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**"HYDRAULIC PRESSURE PULSES
WITH STRUCTURAL FLEXIBILITY:
TEST AND ANALYSIS"
(LWBR Development Program)**

D. A. Prelewicz

**Bettis Atomic Power Laboratory
West Mifflin, Pennsylvania 15122**

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HYDRAULIC PRESSURE PULSES WITH STRUCTURAL
FLEXIBILITY: TEST AND ANALYSIS
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Pressure pulse tests were conducted with both solid and flexible test sections in a test vessel filled with room temperature water. Pressure pulses of magnitude up to 1150 psid and durations from 6 to 47 msec were generated with a drop hammer and piston pulse generator.

FLASH-34 calculations show good agreement with the test data. In particular, FLASH-34 adequately predicts the decrease in peak pressure and the increase in pulse duration due to the presence of a flexible test section. Both test data and FLASH-34 calculations showed the structural response to be approximately quasi-static, except for slight departures from quasi-static response for the most rapid pressure pulses. All of the structural responses were in the elastic range.

The test data versus calculation comparisons presented here provide preliminary qualification for FLASH-34 calculations of transient hydraulic pressures in the presence of elastically deforming flexible structural members for single phase conditions and simple geometries.

I. INTRODUCTION

During the course of a postulated Loss-of-Coolant Accident (LOCA), reactor structural members are subjected to transient loadings as a result of rapid temporal and spatial pressure variations in the coolant. The most severe loadings are calculated to occur during the subcooled blowdown when strong decompression waves propagate from the break through the various flow passages. The FLASH-34* computer program is used to calculate coolant pressures during the subcooled and saturated blowdown. A unique feature of the FLASH-34 program is its ability to account for the coupled effects of structural deflection and coolant hydrodynamics. That is, FLASH-34 has a coupled hydro-elastic capability.

Earlier versions of the FLASH program have been used to calculate transient pressures during decompression (References 3-6). Generally good agreement was obtained with experimental data. In these experiments the test vessels were very stiff and hence a rigid structure was assumed. For the calculation

* Combines both FLASH-3 (Reference 1) and FLASH-4 (Reference 2).

of differential pressures across structural members separating flow channels this is a conservative assumption in that the pressure relief effect which results from structural deflection is neglected. However, for some structural members, particularly in-core structures, the assumption of a rigid flow boundary is questionable. In these cases, the FLASH-34 program with its coupled structural deflection-coolant hydrodynamics capability, referred to as the flexible structural member option, is appropriate for the calculation of differential pressure loadings.

To obtain basic data for the qualification of the flexible structural member option a series of pressure pulse tests were run with flexible test sections in a test vessel. The tests were run with room temperature water in a 2 inch diameter vessel. Pressure pulses of magnitude up to 1150 psig and durations of from 6 to 47 msec were generated by rapidly displacing a piston into the test vessel. Although these tests are not prototypical, the basic mechanism of pressure relief due to structural deflection is clearly operative. Comparisons of the test data with FLASH-34 calculations demonstrate that the FLASH-34 program with the flexible structural member option correctly models the effect of structural deflection on hydraulic pressure for single phase conditions and simple geometries.

II. PRESSURE PULSE TESTS

The pressure pulse test apparatus consists of a 2 inch diameter, 45 $\frac{1}{4}$ inch long test vessel with a piston at one end (see Figure 1). Aluminum test sections are mounted inside the vessel. A drop hammer displaces the piston into the water filled vessel, thus compressing the water and producing a hydraulic pressure pulse. Piezoelectric pressure transducers are located near the top of the vessel and at an elevation corresponding to the midpoint of the aluminum test sections.

The aluminum test sections are 1 $\frac{1}{4}$ inch square extruded aluminum tubing (6063-T5), 34-3/8 inches long. Aluminum was selected because its modulus of elasticity at room temperature is approximately the same as that of Zircaloy at reactor operating temperature. Two test sections were used, one with a solid cross section and one with 1/8 inch thick walls. The 1/8 inch thick wall test section is shown in Figure 2. An

"O-ring" at the test section base provides the pressure boundary for the test vessel. The inside of the test section is open to the atmosphere and contains an eddy current proximeter mounted midway along the test section length. Test section wall deflection is measured by the proximeter and converted to test section volumetric displacement as discussed in Appendix A. Test section volumetric displacement is used here to denote the additional volume available to the test vessel water as a result of inward deflection of the test section walls. Transient data, i.e. test section volumetric displacement and test vessel pressures, were recorded on a light beam oscillograph (Visicorder) with a frequency response which is flat from zero to approximately 900 Hz.

Two different size pistons (1 inch diameter and 2 inch diameter) and three different size drop hammers (16.4 lbs., 42.3 lbs., 68.2 lbs.) were used to obtain pulses of varying durations. Magnitudes of the pulses were controlled by varying drop height as well as drop hammer weight. The tests were initiated with the water in the test vessel at approximately 68°F and 23 psig. Static pressure readings were taken before and after each run using the dial gage indicator shown in Figure 1. During the tests the dial gage was valved out of the system. Equality of the pressure readings before and after each run assures that no leakage or permanent test section deflection occurred as a result of the pressure pulse loading.

A total of 23 runs was made with the 1/8 inch wall test section with various drop hammer weights, piston areas and drop heights. A corresponding set of 23 runs was made with the solid test section. Thus, there are 23 pairs of runs which differ only in that one of the runs has a solid test section while the other run has a flexible test section.

