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**Pressure Pulse Test Results
and Qualification of the FLASH-34
Flexible Structural Member Model
with a Surge Tank Attached
to the Test Vessel
(LWBR Development Program)**

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August 1977

MASTER

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FLEXIBLE STRUCTURAL MEMBER MODEL WITH A SURGE TANK ATTACHED
TO THE TEST VESSEL
(LWBR Development Program)

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ABSTRACT FOR WAPD-TM-1290

PRESSURE PULSE TEST RESULTS AND QUALIFICATION OF THE FLASH-34
FLEXIBLE STRUCTURAL MEMBER MODEL WITH A SURGE TANK ATTACHED
TO THE TEST VESSEL
(LWBR Development Program)

R. E. Schwirian

Pressure pulse tests were conducted with both solid and flexible test sections installed in a test vessel filled with room temperature water. A surge tank whose volume was approximately equal to that of the test vessel with the test section installed was connected to the test vessel by a 1/8 inch I.D., 8 inch long surge line. Pressure pulses of magnitude up to 1275 psid and durations from 4.6 to 55.8 msec were generated in the test vessel with a drop hammer and piston pulse generator.

FLASH-34 calculations show good agreement with the test data. In particular, FLASH-34 accurately predicts (a) the decrease in peak pressure and the increase in pulse duration due to the presence of a flexible test section, (b) the time delay between the occurrence of the pressure pulse in the test vessel and its arrival in the surge tank and (c) the magnitudes of the transient pressure differences between the test vessel and surge tank caused by the time delay. All of the structural responses were in the elastic range and were approximately quasi-static for the pulses tested.

The test data versus calculation comparisons presented here provide preliminary qualification for FLASH-34 calculations of transient hydraulic pressures and pressure differentials in the presence of elastically deforming flexible structural members and with the transmission of pressure waves through a contraction and expansion.

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 resulting from blowdown and check valve slam (References 1-5). 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 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 this case, 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.

Basic data for the qualification of the flexible structural member option in FLASH-34 were reported in Reference 6. In the test series reported therein 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 were not prototypical, the basic mechanism of pressure relief due to structural deflection clearly existed. Comparisons of the test data with FLASH-34 calculations demonstrated that the FLASH-34 program with the flexible structural member option correctly modeled the effect of structural deflection on hydraulic pressure.

The present test series is an extension of the work reported in Reference 6. The primary difference between the tests reported herein and those of Reference 6 is the presence of a surge tank connected to the test vessel by a surge line. The purpose of introducing this complexity is to qualify FLASH-34 for cases where a significant time delay exists between the time a pressure surge is felt in one part of a reactor plant and the time it is felt in another, more remote part of the reactor plant.

* Combines both FLASH-3 (Reference 1) and FLASH-4 (Reference 8).

Because of the relatively complex geometry and the presence of flexible members, these tests provide a severe basis against which the ability of FLASH-34 to predict pressure surge transmission can be measured.

Except for the presence of a surge tank and surge line, the test runs in the present series are identical to those reported in Reference 6. That is, the hammer weights and drop heights were identical. Pressure pulse magnitudes up to 1275 psi and transient durations (including pressure pulse reflection from the surge tank) from 4.6 to 55.8 msec were measured. Comparisons of the test data with FLASH-34 calculations show good agreement, and demonstrate that the flexible structural member option is capable of modeling structural deflections even in non-simple geometries.

II. PRESSURE PULSE TESTS WITH SURGE TANK

The pressure pulse test vessel consists of a 2 inch diameter, $45\frac{1}{4}$ inch long test vessel with a piston at one end (see Figures 1 and 2). Aluminum test sections are mounted inside as in Figure 3. Connected to the test vessel by a $1/8$ inch I.D., 8 inch long surge line is a surge tank whose internal dimensions are 7.59 inches high and 4 inches in diameter (Figure 4). 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 test vessel and at an elevation corresponding to the midpoint of the aluminum test sections. Piezoelectric pressure transducers are also placed at the top and bottom of the surge tank.

The aluminum test sections are $1\frac{1}{4}$ inch square extruded aluminum tubing (6063-T5), $34\text{-}3/8$ 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. A schematic of the $1/8$ inch thick wall test section is shown in Figure 3. 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 of Reference 6. 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 and surge tank 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 and magnitudes. 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 were 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. These are summarized in Table I for both test sections. 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. These two sets of runs duplicate - except for the surge tank - those of Reference 6.

Although not reported, approximately 6-8 check runs were run to assure the repeatability of the test data. These were usually done at the end of a series of runs. In no case were the check runs noticeably different from the original runs with the same piston, hammer weight and drop height.

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 of Reference 6. This flexibility is present with either of the aluminum test sections.

The stiffness of the surge tank was determined in a similar fashion and is discussed in Appendix A of this report. In essence, the total volume displacement (test vessel plus surge tank) was measured for a given static pressure with the solid test section in place. The test vessel displacement previously measured (Appendix A of Reference 6) at the same pressure was subtracted from this measurement. The result was the volume displacement of the surge tank at that pressure. Data at several pressures were used to determine the stiffness of the surge tank.

Tables II and III give a summary of the test parameters and results from each run for the 1/8 inch and solid test sections. The reduced data consist of peak pressure pulse magnitudes in the test vessel and surge tank, duration of the test vessel and surge tank pulses, time to reach a pressure peak in the surge tank, and maximum test section volumetric displacement. For all runs, the static pressure before and after was approximately 23 psig.

