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EFFECT OF TORUS WALL FLEXIBILITY ON FORCES IN THE MARK I BWR
PRESSURE SUPPRESSION SYSTEM - PART I

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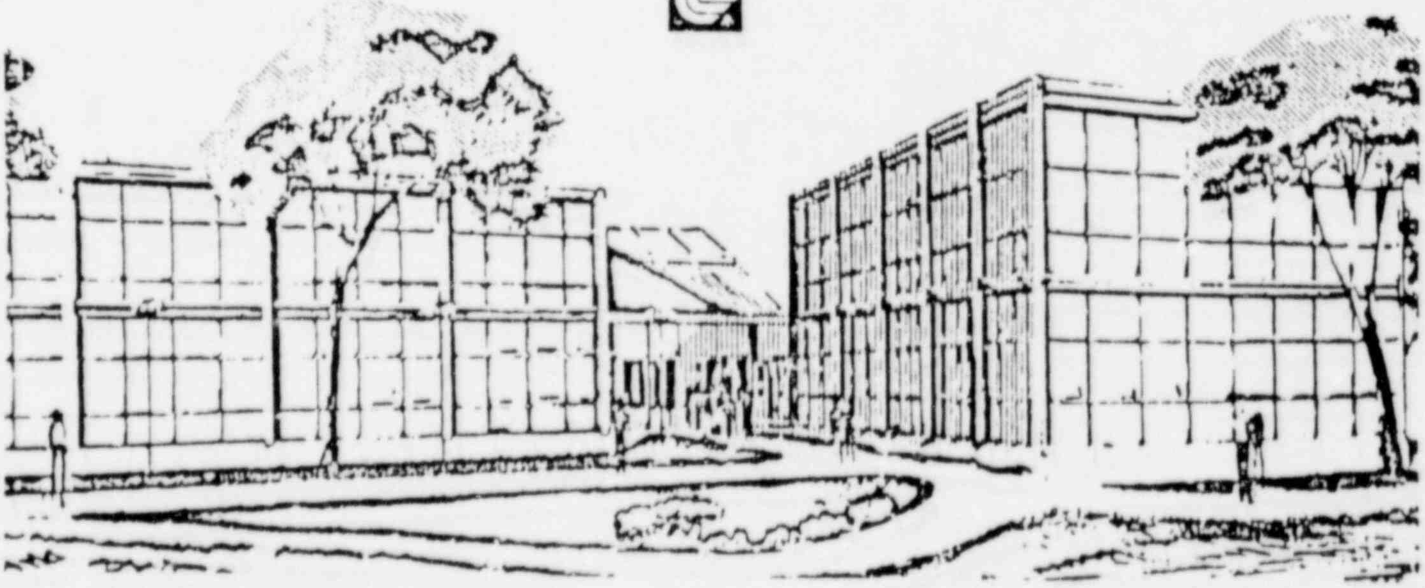

CONTENTS

L. ECT OF TORUS WALL FLEXIBILITY ... FORCES IN THE MARK I BWR PRESSURE SUPPRESSION SYSTEM - PART I*

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ABSTRACT

The effect of torus wall flexibility in the pressure suppression system of a Mark I BWR subjected to hydrodynamic loadings is investigated. The analyses used a recently developed finite element code. Torus minor diameter-to-wall-thickness ratios were varied from 0 (infinitely rigid) to 600.

For steam relief valve (SRV) discharge, the peak vertical reaction force on the torus is reduced by a factor of three for the highly flexible, plant simulated wall (D/t = 600). The reduction factor for the problem of LOCA chugging is shown to be 1.5.

The two-dimensional analyses employed overestimate these reduction factors but do define the effect of torus boundary stiffness. Improved modeling of the structure and of the source is expected to result in factors more directly applicable to actual pressure suppression systems.

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NRC Project Identification Sequence B&R 20 10 04 02 FIN A0208, "Hydrodynamic/Structural Interaction in the Mark I BWR Pressure Suppression System"

1. BACKGROUND AND PURPOSE

In the Mark I BWR pressure suppression containment system, reactor primary coolant is released to a partially water filled toroidal-like shell, thereby dissipating the energy released during a hypothetical loss-of-coolant accident (LOCA) or steam relieve valve (SRV) discharge. Most analytical and experimental approaches toward understanding these phenomena treat the shell as a rigid body. The shell is, in fact, flexible and its response to fluid injection into the pool may significantly affect the total loads experienced by the containment system and its attendant structure. An analytical program was therefore defined to investigate the influence of the shell diameter to thickness ratio (D/t) on the shell boundary and in-pool pressures.

2. DEFINITION OF ANALYTICAL PROGRAM

Three classes of problems are of interest. The first of these is the hypothetical loss-of-coolant accident, or LOCA downcomer clearing problem, characterized by large flow rates and consequently, large pool motions. In this problem, air, followed by steam, is injected into the pool through pairs of downcomers connected to the reactor primary containment through a ring-header and vent lines.

The second problem is that of air discharged from lines connected to the reactor pressure vessel relief valves (SRV) and terminating near the bottom of the suppression pool. This is a normally occurring phenomenon in the BWR operation.

Chugging occurs during the later stages of a LOCA and is caused by rapid condensation of a steam bubble formed at the downcomer exit.

We intend tc xamine the effect 'orus wall f' ibility has on pressures and forces in the suppression pool for these three phenomena for D/t ratios of 0, 100, 300, and 600. In addition, a code verification problem is intended.

3. PROBLEM INPUT DESCRIPTION

This section will describe the geometry and discuss the description of input selected for the cases of LOCA downcomer clearing, SRV discharge, and LOCA chugging.

PROBLEM GEOMETRY

An agreement was reached between LLL and NRC(DOR)[1] staff to utilize the pressure suppression containment geometry representative of the Monticello plant. Figure 1 shows the significant dimensions of that plant.

For computational purposes, the actual three-dimensional geometry was idealized. Our idealization of the geometry is represented by a two-dimensional plane section located midway between rigid stiffeners and is shown in Figure 2. The decision was made to allow no motion at the shell waist; a reasonable structural boundary condition considering the relative shortness of span between ring stiffeners and the actual torus support structure. These conditions would tend to limit the motion of the shell at that location.

LOCA DOWNCOMER CLEARING

A loss-of-coolant accident (LOCA) has never occurred in an actual plant; therefore, we are constrained to model this event using analytical methods, usually in the form of a systems model computer code. We had obtained such a calculation from Idaho Nuclear Engineering Laboratory for other purposes. The calculated event was based on the Brown's Ferry Plant, and provides pressure, temperature, and flow rate values at the inlet to the downcomers. The use of this model was approved by the NRC(DOR) in March 1977.[2]

