (300 Series); and the reference smooth impervious stacked disk (400 Series).

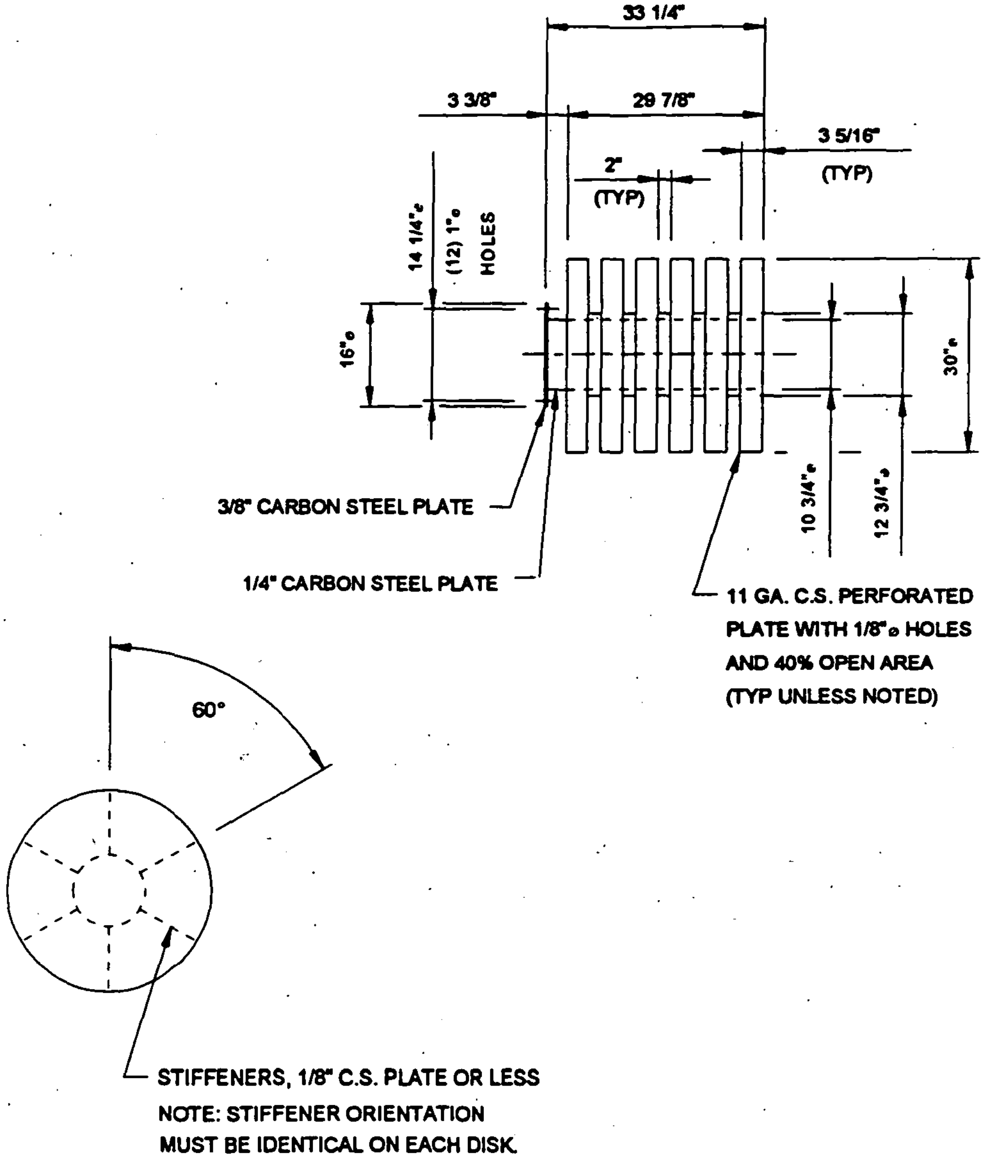
3.2 Description of Test Specimens

The two strainer test specimens consisted of the Performance Contracting, Inc., BWR stacked disk test strainers (PCI Sure-Flow Strainer, Prototype No. Test-1 and Prototype No. 2). The former is a relatively small 6-disk strainer (65 ft^2) for nominal 10-inch pipe, whereas the latter is a large 13-disk strainer (170 ft^2) for 24-inch pipe, detailed respectively in the PCI shop drawings, References 2 and 3, and shown in Figures 3.2 and 3.3. The disks were made from 11 gauge perforated plate with 1/8 inch diameter holes and 40 percent open area.