Although the test vessel might be expected to be rigid, static pressurization of the vessel revealed a significant amount of flexibility. The stiffness of the test vessel was determined as discussed in Appendix A. This flexibility is present with either of the aluminum test sections.

Several pressure pulses of decreasing magnitude occurred during each run as the drop hammer repeatedly rebounded. Figure 3 shows a reproduction of the complete transient data record for a typical run (Run No. 14F).

FIGURE 1: PRESSURE PULSE TEST APPARATUS

FIGURE 2: FLEXIBLE TEST SECTION

Note that the pressure pulses are fairly well separated in time. That is, the duration of each pulse is significantly less than the time between pulses. Resolution on the Visicorder data records is much better than that on the reproduction shown in Figure 3, which is included here to show the type of transient data records obtained and the relative time span between the successive pulses. Table I gives a summary of the test parameters for each run. Reduced data consisting of the vessel gage pressure before and after the test, peak pressure pulse magnitude, duration of the first pulse and maximum test section volumetric displacement are also given in Table I. The reduced transient data were read from Visicorder transient data records.

III. FLASH-34 FLEXIBLE STRUCTURAL MEMBER MODEL

In a FLASH-34 model, the fluid region is divided into a number of control volumes (nodes) connected by flowpaths. Situations may arise in which some of the nodes represent the fluid in flow channels which are separated by flexible structural members (e.g. steam generator divider plate or various reactor vessel internal parts). To model this situation with FLASH-34, the flexible structural member option can be used. Flexible structural members can be located between any two nodes and will deflect in response to changes in differential pressure between the nodes. A derivation of the governing differential equation for the volume displacement of the flexible structural member is given in Appendix B. It is noted that the model includes dynamic effects to the extent that the inertia of the flexible member (plus any fluid that moves with the member) is included in the governing equation. A key parameter in the model is the volumetric stiffness of the flexible member, denoted by K , which has units psi/ft^3 . Both linear elastic and bi-linear elastic stiffness models are available in the program. The area and the virtual mass of the flexible member are also input parameters.

As discussed in Appendix B, each flexible structural member is modeled as a simple spring mass system. However, the stiffness used in this model is generally obtained from detailed stress calculations using elastic or elastic-plastic structural analysis computer programs. These programs are used to calculate the deflection (and hence the volumetric displacement) for a number of uniform static pressure loadings. The volumetric stiffness is determined by curve fitting a linear elastic

FIGURE 3. TRANSIENT DATA RECORD FOR RUN 14F

TABLE I

TEST PARAMETERS AND REDUCED DATA

Run No.	Piston Diameter (inches)	Drop Hammer Weight (inches)	Drop Height (inches)	Gage Pressure Before Test (psig)	Gage Pressure After Test (psig)	Duration of First Pulse (msec)	Peak Pressure Pulse Magnitude-Top Transducer (psid)	Peak Pressure Pulse Magnitude-Bottom Transducer (psid)	Peak Test Section Volumetric Displacement (ft ³ x10 ⁻⁵)
1F	1.0	16.4	2	23.0	23.0	28.0	200	200	2.7
2F			4		22.0	28.5	290	295	4.5
3F			6		22.0	23.0	425	410	6.1
4F			8		22.0	23.5	500	480	7.2
5F			10		23.0	22.0	600	590	8.0
6F			12		22.0	23.0	640	625	8.2
7F			16		21.0	22.5	775	740	10.2
8F		42.3	2		22.5	41.5	385	390	4.8
9F			4		22.5	36.5	685	670	9.0
10F			6		21.0	34.5	850	840	10.8
11F		68.2	2		22.0	47.5	650	645	8.8
12F	2.0	16.4	2		22.0	7.0	245	250	4.8
13F			4		22.0	6.5	380	340	7.2
14F			6		22.0	6.5	490	430	8.7
15F			8		22.0	6.0	540	480	10.4
16F			10		21.0	6.5	640	550	11.2
17F			12		20.0	6.0	725	590	12.1
18F		42.3	2		22.0	9.0	450	420	9.0
19F			4		21.0	9.0	600	590	11.4
20F			6		21.0	9.0	800	790	13.1
21F			8		19.5	9.0	850	900	15.0
22F		68.2	2		21.0	11.5	585	550	10.7
23F			4		20.0	11.5	850	820	12.0

TABLE I (Continued)
TEST PARAMETERS AND REDUCED DATA

Run No.	Piston Diameter (inches)	Drop Hammer Weight (inches)	Drop Height (inches)	Gage Pressure Before Test (psig)	Gage Pressure After Test (psig)	Duration of First Pulse (msec)	Peak Pressure Pulse Magnitude- Top Transducer (psid)	Peak Pressure Pulse Magnitude- Bottom Transducer (psid)
1S	1.0	16.4	2	23.0	22.0	21.5	285	310
2S	↓	↓	4	↓	23.0	19.5	460	465
3S	↓	↓	6	↓	22.5	17.5	600	600
4S	↓	↓	8	↓	22.0	17.5	720	730
5S	↓	↓	10	↓	23.0	17.5	820	840
6S	↓	↓	12	↓	22.0	17.5	900	900
7S	↓	↓	16	↓	22.0	17.0	1050	1075
8S	↓	42.3	2	↓	23.0	33.5	615	640
9S	↓	↓	4	↓	22.5	30.0	880	890
10S	↓	↓	6	↓	22.0	27.5	1130	1150
11S	↓	68.2	2	↓	21.0	42.0	880	880
12S	2.0	16.4	2	↓	22.5	7.0	315	225
13S	↓	↓	4	↓	22.0	6.5	405	370
14S	↓	↓	6	↓	22.0	6.0	520	450
15S	↓	↓	8	↓	22.0	6.0	610	510
16S	↓	↓	10	↓	22.0	5.5	700	620
17S	↓	↓	12	↓	21.0	5.5	730	690
18S	↓	42.3	2	↓	22.5	9.0	470	440
19S	↓	↓	4	↓	22.0	7.5	700	730
20S	↓	↓	6	↓	22.5	7.5	900	975
21S	↓	↓	8	↓	21.5	8.0	1050	1170
22S	↓	68.2	2	↓	22.0	11.0	670	630
23S	↓	↓	4	↓	20.0	10.0	1000	1000

