MASTER

COMPARISONS OF REXCO CODE PREDICTIONS WITH SRI SM-2 EXPERIMENTAL RESULTS

by

Y. W. Chang and J. Gvildys

Prepared for

5th SMiRT Conference

Berlin, Germany

August 13-17, 1979

U of C-AUA-USDOE

ARGONNE NATIONAL LABORATORY, ARGONNE, ILLINOIS

Operated under Contract W-31-109-Eng-38 for the

U. S. DEPARTMENT OF ENERGY

MASTER

SRI International has performed a series of simple model (SM) experiments for the Clinch River Breeder Reactor Project (CRBR). The SM tests consisted of five experiments. The energy source used to simulate the core-disassembly accident loads was a PETN-microsphere mixture, which was well calibrated. These experiments were well instrumented and performed under carefully controlled conditions. The experimental data can be used as reliable test data for validation of computer codes, as well as the modeling technique used in the computer analysis.

This paper deals with the REXCO-HEP code predictions of the SRI SM-2 test, which was a dynamic test performed on 1/20th scale model of the CRBR. Two calculations have been performed: one used the pressure history P(t) of the core detonation products as input, and the other the pressure-volume relation (P-V) of the detonation products as input.

The pressure loadings obtained with the REXCO code calculation are all in good agreement with the experimental records. Not only do the calculations reproduce the general shape of the pressure loading, but also they accurately predict the magnitude of pressures. The calculated wall deformations are also in good agreement with the experimental measurements. However, the upper wall deformation is slightly overpredicted while the lower wall deformation is underpredicted by the code, despite of the good agreement in pressures and impulses. This is believed due to the lack of two-dimensional slidings in the code calculation. It is not due to a discrepancy in properties of the shell, because an adjustment of the shell properties would increase or decrease both deformations at the upper and lower vessel wall in the same proportion. The calculated dynamic strain histories at various gauge positions are also in agreement with the experimental data, but the agreement is not as good as with other experimental data.

The pressure loadings and wall deformations obtained with the P(t) calculations are in better agreement with the experimental measurements than those obtained with the P-V calculations. This is because the P-V relations used in the code calculation were derived from the pressure gauge readings of the core gas, the measured surface motions of the slug and the calculated compressibility of the coolant; they may become less accurate at low pressures. Therefore, in performing code validation calculations, the pressure history of the core gas should be used in the analysis to describe the behavior of the core gas, if the P(t) values are available form the experimental data.

1. Introduction

SRI International (formerly Stanford Research Institute) has performed a series of simple model (SM) experiments [1] for the Clinch River Breeder Reactor (CRBR) Project. The energy source used in these experiments was a PETN-microsphere mixture which was contained in a special designed steel canister to simulate the core-disassembly accident loads resulting from a postulated fuel-vapor expansion. The purposes of these experiments were to (1) study the structural response of the CRBR containment, (2) examine the effects of the upper core internal structures on the slug-impact loads, and (3) provide reliable test data for code validation.

The SM experiments consisted of five tests. Test SM-1 was a static test of the reactor head cover. The other four tests SM-2 to SM-5 were dynamic tests performed on 1/20th scale models of the CRBR. The complexity of the model was gradually increased from a relatively simple cylindrical shell in Test SM-2 to fairly complex models in Tests SM-4 and SM-5.

All tests were performed by SRI, as were the evaluation, assessment, and interpretation of the experimental data. The pretest predictions were performed by General Electric (GE). Argonne National Laboratory (ANL) performed post-test calculations, utilizing the experimental data to validate the REXCO-HEP code and the modeling technique used in the computer analysis.

This paper deals with the REXCO-HEP code predictions of the SRI SM-2 test. Two calculations have been performed: one used the pressure history P(t) of the core detonation products as input, and the other the pressure-volume relation (P-V) of the detonation products as input. The major differences between the two calculations are discussed. The modeling of the segmented radial shield materials and other internals are also discussed.

2. Experimental Apparatus

The apparatus used in the SM-2 test is shown in Fig. 1. It consists of a flexible vessel, a core canister, a core barrel, segmented steel rings, a support platform, and a vessel head cover. The vessel wall and core barrel were made from annealed nickel 200 to simulate the stress-strain properties of the Type 304 stainless steel at reactor operating temperature. The core support platform was a 5.08-cm (2-in.)-thick steel circular plate connected to the bottom of the vessel. The lower part of the reactor below the core support platform was omitted from the experimental model. Three pressure gauges (P1, P2, and P3) were placed inside the segmented steel rings to record the pressure in the core gas. Four pressure-gauge bosses (P4, P5, P6, and P7) were welded on the vessel wall. A single pressure gauge (P8) was mounted at the center of the head cover to measure the slug-impact pressure. Seven strain Gauges (SG1, SG2, SG3, SG4, SG10, SG5, and SG6) were placed on the vessel wall at five different locations. Three strain gauges (SG7, SG8, and SG9) were placed on three of the hold-down studs.

The core canister consisted of a stack of steel rings spaced at even intervals, two end plates, and eight axial studs which held the steel rings and end plates together. The explosive charge was a 19.7-g mixture of 90% PETN and 10% microspheres (by weight), placed inside the canister rings and the steel end plates. The canister was supported by an aluminum stand.

The reactor cover head was a 2.794-cm (1.1-in.)-thick steel circular plate. Steel plates were placed on the top and bottom of the cover head to simulate the weights and reflector plates of the CRBR reactor. The reactor cover head was connected to the vessel flange through shear rings. Two water-position transducers (WS_1 and WS_2) were placed at the bottom of the cover head.

Four accelerometers were used, one on the support platform and three on the head cover, to measure the accelerations of the support platform and the head cover.

3. Mathematical Model

The mathematical model used in the REXCO-HEP analysis is shown in Fig. 2, which has the same dimensions as those in the GE's model used for performing pretest predictions. The core-gas bubble is divided into 8 zones. The volume of the gas zones is 962 cm^3, which was the initial volume of the detonation products.

The radial shield materials are represented by zones. They have the same configurations, mass, and properties as the actual material. Although the radial shields were made of segmented rings, they did exhibit considerable rigidity and strength in both radial and circumferential directions. Therefore, they cannot be represented by a hydrodynamic material. Modeling of the radial shield as a hydrodynamic material can lead to excessive core-barrel deformations. This will in turn lead to an underestimation of the slug-impact loading on the reactor head cover and produce less deformations on the upper vessel wall. Thus, in the REXCO calculations, the radial shield was treated as a solid material with low yield strength.

