ICEPEL ANALYSIS OF AND COMPARISON WITH SIMPLE ELASTIC-PLASTIC PIPING EXPERIMENTS

by

M. T. A-Moneim

Reactor Analysis and Safety Division

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NOMENCLATURE

A  Area
C  Quantity related to the speed of sound and defined by Eq. 9
CG Quantity defined by Eq. 11
CR Quantity defined by Eq. 7
CS Quantity defined by Eq. 8
IE Number of radial zones in the elbow
IP Number of radial zones in the pipe
M  Quantity defined by Eqs. 17-20
F  Pressure
q Quantity defined by Eq. 4
r  Radial coordinate
S  Source term in difference form of z-momentum equation of the pipe
t  Time
u  Radial velocity component
v  Axial or tangential velocity component
θ Time-centering coefficient of the mass equation
Δr  Radial zone size
Δt  Time interval
Δz  Axial zone size
Δθ Tangential zone size
λ  First coefficient of viscosity
μ  Second coefficient of viscosity
φ Time-centering coefficients for momentum equations
ρ  Density
θ  θ-coordinate

Subscripts
  e  Refers to elbow
  i  Counting zones in radial direction
  j  Counting zones in axial or tangential direction
  p  Refers to pipe

Superscripts
  n  Counting time cycles
ICEPEL ANALYSIS OF AND COMPARISON WITH SIMPLE ELASTIC-PLASTIC PIPING EXPERIMENTS

by

M. T. A-Moneim

ABSTRACT

The results of simple elastic-plastic piping experiments for straight pipes and single-elbow loop systems are interpreted and evaluated. The experiments are also analyzed by the ICEPEL piping code, and the analytical results are compared against the experimental data.

Good agreement is obtained in predicting both pressure and circumferential strain histories along the pipe systems. Inside the elbow, however, the analysis showed radial pressure variation while the experiments showed no radial pressure variation. Consequently, the ICEPEL elbow model was modified to resolve this discrepancy. The new model agreed with the experiments in showing no radial pressure variation.

I. INTRODUCTION

Recent advances in computer technology have led to the wide use of computer codes in the safety assessment of Liquid Metal Fast Breeder Reactors (LMFBR's) under postulated accident conditions. However, because of the complexity of the physical phenomena involved in the analysis, assumptions and simplifications are usually made to calculate the consequences of accidental events. Such assumptions are thought of as being insignificant or leading to more conservative estimates.

To increase confidence in the use of computer codes in the safety evaluation of reactors, and to reduce the conservatism introduced in the analysis to reasonable limits, experimental programs designed to help verify the analytical model and to understand the physical phenomena for better analytical representation must parallel the development of the analytical tools. Interpretation of the experimental data and analysis of the experiments by the computer codes can also help design and instrument future experiments.

The ICEPEL code is being developed at Argonne National Laboratory for the safety analysis of piping systems. The code performs a coupled hydrodynamic-structural response analysis of piping systems. A two-dimensional Implicit Continuous-Fluid Eulerian finite-difference technique is
used in the hydrodynamics. The structural analysis treats the walls as axisymmetric thin shells with both the membrane and bending strengths considered. A convected-coordinates finite-element scheme is used in the structural response calculations.\(^3\)

Two-dimensional hydrodynamic models for the different piping components such as pipes, elbows, valves, expansions, reducers, heat exchangers, surge tanks, and tees are included and coupled together hydrodynamically, so that a general piping system can be modeled and analyzed both hydrodynamically and structurally.

A piping experimental program designed at Argonne National Laboratory and performed by SRI International to validate the different aspects of the ICEPEL code was undertaken. The first phase of this program consists of five experiments designed for the validation of the pipe and elbow models.\(^4\)

Two straight-flexible-pipe tests FP-SP-101 and -102 are designed to validate the pipe model and the coupling between the hydrodynamic and structural calculations. Three single-elbow loop tests (FP-E-101, -102, and -103) are designed to check the adequacy of the elbow model and its coupling with the pipe model. Also, some of the basic assumptions in the elbow model are to be evaluated from these tests.