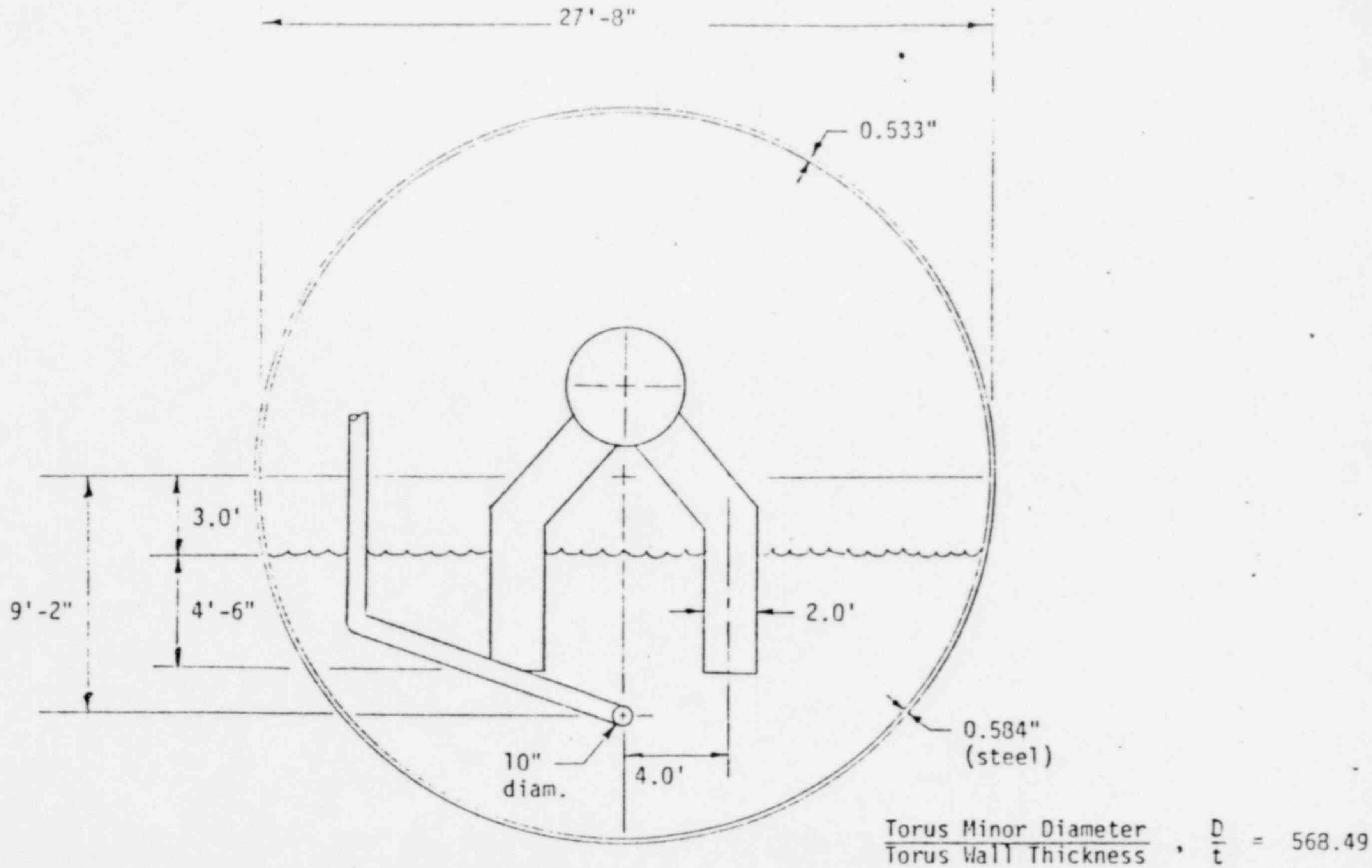

FIGURE 1. Reference Dimensions for Monticello Plant Pressure Suppression System

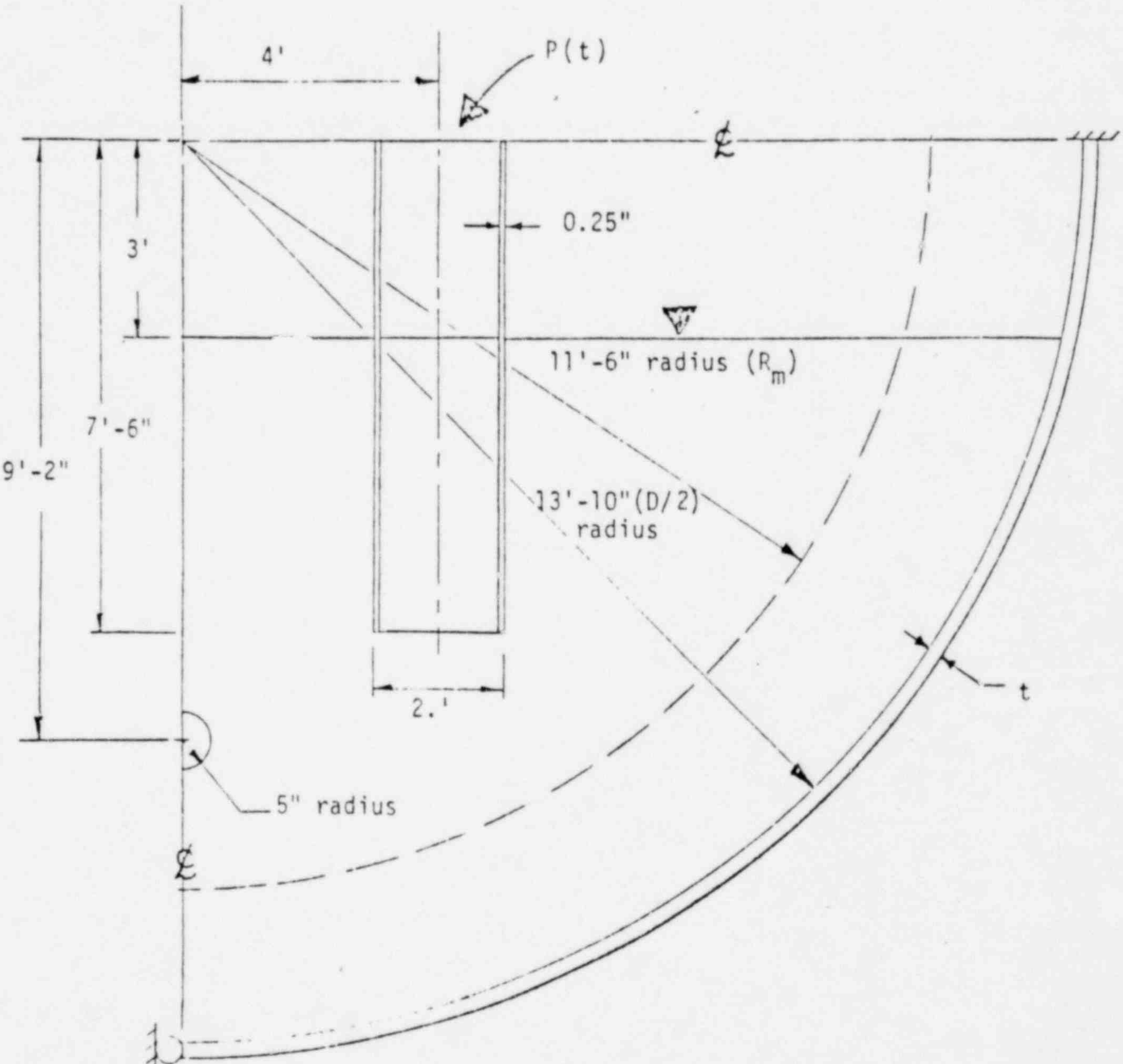

FIGURE 2. Idealized Problem Geometry

STEAM RELIEF VALVE DISCHARGE

The pressure used to drive the SRV discharge problem was taken from Reference 1, in accordance with the agreement made in a meeting with NRC staff and the Mark I Owner's Group, June 30, 1977.[3] The pulse is theoretical in nature and is derived using Rayleigh bubble arguments.[9] The frequency of the pulse was taken as 10 Hz. Figure 3 shows the pulse used in the SRV analyses.

LOCA CHUGGING PULSE

There is very little quantitative information on the shape and frequency content of chugging pulses that occur as a result of steam bubble condensation during the later phase of a LOCA, particularly with geometries and submergences associated with the Mark I torus. As a result of the above mentioned meeting,[3 we agreed to use a single triangular pulse with a magnitude of 20 psig and a duration of 80 milliseconds. Figure 4 shows the pulse used in the chugging analyses.

4. COMPUTER CODES

We had originally anticipated the use of the computer code CHAMP for the three problems of interest. This code, described as a two-dimensional finite difference coupled Eulerian-Lagrangian code, is currently under separate development for LOCA and similar problems at LLL.[4,5] An Eulerian fluid dynamics formulation is necessary when the problem is characterized by significant fluid flow or when fluid motions are large relative to the size of the problem under consideration. Since this is clearly the case in the LOCA downcomer clearing problem, the decision was made in October 1976 to employ CHAMP for all of the problems.