The outside diameters of the disks for the small and large strainers are 30 and 40 inches, respectively. As indicated in Figures 3.2 and 3.3, the overall lengths shown are respectively 33 and 54 inches. The significant dimensions were verified at the test site. The only discrepancy was that for the large strainer the spool length was 5-1/2 inches, not 6 inches, giving an overall length of 53-1/2 inches.

A Reference Smooth Test Cylinder was fabricated by wrapping the small strainer with 33 inch wide, 18 gauge (0.048 inch) aluminum sheet metal. The sheet metal was secured to the outer diameter of the strainer with self-drilling sheet metal screws. The cylinder free end was covered with a 1/8 inch thick circular plastic board and secured to the perforated strainer using the same kind of self-drilling sheet metal screws. The resulting cylinder was 33 inches long and of uniform 30 inches diameter (up to the flange).

The purpose of the Reference Test Cylinder Test was to provide a basis for comparisons with the perforated strainer and standard cylindrical shapes, with end effects.



NOTE: STIFFENER ORIENTATION MUST BE IDENTICAL ON EACH DISK.

FIGURE 3.2

PCI SURE-FLOW™ STRAINER PROTOTYPE NO. TEST-1

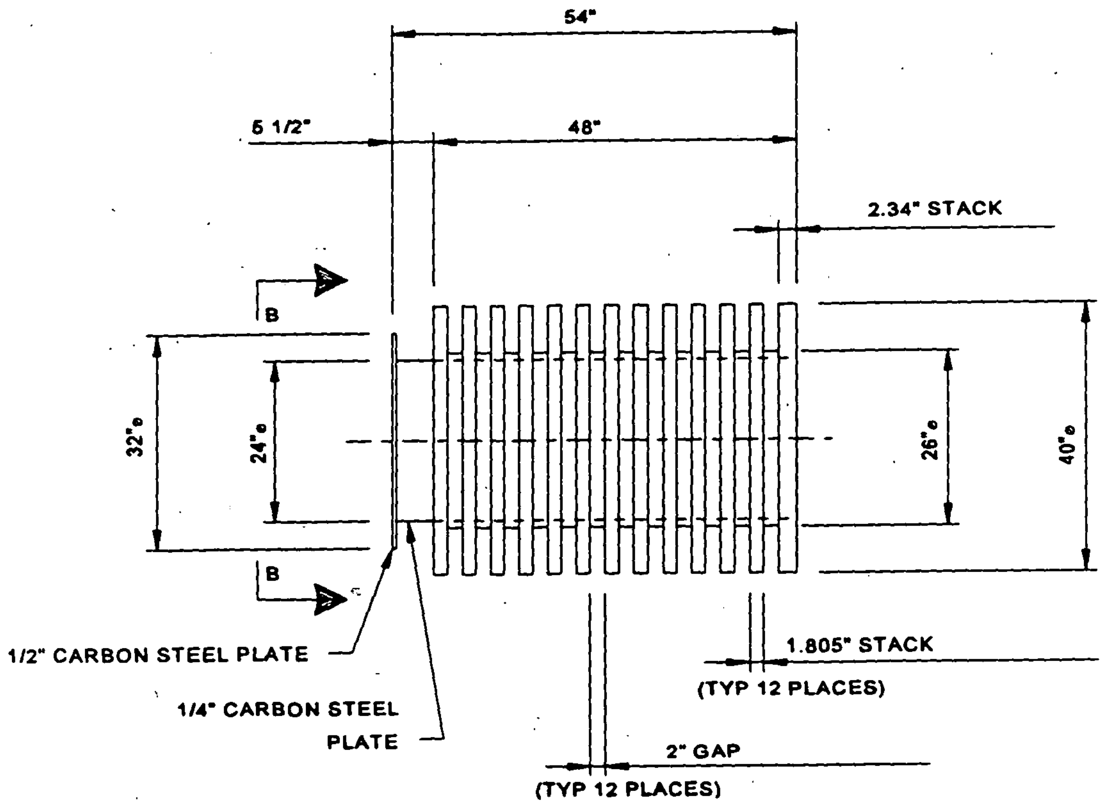


FIGURE 3.3

PCI SURE-FLOW™ STRAINER PROTOTYPE NO.2

A Reference Smooth Impervious Stacked Disk Assembly was created by wrapping the small perforated PCI Strainer Prototype No. Test-1 with self-adhesive clear plastic sheets (contact paper) and duct tape to fully cover the entire strainer. Several 1/8 inch holes were punched through the plastic at the free end to allow flooding.