In many of the test runs, the pressure pulses were characterized by primary and secondary peaks as in Figure 5. The secondary peaks are due to discharge of fluid from the surge tank to the test vessel subsequent to the initial pressure buildup in the surge tank. In these cases, the pulse durations quoted in Tables II and III include both primary and secondary pulses. The criterion used to determine pulse duration in all cases was defined to be the time during which the pressure was above its initial value (e.g. see Figure 11).

III. FLASH-34 FLEXIBLE STRUCTURAL MEMBER MODEL WITH SURGE TANK

In a FLASH-34 model, the fluid region is divided into a number of control volumes (nodes) connected by flow paths. 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 of Reference 6. 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 bilinear 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 of Reference 6, 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 or bilinear 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 WITH SURGE TANK ATTACHED

Schematics of the FLASH-34 models for both the flexible test section configuration and the solid test section configuration are shown in Figures 6 and 7. In each case a total of 11 nodes represent the compressed water volume in the test vessel. A single node represents

the surge tank. Of the eleven nodes in the test vessel, the first two 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 13 flexible members were used. The first member represents the piston and the next 11 represent the vessel stiffness. The final flexible member represents the surge tank. For the flexible test section configuration an additional nine flexible members were used to represent the test section. A listing of an input deck for a typical run is given in Appendix B.

Nodal areas and heights inside the test vessel were the same as in Reference 6. For the one inch piston runs the total volume was $.04825 \text{ ft}^3$; for the two inch piston runs the total volume was $.05285 \text{ ft}^3$. The volume of the surge tank was taken to be $.632 \times (.0872) \approx .05510 \text{ ft}^3$, the volume of a right circular cylinder 7.59 inches high and 4 inches in diameter.

The initial node pressures were calculated as 37.7 psia plus the elevation head from the top of the test vessel. An exception to this was node 13, whose pressure was set equal to that of node 10 in the test vessel. This was simply an oversight which was not discovered until all the FLASH-34 calculations were complete. This error could not have caused more than a .5 psi error in the calculated results. An initial enthalpy of 36 BTU/lb was used for all of the eleven test vessel nodes and the surge tank node. Node 12 was the constant pressure atmosphere node.

Ten flow paths connecting the eleven test vessel nodes in series were given friction factors of 0.06. Sensitivity studies reported in Reference 6 indicated that FLASH-34 calculations were not affected by rather large (factor of 3) changes in the in-vessel flow path friction factors. It is reasonable to assume, and was assumed, that the same holds for the present series of tests. The initial flow in all flow paths was set equal to zero.

In general, the in-vessel modeling of the present tests was the same as that of Reference 6. *The piston mass and damping coefficients reported in Reference 6 were used - 3.11 lbs and 9 lbf-sec/ft for the one inch piston and 10.4 lbs and 100 lbf-sec/ft for the two inch piston. The test vessel and test section flexible member models were identical to those of Reference 6.

The surge tank stiffness was determined to be $1.4 \times 10^7 \text{ psi/ft}^3$. The determination of this quantity is discussed in Appendix A. The flexibility of the surge tank is a small effect compared to that of the test vessel and the compressibility of the water. **

* In this reference, a study was made to determine the optimum number of nodes in the test vessel. The in-vessel modeling in the present study uses this optimum nodalization.

** Only one surge tank node was used for all calculations because both the tests and estimates of the time response of the surge line-surge tank combination showed that only one node was necessary.

V. FLASH-34 SURGE LINE MODEL

Unlike the test vessel flow paths, the surge line K-losses are not negligible. Figures 8, 9 and 10 show the effect of the surge line K-factor on the calculation of the surge tank pressure. Surge line K-factors of 0.0, 1.5 and 10.0 were assumed in the FLASH-34 calculation of run 10SST. For $K = 0$, the predicted peak surge tank pressure is almost 200 psi higher than the test value, reflecting the absence of irreversible losses in the surge line. The existence of a secondary peak in the calculation (unlike the experimental curve, which has none) is also an indication that the irreversible losses in the FLASH-34 model are too low. In effect, the FLASH-34 model is behaving like an underdamped spring-mass system, with the surge line as the "mass" contained between the test vessel and surge tank "springs".

Figure 9 shows the surge tank pressure-time plot obtained when the surge line K-factor is 1.5, which is a typical K-factor for a contraction-expansion geometry when friction is negligible between the contraction and the expansion and the length-to-diameter of the flow path is significantly greater than unity. The comparison with experiment here is much better than in Figure 8. The peak surge tank pressure prediction is about right and there is no secondary peak.

The surge tank pressure-time plot for a K-factor of 10.0 is shown in Figure 10. Here there is obviously too much attenuation of the pulse by the surge line and the predicted pulse is much too low. The experimental value (not shown on Figure 9) is at approximately 790 psia.

Of these three cases, the K-factor of 1.5 gives the most reasonable results. This is not necessarily the appropriate K-factor to use, however, and is typical only if end losses are significantly larger than friction losses in the surge line. To pin down the actual K-factor, a test was run to determine its value. This test is described in Appendix C. From the data taken a K-factor of 3.91 at a Reynolds number of 8580 was determined. Only 1.50 of this can be accounted for on the basis of entrance and exit losses. The difference $3.91 - 1.50 = 2.41$ must be due to surge line friction or some other source of loss. A friction loss factor of 2.41 can be obtained in a 1/8 inch I.D., 8 inch long pipe at a Reynolds number of 8580 if the relative roughness k/D of the pipe is approximately .002 (Reference 7). This corresponds to a k -value of $1/8 (.002) = .00025$ inch, which is somewhat high for commercially available tubing of the type that was used to make the surge line. Since city water is used in the testing, it may be that some solid material originally in the water deposited on the tube walls, thereby increasing the roughness slightly. A relative roughness of .002 is certainly possible even with clean tube walls, given the uncertainties inherent in the manufacture of tubing.