or bi-linear elastic relationship to the pressure versus volumetric displacement data. Since the coolant hydrodynamics depend primarily upon the flexible member volumetric displacement rather than on the detailed stress state or mode shape, the simple spring-mass model should be quite adequate for the calculation of hydraulic pressures in the presence of flexible flow boundaries.*

In addition, the time constants associated with typical reactor structural members are very often calculated to be short in comparison to the time constants associated with the hydraulic pressure pulses. Hence, the structural member response is essentially quasi-static. That is, the inertia of the flexible structural member has a negligible effect on the structural response. The pressure pulse test data presented in the previous section provide an example of a situation where the flexible member deflection is essentially quasi-static. In this case, a precise determination of the virtual mass of the flexible member is not required.

IV. FLASH-34 SIMULATION OF PRESSURE PULSE TESTS

A. The FLASH-34 Model

Figure 4 is a schematic of the test configuration with the flexible test section. Schematics of the FLASH-34 models for both the solid test section configuration and the flexible test section configuration are given in Figure 5. In each case, a total of 11 nodes represent the compressed water volume in the test vessel. The first two nodes represent that portion of the test vessel volume above the test section, while the remaining nine nodes represent the annular region around the test section.

For the solid test section configuration a total of 12 flexible members are used. The first member represents the piston and the remaining 11 represent the vessel stiffness. For the flexible test section configuration an additional nine flexible members are used to represent the test section. A listing of an input deck for a typical run (Run No. 10F) is given in Appendix D.

Nodal areas and heights for the one inch piston runs were determined as follows. The height of the test vessel between the top flange and the top of the test section is approximately 10 inches. Therefore the height of nodes 1 and 2 is five inches or .417 feet. The area of these nodes is the cross-sectional area of the test vessel, or

* Since average nodal pressures are calculated, local spatial variations of pressure in a node are not modeled.

FIGURE 4. SCHEMATIC OF TEST CONFIGURATION

SOLID TEST SECTION

FLEXIBLE TEST SECTION

FIGURE 5. SCHEMATIC OF FLASH MODELS

.02182 ft². For nodes 3 through 11 the nodal area is the cross-sectional area of the annulus between the vessel and the test section or .01097 ft². The total volume of the compressed water is known from experimental measurement to be .04825 ft³. This volume was obtained by measuring the volume of water required to fill the test vessel with the solid test section in place. The total height of the lower section (annular region) was taken as 2.74 feet so as to preserve this volume. Since there are nine nodes in the lower section, the height of each node is .3044 feet.

For the two inch piston runs, the total compressed water volume is .05285 ft³. This total volume was preserved by increasing the height of nodes 1 and 2 to .5225 feet while keeping the same nodal area. Nodal areas and heights for nodes 3 through 11 are unchanged.

The initial node pressures were calculated as 37.7 psia plus the elevation head from the top of the test vessel. An initial enthalpy of 36 BTU/lb was used for all of the 11 nodes. Node 12 represents the constant pressure atmosphere.

Ten flow paths connect the eleven test vessel nodes in series. A friction factor of .06 was used. Sensitivity studies showed that the FLASH-34 calculations were not affected by rather large (factor of 3) changes in flow path friction factors. In fact, runs with a zero friction factor showed only small differences in the highest frequency components. The initial flow in all flow paths is zero.

The first flexible member represents the piston. A piston model option (i.e. a special flexible member) was added to FLASH-34 for the specific purpose of simulating the pressure pulse tests. The governing equations for the piston model are given in Appendix B. One of the input parameters is the mass of the piston (plus any water that is expected to move with the piston). Piston masses are 3.11 lb. for the one inch piston and 10.4 lb. for the two inch piston. One half of the mass of water in node 1 was added to these values to obtain the input parameter value. A sensitivity study was made to determine the effect of including this water mass. Calculations were made for Run 10S with and without the water mass added to the piston mass. Very little change resulted when the water mass was not included (less than 20 psi change in peak pressures). A coefficient of restitution of zero was used for all runs. When the piston was constrained so that it could not move, there was negligible rebound of the

drop hammer indicating that the actual coefficient of restitution was very close to zero. Initial drop hammer velocity was calculated from the drop height assuming free fall. Piston damping coefficients were estimated to be 9 lbf. sec/ft and 100 lbf. sec/ft for the one inch and two inch pistons, respectively. These values were estimated from piston motion tests discussed in Appendix C.

Test vessel stiffness was determined by a combination of static loading tests and analysis as discussed in Appendix A. The stiffness parameters for the bi-linear elastic model given in Figure A1 are for the entire test vessel. Nodal input parameters were obtained from these values by properly proportioning according to node height.