The purpose of this test specimen was to provide a direct comparison with the perforated stacked disk strainer.

3.3 Self-Weights and Enclosed Water Weights of Test Specimen

The test strainers were weighed at the test site. Based on their physical dimensions the enclosed volumes and associated weight of potentially entrapped water are calculated and are given in Tables 3.1, 3.2 and 3.3.

TABLE 3.1

PCI PROTOTYPE NO. TEST-1
PHYSICAL PROPERTIES

Item	Calculation	
Core Volume	$\pi/4*12.75^2*29.875$	3,814 in^3
Disk Annular Volume	$\pi/4*(30^2-12.75^2)*3.3125*6$	11,511 in^3
Spool End Volume	$\pi/4*10.75^2*3.375$	306 in^3
Total Volume	3,814+11,511+306	15,631 in^3
Water Weight	$15,631*62.36/12^3$	564 lbs
Strainer Weight	(measured)	305 lbs

Note: The Impervious Stacked Disk Strainer has the same physical properties, except the additional weight of 3 lbs must be added to the strainer weight to account for the wrapping material.

TABLE 3.2

PCI PROTOTYPE NO. 2
PHYSICAL PROPERTIES

Item	Calculation	
Core Volume	$\pi/4*26^2*48$	25,485 in^3
Disk Annular Volume	$\pi/4*(40^2-26^2)(1.805*12 + 2.34*1)$	17,417 in^3
Spool Volume	$\pi/4*24^2 *5.5$	2,488 in^3
Total Volume	25,485+17,417+2,488	45,390 in^3
Water Weight	$45,390*62.36/12^3$	1,638 lbs
Strainer Self-Weight	(measured)	948 lbs

TABLE 3.3

REFERENCE TEST CYLINDER
PHYSICAL PROPERTIES

Item	Calculation	
Water Weight	$(\pi/4*30^2*33)*62.36/12^3$	842 lbs
Cylinder Self-Weight	305 + 19 (measured)	324 lbs

Note: 19 lbs is the weight of the wrapping material and 305 lbs is the Prototype No. Test-1 self-weight

4.0 TEST RESULTS AND DATA ANALYSIS

4.1 Free Vibration Test Results

The dominant oscillation frequencies were obtained by simple measurements from the oscillation history plots. Acceleration and load cell history records for the duration of free oscillation for both the small and large test strainers are given in Appendix A.

Results for the four test specimens are summarized in Table 4.1.

< Proprietary Information Removed >

4.2 Coefficients of Hydrodynamic Mass

The inertial or added mass accounts for the inertia of the fluid entrained by the accelerating structure. As the structure accelerates, the fluid surrounding the structure must accelerate as well. The inertia of the entrained fluid is the added mass. The hydrodynamic mass for the structural analyses of two dimensional cylindrical structures is generally based on an inertial mass coefficient, C_m, of 2.0 (added mass coefficient of 1.0).

As long as we maintain dimensional consistency we can equate the added mass term to an added weight term. For the remainder of this report, we will utilize units of pounds force and refer to added weight and hydrodynamic weight. The total effective weight of a specimen vibrating in water is thus, the specimen weight, W, plus the hydrodynamic weight, $C_m \cdot \rho V g$ (contained and added weight).

4.3 Interpretation of Results

Each strainer test specimen is supported by the same support system. The support system is effectively a rotational spring support at the strainer flange. Since the transverse flexural stiffness of the strainer is sufficiently high relative to the rotational stiffness of the support system, the frequency response of the combined system is not significantly affected by the strainer stiffness.

TABLE 4.1

FREE VIBRATION TEST RESULTS

Test Number	Test Specimen	Frequency (Hz)
d198	Prototype No. Test-1	< Proprietary Information Removed >
d198a		
d198b		
d398	Smooth Cylinder	
d398a		
d398b		
d498	Smooth Impervious Strainer	
d498a		
d498b		
d598	Prototype No. 2	
d598a		
d598b		
d598c		

Given that the stiffness of the support system is the same for each specimen and test, the ratio of frequencies is inversely proportional to the square root of the effective mass of the system. Thus, if the hydrodynamic weight (self-weight and added weight) of the Reference Test Cylinder is known, the ratio of the natural frequencies can be used to estimate the added weight of the other specimens as follows.