There is no way to tell from the measurements described in Appendix C whether relative roughness of the pipe or some other mechanism is responsible for the added loss in the surge line beyond the entrance and exit losses and the normal, smooth pipe friction. A significant viscous pressure drop within the test section or surge tank is highly unlikely due to the low velocity there compared with that in the surge line. Consequently, roughness was assumed to be the mechanism and frictional K-losses for $3000 < Re < 10^5$ were evaluated on this basis. For $Re < 2000$, the laminar flow friction factor $64/Re$ was used to estimate the K-loss and a linear interpolation between $Re = 2000$ and $Re = 3000$ was used to join the laminar and turbulent regimes. The

total K-loss at a given Reynolds number was taken to be the frictional K-loss as evaluated above plus the entrance - exit loss factor 1.5.

To permit a variable K-loss in the calculations, the surge line was made a type 13 flow path. For flow paths of this type, a K-factor versus flow rate table is part of the program input. For this purpose the 4971-5000 card series is used (see Appendix B for this input). All subsequent FLASH-34 calculations were made with this surge line model.

VI. COMPARISON OF FLASH-34 SIMULATIONS WITH TEST DATA

FLASH-34 calculations were made for all of the 23 pairs of runs. The data for all runs is summarized in Tables I, II and III. Generally speaking, the accuracy obtained in the FLASH-34 calculations is as good as was obtained in Reference 6. Because of the similarity of much of the test data and calculations to that of Reference 6 detailed comparisons of FLASH-34 calculations with test data are presented here for only two runs, run 10SST and run 10FST. Test parameters for these two runs are the same (42.3 lb drop hammer weight, 6 inch drop height, one inch piston). The comparisons of test data and FLASH-34 calculations for these two runs are representative of results which were obtained for other runs.

Figures 11 and 12 show comparisons of FLASH-34 calculated pressures in the test section (node 7) and the surge tank (node 13) with test data for run 10FST. Figure 13 is a comparison of the calculated and measured pressure difference between nodes 7 and 13 for the same run. In general, the comparisons are good, indicating that FLASH-34 is quite capable of treating the modeling complexities associated with the presence of a surge line and surge tank. There is still the tendency of FLASH-34 to slightly overpredict pulse duration, a tendency which was observed in Reference 6. Unlike the Reference 6 results, however, the high frequency oscillations associated with the natural frequency of the test vessel water column are not severely damped and as a result, the test results look much more like the FLASH-34 calculations than was the case in Reference 6. It is not clear why this is so. The test vessel pressure transducer used for the present test are the same ones used in the Reference 6 tests. It is possible that different signal conditioning or recording instruments were used. However, the same types of instruments that were used in Reference 6 testing were used in the present tests. Another possibility is a slight difference in instrumentation settings, particularly frequency response settings. This is, and must remain speculation, however, since there is no way of determining if there was a difference.

A comparison of the test vessel (node 7) and surge tank (node 13) pressures, shows that the surge line acts like a high frequency filter. This is to be expected, since the surge line was designed to produce a significant time delay between the time a pulse occurred in the test vessel and the time it was transmitted to the surge tank. The response time of the surge line is simply too low to permit the transmission of high frequency oscillations to the surge tank. The fact that both FLASH-34 and test data show this filtering of high frequency oscillations is a further

confirmation of the adequacy of FLASH-34 for such calculations.

Figures 14, 15 and 16 show comparisons of FLASH-34 calculated pressures in the test vessel and surge tank and the pressure difference between the two with test data for run 10SST. Again, the comparisons are good. As in Reference 6, the pulses are shorter and the test vessel pressure pulse magnitudes are higher for the solid test section than for the flexible test section. Figures 12 and 15 and Tables II and III show peak surge tank pressures - both experimentally determined and FLASH-34 calculated - to be about the same for the two cases, however, particularly for the shorter pulses. This can be explained as follows.

The pressure peak in the test vessel is determined largely by the piston displacement and the wall deflection. This is especially true for short pulses, when the surge line flow cannot build up fast enough to provide significant pressure relief of the test vessel. Consequently, the test vessel pressure peak is substantially lower when the flexible test section is in place. The pressure peak in the surge tank, however, is primarily determined by the total amount of fluid transferred through the surge line. This, in turn, is determined by both the magnitude and the duration of the surge line driving force, (i.e. the pulse in the test vessel). Even though the peak test vessel pressure is lower with the flexible test vessel installed, the duration of the pulse is greater, resulting in surge tank peak pressures which are about the same for both cases. This effect is especially pronounced for low test vessel pulse durations (e.g. runs 12-17), for which the test vessel pressure and test section displacement have returned to their original values before the surge tank pressure peak is attained.

It can be seen in Tables II and III that for short duration, high magnitude pulses, the peak surge tank pressure is actually higher with the flexible test section installed. This can be attributed to the influence of hydraulic losses in the surge line. For large test vessel pulse magnitudes, the surge line velocities are very high. Since hydraulic losses increase with the square of the velocity and temporal inertia increases only with the first power of velocity, hydraulic losses are of major importance primarily for large magnitude pulses. The effect of this is to diminish the flow of fluid to the surge tank by a greater percentage for large magnitude pulses than for small magnitude pulses. Since the test vessel pulse magnitudes, and thus the surge line flow velocities, are greatest with the solid test section in place, the transfer of fluid to the surge tank is retarded to a greater extent than is the case with the flexible test section installed. Since the hydraulic losses have little effect on the test vessel pulse duration, the result is relatively lower surge tank pressure peaks when the solid test section is in place and the test vessel pulse magnitude is large.