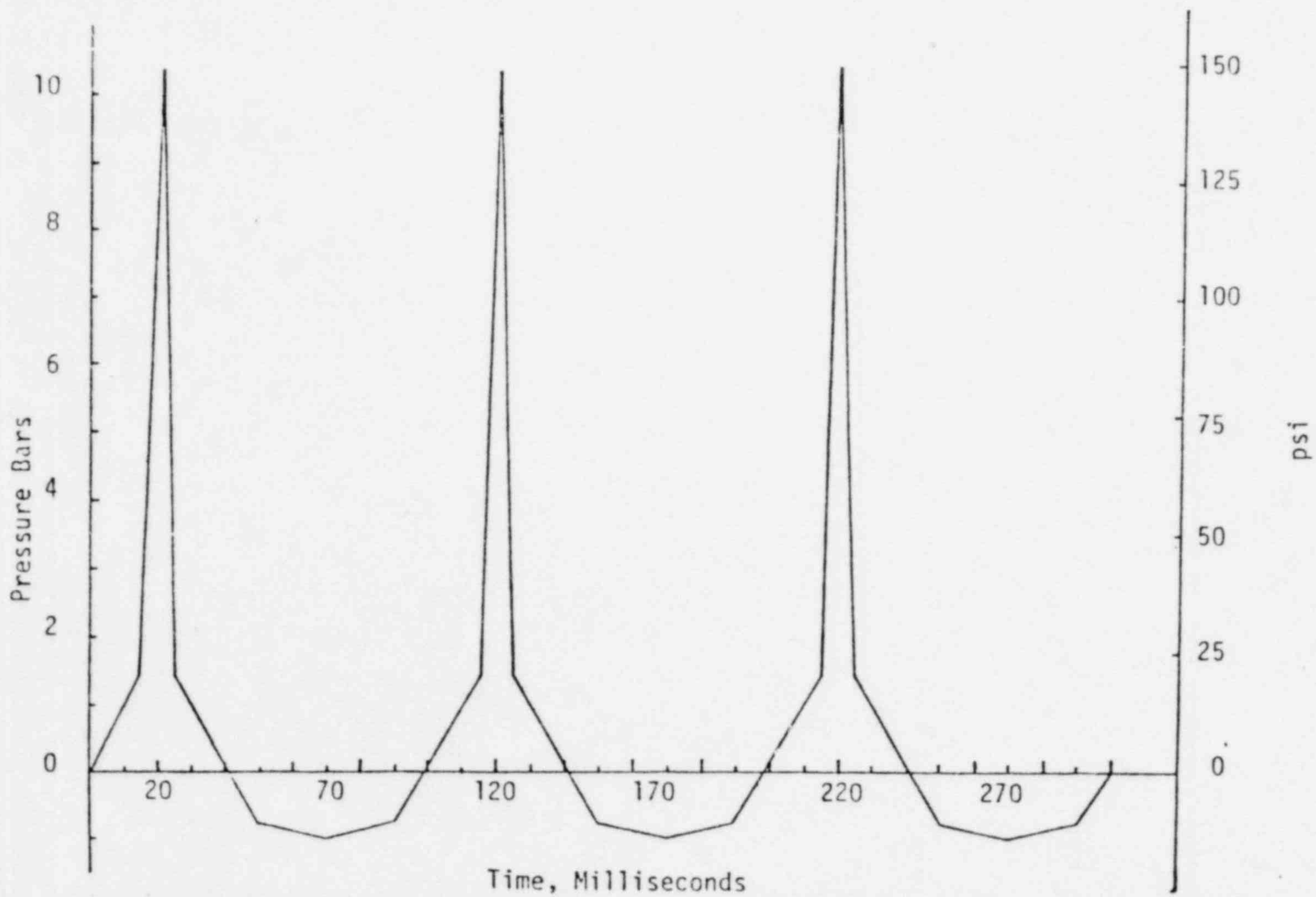

FIGURE 3. Input Pulse for SRV Discharge Problem

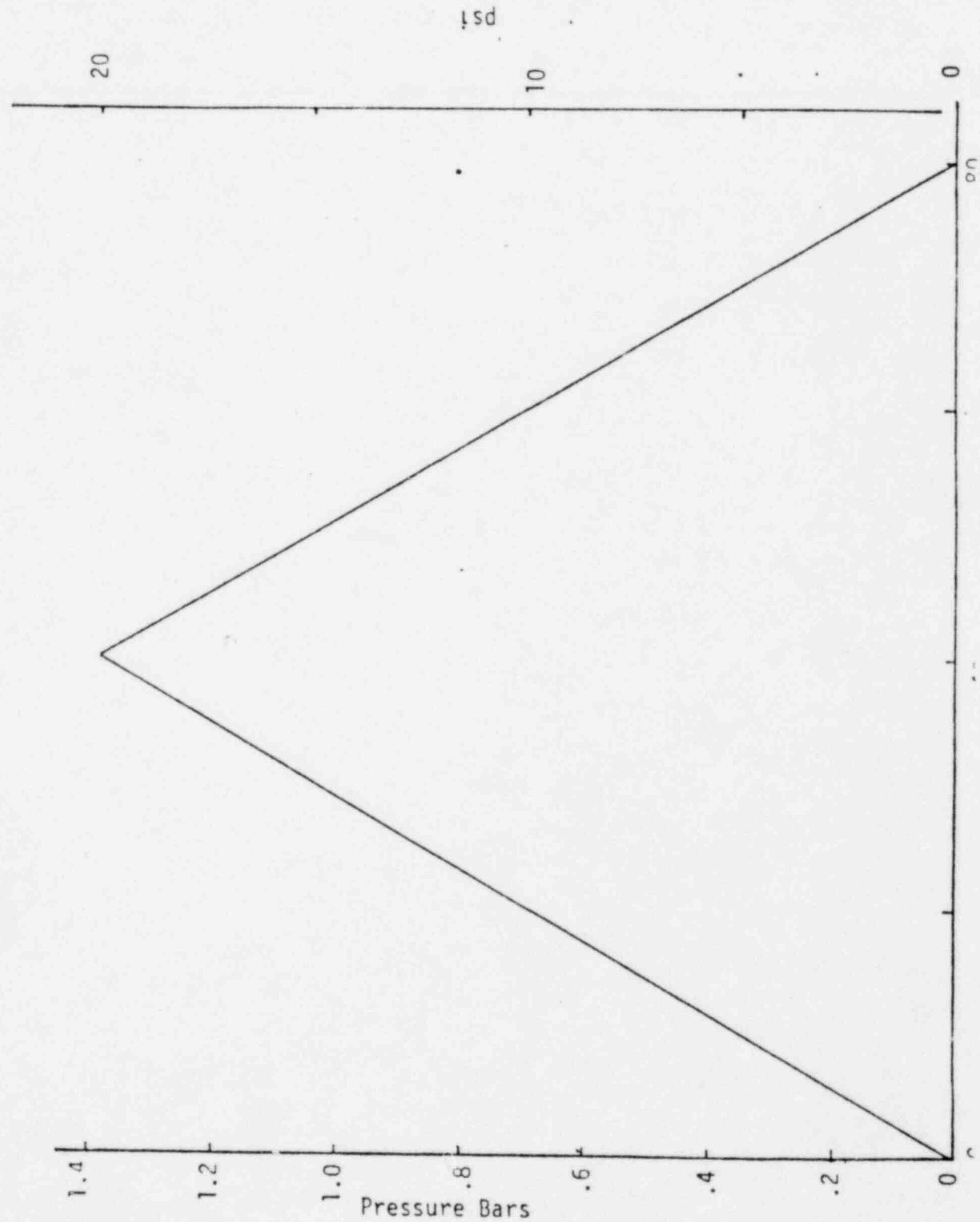

FIGURE 4. Input Pulse for LOCA Chugging Problem

Prior to firm definition of the various probl input descriptions, two test problems were calculated using the CHAMP code in February 1977 and reported to the NRC in the progress report of May 16, 1977.[6] These problems represented hypothetical SRV discharge for both a rigid (D/t = 0) and a flexible-walled (D/t = 300) torus section, and their purpose was to assess the capability of the CHAMP code to perform correct fluid dynamic problems. The SRV problem was chosen rather than a LOCA downcomer clearing problem since the latter involved larger computational time. The results of these two problems indicated that the code performed satisfactorily but with per-cycle/node running times longer than were originally anticipated. In addition, other CHAMP applications were reported in the May report as part of a separate water hammer investigation.[7]

During the period from March 1977 to July 1977, the CHAMP code underwent extensive modifications by its developers to improve both the physics being modeled and the running times necessary to perform the LOCA class of calculation. Significant effort was made by us to apply the new version to the problems at hand. Due, however, to its developmental nature, continuing "debug" problems made clear in August that consideration of other methods was required for at least the small displacement SRV and LOCA chug problems.

Recent developments in fluid finite element techniques by the Code Development Group of Mechanical Engineering at LLL provided us with an alternative method of calculating the two problems having relatively small deformations and no appreciable flow (SRV discharge and LOCA chugging). In addition, the running times of such codes for this more limited class of problems are on the order of 30 to 50 times faster than the CHAMP code. We therefore chose this calculational method for the problems involving SRV

discharge and LOCA chugging. Appendix C describes the finite element code in more detail.

A comparison problem was run on both the finite element code and CHAMP. The SRV discharge pulse was used with a D/t ratio of 300. It can be seen from Figures 5 and 6 that the results are in reasonable agreement.

The CHAMP code is at this time capable of calculating the SRV discharge or LOCA chugging problems, but it cannot yet perform satisfactorily the calculations involved in the LOCA downcomer clearing problem. Additionally, continuing restrictions involving Lagrangian zoning will not permit acceptable modeling of a very thin shell; the limit currently corresponds to a torus minor diameter-to-wall-thickness (D/t) ratio of about 300. Development work is continuing on the CHAMP code by its authors, particularly in regard to the downcomer clearing problem.

5. WORK COMPLETED

INTRODUCTION

In Section 2 we described the analytical program. A total of twelve calculations were to be considered. Six of these have been completed; three each for both the SRV and chug problems. The computational difficulties described in Section 4 require that the four calculations associated with the LOCA downcomer clearing problem be deferred until later in FY78.