In this report, the experimental data, as reported by SRI, are interpreted and evaluated, the experiments are analyzed by the ICEPEL code, the analytical results are compared against the experimental data, the elbow model of the ICEPEL code is modified accordingly, and conclusions and recommendations for future experiments are discussed.

II. DESCRIPTION OF EXPERIMENTS

A. Straight-flexible-pipe Tests

Figure 1 shows the experimental layout and the locations of instrumentation for the straight-flexible-pipe tests, FP-SP-101 and -102.

![Figure 1. Layout for Straight-flexible-pipe Tests. Conversion factors: 1 in. = 2.54 cm; 1 ft = 30.48 cm.](image)
layout consisted of a calibrated pulse gun directly flanged to a thick-walled stainless steel pipe, which was flanged to a flexible test pipe that ended with a heavy blind flange.

The calibrated pulse gun was developed by SRI International to produce well-controlled and -tailored pressure pulses for testing reactor components under postulated accident conditions. A mixture of explosives detonated by PETN is used to produce pulses of sharp peaks. The pressure-peak magnitude is controlled by the mass of the explosives used. The rise time of the pressure peaks and the duration of the pressure pulses are controlled, respectively, by the clearances between the stack of washers surrounding the charge and the area available for venting of the explosive gases.

A mixture of 3.5 g of explosives detonated by 0.15 g of PETN consistently produced pressure peaks of about 16 MPa in the thick-walled stainless steel pipe. The rise time was about 200 μs, and the duration was about 3 ms.

The thick-walled stainless steel pipe was 304.8 cm (10 ft) long and of 8.26-cm (3.25-in.) outside diameter. Its wall thickness was 0.46 cm (0.188 in.). The pipe was intended to behave only classically, so that a well-defined pressure pulse could be stabilized and established before entering the flexible test pipe.

The flexible test pipe was 152.4 cm (5 ft) long and of 7.62-cm (3-in.) outside diameter. Its wall thickness was 0.165 cm (0.065 in.). The pipe was made of nickel-200 whose stress-strain properties resemble those of Type 304 stainless steel at reactor operating temperatures.

Reactor coolant was simulated by water, which filled the pipe system at the moment of charge detonation.

All pipe flanges were heavy, well sealed, and bolted to heavy brackets, which were anchored to the ground to limit both the lateral and axial motions of the flanges. This is a requirement of the ICEPEL code which cannot treat pipe centerline motions.

The pipe system was instrumented with 11 pressure transducers axially distributed along the pipe system, as shown by gauges P1-P11 in Fig. 1, to monitor the pressure-pulse propagation along the system. Twenty strain gauges, shown by SG1-SG20 in Fig. 1, were used at four axial locations of the flexible test pipe to monitor the pipe dynamic response to the traveling pulses. Five strain gauges circumferentially spaced at uniform intervals of 60° were used at each axial strain location to check the uniformity of strains around the pipe circumference.

B. Single-elbow Loop Tests

Figure 2 shows the layout and the location of instrumentation for the single-elbow loop tests, FP-E-101, -102, and -103. Upstream from the elbow,
the pipe system is identical in dimensions and material to that used in the straight-flexible-pipe tests. A second flexible test pipe, identical in size and material to the first one, was connected to the other end of the elbow.

![Diagram of pipe system](image)

**Fig. 2. Layout for Single-elbow Loop Tests**

This second flexible pipe ended with a heavy blind flange in tests FP-E-102 and -103. In test FP-E-101, however, the second flexible pipe ended with a membrane representing a simple open-end boundary.

The 90° elbow was made of stainless steel, which was welded to short transition pieces that terminated in connecting flanges. The elbow radius of curvature was 11.43 cm (4.5 in.), and the nominal wall thickness was 0.76 cm (0.3 in.).