Test section flexible member parameters were also proportioned according to node height. The stiffness was calculated to be 2.168×10^7 psi/ft³ per foot of test section length. Using 2.865 feet as the length of the test section which can deflect gives a stiffness of 7.57×10^6 psi/ft³ for the entire test section. Test section total area is 1.124 ft² and total mass is 2.72 lb.

B. Noding and Time Step Sensitivity Studies

For the noding sensitivity study, runs were made with the compressed water volume represented by 1, 2, 4, 6, 7, 11, 13 and 23 nodes. Not all of the tests were simulated with all of these models. However, sufficient runs were made with these models to justify the following observations:

1. For the one inch piston runs only very slight differences were noted between the 4, 6, 7 and 11 node models. These differences were in the high frequency components which are superposed on the overall pressure pulse. The 11 node model was used for all runs.
2. Many of the short duration runs with the two inch piston represent a severe test of the ability of FLASH-34 to predict transient pressures and deflections. The test data exhibited extremely rapid variations in pressure and deflection. True nodal convergence was not obtained for these cases. In its attempt to predict the very rapid spikes in pressure, FLASH would calculate negative pressures at the pressure troughs. This trend increased as the number of nodes increased so that the 23 node model could not be run long enough to get useful results. Decreasing the time step size did not alleviate

this difficulty. The basic problem appears to be that increasing the number of nodes increases the high frequency content of the calculated solutions causing the pressure troughs to deepen and reach negative values. Unlike the FLASH calculations, the actual test data clearly exhibit dissipative mechanisms (e.g. structural damping) which reduced the high frequency content of the response. Since the FLASH calculations with fewer nodes exhibit less high frequency content, they resemble the data more accurately than do the calculations for the models with more nodes. Since no terminations on negative pressure calculation occurred for the 11 node model until near the end of the pulse, this nodal representation was also used for the two inch piston runs.

3. Time steps of 1×10^{-6} and 3×10^{-7} gave identical calculated results. Hence a time step of 1×10^{-6} was used.

V. COMPARISON OF FLASH-34 SIMULATIONS WITH TEST DATA

FLASH-34 calculations were made for all of the 23 pairs of runs. Detailed comparisons of FLASH-34 calculations with test data are presented here for two pairs of runs (10S, 10F) and (20S, 20F). Test parameters for these pairs of runs are the same (42.3 lb. drop hammer, 6 inch drop height) except that runs 10S and 10F have the one inch diameter piston while runs 20S and 20F have the two inch diameter piston. The comparisons of test data and FLASH-34 calculations for these two pairs of runs are representative of results which were obtained for other runs with the one inch and two inch pistons.

Figure 6 shows a comparison of FLASH-34 calculated pressure in node 2 with test data (top transducer) for runs 10S and 10F). These runs differ only in that run 10S has the solid test section while run 10F has the flexible test section. Figure 7 is similar to Figure 6 except that the pressure response at FLASH node 7 (bottom transducer) is given. Comparison of the pressure transient response (broken curves) for the two runs reveals that there is a significant reduction in peak pressure (~300 psi) when the flexible test section is used. Also, the duration of the pulse is increased when the flexible test section is used. This comparison illustrates the pressure relief effect due to structural deflection. Notice that the FLASH-34 calculations adequately

FIGURE 6. TEST DATA VS FLASH-34 COMPARISON
(PRESSURE-TOP TRANSDUCER-RUNS IOS & IOF)

FIGURE 7. TEST DATA VS FLASH-34 COMPARISON
(PRESSURE-BOTTOM TRANSDUCER - RUN 10S & 10F)

represent the changes in response due to structural flexibility. Also, the FLASH-34 calculations compare reasonably well with the test data for the individual runs. However, there is a slight tendency of FLASH-34 to overpredict peak pressure and pulse duration. The higher frequency components superposed on the basic pulse are reproduced in the FLASH-34 calculations. The frequency of the superposed oscillation corresponds to the natural frequency of vibration of the test vessel water column (in a flexible elastic vessel). Note that these higher frequencies are damped out in the test data but not in the FLASH-34 calculations. This difference between calculations and test data is apparently due to the presence of significant structural damping and other dissipative mechanisms which are not represented in the FLASH-34 model. This tends to make the FLASH-34 calculations conservative in predicting peak pressures and peak pressure differences since the superposed high frequency components tend to increase peak pressures and peak pressure differences.

Figure 8 shows the measured and calculated test section volume displacement at FLASH node 7 for run 10F. The calculated maximum test section volume displacement compares quite favorably with the test data. Note that both the test data and the FLASH-34 calculations show the displacement to be in-phase with the pressure pulse. Also, the peak volume displacement is approximately the same as the peak volume displacement which would result from a static pressure loading of the same magnitude as the peak pressure. That is, the test section displacement response is quasi-static.

The deflection measurement corresponding to the peak test section volume displacement is approximately 3 mils. Since the proximeter is mounted on an inside wall of the test section it is difficult to interpret this number. The proximeter stiffens one face of the test section (locally at the mounting location) so that the total three mils deflection consists of the total deflection of one test section wall plus the constrained (by the proximeter mounting bracket) displacement of the opposite wall.