The importance of hydraulic losses in the surge line for high pulse magnitudes also makes the accuracy of FLASH-34 calculations in this regime more dependent on the accurate calculation of hydraulic losses in the surge line. If, for some reason, hydraulic losses are

underestimated, one would expect surge tank pressures to be overpredicted. Conversely, the overestimation of hydraulic losses should lead to underprediction of surge tank pressures. In Figures 17 and 18 the ratios of peak predicted surge tank pressure to peak measured surge tank pressure are shown for all runs as a function of peak test vessel pressure pulse magnitude. The K-factor representation used in the FLASH calculations is discussed in Section V and Appendix C. Although the ratios are seldom inaccurate by more than 10-15%, Figures 17 and 18 do show a tendency for FLASH-34 to underpredict surge tank pressures slightly for high pulse magnitudes. Furthermore, this underprediction appears to be more substantial for short duration pulses, i.e. those generated using a smaller number of bricks.

This tendency to underpredict suggests that the surge line hydraulic losses used in the FLASH-34 calculations are somewhat high compared with those that actually occur in the tests. Since the steady-state K-factor of the surge line was measured (Appendix C), the conclusion that must be drawn is that the surge line K-factors attained during dynamic testing are less than the static or fully developed values. In Appendix D it is shown that the time scale for the development of a boundary layer thick enough to retard the surge line flow by an amount which would be predicted by a fully developed K-factor is of the same order as the pulse duration. It is quite likely, therefore, that surge line K-factors do not reach fully-developed values during dynamic testing and that the tests with the shortest pulse durations and highest pulse magnitudes will be most affected.

At this point it should be re-emphasized that this tendency of FLASH-34 to underpredict surge tank pressures when fully developed surge line K-factors are used results in discrepancies of, at most, only 10-15%. As Figures 17 and 18 indicate, however, the trend is a clear one. At present, FLASH-34 does not have the capability of predicting boundary layer development in a flow path. In Appendix D, however, a method of estimating the time necessary before friction plays an important role in the flow development in a flow path like the surge line is presented. Applied to run 10SST, this method indicates that approximately 10 msec (or about 20% of the pulse duration) are required for full flow development. Although the method does not affect the FLASH-34 modeling of the problem, it can be used to determine whether or not the lack of full flow development is a problem and, if so, what assumptions can be made to insure that the FLASH-34 calculations are conservative.

VII. CONCLUSIONS

Pressure pulse tests were conducted with both solid and flexible test sections in a test vessel filled with room temperature water and connected to a surge tank by a surge line whose response time was low enough to cause a significant time delay in the pressure pulse transmission between the two vessels. A drop hammer and piston pulse generator were used to generate pulses of up to 1275 psid and durations from 4.6 to 55.8 msec. The results of these tests lead to the following conclusions.

- a) Comparisons of FLASH-34 simulations with the test data show that the FLASH-34 calculated pressures in the test vessel are in good agreement with the measured values.
- b) Comparisons of FLASH-34 calculated surge tank pressures also are in good agreement with the test data. In general, the comparisons of calculated and experimental pressures with a surge tank attached to the test vessel are as good as those of Reference 6, in which testing and analysis involved only the test vessel and test section.
- c) The tendency of FLASH-34 to overpredict pressure pulse magnitude and duration slightly in the test vessel, as reported in Reference 6, is also present in the current series of tests. The magnitude of surge tank pressures is not, in general, significantly overpredicted, however, being more often than not underpredicted. This is probably due in part to the fact that the surge line filters out the high frequency pressure pulse components present in the test vessel.
- d) Surge tank pressure peak magnitude - both experimentally determined and calculated - appears to be about the same regardless of whether the solid or flexible test section is installed in the test vessel. This is in contrast to the pulse magnitudes in the test vessel, which are significantly lower with the flexible test section. This is attributed to the fact that the mass transfer of fluid to the surge tank is proportional not only to the magnitude of the pulse in the test vessel but also to the duration of that pulse, the latter of which is greater with the flexible test section in place.
- d) There is a tendency for FLASH-34 to underpredict surge tank pressures at high pulse magnitudes and low pulse durations. This is thought to be due to the fact that, except for pulses of long duration, the flow does not become fully developed in the surge line during the transients.

It is emphasized that the trends discussed above, while present, result in calculated surge tank pressure peaks which seldom differ from measured values by more than 10-15%. A means of determining whether or not the lack

of full flow development is a problem in FLASH-34. Calculations of this type is presented in Appendix D. A sample calculation based on run 10SST indicates that flow development times for the present series of runs can be a substantial portion ($\approx 20\%$) of the total pulse duration, suggesting that full flow development may not have occurred.