The short transition pieces gradually increased the inside diameter of the elbow from 7.06 to 7.24 cm (2.78 to 2.85 in.), which is less than the inside diameter of the connected pipes, 7.29 cm (2.87 in.). Measurements of the elbow cross section at the different locations showed a slightly egg-shaped cross section, with the inside diameter varying from one end to the other.

All flanges were connected to heavy brackets, which were anchored to the ground to limit the lateral and axial motion of the flanges.

Eighteen pressure transducers, shown by P1-P18 in Fig. 2, were used to monitor the pressure-pulse propagation along the system. Up to three pressure transducers circumferentially distributed around the pipe were used at one axial location to check the effects of the elbow on the axisymmetry of the flow in the pipes upstream and downstream from the elbow. Also, three pressure gauges, P11-P13, were used at the midsection of the elbow to record any radial pressure distribution inside the elbow.

Twenty strain gauges, shown by SG1-SG20 in Fig. 2, were used at four axial locations in the first flexible pipe to monitor its response to the traveling
pressure pulses. Similar to the straight-flexible-pipe tests, they were distributed in groups of five at each axial location to check the uniformity of strains around the circumference of the pipe. The second flexible pipe was not instrumented with strain gauges.

III. DISCUSSION OF EXPERIMENTAL RESULTS

A. Straight-flexible-pipe Tests

The experimental results of the two straight-flexible-pipe tests FP-SP-101 and -102 are summarized in Fig. 3, which shows the peak pressures along the pipe system and their relation to the deformation of the flexible pipe walls.

![Peak Pressure and Pipe-wall Deformed Shape for Straight-flexible-pipe Tests](image)

Plastic wall deformation at the beginning of the flexible test pipe rapidly reduces the pressure peak from about 13.8 MPa (2000 psi) in the thick-walled pipe to about 6.9 MPa (1000 psi) in only 3.81 cm (1.5 in.) of the flexible pipe. The pressure peaks drop further as they propagate along the flexible pipe to a value of about 3.8 MPa (550 psi), which is slightly higher than the yield pressure of the pipe of about 3.5 MPa (510 psi) in 45.7 cm (18 in.) of the flexible test pipe. The difference is due to the inertia of the pipe walls.

Beyond the region of plastic wall deformation the peak pressure remains at the same level until the incident pulse hits the blind flange. A pressure pulse of larger magnitude reflects back to the pipe moving from right to left.
This reflected pulse causes plastic wall deformation to occur in the vicinity of the blind flange, reducing the pressure peaks of the reflected pulse to a value slightly higher than the yield pressure of the pipe in about 30 cm (12 in.). Thus, the middle part of the test pipe shows no plastic wall deformation, and the level of the pressure peaks there remains constant at a slightly higher value than the yield pressure of the pipe.

Besides physically describing the phenomena, Fig. 3 also helps in evaluating and interpreting the records of the different pressure gauges. For example, the pressure peak at P1, the first gauge in the thick-walled pipe, is shown to differ between the two tests, and both are lower than expected. In the pulse-gun calibration tests, the pressure peak at the same location was recorded consistently at about 15.9 MPa (2300 psi). The same explosive charge (3.65 g) used in the calibration tests was used in tests FP-SP-101 and -102. The fact that the pressure peaks at location P2 in test FP-SP-101 and at location P3 in test FP-SP-102 were higher than that at P1 also indicates that the pressure peak at P1 was on the low side. The pressure pulse at P1 is to be used in the analysis as an input source to the ICEPEL model.

Another example is the pressure records at gauges P7 and P9, which are shown to have peak pressures lower than the yield pressure of the pipe and also lower than the peak pressures at gauges P6 and P8. Intuitively, as explained before, plastic pipe wall deformation cannot reduce the peak pressure of the traveling pulses below the yield pressure of the pipe.

Furthermore, the fact that the pipe wall has been deformed plastically at location P9, as shown by the deformed configuration of the pipe, indicates that the pressure peak at this location must have been above the yield pressure of the pipe. Thus, it can be concluded that both gauges P7 and P9, which recorded lower pressures were in error in both tests.