The natural frequencies measured during the tests includes the effects of the hydrodynamic weight of both the test specimen and the support, thus

$$(f_{ST}/f_{CYL})^2 = (W_{CYL} + W_{CYL.H2O} + W_{SUP})/(W_{ST} + W_{ST.H2O} + W_{SUP})$$

or

$$(f_{ST}/f_{CYL})^2 = (W_{CYL.TOT} + W_{SUP})/(W_{ST.TOT} + W_{SUP})$$

The C_m of the Reference Test Cylinder was conservatively set to 2.0. The standard inertial mass coefficient of 2.0 for a cylinder refers to the two-dimensional body i.e., an infinitely long cylinder. Use of 2.0 is clearly conservative for a cylinder of finite l/d ratio.

Assuming the Reference Test Cylinder with $C_m = 2.0$, the total hydrodynamic weight of the Reference Test Cylinder can be calculated using the data given in Table 3.3 as:

$$W_{CYL.TOT} = W_{CYL} + W_{CYL.H2O} = 324 + 2.0*842 = 2008 \text{ lbs}$$

Since the support structure will also vibrate along with the test specimen an estimate of its total effective weight (self-weight and hydrodynamic weight) is needed. Although the weight of the support assembly is known, its precise hydrodynamic weight is not. However, an upper and lower bound of its hydrodynamic weight can be used in the calculations to bracket the resulting C_m.

4.3.1 Support Assembly Hydrodynamic Weight - Upper Bound

Given a natural frequency of < Proprietary Information Removed > for the submerged free-vibration tests of the support system alone, an upper bound of its total effective weight can be calculated using the results from the Reference Test Cylinder tests as a reference frame. As before with $C_m = 2.0$,

$$W_{CYL.TOT} = 2008 \text{ lbs}$$

The natural frequency from the Reference Test Cylinder test is < Proprietary Information Removed > and includes the weight of the Reference Test Cylinder and the support structure, thus

$$(f_{SUP}/f_{CYL})^2 = (W_{CYL.TOT} + W_{SUP})/W_{SUP}$$

or

$$W_{SUP} = W_{CYL.TOT}/[(f_{SUP}/f_{CYL})^2 - 1]$$

< Proprietary Information Removed >

4.3.2 Support Assembly Hydrodynamic Weight - Best Estimate

Similarly, a best estimate can be obtained by considering the three-dimensional nature of the Reference Test Cylinder. Three-dimensional correction to C_m, per accepted ABS rules (Reference 4), for the Reference Test Cylinder would suggest a correction factor, K, of 0.83 considering the flanged-end boundary as infinite (length to diameter ratio, $l/d = 33.25/30. = 1.108$ with one free end, so that the effective l/d is 2.217).

$$C_m = 0.83*2.0 = 1.66$$

< Proprietary Information Removed >

4.3.3 Support Assembly Hydrodynamic Weight - Lower Bound

As a third comparison the hydrodynamic weight of the strainer support system is neglected and the coefficients derived directly from the square of the frequency ratios between the Reference Test Cylinder (with $C_m = 2.0$) and the strainer specimens. As can be seen in Table 4.4, the derived values of C_m for Prototype No. Test-1 and Prototype No. 2 are now less consistent, indicating the importance of considering the hydrodynamic effects of the support system on the test results. This is because the added hydrodynamic weight of the support system, though the same for both prototype tests, is a higher proportion of the total hydrodynamic weight for the Prototype No. Test-1 test than it is for the Prototype No. 2 test.

4.4 Derivation of Inertial Mass Coefficients (C_m)

As discussed previously, C_m for any strainer specimens can be generally calculated as follows:

$$C_m = W_{ST.H2O}/\rho V g = (W_{ST.TOT} - W_{ST})/\rho V g$$

Also, as previously discussed, C_m for the strainer test specimens will be calculated relative to the Reference Test Cylinder (C_m=2.0).