One of the original tasks in this contract was to provide an exhibit of code verification. It was agreed that the verification would be based on experiments performed at the Monticello plant. After reviewing the experimental results[10] with the NRC(DOR) it was concluded[1] that an insufficient amount of data was reported to evaluate the boundary condition driving the phenomena and that the marked asymmetries in the data could not possibly be

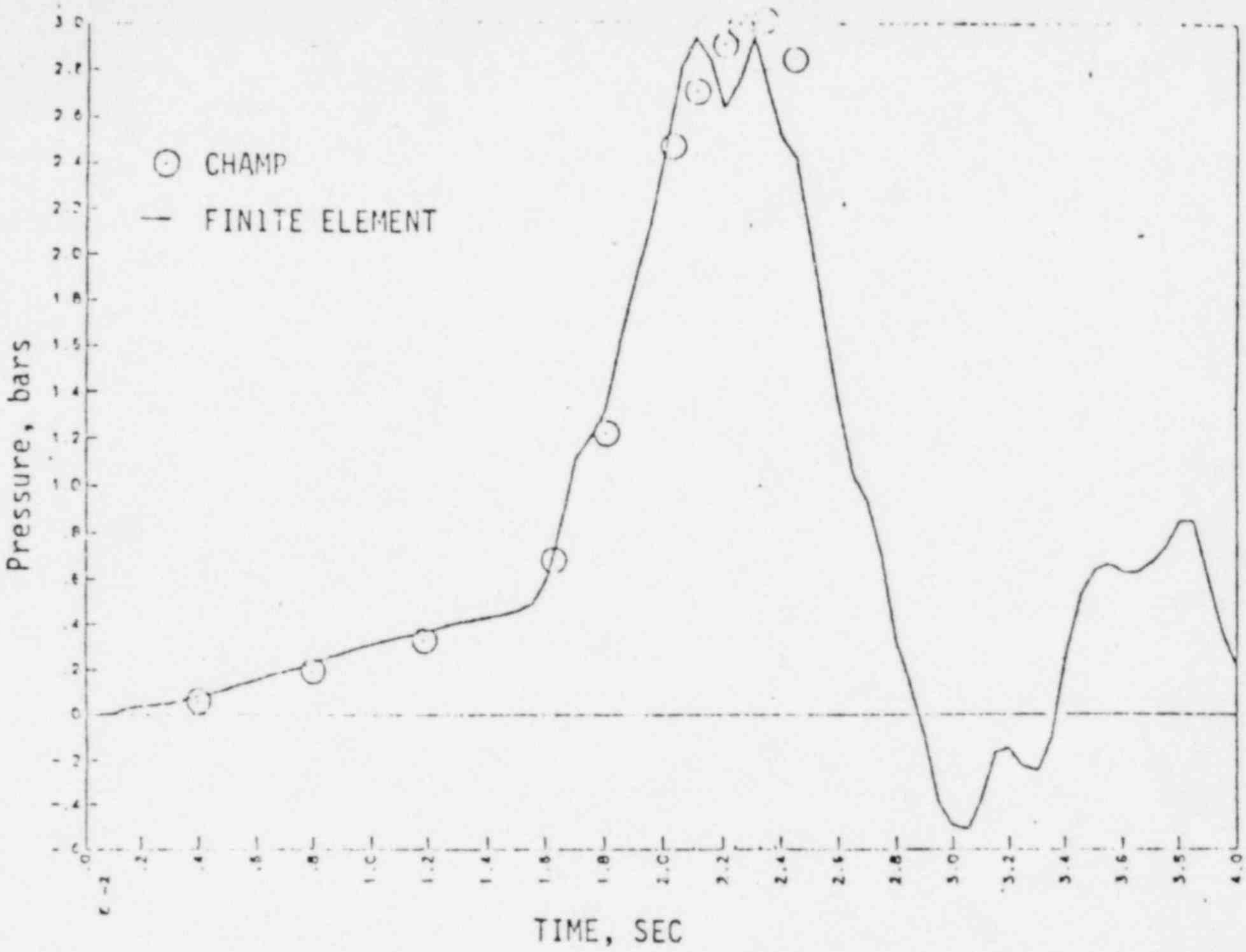

FIGURE 5. Pressure at Pool Bottom, D/t = 300 (SRV Problem)

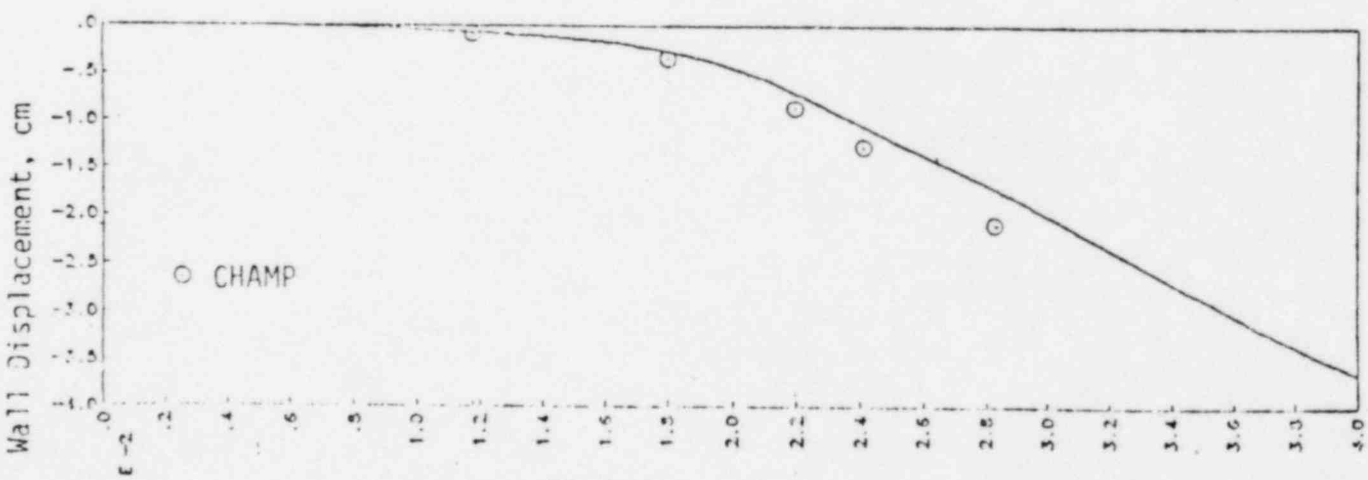

FIGURE 6. Wall Displacement at Pool Bottom, D/t = 300 (SRV Problem)

captured through t use of a two-dimensional comp r code. For these reasons the intended verification was not completed. More limited verification was performed earlier,[7] to which the reader is referred. The steam relief valve (SRV) discharge and LOCA chugging problems have been completed for diameter-to-wall-thickness (D/t) ratios of 0 (rigid), 300, and 600. Calculations hav'ng a D/t ratio of 100 were omitted since the monotonic variation of mass and flexibility with wall thickness would not have provided any additional useful information.

Generalized results for these problems appear in the next two sections along with comments about the specified forcing functions. Detailed results for the problem cases of SRV and chugging appear in Appendices A and B, respectively.

5.A SRV DISCHARGE - GENERALIZED RESULTS

The SRV discharge problem was run using a single pulse having a total width of 40 milliseconds and a peak overpressure of 150 psi (10.35 bars). The reasons for using only a single pulse will be discussed later in this section. For the pulse described above, Figure 7 shows the pressure history in the fluid adjacent to the shell at the bottom centerline for three cases of differing flexibility; D/t = 0, 300, and 600. It can be seen from this figure that along with the decrease in peak pressure with increasing D/t, the pulse shape is both shifted in time and broadened. The temporal shift is caused by both the short transit time (order 1 ms) for the signal to travel between source and shell wall and by motion of the wall itself. As flexibility increases, earlier motion of the shell wall is responsible for the lag time seen in the rising portion of the pulse. The broadening of the pulse is a result of momentum conservation, i.e., the total impulse of the signal is apportioned between the shell and the fluid.