Figures 9 and 10 show the pressure response at the top transducer for runs 20S and 20F, respectively. FLASH-34 calculated pressures are also shown. Figures 11 and 12 show similar comparisons for the bottom transducer. Although the agreement between FLASH-34 calculations and test data is not as good as in runs 10S and 10F, the calculations still have the same general trends as the test data and FLASH-34 overpredicts both peak pressure measurements. The pressure relief due to structural deflection is reasonably well

FIGURE 8. TEST DATA VS FLASH-34 COMPARISON
(TEST SECTION VOLUME DISPLACEMENT - RUN 10F)

FIGURE 9. TEST DATA VS FLASH-34 COMPARISON
(PRESSURE-TOP TRANSDUCER-RUN 20S)

FIGURE 10. TEST DATA VS FLASH-34 COMPARISON
(PRESSURE-TOP TRANSDUCER-RUN 20F)

FIGURE II. TEST DATA VS FLASH-34 COMPARISON
(PRESSURE-BOTTOM TRANSDUCER-RUN 20S)

FIGURE 12. TEST DATA VS FLASH-34 COMPARISON
(PRESSURE-BOTTOM TRANSDUCER-RUN 20F)

portrayed by the FLASH-34 calculations. That is, calculated peak pressures are reduced in proportions similar to those observed in the data and the increase in pulse duration due to structural flexibility is predicted well. In terms of time rate of change of absolute pressure, this transient is significantly more severe than the pressure transient which is calculated to occur at a typical reactor core as the result of a postulated major LOCA. Simulation of this pressure transient represents a severe test of the ability of FLASH-34 to predict rapid pressure variations.

Figure 13 shows a comparison of calculated test section volume displacement with test data for run 20F. As in run 10F the volume displacement follows the pressure response very closely for both the test data and FLASH-34 calculations. In this case, however, the peak volume displacement seems to be somewhat greater than that for run 10F even though the peak differential pressure is greater for run 10F. Also, the peak volume displacement occurred at about 2 msec during a local pressure peak which was less than the overall peak pressure during the run. The maximum deflection is about 3.6 mils. This overshoot may indicate that dynamic response effects are beginning to occur for these rapid transients.

Table II gives a comparison of the reduced test data for all of the runs with calculated quantities determined from the FLASH-34 simulations. The reduced data consists of pressure pulse magnitude as measured at each transducer, pulse duration and maximum test section volume displacement for the flexible test section runs. Notice that in all cases the FLASH-34 calculated peak pressure is greater than the measured value.

VI. SUMMARY AND CONCLUSIONS

Pressure pulse tests were conducted with both solid and flexible test sections in a test vessel filled with room temperature water. A drop hammer and piston pulse generator was used to generate pressure pulses of magnitude up to 1150 psid and durations of from 6 to 47 msec.

Comparisons of FLASH-34 simulations with the test data show that FLASH-34 is capable of accurately predicting the test results, in particular, the effect of structural flexibility on hydraulic pressure. This implies that the procedure used to calculate the volumetric stiffness of the flexible structural member was also acceptable for this test. This procedure consists of determining the deflections for several spatially uniform static pressure loadings and then fitting a (elastic or bi-linear elastic) curve to the pressure versus volume displacement data.

FIGURE 13. TEST DATA VS FLASH-34 COMPARISON
(TEST SECTION VOLUME DISPLACEMENT - RUN 20F)

TABLE II

COMPARISON OF REDUCED TEST DATA WITH FLASH-34 CALCULATIONS

Run No.	Duration of First Pulse (msec)		Peak Pressure Pulse Magnitude- Top Transducer (psid)		Peak Pressure Pulse Magnitude- Bottom Transducer (psid)		Peak Test Section Volume Displacement (ft ³ x 10 ⁻⁵)	
	Test	FLASH-34	Test	FLASH-34	Test	FLASH-34	Test	FLASH-34
1F	28.0	30.0	200	330	200	310	2.7	4.2
2F	28.5	28.0	290	440	295	460	4.5	6.0
3F	23.0	26.0	425	530	410	540	6.1	7.1
4F	23.5	26.0	500	620	480	620	7.2	8.3
5F	22.0	25.0	600	720	590	710	8.0	9.6
6F	23.0	25.0	640	810	625	810	8.2	10.3
7F	22.5	24.0	775	960	740	950	10.2	12.6
8F	41.5	42.0	385	585	390	585	4.8	7.7
9F	36.5	39.5	685	790	670	810	9.0	10.8
10F	34.5	38.0	850	950	840	935	10.8	12.2
11F	47.5	52.0	650	780	645	760	8.8	10.1
12F	7.0	9.0	245	295	250	275	4.8	3.5
13F	6.5	7.5	380	420	340	395	7.2	5.6
14F	6.5	7.0	490	520	430	520	8.7	6.9
15F	6.0	7.0	540	600	480	600	10.4	7.6
16F	6.5	7.0	640	710	550	660	11.2	8.6
17F	6.0	6.5	725	760	590	720	12.1	9.8
18F	9.0	10.5	450	470	420	590	9.0	8.0
19F	9.0	10.5	600	720	590	810	11.4	10.6
20F	9.0	10.0	800	880	790	980	13.1	12.9
21F	9.0	9.5	850	1130	900	1230	15.0	15.9
22F	11.5	12.0	585	670	550	730	10.7	9.3
23F	11.5	12.0	850	945	820	995	12.0	13.3

TABLE II (Continued)