Since the radial shield material was treated as a solid material, sliding lines must be provided at the interfaces of the fluid and solid materials to avoid excessive zone distortions. In SM-2 calculations, the sliding line was placed at the inner surface of the radial shield, starting at the top of the platform and extending all the way to the water surface, as indicated by a heavy line in Fig. 2.

It should be pointed out that the sliding lines allow the fluid to slide in one direction only. The expansion of the core gas after moving above the top of the radial shield and core barrel was still severely hindered by the lack of the radial motion of the fluid at points which were also the boundary points of the core barrel and radial shield material. As a result, the magnitudes of the pressure waves transmitted through the fluid to the lower vessel wall are somewhat reduced. This reduction in pressures will affect the deformation of the lower vessel wall quite substantially, for the lower vessel wall is often just strained beyond its elastic limit. One way to improve this situation is to treat the top radial shield zones as a hydrodynamic material, so that they can undergo some radial motion to facilitate the transmission of a pressure wave around the radial shield. Similarly, the core-barrel length must be also shortened by one zone length (3.28 cm) to accommodate the radial motion of the fluid.

The core barrel is the first structural member placed next to the core canister. Therefore, the modeling of the core barrel is very important in the computer analysis. There are two ways in which a core barrel can be modeled: one by continuum solid materials and the other by thin shell structures. In numerical analysis, the choice of a continuum or thin-shell approach depends both on the geometry of the core barrel, and on the loading and response that is of interest. If the pressure-wave propagation through the thickness of the core barrel is of importance, a continuum approach is more appropriate. If the thickness of the core barrel is relatively thin compared to other dimensions, and if the wave propagation through the thickness of the core barrel is of no interest, then it is advantageous to model the core barrel as a thin-shell structure. Thus the motion of the core barrel can be defined by that of the midplane, thereby reducing the number of degree of freedom and improving the stability of numerical computations. If the core barrel is to be treated as a continuum solid material, the thickness of the core barrel will have to be divided into at least three to five zones, so that the bending strength of the shell can be properly included in the analysis. This not only requires a large number of zones, but also limit the time steps to very small values if an explicit integration scheme is used. Since the core barrel in the SM-2 test is a slender member, it was therefore modeled as a thin-shell in the REXCO calculations. Again, sliding lines were provided at both sides of the core barrel.

As mentioned earlier, the expansion of the core gas after moving above the top of the radial shield and core barrel is hindered by the lack of the radial motion of the fluid particles at the boundary points of the core barrel and radial shield material. The core-barrel length was shortened by one zone length to facilitate the radial motion of the fluid.

The 500 g of #12 lead shot in the experiment were placed on the Mylar diaphragm above the core canister. The spaces between lead shot were filled with water. In the REXCO model, the lead shot was treated as a composite material which had a density equivalent to that of the mixture of lead shot and water. Therefore, the inertia effect was properly included in the analysis. However, the effects of core-gas flow through the spaces between the lead shot and the relative motion of the lead shots with respect to the surrounding fluid were ignored.

The aluminum-canister support stand was represented by four Lagrangian meshes.

The reactor vessel was modeled as a thin-shell (0.30226 cm thick). It consisted of 23 finite elements. The thicknesses of the two top vessel elements were increased to 0.39624 and 1.0 cm to account for the increase in thickness due to the tapered section and the vessel flange of the SRI test model.

The reactor cover was made of 2.794-cm (1.1-in.)-thick steel plate. It was connected to the vessel flange through shear rings. Thus, the reactor cover is strong enough to be considered as a nondeformable plate, and the motion of the reactor head depends on the movement of the vessel flange which was connected to the support ledge by 72 holddown studs. The mass of air above the water surface was ignored in the analysis.

4. Energy Source Input

Two types of input data can be used in the analysis to describe the behavior of the core detonation products: a P-V relationship and a pressure-time history. The P-V relationship is determined form the measurements of core pressure gauge and the corresponding increase of core-gas volume. The latter increase was determined from the motion of the water slug. The displacement of the slug was measured by means of a light ladder mounted on the water surface. Since the increase in the volume of the vessel and the compression of the water affect the upward motion of the water slug, these changes must be taken into account in the determination of the P-V relationship for the core gas.

The pressure-time history of the core gas can be obtained relatively easily if pressure transducers can be mounted on the core barrel. However, the pressure-time history depends very strongly on the reactor configuration. In other words, the pressure-time history of the core gas in one reactor cannot apply to other reactors if they have different configurations.

The P-V relationship of the SM-2 test was determined by SRI. Since the P-V determination involved the observed motion of the slug surface and the calculated values of the coolant compressibility, the calculated P-V values are expected to be less accurate than those of the pressure-time history taken directly from the pressure record of the core gas. In view of the availability of the P-t values, two calculations were performed with the REXCO-HEP code. One used the measured pressure-time history of the core detonation products as input, and the other the P-V relationship as input.

5. Comparison of REXCO Predictions with Experimental Results

Here only the REXCO results which were obtained with P-t as input are compared with the experimental data; the results obtained with P-V as input will be discussed in Sect. 6.

5.1 Pressure Loadings

The pressure loadings at gauge positions P4, P5, P6, P7, and P8 are given in Figs. 3-7, respectively, in which the REXCO results are shown in solid lines and the experimental in dotted lines. The pressure loadings at gauge positions P4, P5, and P6 on the vessel wall have direct incident pressures and reflections from the slug impact and subsequent wave interactions, whereas the pressure loadings at gauge positions P7 on the vessel wall (above the water surface) and P8 on the head cover are due mainly to slug-impact pressures.

The REXCO-calculated incident pressure loadings at the vessel wall are in excellent agreement with the experimental records. This can be seen from the comparisons shown in Figs. 3-5. Not only the peak pressure and pulse shape are in agreement, but also are the wave-arrival time and the duration of the pulse. However, the REXCO-calculated slug-impact pressure loadings on the vessel wall are higher than the experimental results. This is believed due to the use of sliding lines. Another factor which resulted in higher slug-impact pressures in the REXCO predictions was the mathematical model used in representing the lead shot. As mentioned earlier, the lead shot in the REXCO model was treated as a mixture of liquid (water) and solid (lead shot). Therefore, only the inertia effect was included in the analysis. The effects of core-gas flow through the spaces between the lead shot and the relative motion of the lead shot with respect to the surrounding fluid were ignored. As a result, more energy was imparted to the coolant slug. Also, the lack of the radial sliding caused more energy to be directed to the axial direction. Therefore, REXCO-calculated slug-impact pressures are expected to be higher than the experimental measurements. This can be seen from the comparisons given in Figs. 4-6.