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8. T. A. Porsching, J. H. Murphy, J. A. Redfield and V. C. Davis, "FLASH-4: A Fully Implicit FORTRAN-IV Program for the Digital Simulation of Transients in a Reactor Plant," WAPD-TM-840, dated March 1969

TABLE I
TEST PARAMETERS

Run No.	Piston Diameter (inches)	Number of Bricks on Drop Hammer	Drop Hammer Weight (lbs)	Drop Height (inches)
1J*	1.0 ↓	0	16.4	2
2J		↓	↓	4
3J		↓	↓	6
4J		↓	↓	8
5J		↓	↓	10
6J		↓	↓	12
7J		↓	↓	16
8J	↓	1	42.3	2
9J		↓	↓	4
10J		↓	↓	6
11J	2.0 ↓	2	68.2	2
12J		0	16.4	2
13J		↓	↓	4
14J		↓	↓	6
15J		↓	↓	8
16J		↓	↓	10
17J	↓	↓	12	
18J	↓	1	42.3	2
19J		↓	↓	4
20J		↓	↓	6
21J		↓	↓	8
22J	↓	2	68.2	2
23J		↓	↓	4

Each of the runs in this table was performed twice, once with the solid test section in place (J = SST) and once with the flexible test section in place (J = FST). The suffixes SST and FST have the following meanings:

J = SST for solid test section runs with surge tank attached

J = FST for flexible test section runs with surge tank attached

TABLE II
1/8 INCH FLEXIBLE TEST SECTION RESULTS

Run No.	Duration of Bottom Transducer Pulse (msec)		Peak Pressure Pulse Magnitude-Bottom Transducer (psi)		Time to Surge Tank Pressure Peak (msec)		Duration of Surge Tank Pulse (msec)		Peak Pressure Pulse Magnitude- Surge Tank (psi)		Peak Test Section Volume Displacement (ft ³ x 10 ⁻⁵)	
	Test	FLASH-34	Test	FLASH-34	Test	FLASH-34	Test	FLASH-34	Test	FLASH-34	Test	FLASH-34
1 FST	33.7	33.9	205	225	17.3	18.3	29.5	31.5	238	235	4.15	2.98
2	31.9	33.0	300	348	17.4	20.8	29.4	34.5	335	310	5.80	4.62
3	31.0	33.0	385	404	16.5	20.3	29.3	34.5	400	390	6.62	5.35
4	29.0	30.0	450	470	16.6	20.0	29.1	34.5	450	405	8.28	6.20
5	28.8	29.5	525	520	16.2	20.0	29.3	35.7	500	445	9.10	6.93
6	27.2	28.0	570	580	17.0	20.0	30.0	35.2	540	480	9.95	8.55
7	26.0	25.6	660	698	16.4	20.0	31.0	36.0	600	530	10.80	9.11
8	45.6	55.0	335	398	21.9	27.0	46.2	53.7	415	415	6.21	5.31
9	41.5	50.7	515	580	22.0	27.7	44.0	52.5	580	545	7.45	7.65
10	42.5	51.5	620	685	22.0	27.3	44.0	52.0	687	645	9.11	8.77
11	55.8	68.0	500	530	25.2	30.0	55.5	67.0	550	545	6.63	7.03
12	5.0	6.8	240	260	11.0	11.9	18.8	19.2	93	104	4.97	3.38
13	4.6	6.2	340	373	10.5	11.0	17.6	19.3	130	135	7.87	5.22
14	4.8	6.0	445	496	10.0	10.8	18.6	19.6	167	157	8.70	6.39
15	5.1	6.5	535	547	9.9	11.0	19.2	19.9	190	173	9.95	7.00
16	5.2	6.0	600	624	9.3	10.4	18.9	20.2	210	190	12.00	8.10
17	6.0	6.0	690	640	9.0	10.2	19.0	20.3	220	199	12.43	8.55
18	10.0	10.8	362	550	11.5	12.2	20.4	21.4	235	218	7.70	7.56
19	9.6	10.5	620	735	11.0	11.8	21.0	22.2	315	272	11.60	9.40
20	9.2	10.5	770	885	11.0	11.7	21.4	23.2	350	310	12.42	11.70
21	9.3	10.3	907	1034	10.0	11.5	21.3	23.7	390	343	13.26	13.50
22	13.0	13.5	525	670	12.6	13.6	23.0	23.5	337	303	8.28	8.78
23	12.7	12.5	780	935	12.5	13.2	24.0	25.0	446	377	12.28	12.60

TABLE III

SOLID TEST SECTION RESULTS

Run No.	Duration of Bottom Transducer Pulse (msec)		Peak Pressure Pulse Magnitude-Bottom Transducer (psi)		Time to Surge Tank Pressure Peak (msec)		Duration of Surge Tank Pulse (msec)		Peak Pressure Pulse Magnitude- Surge Tank (psi)		Peak Test Section Volume Displacement (ft ³ x 10 ⁻⁵)	
	Test	FLASH-34	Test	FLASH-34	Test	FLASH-34	Test	FLASH-34	Test	FLASH-34	Test	FLASH-34
1 SST	33.8	38.8	265	291	15.5	17.4	27.2	33.5	224	244	-	-
2	30.5	33.0	375	430	14.0	17.8	27.5	32.0	310	317	-	-
3	28.9	31.0	500	500	15.5	17.5	27.5	31.4	400	372	-	-
4	28.7	29.0	575	602	15.5	17.3	27.5	31.8	425	413	-	-
5	28.3	28.9	670	770	15.4	17.0	28.0	32.0	470	448	-	-
6	26.3	28.5	740	760	15.2	17.0	27.8	32.2	505	481	-	-
7	24.0	25.0	860	945	14.6	17.0	28.8	32.3	575	535	-	-
8	42.0	49.0	380	487	18.8	23.8	44.0	48.5	420	435	-	-
9	39.6	42.0	610	646	19.7	23.5	41.0	47.5	640	574	-	-
10	39.0	42.5	750	795	20.5	23.2	41.0	46.9	750	670	-	-
11	53.0	55.0	500	585	23.8	28.0	52.1	60.0	580	576	-	-
12	5.0	7.2	295	320	10.1	10.8	18.5	18.5	90	104	-	-
13	4.7	6.8	445	568	8.1	9.7	16.0	18.7	125	135	-	-
14	4.8	6.4	560	698	8.0	9.5	16.1	19.4	150	156	-	-
15	4.7	6.2	690	755	8.0	9.4	17.6	19.8	175	173	-	-
16	5.3	5.9	800	847	8.0	9.3	18.5	20.3	190	188	-	-
17	5.0	5.9	900	850	7.5	9.3	18.0	20.8	210	198	-	-
18	6.0	8.7	575	740	9.1	10.8	19.3	20.5	215	214	-	-
19	6.8	8.2	840	1007	9.4	10.6	20.5	21.6	285	278	-	-
20	7.0	8.2	1090	1190	9.5	10.5	22.1	22.7	325	307	-	-
21	7.0	8.1	1275	1390	8.7	10.3	22.2	23.9	360	330	-	-
22	8.0	8.5	720	845	11.0	11.7	21.8	22.3	298	295	-	-
23	8.6	8.5	1100	1215	10.5	11.3	23.3	24.2	395	368	-	-