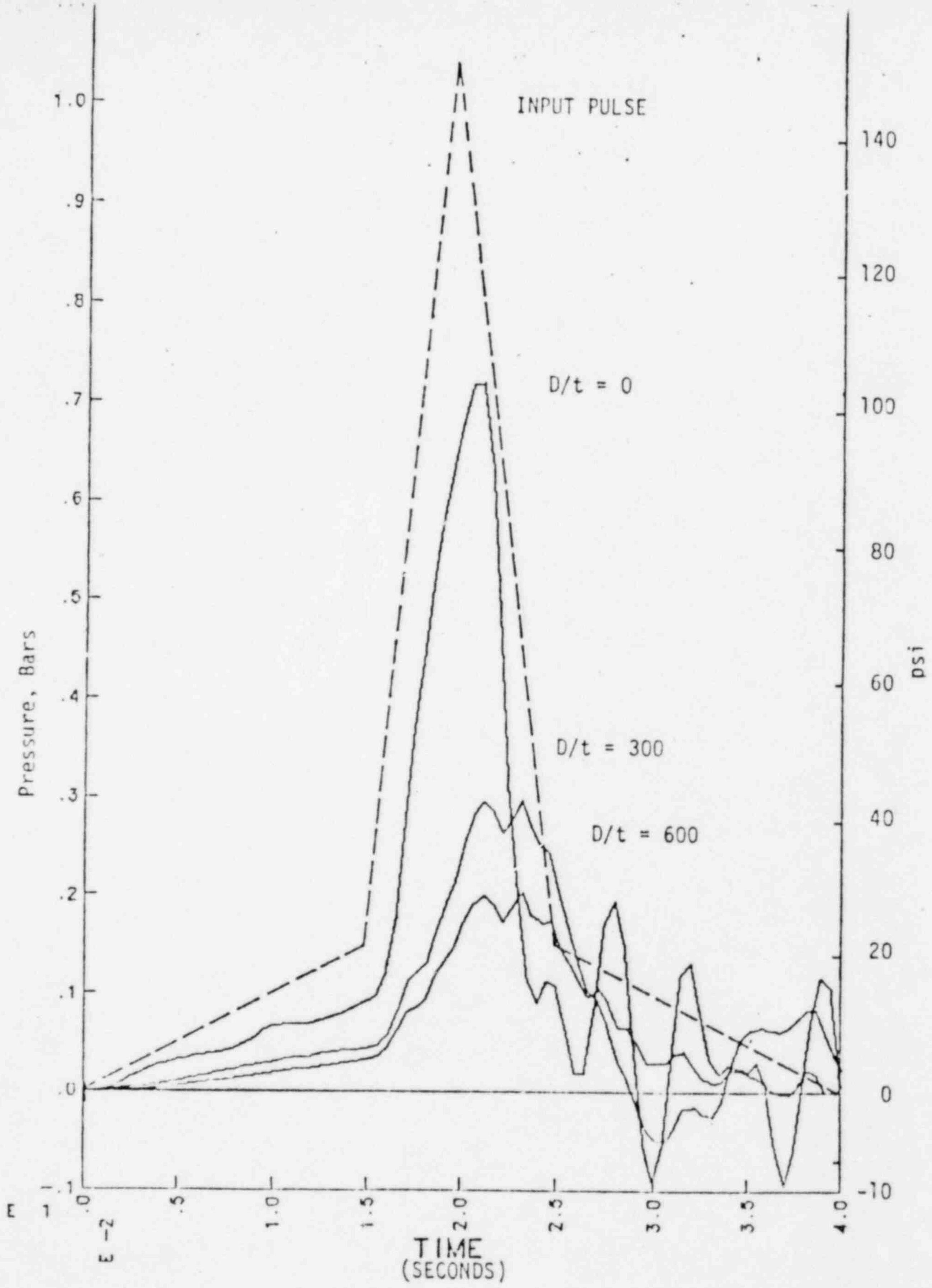

FIGURE 7. Effect of Torus Shell Thickness on the Pressure History at the Pool Bottom (SRV Discharge)

The total vertical force on the shell resulting from the SRV pulse is shown in Figure 8 for the D/t ratios considered. The general characteristics of these curves follow those of the above mentioned pressure histories.

Figure 9 shows a plot of peak overpressure normalized to the peak source pressure at the shell-fluid interface at the pool bottom versus the D/t ratio. Figure 10 shows the variation in peak vertical reaction force (normalized to the infinitely rigid case) with the D/t ratio. Increased shell flexibility results in reduced net vertical force acting on the shell.

The arguments for using only a single SRV pulse for this analysis will be discussed at this point. An examination of the pulse (Figure 3) will reveal that the positive portion of the pulse contains approximately 1.85 times the impulse carried by the negative portion. Separate calculations were carried out for times in excess of 100 milliseconds with the result that "bubble" growth continued to increase even at late times; i.e., the initiation time of the second pulse. It follows that an equal amount of negative impulse would be required just to return the "bubble" to its original position. The effect of continuing the calculation past the point of a single pulse would be that of applying an increasing pressure to an already enlarged surface, resulting in the physically incorrect situation of a bubble of ever-increasing, rather than oscillating, radius.

It should also be pointed out that in the plane geometry chosen for this problem, the "bubble" is not spherical in nature, but rather a cylinder of infinite length. The lack of geometric limit in the out-of-plane direction serves to introduce more energy into the problem than is actually encountered in a real plant.

These limitations were the determining factors in the decision to limit the calculation to a single, positive pulse.

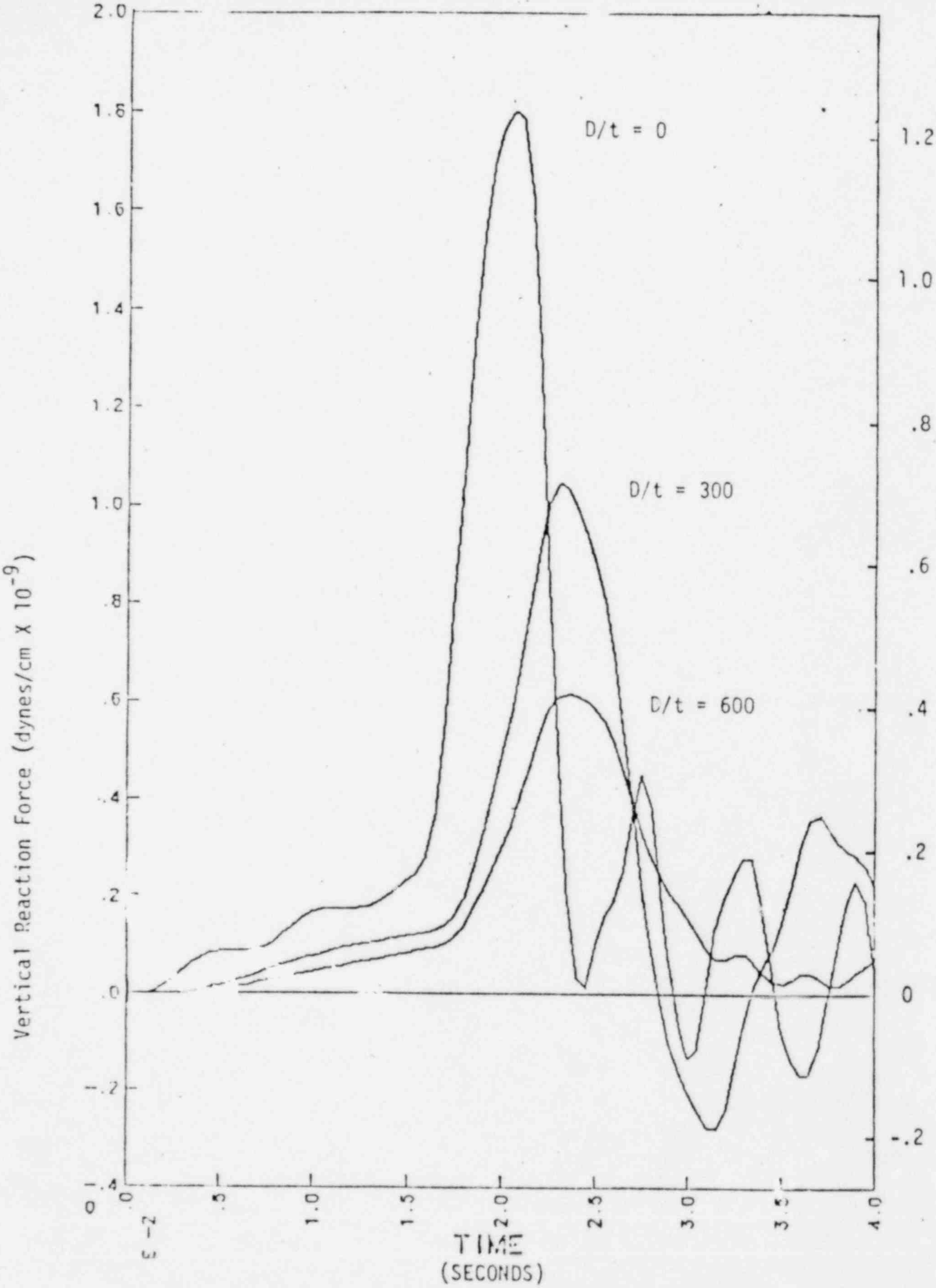

FIGURE 8. Effect of Torus Shell Thickness on Total Vertical Reaction Force History. (SRV Discharge)