COMPARISON OF REDUCED TEST DATA WITH FLASH-34 CALCULATIONS

Run No.	Duration of First Pulse (msec)		Peak Pressure Pulse Magnitude- Top Transducer (psid)		Peak Pressure Pulse Magnitude- Bottom Transducer (psid)		Peak Test Section Volume Displacement (ft ³ x 10 ⁻⁵)	
	Test	FLASH-34	Test	FLASH-34	Test	FLASH-34	Test	FLASH-34
1S	21.5	25.0	285	430	310	420	-	-
2S	19.5	22.0	460	580	465	585	-	-
3S	17.5	21.0	600	690	600	700	-	-
4S	17.5	20.0	720	790	730	810	-	-
5S	17.5	20.0	820	910	840	900	-	-
6S	17.5	19.0	900	1000	900	1050	-	-
7S	17.0	18.5	1050	1130	1075	1250	-	-
8S	33.5	34.0	615	720	640	760	-	-
9S	30.0	31.0	880	990	890	1010	-	-
10S	27.5	29.0	1130	1190	1150	1260	-	-
11S	42.0	41.0	880	960	880	1000	-	-
12S	7.0	7.0	315	320	225	380	-	-
13S	6.5	6.0	405	485	370	610	-	-
14S	6.0	*	520	610	450	750	-	-
15S	6.0	*	610	720	510	840	-	-
16S	5.5	*	700	850	620	910	-	-
17S	5.5	*	730	920	690	1030	-	-
18S	9.0	8.5	470	620	440	740	-	-
19S	7.5	8.0	700	890	730	1190	-	-
20S	7.5	8.0	900	1130	975	1330	-	-
21S	8.0	*	1050	1280	1170	1500	-	-
22S	11.0	9.5	670	820	630	1000	-	-
23S	10.0	*	1000	1190	1000	1380	-	-

* Run terminated prematurely on negative pressure calculation so duration could not be determined.

All of the deflections obtained during the testing were in the elastic range. Both the linear elastic and bi-linear elastic FLASH-34 flexible structural member models were used successfully to simulate the test data. Since no plastic deflections occurred during this testing no information was obtained concerning the ability of FLASH-34 to calculate hydraulic pressures in the presence of plastically deforming flexible members. At present, the FLASH-34 flexible structural member model does not allow for plastic deformation effects. Some test data on plastic deformation resulting from pressure pulses is available in Reference 7 where it is reported that explosive charges were used to provide pressure pulses of sufficient magnitude to cause permanent deformation.

The FLASH-34 program is used to calculate the differential pressure loadings resulting from a hypothetical LOCA or check valve slam. Even though the effect of structural flexibility is included in the FLASH-34 calculation, the deflections are not used directly to assess structural integrity. Rather, the FLASH-34 calculated hydraulic pressure loadings are used as input to more detailed stress analysis computer programs. Of course, the volumetric displacements computed with the detailed stress analysis program should agree with the FLASH-34 calculated values.

In summary, the test data versus calculation comparisons presented here provide preliminary qualification for FLASH-34 calculations of transient hydraulic pressures in the presence of elastically deforming flexible structural members for single phase conditions and simple geometries.

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The conceptual design of the room temperature pressure pulse test facility is due to G. H. Cohen, who provided continued consultation and encouragement throughout the course of this work.

D. R. Johnston designed the pressure pulse test apparatus and provided technical lead for the testing in the Thermal and Hydraulics Laboratory. The flexible and solid test sections were designed by A. Weiss. R. J. Rihn handled the transducers and data recording instrumentation.

The FLASH-34 flexible structural member model was developed by J. H. Murphy.

FLASH-34 program modifications in support of the test simulations were performed by G. W. Swartele and W. D. Peterson.

The volumetric stiffness of the flexible test section was calculated by R. M. Clark.

Contributions and/or technical advice from the following individuals is gratefully acknowledged: C. S. Myers, N. J. Curlee, Jr., K. J. Coeling, P. J. Crescimanno, J. J. Beyer, C. J. Deal, J. W. Hunter and H. A. Beharna.

APPENDIX A

PROXIMETER CALIBRATION AND STIFFNESS DETERMINATION

PROXIMETER CALIBRATION AND STIFFNESS DETERMINATION

Calibration runs were made with both the solid test section and the 1/8 inch wall aluminum test section. Static loads of up to about 275 pounds were applied to the one inch piston. The test vessel gage pressure (Δp) and the piston displacement (Δx_p) were measured. The volume displacement resulting from structural deflection was then calculated from:

$$\Delta V_D = A_p \Delta x_p - \frac{V_o \Delta p}{\beta} \quad (A-1)$$

where:

ΔV_D = volume displacement from structural deflection

A_p = piston area

Δx_p = piston (linear) displacement

V_o = initial vessel volume (before loading)

Δp = gage pressure

β = bulk modulus of water

Figure A-1 shows the differential pressure versus volume displacement data for the solid test section configuration. From this data it is apparent that for low differential pressures the vessel appears to be quite flexible. The source of this flexibility is now known. However, the data showed good repeatability so it is doubtful that air was trapped in the vessel. There are many possible sources of flexibility including the shut valves, the water fill line, the test vessel, etc.

In the FLASH-34 model this flexibility is attributed to the test vessel and is included by using the flexible structural member option. The bi-linear curve shown in Figure A-1 was used to represent the stiffness. Because of the data scatter it was difficult to determine a slope for the upper part of the curve. Therefore, the calculated stiffness of the test vessel was used for this purpose. The stiffness was calculated using the standard formula for elastic deformation of a thick walled cylinder (Reference A-1).

Figure A-2 shows the differential pressure versus volume displacement data for the configuration with the 1/8 inch wall test section. Of course,

FIGURE A1. VESSEL STIFFNESS CURVE

FIGURE A-2. STIFFNESS CURVE WITH 1/8 INCH WALL TEST SECTION

the vessel flexibility is also present in addition to the added flexibility of the test section. Because of the limited accuracy of the data and the difficulty of separating out the flexibilities based on the data, no experimental value was obtained for test section stiffness.