Slug-impact time provides another comparison for code validation. Experimental measurements indicated that the slug impact at gauge position P7 occurred at 2.36 ms, whereas the calculations indicate that the impact was at 2.50 ms. The REXCO-predicted impact time was about 0.14 ms later than the experimental value. Both experiment and REXCO calculation showed two peaks. The calculated peak values are in good agreement with the measurements. At the center of the head cover at gauge position P8, the REXCO-calculated slug-impact pressures are somewhat higher than the experimental values, but the slug impact time in the REXCO prediction is again about 0.14 ms later than the experimental value. Ordinarily, for a larger slug-impact pressure, one could expect a higher slug velocity and an earlier slug-impact time. However, this is not the case in the SM-2 comparisons. Experimental results showed that the coolant slug had produced a smaller impact-pressure loading on the head compared with the REXCO predictions, but the slug impact time in the experiment was 0.14 ms earlier than the REXCO prediction. The exact reason for these contradictory results is not yet known. One possible explanation is that the air space above the coolant surface in the SM-2 test may have had a gap less than the 3.429 cm (1.35 in.) specified in the REXCO calculations.

5.2 Wall Deformations

The profiles of the vessel and core barrel wall deformations are shown in Fig. 8, where the experimental measurements are shown in solid lines and the calculated results in dotted lines. The experimental measurements of the deformed vessel and core-barrel walls were taken at six different meridians; the spread in experimental data is also indicated. The overall agreement between the calculated and measured results is reasonable good. However, the REXCO results on the deformation of the upper vessel wall are slightly larger than the experimental data, whereas the REXCO results are slightly underestimated for the lower vessel-wall deformations. As mentioned earlier, those differences can be partly attributed to the use of sliding lines which allow the water to slide more freely in the REXCO calculations than actually occurs in the experiment along the designated sliding surfaces. This can be further seen from the comparisons of slug-impact pressures shown in Figs. 5 and 6: the REXCO-calculated slug-impact pressures are higher than the experimental measurements. The reason for a smaller wall deformation predicted in REXCO calculations for the lower vessel wall is probably due to the lack of a true two-dimensional sliding capability in the REXCO code. Although two top radial shield zones were treated as hydrodynamic material, the radial motion of the core gas in the Lagrangian calculations was still not large enough to account for the actual movement of the detonation products in the experiment. This can be further seen from the comparisons of slug-impact pressures: the differences between the REXCO-predicted slug-impact pressures and the experimental measurements shown in Figs. 3 and 4 are less than those shown in Figs. 5 and 6.

5.3 Strain Measurements

The dynamic-strain measurement is perhaps the least accurate record in the experimental data. As can be seen from Fig. 8, the strain-gauge records of wall deformation (shown in dots) did not agree with those obtained from the post-test measurement. Moreover, in the experiment, the dynamic strain gauge is often limited to strains of 2-3%. On the other hand, the calculated dynamic strain values depend very strongly on the vessel-wall properties used in the calculations. Therefore, the dynamic-strain records obtained by strain gauges are not suited for code-validation purposes. Nevertheless, the agreement between the calculated and measured strains is considered to be reasonably good. Detailed comparisons can be seen in Ref. [2]. Due to space limitation, they are not given here.

6. Comparison of P-V Predictions with P-t Results

The P-V relationship used in the REXCO calculation was taken from Ref. [1], which was compiled by SRI from the data obtained in the four calibration tests. For the incident pressure loads, the P-V results are in good agreement with the P-t results. The two loadings have almost the same magnitude, duration, and shape. for the slug-impact loads, the P-V results are slightly larger than the P-t results.

It should be mentioned that the values of core-gas pressure were taken from the pressure oscillograms, and the increases of core-gas volume were calculated from the movement of the slug surface and the compressibility of the coolant. Therefore, at low pressure levels, the accuracy of the pressure values will decrease and the computations for core-gas volume will become less accurate due to formation of cavitation and spallation of the coolant surface.

The profiles of the vessel and core-barrel wall deformation obtained with P-V as input are shown in Fig. 9. For the purpose of comparison, the results obtained with P-t as input are also plotted. As can be seen, the agreement in the lower vessel wall deformation is quite good. Both calculations predict a maximum wall deformation of 2%. However, at the upper vessel wall, the deformations obtained with the P-V data as input are considerably larger than those with the P-t data as input. This indicates that there are some differences in those two source terms. As mentioned earlier, the P-V data used in the computer calculations is believed to be quite accurate at the early stage of the excursion when the core pressure is relatively high. However, at low pressures, the data obtained from the pressure oscillograms and the increase of core volume calculated from the slug-surface motion and coolant compressibility could become less and less accurate. Detailed comparison of P-V prediction with P-t result at various gauges can be seen in Ref. [2].

7. Conclusions

SRI SM-2 experiment was performed with a calibrated energy source in a simple cylindrical vessel. The experimental data can be used as reliable test data for validation of computer codes, as well as the modeling techniques used in the computer analysis.

Of the three available experimental records: (1) pressure loadings, (2) final wall deformations, and (3) dynamic-strain histories, the best data for accurate comparison between experiments and computer results are the pressure loadings. This is because the pressure loading on the wall is least affected by the frequency response of the discretized system and the wall material properties used in the analysis. Therefore, comparison of pressure loadings is more reliable than comparison of wall deformatirns, for the latter depend very strongly on the material properties of the vessel wall. The least reliable experimental data are the dynamic-strain measurements.

The pressure loadings obtained with the REXCO code are all in good agreement with the experimental records. Not only do the calculations reproduce the general shape of the pressure loading, but also they accurately predict the magnitude of pressures. The calculated wall deformations are also in good agreement with the experimental measurements. This indicates that the mathematical model used in the REXCO analysis is quite adequate. From the comparison of P-t and P-V results, it can be concluded that the P-V data used in the computer calculations is quite accurate at the early stage of the excursion when the core pressure is relatively high. For low pressures, the P-V data derived from the pressure-gauge readings, and the surface movements and compressibility of the coolant may become less accurate compared with the P-t records obtained directly from the pressure-gauge readings.