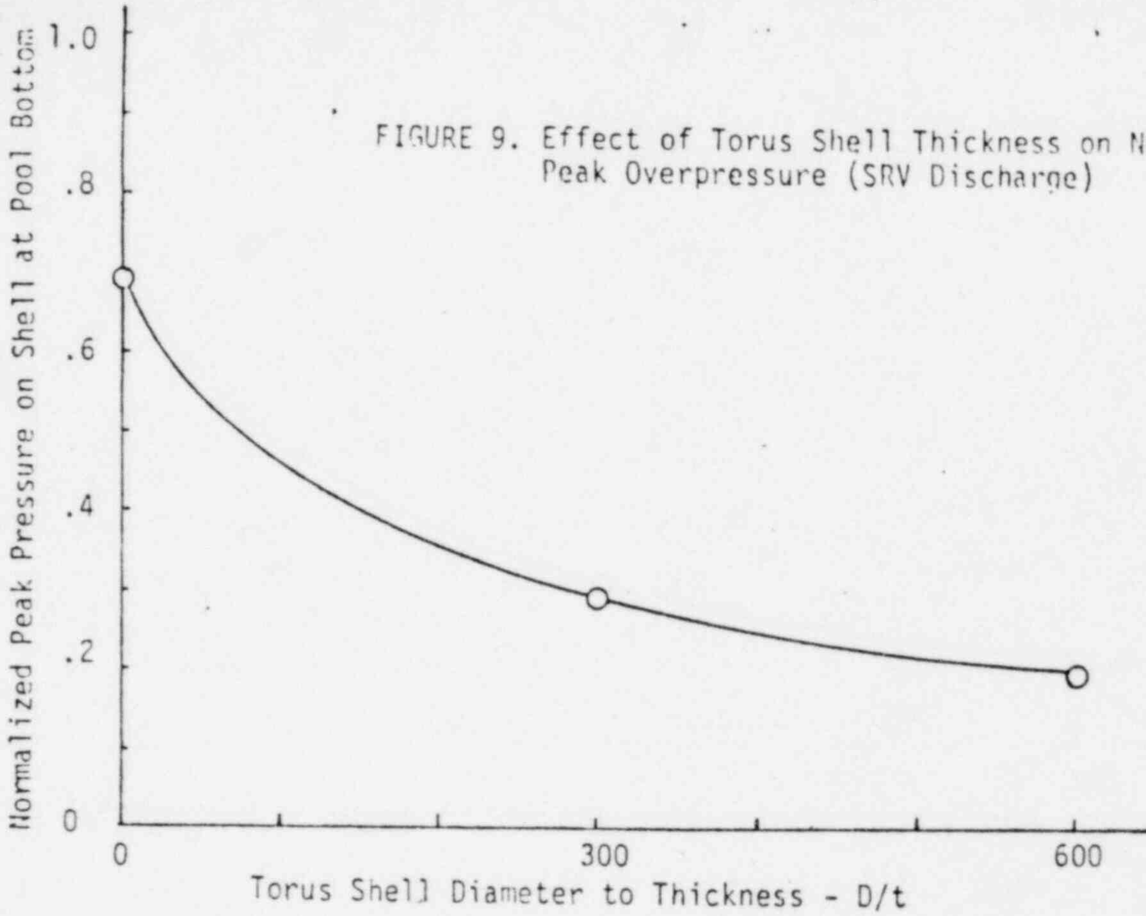

FIGURE 9. Effect of Torus Shell Thickness on Normalized Peak Overpressure (SRV Discharge)

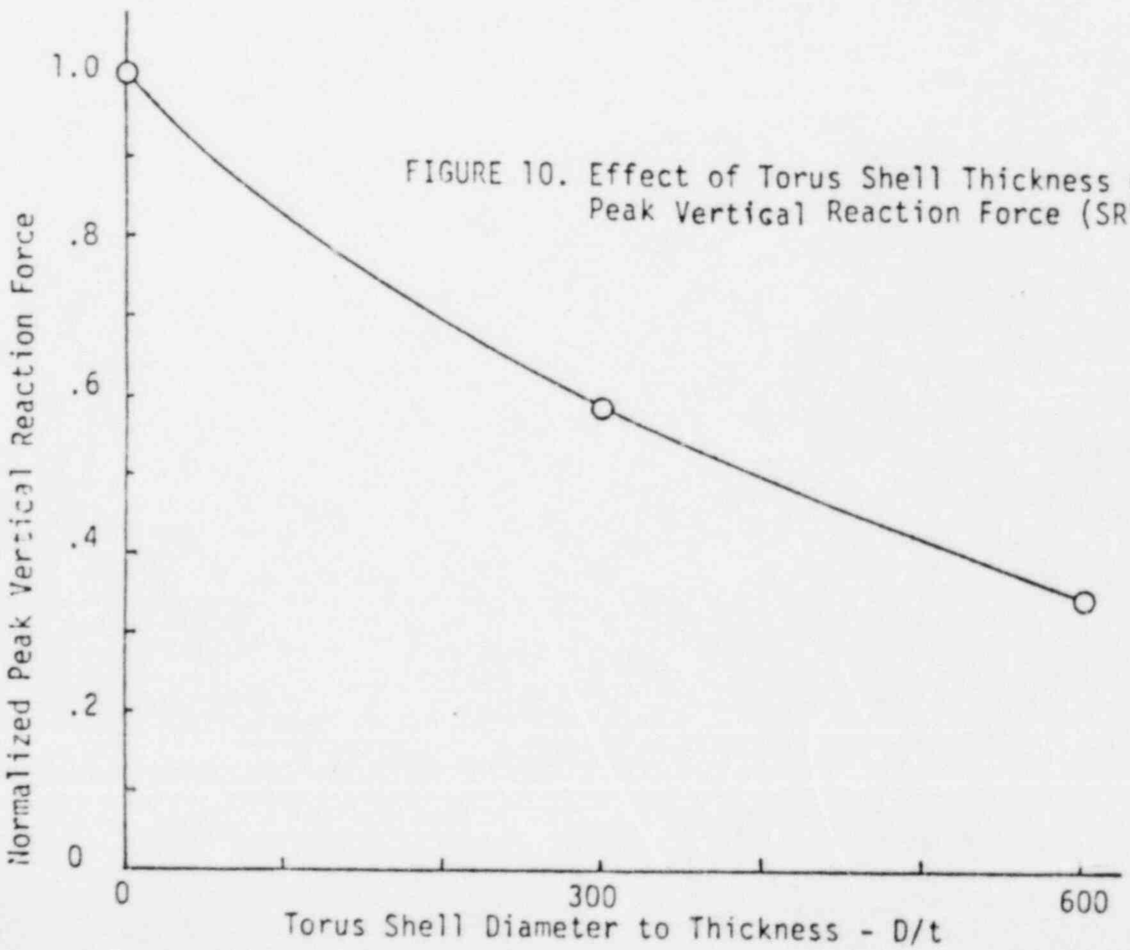

FIGURE 10. Effect of Torus Shell Thickness on Normalized Peak Vertical Reaction Force (SRV Discharge)

5.B LOCA CHUG - GENERALIZED RESULTS

Chugging is expected to occur in the later phases of the hypothetical loss-of-coolant accident (LOCA) when steam exiting from the downcomer forms a partial bubble which subsequently collapses due to heat transfer in the vent header and in the water of the torus. Complete modeling of this process would require the use of a multiphase computer code. Our model of the LOCA chug begins with a "bubble" having the diameter of the downcomer and located tangent to the downcomer exit. A pressure history is applied to its inner surface. The chosen pressure pulse (Figure 4) has a triangular form with a peak overpressure of 20 psi (1.38b) and a total duration of 80 milliseconds. While this results in a situation of "bubble" growth rather than collapse, it is a reasonable first approximation to the problem.

Figure 11 shows the pressure history on the shell at the pool bottom for the three D/t ratios investigated. There is a slight temporal shift due to shell motion but it is considerably less noticeable than in the SRV discharge case. This is to be expected considering the relatively smaller peak pulse, i.e., lower shell velocities result.

The total vertical force resulting from the chug pulse is shown in Figure 12. The variation in peak normalized pressure on the shell at the bottom of the pool and peak normalized vertical load with shell flexibility (D/t) is shown in Figures 13 and 14.

It must be remembered that here too, due to the choice of plane section modeling, the "bubble" is actually a cylinder of infinite length. The lack of out-of-plane limits on the source again results in the introduction of too much energy into the problem.