Table I summarizes the strain results for the straight-flexible-pipe tests. The table indicates variations in the strain records at the same axial location. SRI attributed this variation to variations in pipe-wall thicknesses around the circumference, which were measured before and after the tests and are also shown in Table I.

Although the records of tests FP-SP-101 almost indicate that highest strains were recorded at locations of smallest thickness, and vice versa, the records of test FP-SP-102 was not consistent with that. This indicates that the variation in strains around the pipe circumference was not totally due to pipe-wall-thickness variation, which was within ±5%. Another source of such variations is the pipe bending resulting from imperfections in the test pipe, which was a commercial off-the-shelf pipe. Appendix A presents an analytical study of the effect of thickness variations on strain predictions.
TABLE I. Summary of Strain Results for Straight-flexible-pipe Tests

<table>
<thead>
<tr>
<th>Strain Gauge</th>
<th>Test FP-SP-101</th>
<th>Test FP-SP-102</th>
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<tr>
<td></td>
<td>Wall Thickness, in.</td>
<td>Dynamic Strain, %</td>
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<tr>
<td>SG1</td>
<td>0.064</td>
<td>1.18</td>
</tr>
<tr>
<td>SG2</td>
<td>0.063</td>
<td>1.21</td>
</tr>
<tr>
<td>SG3</td>
<td>0.064</td>
<td>1.04</td>
</tr>
<tr>
<td>SG4</td>
<td>0.065</td>
<td>0.97</td>
</tr>
<tr>
<td>SG5</td>
<td>0.066</td>
<td>0.78</td>
</tr>
<tr>
<td>SG6</td>
<td>0.065</td>
<td>0.20</td>
</tr>
<tr>
<td>SG7</td>
<td>0.063</td>
<td>0.43</td>
</tr>
<tr>
<td>SG8</td>
<td>0.065</td>
<td>0.37</td>
</tr>
<tr>
<td>SG9</td>
<td>0.066</td>
<td>0.32</td>
</tr>
<tr>
<td>SG10</td>
<td>0.067</td>
<td>0.15</td>
</tr>
<tr>
<td>SG11</td>
<td>0.065</td>
<td>0.04-0.08</td>
</tr>
<tr>
<td>SG12</td>
<td>0.063</td>
<td>0.03-0.22</td>
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<tr>
<td>SG13</td>
<td>0.062</td>
<td>0.03-0.19</td>
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<td>SG14</td>
<td>0.063</td>
<td>0.04-0.25</td>
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<td>SG15</td>
<td>0.065</td>
<td>0.04-0.05</td>
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<td>SG16</td>
<td>0.068</td>
<td>0.19</td>
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<tr>
<td>SG17</td>
<td>0.065</td>
<td>0.37</td>
</tr>
<tr>
<td>SG18</td>
<td>0.065</td>
<td>0.29</td>
</tr>
<tr>
<td>SG19</td>
<td>0.066</td>
<td>0.30</td>
</tr>
<tr>
<td>SG20</td>
<td>0.067</td>
<td>0.16</td>
</tr>
</tbody>
</table>

Conversion factor: 1 in = 2.54 cm.

The pressure-transducer mounting bosses may also contribute to the strain variation around the circumference. The mounting bosses are likely to stiffen the pipe walls in their vicinity. Test FP-SP-101 records showed that, except for the first axial location, the strain records at gauges closest to the mounting bosses were the lowest. However, test FP-SP-102 did not show the same consistent trend.

B. Single-elbow Loop Tests

The experimental results for three single-elbow loop tests, FP-E-101, -102, and -103, are summarized in Fig. 4, which shows the pressure peaks along the system and the posttest deformed-pipe configuration for the two flexible pipes. Similar to the straight-flexible-pipe tests, the plastic wall deformation at the beginning of the flexible pipe reduced the pressure peaks rapidly to less than half its value in the thick-walled pipe in only 3.81 cm (1.5 in.). The pressure peaks reached a level slightly higher than the yield pressure in 45.7 cm (18 in.).