Recalling that:

$$(f_{ST}/f_{CYL})^2 = (W_{CYL.TOT} + W_{SUP})/(W_{ST.TOT} + W_{SUP})$$

Then:

$$C_m = [(f_{CYL}/f_{ST})^2 (W_{CYL.TOT} + W_{SUP}) - (W_{ST} + W_{SUP})]/\rho V g$$

For convenience, we develop an effective weight ratio by defining the frequency ratio:

$$f_r = f_{ST}/f_{CYL}$$

Then the effective weight ratio can then be defined as:

$$(1/f_r)^2$$

This results in:

$$C_m = [(1/f_r)^2 (W_{CYL.TOT} + W_{SUP}) - (W_{ST} + W_{SUP})]/\rho Vg$$

Additionally, the effective specimen hydrodynamic weight can be calculated as:

$$W_{ST.H2O} = C_m \rho Vg$$

The effective total test specimen weight is calculated as:

$$W_{SPC.TOT} = W_{ST.H2O} + W_{ST} + W_{SUP}$$

The resulting mass coefficients are given in Tables 4.2 through 4.4 for a complete range of strainer support weights. Additionally, by changing the volume, V, to equal the volume of an equivalent cylinder based on the disk diameter, a direct comparison to a cylindrical body can be made.

PCI Prototype No. Test-1

$$\text{Volume} = \pi/4(30\text{ in})^2\ (33\text{ in}) = 23{,}326\text{ in}^3$$
$$\text{Weight } (\rho Vg) = [(23{,}326\text{ in}^3)/(1728\text{ in}^3/\text{ft}^3)](62.36\text{ lb/ft}^3) = 842\text{ lbf}$$

PCI Prototype No. 2

$$\text{Volume} = \pi/4\ (40\ \text{in})^2 (54\ \text{in}) = 67{,}858\ \text{in}^3$$
$$\text{Weight } (\rho Vg) = [67{,}858\ \text{in}^3/1728\ \text{in}^3/\text{ft}^3]\ 62.36\ \text{lb/ft}^3 = 2449\ \text{lbf}$$

The values of C_m based upon the uniform cylindrical volume are also shown in Tables 4.2 through 4.4. The results provide additional insight into the effect of the perforated nature of the strainers. Using the derived C_m values in Tables 4.2 through 4.4, an upper and lower bound and a best estimate of the ratio of C_m for the perforated strainer to C_m for the smooth impervious strainer is calculated and provided in Table 4.5.

TABLE 4.2

DERIVED INERTIAL MASS COEFFICIENTS
STRAINER SUPPORT HYDRODYNAMIC WEIGHT W_{SUP} = < Proprietary Information Removed >

Test Specimen	Specimen Air Weight (W_{CYL} or W_{ST})	ρVg (lbf) (Enclosed Strainer Volume)	ρVg (lbf) (Enclosed Cylinder Volume)	Frequency (Hz)	Frequency Ratio f_r	Effective Weight Ratio $(1/f_r)^2$	Effective Specimen Total Weight (lbf) ($W_{CYL.TOT} + W_{SUP}$) or ($W_{ST.TOT} + W_{SUP}$)	Hydrodynamic Mass Coefficient w/Respect to Enclosed Strainer Volume C_m	Hydrodynamic Mass Coefficient w/Respect to Enclosed Cylinder Volume C_m
Reference Test Cylinder	324	N/A	842						
Smooth Impervious Strainer	308	564	842			< Proprietary Information Removed >			
Prototype No. Test-1	305	564	842						
Prototype No. 2	948	1638	2449						

Note: 1. C_m for the Reference Test Cylinder is conservatively assumed to be 2.0.

2. $C_m = [(1/f_r)^2\ (W + W_{CYL.TOT}) - (W_{SUP} + W_{ST})]/\rho Vg_{SUP}$

3. $W_{SUP} = C_m(\rho Vg)_{STC} + (W + W_{ST})$

TABLE 4.3

DERIVED INERTIAL MASS COEFFICIENTS
STRAINER SUPPORT HYDRODYNAMIC WEIGHT W_{SUP} = < Proprietary Information Removed >