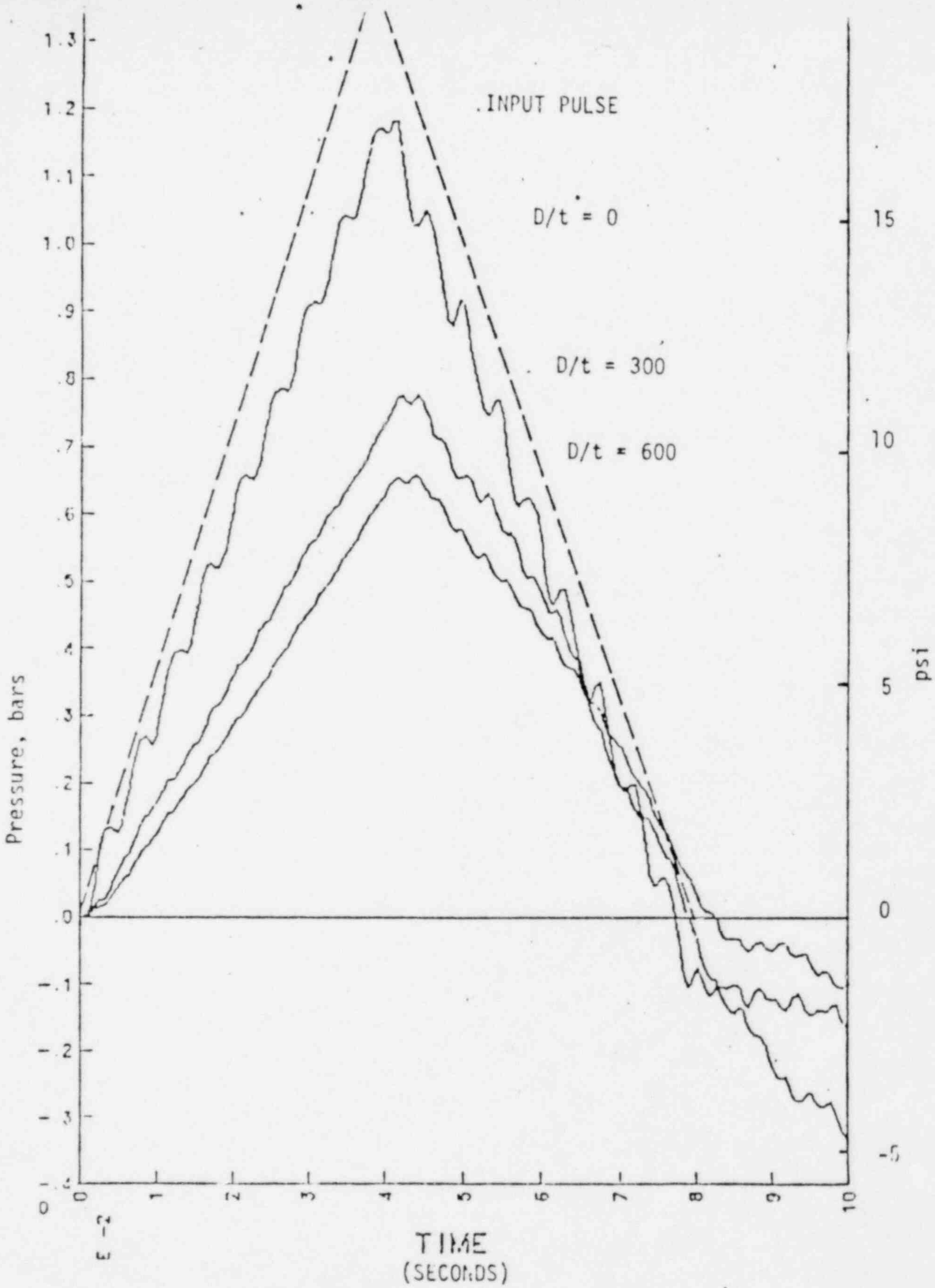

FIGURE 11. Effect of Torus Shell Thickness on Pool Bottom Pressure History (LOCA Chug)

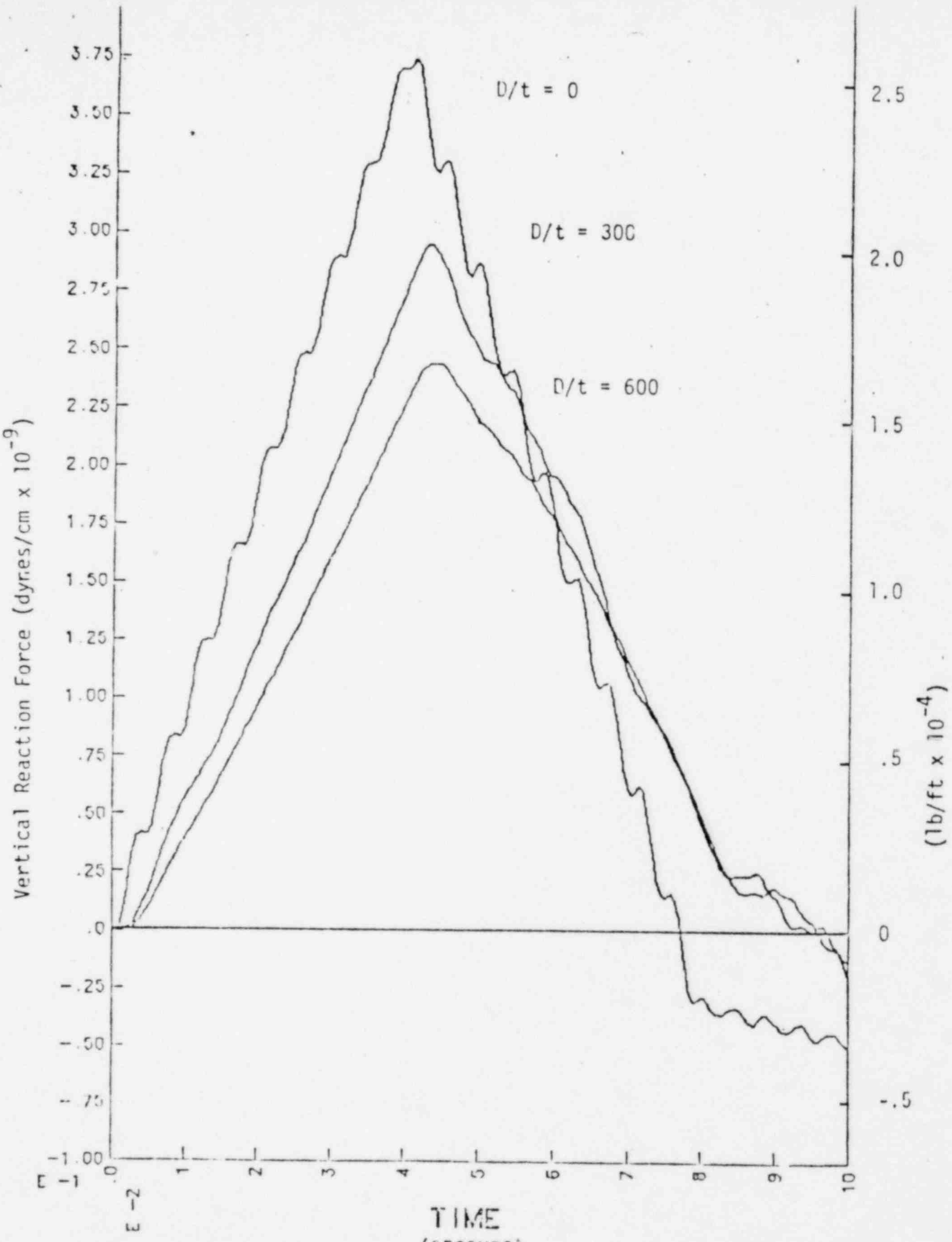

FIGURE 12. Effect of Torus Shell Thickness on Total Vertical Force (LOCA Chug)