The pressure peaks are shown to remain at that level until it suffers a reduction of around 18% as it moves around the elbow. However, both tests FP-E-101 and -103 showed the pressure peaks to increase slightly in the second flexible pipe as the distance increased from the elbow. The reason could be the blind flange at the end of the second flexible pipe in test FP-E-103. But test FP-E-101, in which the second flexible pipe ended with a simple open end, also showed the same trend. In the elastic test, FP-E-102, all records in the second flexible pipe were lost.
Fig. 4. Peak Pressure and Pipe-wall Deformed Shape for Single-elbow Loop Tests. Conversion factors: 1 psi = 6.895 kPa; 1 in. = 2.54 cm; 1 mil = 2.54 \times 10^{-2} \text{ mm.}
In test FP-E-103, the incident pressure pulse hit the blind flange and reflected a pressure pulse of larger peaks, which caused plastic wall deformation to occur in the vicinity of the blind flange. This, in turn, reduced the pressure peaks to a level slightly higher than the yield pressure of the pipe. The only dynamic-strain or pressure measurements taken in the second flexible pipe were pressures near the elbow.

The posttest measurements of the deformed configuration of the two flexible pipes for tests FP-E-101 and -103 show that plastic wall deformation occurred at the beginning of the first flexible pipe, around the elbow, and near the blind flange for test FP-E-103. For test FP-E-101, no measurable change in the dimensions of the second flexible pipe was recorded.

The bulges in the two flexible-pipe ends near the elbow may suggest a reflected pressure pulse from the elbow due to the heavy (rigid) wall of the elbow. However, such measurements are not reliable enough to make such a conclusion, particularly because the pipes were commercial pipes with imperfections in their dimensions, and because insufficient dynamic-strain measurements were taken in the two flexible pipes near the elbow.

Comparing the records of the different gauges in each test, one can conclude that gauge P3 recorded higher pressures in tests FP-E-101 and -103. Gauges P5-P7 in tests FP-E-101 are believed to be recording slightly lower pressures, in particular, gauge P6, which is recording pressure peaks even lower than the yield pressure of the pipe. Also, gauges P4 and P6 in the elastic test FP-E-102 are believed to record lower pressures.

As in the straight-flexible-pipe tests, using the same explosive charge (3.65 g) in tests FP-E-101 and -103 as that used in the pulse-gun calibration tests produced lower pressure peaks at gauge P1, especially in test FP-E-101. However, the posttest deformed configuration of the first flexible pipe is compatible with the low pressure peaks, when compared with the posttest deformed configuration of the first flexible pipe of test FP-E-103. In test FP-E-103, the deformed pipe configuration shows the largest change in diameter 2.03 cm (0.8 in.) from the flange; in test FP-E-101, the largest change in diameter was measured 3.81 cm (1.5 in.) from the flange. In other words, the difference in deformation of the first flexible pipe, shown in Fig. 4, cannot be relied on to indicate that the pressure peak in the thick-walled pipe was in fact low in test FP-E-101.

The dynamic-strain measurement at one axial location showed an even wider scatter than that of the straight-flexible-pipe tests. Again, this cannot be totally attributed to variations in the wall thickness around the circumference of the pipe. Bending of the pipes is more likely in the single-elbow loop tests because of the changes in the direction of the flow due to the elbow.
IV. ICEPEL ANALYTICAL MODELS

Since only pressure histories of the form $P(t)$ can be used as an input to an ICEPEL model of a piping system, the pressure history recorded by gauge P1 is used as an input pulse to the pipe system downstream from the gauge. The duration of the pressure history as recorded by gauge P1 is 3 ms, and a pressure pulse requires more than 3 ms to travel from gauge P1 to the entrance to the thin-walled flexible nickel-200 pipe and back to gauge P1. The pressure record at P1 therefore does not include any interactions between the incident pulse and any possible reflections from the flexible pipe. Hence, the pressure pulse at P1 can be safely used as an input to the analytical model.