The test section stiffness used in the FLASH-34 model was calculated* using the GAPL^(A-2) computer program. This calculated stiffness is consistent with the limited static test data.

To determine the test section volume displacement corresponding to a given proximeter reading, the calculated test section stiffness was used in conjunction with a linear calibration curve of proximeter reading versus differential pressure. By eliminating the differential pressure between the two curves, the test section volume displacement versus proximeter reading ratio was determined to be $3.6 \times 10^{-5} \text{ ft}^3/\text{mill}$.

REFERENCES:

- A-1 W. F. Hughes and E. W. Gaylord, "Basic Equations of Engineering Science," Schaum Publishing Co., New York (1964)
- A-2 A. L. Thurman, "GAPL-3 - A Computer Program for the Inelastic Large-Deflection Stress Analysis of a Thin Plate or Axially Symmetric Shell with Pressure Loading and Deflection Restraints," WAPD-TM-791, June 1969

* This calculation was performed by R. M. Clark.

APPENDIX B

FLASH-34 FLEXIBLE STRUCTURAL MEMBER OPTION

FLASH-34 FLEXIBLE STRUCTURAL MEMBER OPTION

In FLASH-34 a flexible structural member is represented by a movable wall located between two nodes. Figure B-1 is a schematic showing a flexible member of mass m and stiffness K located between FLASH nodes a and b . Let x represent the linear displacement of the wall from node a into node b . Then the governing equation of motion for the plate is:

$$\frac{m}{g_c} \ddot{x} + 144 KA^2 x = 144A (p_a - p_b) \quad (B-1)$$

or, in terms of volume displacement $X = xA$,

$$\frac{m \ddot{X}}{144 g_c A^2} + KX = (p_a - p_b) \quad (B-2)$$

In the above equations,

m = mass of movable wall plus any water expected to move with the wall (lbm)

K = volumetric stiffness (psi/ft³)

A = wall area (ft²)

p = node pressure (psi)

g_c = gravitational constant (lbm-ft/lbf-sec²)

Defining,

$$M = \frac{m}{144 g_c A^2} \quad (B-3)$$

the governing equation can be written

$$M \ddot{X} + KX = p_a - p_b \quad (B-4)$$

Two stiffness models are available, the inlear elastic model (i.e. K constant) or the bi-linear elastic model, with stiffness (Δp versus X relationship) as shown in Figure B-2. Input parameters for the flexible member

FIGURE B-1. FLEXIBLE MEMBER SCHEMATIC

FIGURE B-2. BILINEAR STIFFNESS MODEL

option are the wall mass (m), the wall area (A) and the stiffness (either K for the linear elastic model, or K_1 , K_2 and X_1 for the bi-linear elastic model).

For the purpose of simulating the pressure pulse tests, a piston model was added to the FLASH-34 program. This model is similar to the flexible structural member model in that the piston is represented by a movable node boundary. The governing equation is:

$$\frac{m_p}{g_c} \ddot{X} + c \dot{X} = -144 A_p^2 (p - p_o) \quad (B-5)$$

where:

- X = piston volume displacement into node (ft^3)
- p = node pressure (psia)
- p_o = initial node pressure (psia)
- m_p = piston mass (lbm)
- g_c = gravitational constant (lbm-ft/lbf-sec^2)
- c = damping coefficient (lbf.sec/ft)
- A_p = piston area (ft^2)

Note that the piston volume displacement X is simply related to the piston linear displacement x by:

$$X = x A_p \quad (B-6)$$

The transfer of momentum and energy from the drop hammer to the piston is modeled as a collision process. That is, the drop hammer is assumed to have an initial velocity $\dot{y}_o$ and to collide with the piston at time zero. The conservation of momentum and energy equations are solved assuming an instantaneous collision to obtain the post collision velocities for the drop hammer ($\dot{y}_1$) and the piston ($\dot{x}_1$). This gives,

$$\dot{y}_1 = \frac{(m_h - \epsilon m_p) \dot{y}_o + (1 + \epsilon) m_p \dot{x}_o}{(m_h + m_p)} \quad (B-7)$$

$$\dot{x}_1 = \frac{(1 + \epsilon) m_h \dot{y}_o + (m_p - \epsilon m_h) \dot{x}_o}{(m_h + m_p)}$$

where m_h and m_p are the drop hammer and piston masses, respectively, and ϵ is the coefficient of restitution. Until the next collision, the motion of the piston is governed by equation (B-5) and the motion of the drop hammer is given by,

$$y = \frac{g}{2} t^2 + \dot{y}_1 t + y_1 \quad (B-8)$$

which is the free fall trajectory from position y_1 with initial velocity $\dot{y}_1$. The positions of the piston and drop hammer are monitored to determine if and when another collision occurs. In the event of another collision equations (B-7) are again solved to obtain the post collision velocities. This process is continued to obtain the drop hammer and piston trajectories. In equation (B-8), t is the time since the last collision.

Input parameters for the piston model are m_p , m_h , A_p , c , e and $\dot{y}_o$. The initial piston velocity is assumed to be zero.