8. Acknowledgments

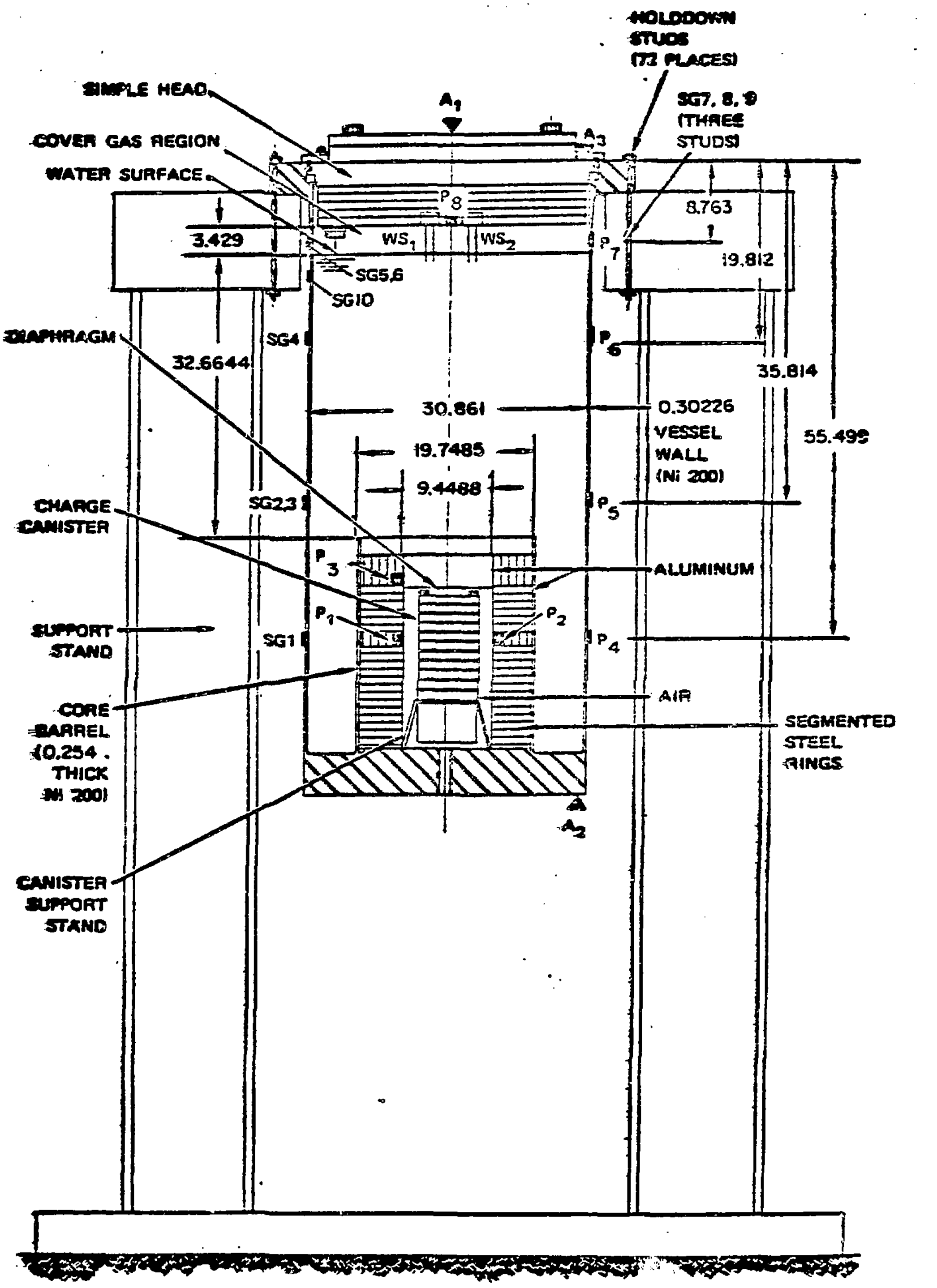
The authors wish to thank Dr. S. H. Fistedis for the useful discussions. This work was performed in the Engineering Mechanics Section of the Reactor Analysis and Safety Division at Argonne National Laboratory, under the auspices of the U. S. Department of Energy.

References

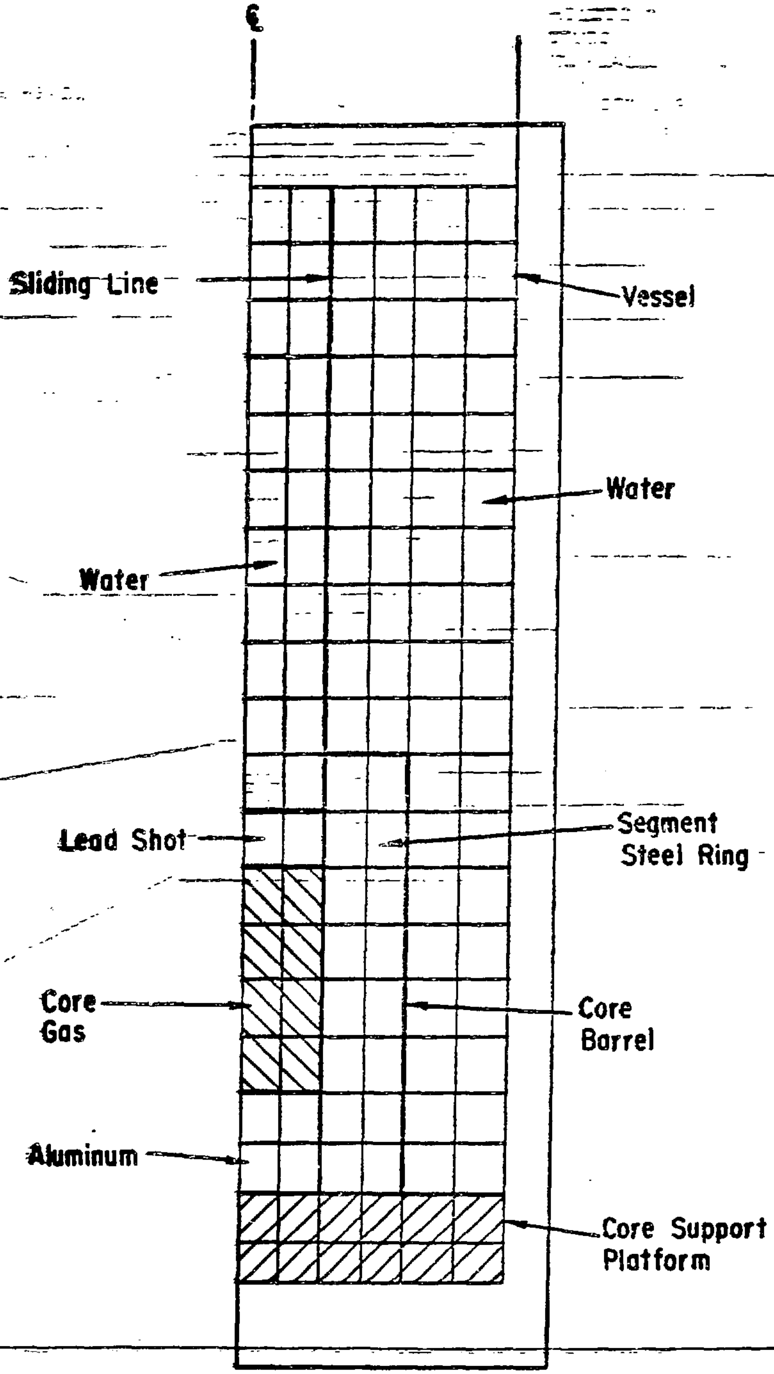
[1] ROMANDER, C. M., CAGLIOSTRO, D. J., "Structural Response of 1/20-scale Models of the Clinch River Breeder Reactor to a Simulated Hypothetical Core Disruptive Accident," SRI International Technical Report 4 (October 1978).