Thus, Fig. 5 shows that the ICEPEL model of the straight-flexible-pipe tests considers only 228.6 cm (90 in.) of the thick-walled pipe directly flanged to 152.4 cm (60 in.) of flexible test pipe, which ends with a rigid dead end. Both the thick-walled pipe and the test pipes are divided into equal-size zones of 1.82 cm (0.72 in.) radial zone size and 2.54 cm (1 in.) axial zone size.

The walls of the thick-walled stainless steel pipe are considered in the model as made of nickel-200, the same material as the flexible test pipe, but with a 1-cm-thick wall, because the material properties of thick-walled stainless steel pipes were not measured by SRI. Since elastic-pipe-wall response does not significantly alter the shape or magnitude of traveling pressure pulses, the substitution of the thick-walled stainless steel pipe by a thick-walled nickel-200 pipe is not expected to affect the results in the region of interest, the flexible nickel-200 pipe system, as long as the response of the thick-walled pipe remains elastic in the analysis and in the experiment. The walls of the flexible test pipe are 0.165 cm (0.065 in.). The heavy blind flange at the end of the flexible pipe is further represented by a fixed boundary condition for the pipe walls; i.e., neither translation nor rotation is permitted at the last wall nodal point.

The system is considered full of stagnant water at the moment of application of the input pressure pulse.

Similarly, for the single-elbow loop tests, the ICEPEL model, shown in Fig. 6, consists of three pipes divided into uniform zones of the same size as those of the straight-flexible-pipe test model. The thick-walled elbow is represented by a rigid elbow connecting the two flexible pipes in series.
Fig. 6. ICEPEL Model of Single-elbow Loop Tests
The elbow itself has a radius of curvature of 11.43 cm (4.5 in.) and is divided into four radial zones and five tangential zones. The rigidity of the elbow is represented by fixing the fictitious nodes between the two flexible pipes.

For tests FP-E-102 and -103, the end of the second flexible pipe is modeled as a rigid dead end, allowing neither translation nor rotation at the last wall node. For test FP-E-101, the end of the second flexible pipe is considered open to zero pressure at all times, representing the open-end boundary condition there.

The walls of the thick-walled stainless steel pipe and the flexible nickel-200 pipes are modeled in exactly the same way as in the straight-flexible-pipe test model described above. Again, the system is considered full of stagnant water at the moment of input-pulse application.
V. PIPE-WALL MATERIAL PROPERTIES

Stress-strain properties of nickel-200 were measured by SRI on specimens cut from a scrap section of the nickel-200 pipes. The specimens were flattened, then annealed in exactly the same way as the test pipes.

Stress-strain properties were measured at two strain rates to determine if nickel-200 is strain-rate-dependent. The results are shown in Fig. 7 at two different strain rates. No significant effect was found for a three-order-of-magnitude increase in strain rate. Hence, SRI concluded that nickel-200 is nearly free of strain-rate effects. More tests at higher strain rates would have been more desirable to closely define the material properties at test conditions.

Since the actual strain rate in the pipe tests is about three orders of magnitudes higher than the highest strain rate of the material-property tests, the stress-strain properties at the higher strain rate is considered to approximate those of the test pipes.

In the ICEPEL code, stress-strain relationships are approximated by a piecewise stress-strain curve. Attempts to closely approximate such a behavior with a bilinear relationship usually end with an artificially higher yield stress than the true yield stress of the material in order to approximate the plastic part of the curve. Such an approximation is acceptable if the strains are known to be well in the plastic region.

However, in a piping system, the magnitude of the pressure peaks transmitted beyond the region of plastic wall deformation depends on the yield pressure of the pipe. A higher yield stress for the pipe-wall material permits transmission of higher pressure peaks.