Test Specimen	Specimen Air Weight (W_{CYL} or W_{ST})	ρVg (lbf) (Enclosed Strainer) Volume	ρVg (lbf) (Enclosed Cylinder Volume)	Frequency (Hz)	Frequency Ratio f_r	Effective Weight Ratio $(1/f_r)^2$	Effective Specimen Total Weight (lbf) ($W_{CYL.TOT} + W_{SUP}$) or ($W_{ST.TOT} + W_{SUP}$)	Hydrodynamic Mass Coefficient w/Respect to Enclosed Strainer Volume C_m	Hydrodynamic Mass Coefficient w/Respect to Enclosed Cylinder Volume C_m
Reference Test Cylinder	324	N/A	842						
Smooth Impervious Strainer	308	564	842			< Proprietary Information Removed >			
Prototype No. Test-1	305	564	842						
Prototype No. 2	948	1638	2449						

Note:
1. C_m for the Reference Test Cylinder is conservatively assumed to be 2.0.
2. $C_m = [(1/f_r)^2 (W + W_{CYL.TOT}) - (W_{SUP} + W_{ST})]/\rho V g_{SUP}$
3. $W_{SUP} = C_m (\rho V g)_{STC} \pm (W + W_{ST})$

TABLE 4.4

DERIVED INERTIAL MASS COEFFICIENTS
STRAINER SUPPORT HYDRODYNAMIC WEIGHT W_{SUP} = < Proprietary Information Removed >

Test Specimen	Specimen Air Weight (W_{CYL} or W_{ST})	ρVg (lbf) (Enclosed Strainer) Volume	ρVg (lbf) (Enclosed Cylinder Volume)	Frequency (Hz)	Frequency Ratio f_r	Effective Weight Ratio $(1/f_r)^2$	Effective Specimen Total Weight (lbf) ($W_{CYL.TOT} + W_{SUP}$) or ($W_{ST.TOT} + W_{SUP}$)	Hydrodynamic Mass Coefficient w/Respect to Enclosed Strainer Volume C_m	Hydrodynamic Mass Coefficient w/Respect to Enclosed Cylinder Volume C_m
Reference Test Cylinder	324	N/A	842	< Proprietary Information Removed >					
Smooth Impervious Strainer	308	564	842						
Prototype No. Test-1	305	564	842						
Prototype No. 2	948	1638	2449						

Note: 1. C_m for the Reference Test Cylinder is conservatively assumed to be 2.0.
2. $C_m = [(1/f_r)^2 (W + W_{CYL.TOT}) - (W_{SUP} + W_{ST})]/\rho Vg_{SUP}$
3. $W_{SUC} = C_m (\rho Vg) + (W + W_{ST})_{SUP}$

TABLE 4.5

HYDRODYNAMIC MASS COEFFICIENT (C_m) COMPARISON FOR A PERFORATED AND A SMOOTH IMPERVIOUS STRAINER

Estimate	Support Weight W_{SUP}	C_m Ratios (Perforated/Impervious)
Upper Bound		
Best Estimate	< Proprietary Information Removed >	
Lower Bound		

5.0 CONCLUSION

Using a C_m of 2.0 for the smooth Reference Test Cylinder as reference, the results indicate a very consistent inertial mass coefficient, < Proprietary Information Removed >.

Comparison of the results for the small strainer tests alone, as a impervious non-perforated smooth strainer, and as a perforated strainer exhibits the change in free oscillation frequency, which is indicative of the change in inertial mass of the test specimen. Using the derived C_m values, the C_m ratios (perforated strainer/smooth impervious strainer) range from < Proprietary Information Removed >.

< Proprietary Information Removed >

6.0 REFERENCES

1. Duke Engineering & Services, Inc., Report No.: TR-ECCS-GEN-01, "Hydrodynamic Inertial Mass Testing of ECCS Suction Strainer", File A16800.F10-001, Revision 2, July, 1997

2. Performance Contracting, Inc., Engineered Systems Division, Kansas, BWR Test Strainer, Drawing Numbers: ECCS-1, ECCS-2, Rev 0, 02-10-93

3. Performance Contracting, Inc., Engineered Systems Division, Kansas, ECCS Suction Strainer, Drawing Number: ECCS-003, Rev 1, 07-31-95

4. American Bureau of Shipping, "Rules for Building and Classing Mobile Offshore Drilling Units," 1980 Edition.

APPENDIX A

FREE VIBRATION TIME SERIES PLOTS

NOTE: In the plots for Tests d598, d598b and d598c, the time scale is factored by 6.25, i.e. 100 seconds displayed on the plots is 16 seconds real time.

< Information on pp. A-3 through A-87 are proprietary and have been removed >.