PRESSURE PULSE TEST VESSEL

FIGURE 1

Negative No. 49710

**G.3 BENCH TEST
PRESSURE PULSE RIG ASSY**

FIGURE 2

SCHEMATIC OF TEST VESSEL CONFIGURATION

FIGURE 3

SCHEMATIC OF TEST CONFIGURATION
WITH SURGE TANK ATTACHED

FIGURE 4

TRANSIENT DATA RECORD FOR RUN 1 FST

FIGURE 5

FLASH FLEXIBLE TEST SECTION MODEL
WITH SURGE TANK ATTACHED

FIGURE 6

FLASH SOLID TEST SECTION MODEL
WITH SURGE TANK ATTACHED

FIGURE 7

PREDICTED SURGE TANK PRESSURE TRANSIENT
WITH 0.0 SURGE LINE K-FACTOR

FIGURE 8

PREDICTED SURGE TANK PRESSURE TRANSIENT
WITH SURGE LINE K-FACTOR OF 1.5

FIGURE 9

PREDICTED SURGE TANK PRESSURE TRANSIENT WITH
SURGE LINE K-FACTOR OF 10.0

FIGURE 10

COMPARISON OF FLASH-34 CALCULATED AND EXPERIMENTALLY
MEASURED NODE 7 PRESSURE FOR RUN 10 FST

(1/8 INCH TEST SECTION)

FIGURE 11

COMPARISON OF FLASH-34 CALCULATED AND EXPERIMENTALLY
MEASURED NODE 13 (SURGE TANK) PRESSURES FOR RUN 10 FST
(1/8 INCH TEST SECTION)

FIGURE 12

COMPARISON OF FLASH-34 CALCULATED AND EXPERIMENTALLY
DETERMINED PRESSURE DIFFERENCE BETWEEN NODE 7
(TEST VESSEL) AND NODE 13 (SURGE TANK) FOR RUN 10 FST
(1/8 INCH TEST SECTION)

FIGURE 13

COMPARISON OF FLASH-34 CALCULATED AND EXPERIMENTALLY
MEASURED NODE 7 PRESSURES FOR RUN 10 SST

(SOLID TEST SECTION)

FIGURE 14

COMPARISON OF FLASH-34 CALCULATED AND EXPERIMENTALLY
MEASURED NODE 13 (SURGE TANK) PRESSURES FOR RUN 10 SST
(SOLID TEST SECTION)

FIGURE 15

COMPARISON OF FLASH-34 CALCULATED AND EXPERIMENTALLY
DETERMINED PRESSURE DIFFERENCE BETWEEN NODE 7
(TEST VESSEL) AND NODE 13 (SURGE TANK) FOR RUN 10 SST
(SOLID TEST SECTION)

FIGURE 16

RATIO OF FLASH PREDICTED TO EXPERIMENTAL PEAK SURGE TANK PRESSURES
AS A FUNCTION OF PEAK TEST SECTION PRESSURE - 1 INCH PISTON

FIGURE 17

RATIO OF FLASH PREDICTED TO EXPERIMENTAL PEAK SURGE TANK PRESSURES
AS A FUNCTION OF PEAK TEST SECTION PRESSURE - 2 INCH PISTON

FIGURE 18

APPENDIX A

DETERMINATION OF SURGE TANK STIFFNESS

Calibration runs were made with the surge tank attached and the solid test section in place by loading lead bricks on top of the one inch piston. Static loads of up to about 275 lbs. (10 bricks) were applied. In this system, the piston displacement is caused by the combined effects of fluid compressibility, test vessel displacement, and surge tank displacement. The piston volume displacement is given by:

$$A_p \Delta x_p = \frac{V_{TO} \Delta p}{\beta} + \Delta V_{TV} + \Delta V_{ST} \quad (A-1)$$

where:

- A_p = piston area
- Δx_p = piston (linear) displacement
- V_{TO} = initial system volume (test vessel + surge tank + surge line) before loading
- Δp = gage pressure
- β = bulk modulus of water
- ΔV_{TV} = volume displacement of test vessel boundaries
- ΔV_{ST} = volume displacement of surge tank boundaries

Equation (A-1) can be solved for ΔV_{ST} to give

$$\Delta V_{ST} = A_p \Delta x_p - \frac{V_{TO} \Delta p}{\beta} - \Delta V_{TV} \quad (A-2)$$

In Reference A-1 a curve of ΔV_{TV} as a function of loading is given in Appendix A of that document. All other quantities on the right hand side of Equation (A-1) are known or were measured. In this way ΔV_{ST} as a function of pressure loading Δp was obtained. The results are shown in Figure A-1,

A good deal of scatter was evident in the experimental points. This is due primarily to the fact that ΔV_{ST} is a small number whereas the other quantities on the right hand side of Equation (A-2) are, by comparison, large numbers. A small error in each of these can thus produce a large error in ΔV_{ST} . What this, in essence, means is that the flexibility of the surge tank is a small effect compared to that of the test vessel and the compressibility of the water. Therefore, it would be of little value to employ a more accurate means of determining the surge tank stiffness than the one described in this appendix, since the expansion of the surge tank is a secondary effect in the overall pressure attenuation. For this reason, a simple, linear $\Delta V_{ST} - \Delta p$ relationship was deemed most appropriate for use in the FLASH-34 calculation. This is shown in Figure A-1 and corresponds to a stiffness of 1.4×10^7 psi/ft³.