APPENDIX C

ESTIMATE OF DAMPING COEFFICIENTS
FROM PISTON MOTION TESTS

ESTIMATION OF DAMPING COEFFICIENTS
FROM PISTON MOTION TESTS

Piston motion tests were conducted with the piston and piston sleeve removed from the test vessel. If the sleeve is held in a fixed position and the piston is subjected to a constant force F the equation of motion of the piston is:

$$m_p \ddot{x} + c \dot{x} = F \quad (C-1)$$

where:

- m_p = piston mass (slugs)
- x = piston displacement (ft)
- c = damping coefficient (lbf-sec/ft)
- F = force (lbf)

If the damping coefficient is large enough and the force F is small then the piston will reach a constant velocity very quickly after the constant force F is applied. This constant velocity is:

$$\dot{x} = F/c \quad (C-2)$$

When the force is known and the velocity is measured, then the damping coefficient can be found from equation (C-2).

The one-inch diameter piston was allowed to fall out of the sleeve under its own weight. Observations of the approximately four inch drop (terminated when the O-ring left the sleeve) revealed that a constant velocity was reached very quickly. The time constant for the decay of the acceleration transient is c/m_p . Since the drop took slightly over one second, this gives a damping coefficient of approximately 9 lbf sec/ft. A similar test for the two inch piston gave an estimate of 100 lbf sec/ft for the damping coefficient.

The FLASH-34 predicted peak pressures and pulse durations were not affected significantly by changes in the piston damping coefficient. However, the piston damping did remove some high frequency components from the predicted pressure response especially in nodes 1 and 2.

APPENDIX D

FLASH-34 INPUT LISTING

* APPENDIX D FLASH-34 INPUT LISTING

*

* G.3 PRESSURE PULSE TEST - RUN NO. 10F

*

= G.3 1 IN. PISTON 1/8 IN. TEST SECTION 11 NCDE

1001,.045,2.0,1.0

2001,1.-6,.045

*CONTROL VOLUME SPECIFICATIONS

3001,.02182,.41705, 3.17, 3.17,3.157,37.70,36.0,0.0

3002,.02182,.41705, 2.76, 3.14,2.740,37.88,36.0,0.0

3003,.01097,.3044,2.450,2.700,2.435,38.060,36.0,0.0

3004,.01097,.3044,2.140,2.400,2.131,38.192,36.0,0.0

3005,.01097,.3044,1.840,2.100,1.826,38.324,36.0,0.0

3006,.01097,.3044,1.530,1.800,1.522,38.456,36.0,0.0

3007,.01097,.3044,1.230,1.500,1.218,38.588,36.0,0.0

3008,.01097,.3044,0.930,1.200,.9132,38.720,36.0,0.0

3009,.01097,.3044,0.620,0.900,.6088,38.852,36.0,0.0

3010,.01097,.3044,0.320,0.590,.3044,38.984,36.0,0.0

3011,.01097,.3044,0.290,0.290,0.000,39.116,36.0,0.0

3012, 1.+10,100.0, 0.0, 0.0, 0.0,14.700,1300.0,0.0

\$ ATMOSPHERE

*FLOW PATH SPECIFICATIONS

4001,8,1,2,0.0,23.9,.02182,0.188

4002,8,2,3,0.0,25.9,.01097,4.310

4003,8,3,4,0.0,27.8,.01097,0.39

4004,8,4,5,0.0,27.8,.01097,0.39

4005,8,5,6,0.0,27.8,.01097,0.39

4006,8,6,7,0.0,27.8,.01097,0.39

4007,8,7,8,0.0,27.8,.01097,0.39

4008,8,8,9,0.0,27.8,.01097,0.39

4009,8,9,10,0.0,27.8,.01097,0.39

4010,8,10,11,0.0,27.8,.01097,0.39

*FLEXIBLE PLATES

7501,3.39,42.3,.005454,-1,1,0.0,5.67,9.0

\$ 1 IN. PISTON 6 IN. DROP

7502,3.04,7.24+6,0.265,12,1,1.10-5,1.29+8

\$ VESSEL STIFFNESS

7503,3.04,7.24+6,0.265,12,2,1.10-5,1.29+8

7504,1.66,1.24+7,0.155,12,3,0.643-5,2.21+8

7505,1.66,1.24+7,0.155,12,4,0.643-5,2.21+8

7506,1.66,1.24+7,0.155,12,5,0.643-5,2.21+8

7507,1.66,1.24+7,0.155,12,6,0.643-5,2.21+8

7508,1.66,1.24+7,0.155,12,7,0.643-5,2.21+8

7509,1.66,1.24+7,0.155,12,8,0.643-5,2.21+8

7510,1.66,1.24+7,0.155,12,9,0.643-5,2.21+8

7511,1.66,1.24+7,0.155,12,10,0.643-5,2.21+8

7512,1.66,1.24+7,0.155,12,11,0.643-5,2.21+8

7513,0.3022,6.813+7,0.1249,12,3 \$ 1/8 IN. TEST SECTION

7514,0.3022,6.813+7,0.1249,12,4

7515,0.3022,6.813+7,0.1249,12,5

7516,0.3022,6.813+7,0.1249,12,6

7517,0.3022,6.813+7,0.1249,12,7

7518,0.3022,6.813+7,0.1249,12,8

7519,0.3022,6.813+7,0.1249,12,9

7520,0.3022,6.813+7,0.1249,12,10

7521,0.3022,6.813+7,0.1249,12,11

*PLOTTING INFORMATION

20001,1,0,1

20002,4,2,2,2
20011,4,1
20012,4,2
20013,4,3,4,5,6
20014,4,7
20015,4,8,9,10,11
20016,5,11
20017,5,12,15,17,19,22
20018,5,23,25,29,31
20019,5,27