[2] CHANG, Y. W., GVILDYS, J., "Comparison of REXCO Code Predictions with SRI SM-2 Experimental Results," ANL-78-18 (August 1978).

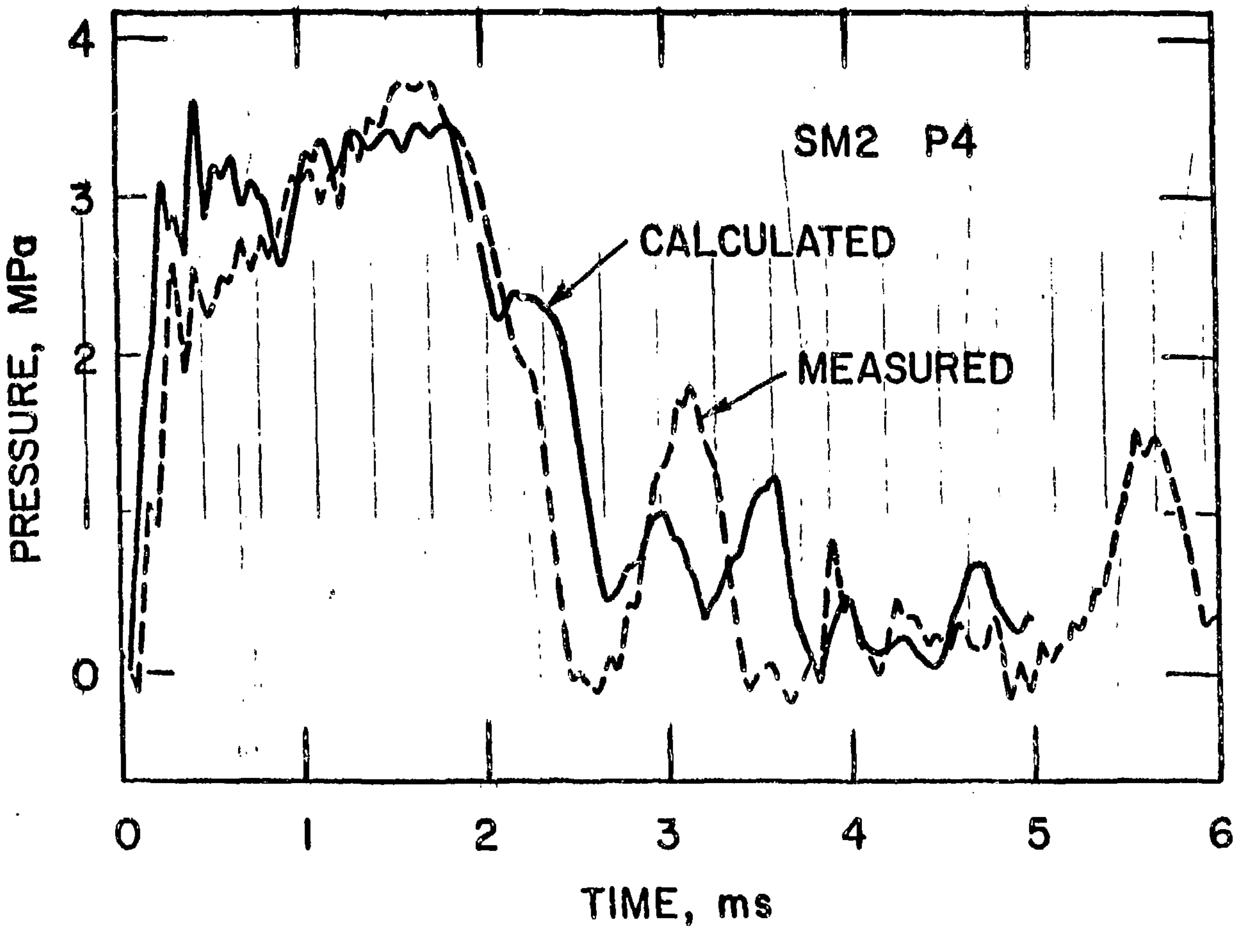
SM 2 WITH INSTRUMENTATION