Reference: A-1 WAPD-R(TH)-2090, dated May 1975

SURGE TANK STIFFNESS CURVE

FIGURE A-1

APPENDIX B

SAMPLE FLASH-34 INPUT LISTING - RUN 10 FST

G.3 1 IN. PISTON, FLXBL TEST SECTION -WITH SURGE TANK-6 IN DROP, 1 BR.
201,1,1,1
1001,.040,2.0,1.0
1001,.055,2.0,1.0
2001,1.5-6,.040
2001,1.6-6,.055
2001,1.7-6,.055
*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 \$ ATMOSPHERE
3013,0.0872,0.632,.3333,.3333,.3333,38.984,36.0,0.0 \$ SURGE TANK
*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
4011,13,10,13,C,.7950.,8.400-5,11.50 \$ SURGE LINE
4971,11.5,0.00,6.66,.00439,5.53,.00543,4.24,.00823,3.56,.01096
4972,4.40,.01645,4.08,.0274,3.76,.0543,3.50,.1096,3.31,.274
4973,3.18,.549,3.11,1.096,3.068,2.74,3.048,5.49,0.0,1.+10

*FLEXIBLE PLATES

7501,3.390,42.3,.005454,-1,1,0.0,5.67,9.0
 7502,3.04,7.24+6,0.265,12,1,1.10-5,1.29+8
 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,.643-5,2.21+8
 7512,1.66,1.24+7,0.155,12,11,.643-5,2.21+8
 7513,0.3022,6.813+7,0.1249,12,3
 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
 7522,22.8,1.40+7,0.842,12,13

\$1 IN. PIST.,1 BR.,6 IN. DR.
 \$ VESSEL STIFFNESS

\$ 1/8 IN. TEST SECTION

\$ SURGE TANK

*PLOTING INFORMATION

20001,1,0,1
 20002,.4,.2,.2,.2
 20011,4,1
 20012,4,2
 20013,4,13
 20014,4,7
 20015,4,10
 20016,5,11
 20017,5,28
 20018,4,7,13
 20019,4,2,13
 20101,13,2,13,7

APPENDIX C

DETERMINATION OF SURGE LINE K-FACTOR

The experimental setup for the determination of the surge line K-factor is shown in Figure C-1. A static pressure transducer was installed between the test vessel and the surge tank. Flow was directed into the test vessel, through the surge line to the surge tank, and into a collecting bucket.

The test was initiated by first establishing a steady flow through the surge line. When the reading of the pressure transducer had settled down the collecting bucket was placed under the stream flowing from the surge tank. Simultaneously, a stop watch was started. As the bucket filled, the reading of the pressure transducer was observed to assure that it did not change significantly with time during the test. After a period of time approximately equal to the time necessary to fill the bucket (almost three minutes), the bucket was removed and the stop watch stopped. The volume of water was then measured and, together with the time elapsed and measured pressure drop was manually recorded.

Three such tests were performed and are summarized in Table C-I below.

TABLE C-I

<u>Pressure Drop</u> <u>(psi)</u>	<u>Time Elapsed</u> <u>(seconds)</u>	<u>Volume Collected</u> <u>(cc)</u>	<u>Volume Flow Rate</u> <u>(cc/sec)</u>
2.125	175.3	3785	21.5916
2.125	179.7	3805	21.1742
2.125	177.5	3800	21.4085

The average volume flow rate of the three tests is 21.39 cc/sec. For water at 68°F the kinematic viscosity, ν , and density, ρ , of water are 1.083×10^{-5} ft²/sec and 62.46 lb/ft³, respectively. The surge line dimensions are 8 inches long and 0.124 inches I.D. With the above information the Reynolds number and K-factor of the surge line can be calculated from

$$Re = \frac{VD}{\nu} \quad (C-1)$$

$$K = \frac{288g \Delta p}{\rho V^2} \quad (C-2)$$

where V = fluid velocity in surge line (≈ 8.99 ft/sec) during the test, $D = 0.124/12 = 0.01033$ ft, $g = 32.2$ ft/sec², and Δp is the measured pressure drop (2.125 psi). The result is

$$Re = 8580$$

$$K = 3.914$$

at the test conditions. This K-factor comprises entrance, exit and surge line viscous losses. Entrance and exit losses alone account for a K-factor of 1.5, which leaves 2.414 for viscous effects. For an 8 inch smooth tube with a 0.124 inch in I.D., a K-factor of 2.128 due to friction at $Re = 8580$ is appropriate. The difference $(2.414 - 2.128) = 0.286$ can be considered as due to roughness. At $Re = 8580$ a relative roughness of k/D of 0.002 gives a viscous K-factor of approximately 2.414.