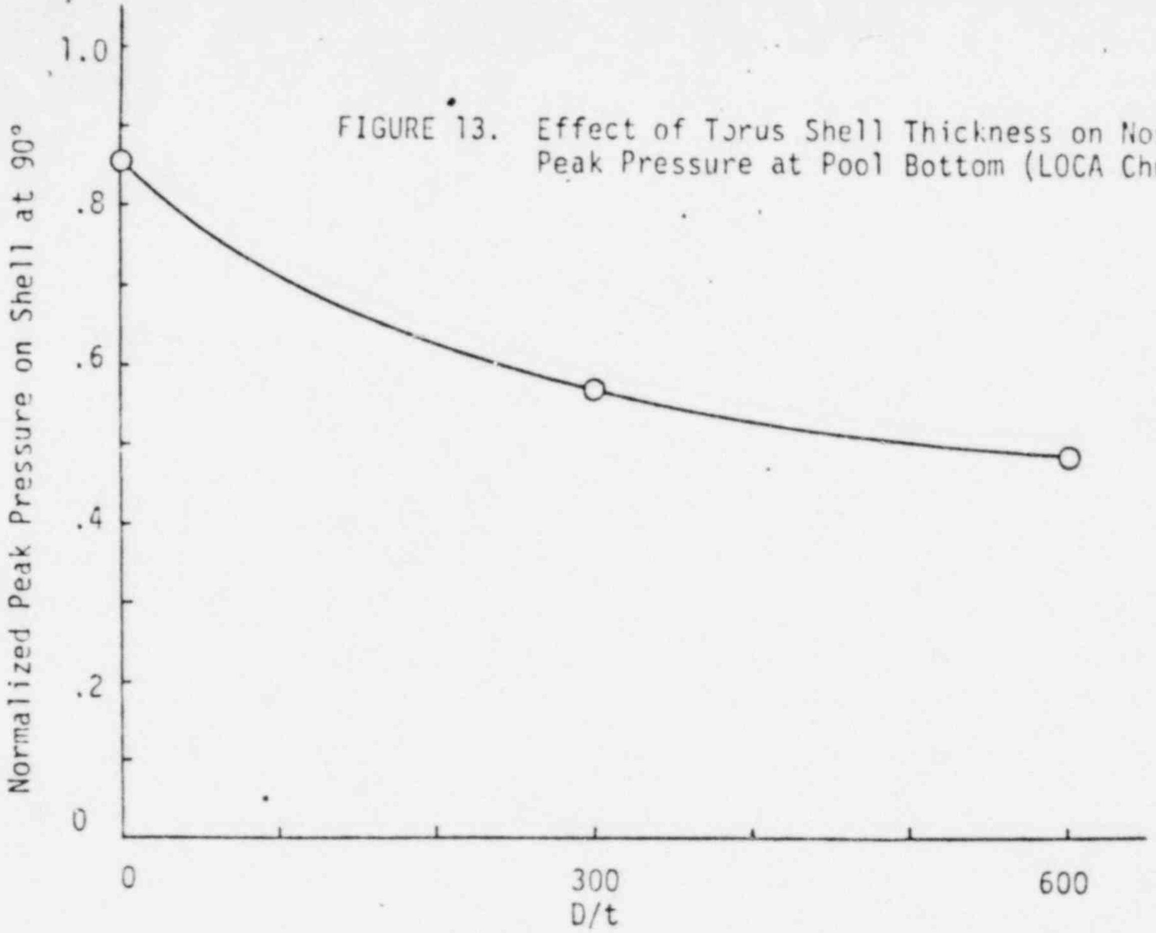

FIGURE 13. Effect of Torus Shell Thickness on Normalized Peak Pressure at Pool Bottom (LOCA Chug)

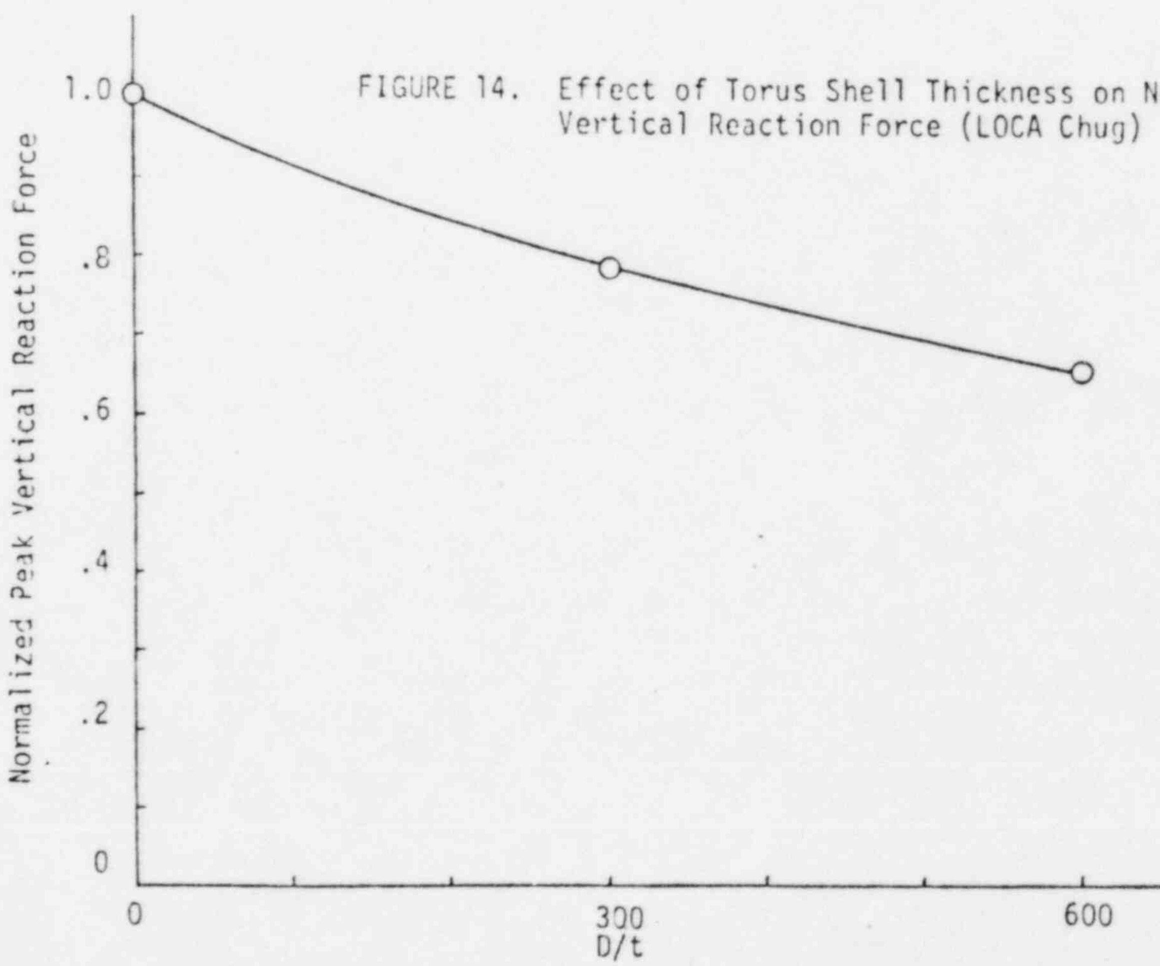

FIGURE 14. Effect of Torus Shell Thickness on Normalized Vertical Reaction Force (LOCA Chug)

6. CONCLUSIONS AND RECOMMENDATIONS

The general conclusion reached from these analyses is that torus wall flexibility will decrease both the maximum pressures seen by the wall and the total vertical load. These results are in principle, those reached earlier by Koch.[8] Great care however, is necessary in the application of these results to actual Mark I plants. Certainly, results from experiments performed on systems having little or no flexibility in the container wall will be conservative when applied to actual highly flexible systems.[a] The quantification of the magnitude of the reduction experienced by flexible systems is however, more difficult than simple application of the results produced here.

Consider first that the system modeled here is a flexible cylinder, infinite in extent, whereas the actual Mark I torus has an out-of-plane stiffness unaccounted for in these analyses. In addition, the shortness of span between mitered sections of the torus will contribute additional stiffness even over that of a purely toroidal shell.

The second consideration is that the source geometries in these problems are also cylinders infinite in extent. This lack of limit in the out-of-plane direction leads to the introduction of excess energy in the problem. Also, in the case of spherical sources, a stronger divergence of a pressure wave is experienced over that of a cylindrical wave.

The work reported here has served to verify that increased flexibility will, in fact, result in a reduction of both wall pressures and vertical loads experienced by the system, but indicates that more work is necessary in order

[a] which exhibit D/t ratios of 500-600.

to approach a qua. fication of that reduction.

Several improvements in treatment of this problem should be considered in future work. The first consideration should be in the area of a more correctly posed geometrical model while still retaining the relative simplicity of two-dimensional analysis:

a) The calculation of these problems in purely toroidal geometry is within our capability at this time.

b) Additional work correlating separate structural analyses could result in modification of the stiffness properties of the torus to account for the ring stiffeners.

We intend to investigate the use of a three-dimensional model of a 22-1/2° sector of the problem incorporating the entire shell and stiffening structure. Before embarking on significantly more detailed calculations, it would be highly desirable to have better information on the characteristics of the source, particularly for the case of chugging. In this regard, it would be useful if future in-plant experiments were designed to provide data directly applicable to the needs of analytical modeling.

ACKNOWLEDGMENTS

Appreciation is extended to S. Sutton for his assistance in running and analyzing the results of several CHAMP problems. G. Goudreau and W. Mason of the Mechanical Engineering, Code Development Group were responsible for the timely modifications to the finite element code to include fluid elements. B. Benda, M. Gerhard, and T. Wilson of the Engineering Mechanics Section performed and processed the finite element problems. Finally, thanks are expressed to J. Hobson and T. Michels of H-Division for their assistance in the use of the CHAMP code, and to Ms. S. Calvert for preparing this report.

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