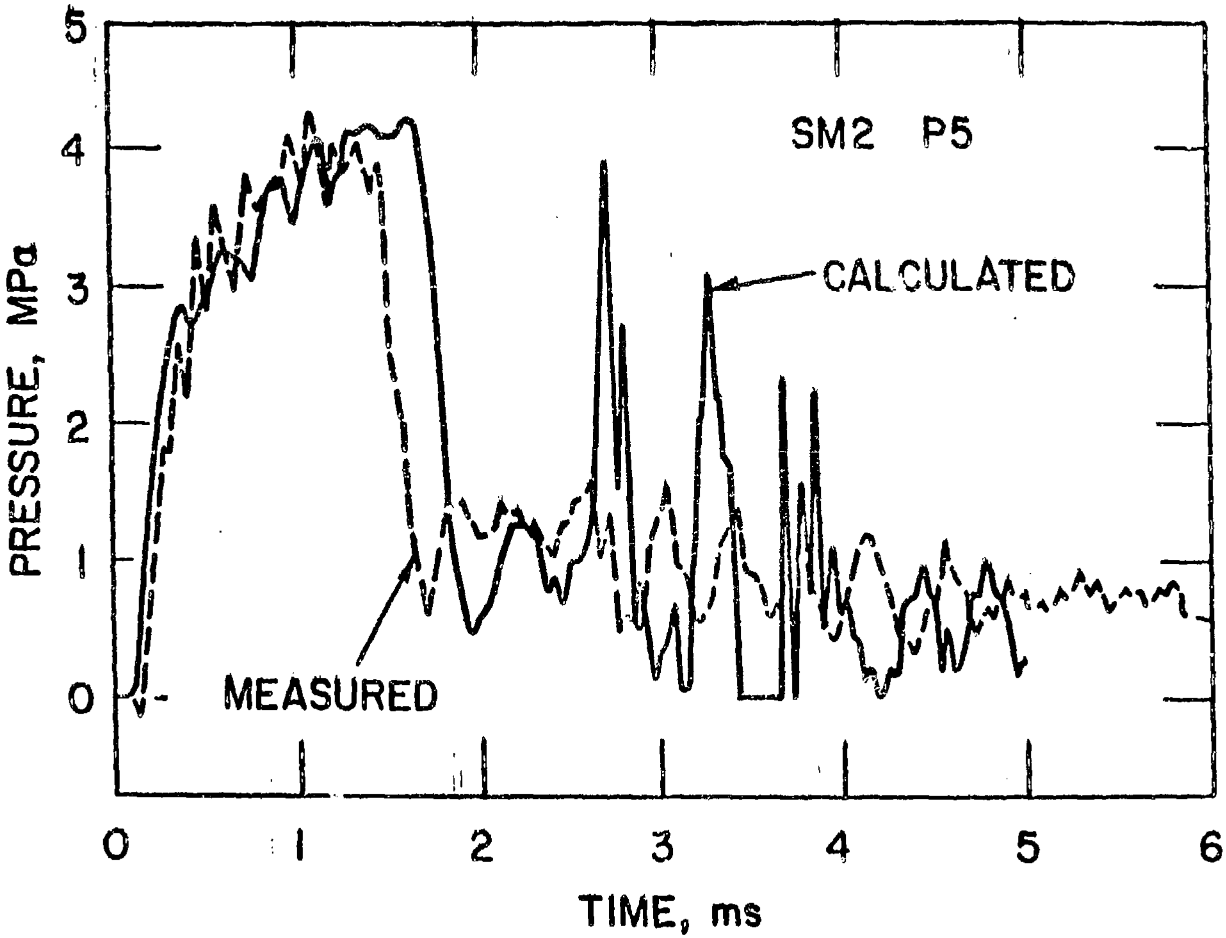


ALL DIMENSIONS IN cm

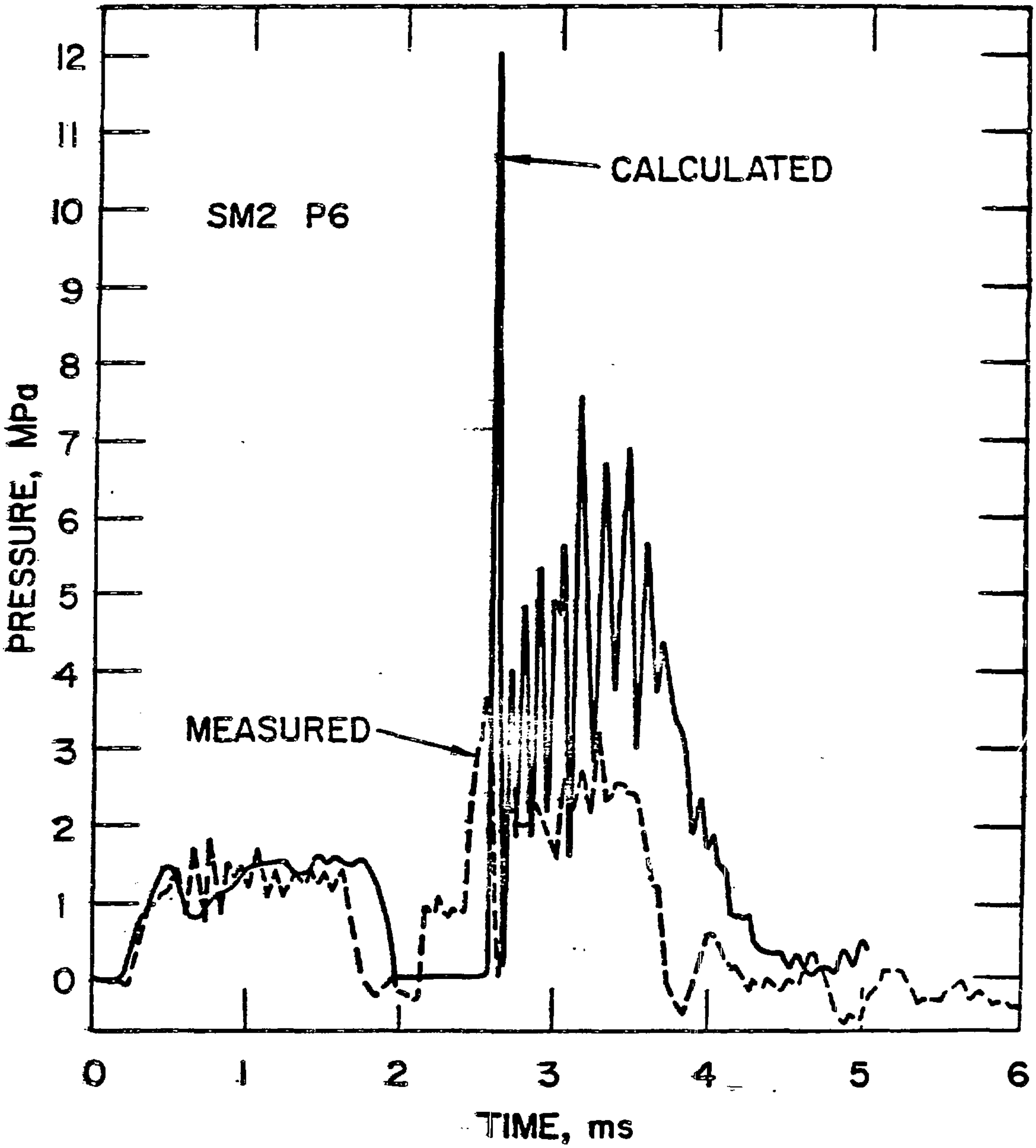


Sliding Line
Vessel
Water
Water
Lead Shot
Segment
Steel Ring
Core
Gas
Core
Barrel
Aluminum
Core Support
Platform