This relative roughness was used to calculate the viscous K-loss in the Reynolds number range $3000 < Re < 10^5$. For $Re < 2000$ the laminar flow friction factor $64/Re$ was used and a linear interpolation between $Re = 2000$ and $Re = 3000$ was used to join laminar and turbulent regimes. Viscous K-losses were evaluated in this manner and added to the end loss K-factor of 1.5 to give the total K-factor versus flow rate table (card series 4971-4973) shown in Appendix B and Table C-1 below.

TABLE C-1

Surge Line K-Factor

<u>Surge Line K-Factor (dimensionless)</u>	<u>Flow (lb/sec)</u>
11.5	0.00
6.66	0.00439
5.63	0.00543
4.24	0.00823
3.56	0.01096
4.40	0.01645
4.08	0.0274
3.76	0.0543
3.50	0.1096
3.31	0.274
3.18	0.549
3.11	1.096
3.068	2.74
3.048	5.49
0.00	10 ¹⁰

SCHEMATIC OF SURGE LINE K-FACTOR TEST

FIGURE C-1

APPENDIX D

TIME SCALE FOR DEVELOPMENT OF STEADY-STATE SURGE LINE FRICTION FACTOR

An exact determination of the time scale necessary for the development of the steady-state friction factor in the surge line is beyond the scope of this report. However, an estimate of this time scale can be obtained by recourse to a simpler problem, namely, the boundary layer development on a flat plate immersed in an infinite stream whose velocity changes from 0 to a value U instantaneously (see Figure D-1). The time necessary for the boundary layer thickness in this geometry to increase to a value equal to the inside radius of the surge line will be the time scale sought.

The equation of motion of the boundary layer flow depicted in Figure D-1 (assuming the plate is of infinite extent in the X-direction) is

$$\rho \frac{\partial u}{\partial t} = - \frac{\partial \tau}{\partial y} \quad (D-1)$$

where u = velocity in the boundary layer at a point y and t , ρ = fluid density, and τ = shear stress in the boundary layer at the same point and time. For a turbulent boundary layer the following velocity profile can be assumed (Reference D-1):

$$u = U \left(\frac{y}{\delta} \right)^{1/7} \quad (D-2)$$

where δ is the boundary layer thickness at time t . Since y and t are independent variables and U has a constant value for all $t > 0$ the quantity $\partial u / \partial t$ is

$$\frac{\partial u}{\partial t} = U(y)^{1/7} * \left(- \frac{1}{7\delta^{8/7}} \right) \frac{d\delta}{dt} \quad (D-3)$$

Integrating Equation (D-1) over y from $y = 0$ to $y = \delta$ gives:

$$\int_0^{\delta} \rho \frac{\partial u}{\partial t} dy = - \int_0^{\delta} \frac{d\tau}{dy} dy$$

$$- \frac{\rho U}{7\delta^{8/7}} \frac{d\delta}{dt} \int_0^{\delta} y^{1/7} dy = \tau(y=0)$$

$$- \frac{\rho U}{7\delta^{8/7}} \frac{d\delta}{dt} * \frac{7}{8} \delta^{8/7} = \tau(y=0)$$

$$- \frac{\rho U}{8} \frac{d\delta}{dt} = \tau(y=0) \quad (D-4)$$

In the derivation of Equation (D-4), the shear stress at the edge of the boundary layer has been set equal to zero. The shear stress at $y = 0$ can be estimated from (Reference D-1):

$$\tau (y = 0) = -0.0225 \left(\frac{\nu}{U\delta} \right)^{1/4} \rho U^2 \quad (D-5)$$

where ν is the kinematic viscosity of the fluid. Substituting this in Equation (D-4) gives

$$\frac{\rho U}{8} \frac{d\delta}{dt} = 0.0225 \left(\frac{\nu}{U\delta} \right)^{1/4} \rho U^2$$

$$\frac{1}{8U} \frac{d\delta}{dt} = 0.0225 \left(\frac{\nu}{U} \right)^{1/4} \frac{1}{\delta^{1/4}}$$

$$\frac{1}{10U} \frac{d\delta^{5/4}}{dt} = 0.0225 \left(\frac{\nu}{U} \right)^{1/4}$$

or, rearranging

$$dt = \frac{1}{10U (0.0225)} \left(\frac{U}{\nu} \right)^{1/4} \delta^{5/4} \quad (D-6)$$

Since $\delta = 0$ at $t = 0$, integration of Equation (D-6) gives

$$t = \frac{1}{0.225U} \left(\frac{U}{\nu} \right)^{1/4} \delta^{5/4} \quad (D-7)$$

As an example, consider run 10 SST. For this run the calculated surge line fluid velocity averages approximately 35 ft/sec. For $\delta = 0.124/(2 \times 12)$ ft (surge line radius) and $\nu = 1.083 \times 10^{-5}$ ft²/sec, Equation (D-7) gives

$$t = \frac{1}{0.225(35)} \left(\frac{35}{1.083 \times 10^{-5}} \right)^{1/4} \left(\frac{0.124}{24} \right)^{5/4}$$

$$t = 0.00746 \text{ sec} = 7.46 \text{ msec} \quad (D-8)$$

Equation (D-8) can be interpreted as an estimate of the time necessary before surge line friction plays an important role in the flow development in the surge line (at least for run 10 SST). Only for pulse durations considerably greater than this will the fully developed surge line friction factor be appropriate to use in FLASH-34 calculations. For pulse durations less than or of the same order as this, the fully developed friction factor is too large to

yield correct results. Most of the pulses tested fall into this latter category.

Reference:

D-1 H. Schlichting, "Boundary Layer Theory," Pergamon Press, 1955,
pg. 432

BOUNDARY LAYER DEVELOPMENT ON AN INFINITE FLAT PLATE
FIGURE D-1