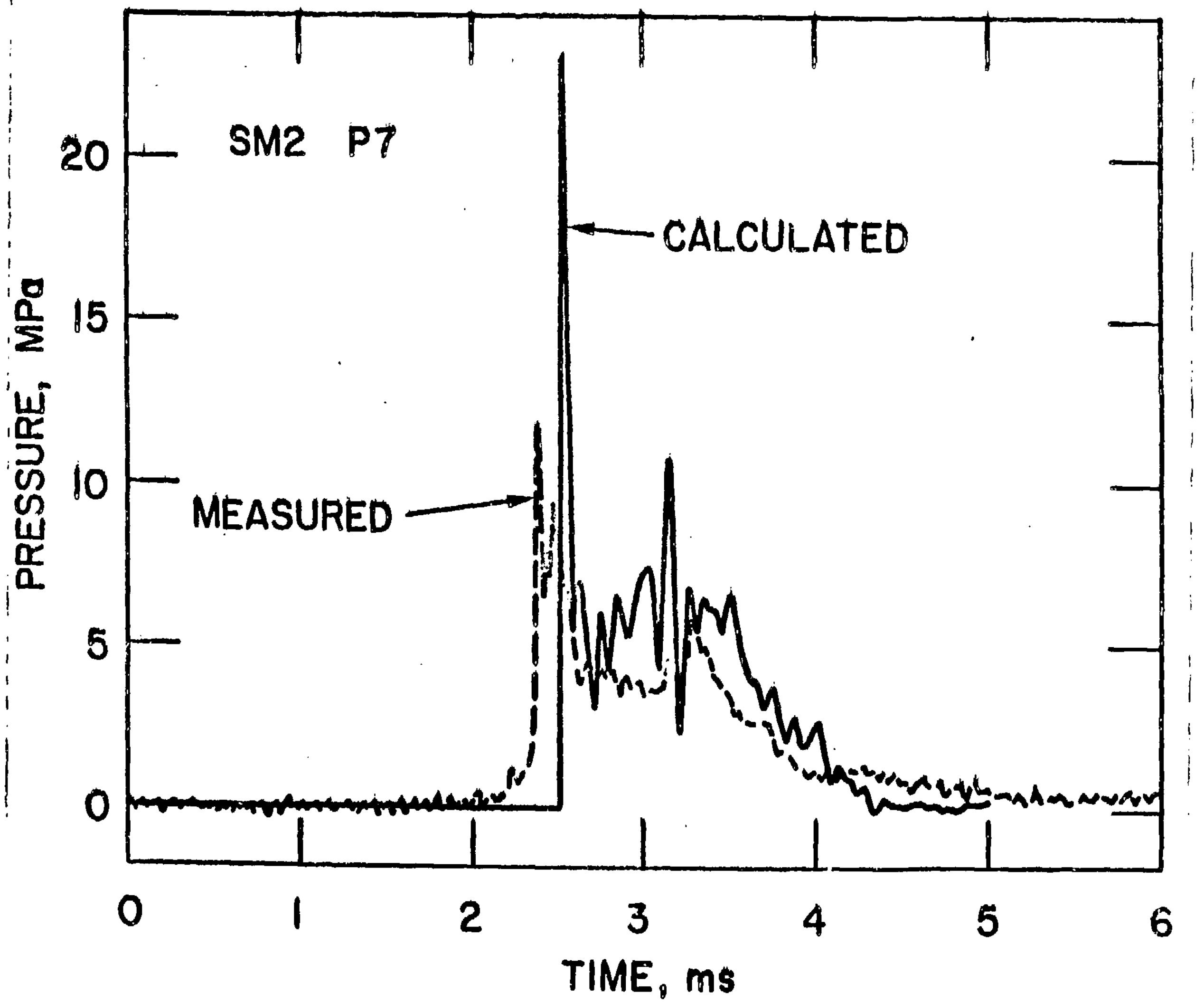

SM2 P4
CALCULATED
MEASURED
PRESSURE, MPa
TIME, ms
0
1
2
3
4
5
6

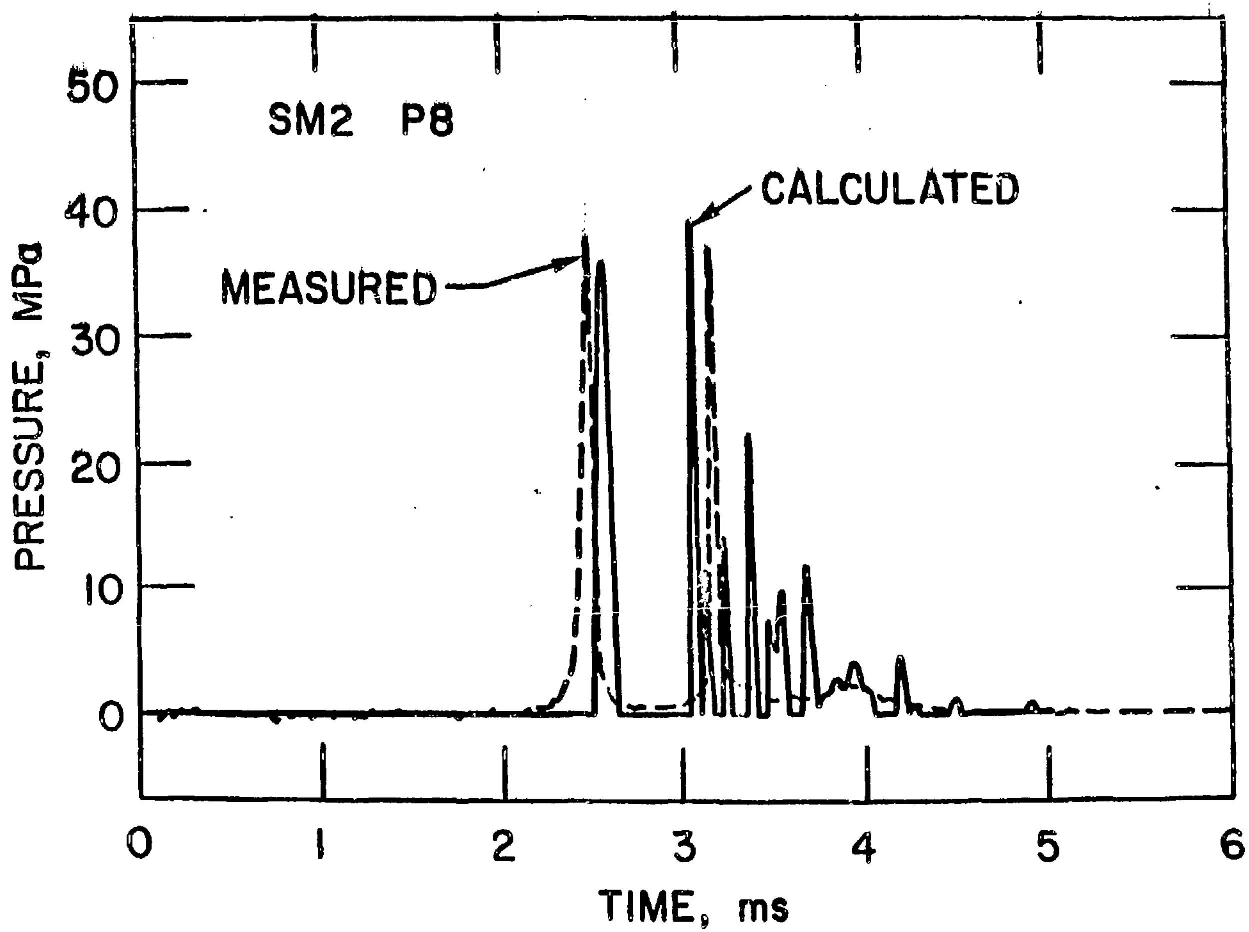


SM2 P5
CALCULATED
MEASURED
PRESSURE, MPa
TIME, ms
0
1
2
3
4
5
6

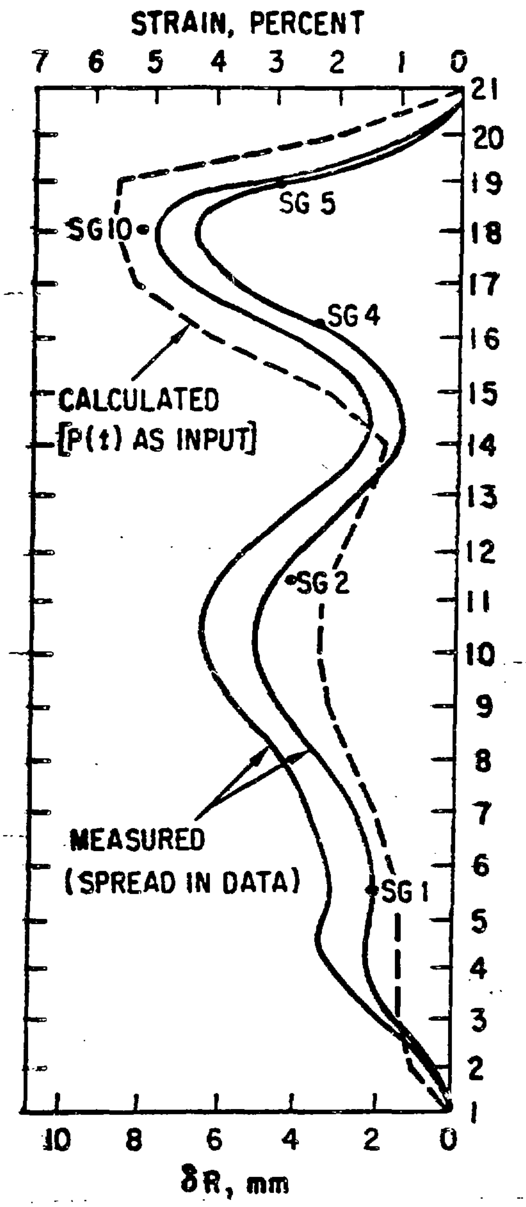


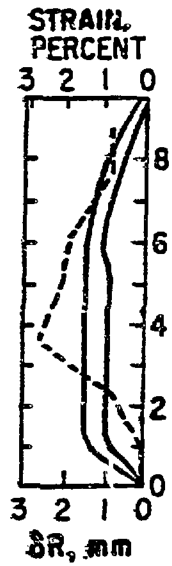
PRESSURE, MPa
12
11
10
9
8
7
6
5
4
3
2
1
0
SM2 P6
CALCULATED
MEASURED
0
1
2
3
4
5
6
TIME, ms

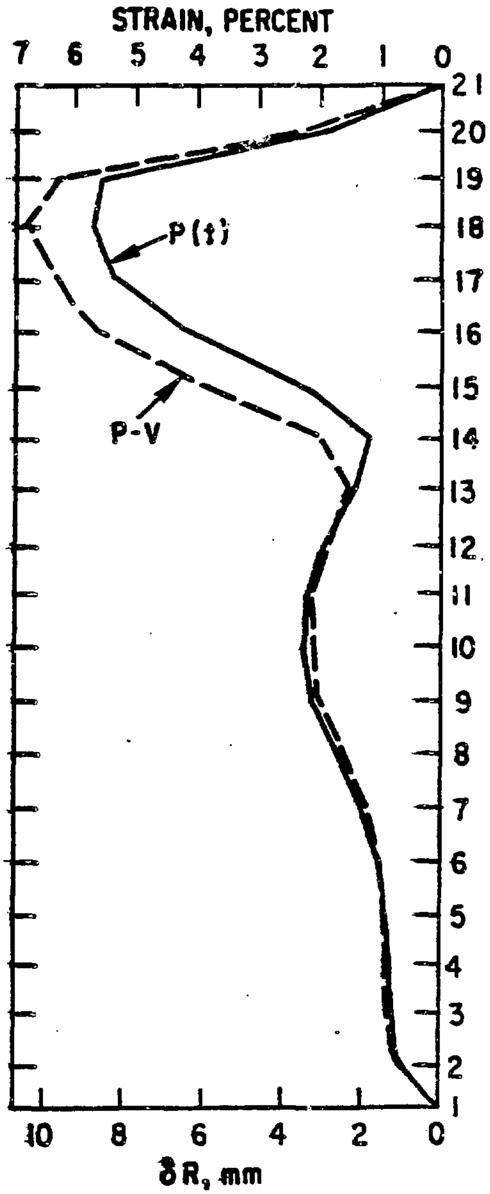

SM2 P7
CALCULATED
MEASURED
PRESSURE, MPa
TIME, ms
0
5
10
15
20
0
1
2
3
4
5
6



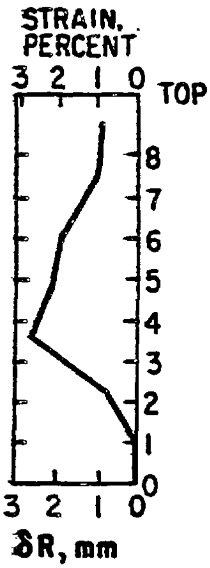
SM2 P8
CALCULATED
MEASURED
PRESSURE, MPa
50
40
30
20
10
0
0
1
2
3
4
5
6
TIME, ms


STRAIN, PERCENT
7 6 5 4 3 2 1 0
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
SG 5
SG10
SG 4
CALCULATED
[P(t) AS INPUT]
SG 2
MEASURED
(SPREAD IN DATA)
SG 1
10 8 6 4 2 0
δR, mm


STRAIN, PERCENT
3 2 1 0
8
6
4
2
0
3 2 1 0
δR, mm



STRAIN, PERCENT
7 6 5 4 3 2 1 0
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
P(t)
P-V
10 8 6 4 2 0
δR, mm



STRAIN, PERCENT
3 2 1 0
TOP
8
7
6
5
4
3
2
1
0
3 2 1 0
δR, mm