Consequently, the pressure pulses that result from the interaction of the transmitted pressure pulse with piping components or with flow-area changes in the system, as well as the plastic wall deformation resulting from these pulses, are bound to be overestimated as a result of the artificially higher yield stress for the wall material.

This type of result was observed on a preliminary model of the straight-flexible-pipe tests in which a bilinear stress-strain relationship was used. Higher pressure peaks were transmitted beyond the region of plastic wall
deformation. This resulted in higher pressures reflecting from the blind flange and higher strains in the flange vicinity. Reducing the yield stress in a bilinear relationship or using a multilinear stress-strain relationship reduced the transmitted pressure peaks and, hence, reduced the strain at the right end of the pipe. The details of this preliminary study are presented in Appendix B.

Therefore, a four-segment piecewise linear stress-strain relationship is used to approximate the stress-strain properties at the higher strain rate. This relation is shown in Fig. 7 by the circles and is listed in Table II.

### TABLE II. Stress-Strain Values of Nickel-200 Used in ICEPEL Calculations

<table>
<thead>
<tr>
<th>Stress, MPa</th>
<th>Strain, cm/cm</th>
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</thead>
<tbody>
<tr>
<td>76</td>
<td>0.000393</td>
</tr>
<tr>
<td>95</td>
<td>0.00127</td>
</tr>
<tr>
<td>118.6</td>
<td>0.0058</td>
</tr>
<tr>
<td>384</td>
<td>0.1</td>
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</tbody>
</table>

VI. COMPARISON OF ANALYTICAL AND EXPERIMENTAL RESULTS

**A. Straight-flexible-pipe Tests**

Most of the figures of this section comparing the analytical and experimental results consist of two parts: part (a) for test FP-SP-101, and part (b) for test FP-SP-102. The solid line represents the experimental results and the dashed line the analytical results from ICEPEL.

Figure 8 shows the input pressure pulses for the ICEPEL model as recorded by gauge P1 for both tests. The input pressure pulse for test FP-SP-101 is seen to have a lesser magnitude and smaller duration than that of test FP-SP-102, even though the same calibrated charge of 3.65 g was used in both tests, as well as in all the pulse-gun calibration tests, where it consistently produced a pressure peak of about 15.8 MPa (2300 psi) at gauge P1.

Figures 9 and 10 compare the experimental and calculated pressure histories at locations P2 and P3, respectively, of the thick-walled pipe. As can be seen, there is good agreement in the pulse shape and arrival time. However, the calculated peak pressure at the two locations are shown to be less than the experimental ones, particularly at location P3 of test FP-SP-102.
This is to be expected because of the inherent feature of the implicit finite-difference methods in smearing off sharp pressure peaks such as those at P2 and P3. Decreasing the hydrodynamic time step in the calculations results in better resolution of sharp pressure peaks. Another reason for this difference is the high experimental pressure peak at location P3 which is even higher than the pressure peaks at location P1 and P2 upstream from P3. However, because of the consistently higher peak pressure obtained at P1 in all the pulse-calibration tests, one can argue that the pressures at locations P1 and P2 may have been low.

Fig. 8
Input Pressure Pulses for Tests FP-SP-101 and -102

Fig. 9. Comparison of Analytical and Experimental Pressure Histories at Location P2 in Thick-walled Pipe. (a) Test FP-SP-101; and (b) Test FP-SP-102.
The figures also indicate the occurrence of cavitation at location P2, a result of the right-to-left rarefaction wave reflecting from the flexible pipe. Cavitation is indicated in the calculation by the zero cutoff pressure; i.e., pressures in the calculation are not allowed to go below zero. In the experiment, cavitation is indicated also by the zero record of the pressure gauge. The calculation also shows the last peak as the reflected pressure pulse from the blind flange at the end of the flexible pipe. The experimental records were cut off before the arrival of the reflected pulse.

Figures 11 and 12 compare the calculated and measured pressure histories at locations P4 and P5. The plastic wall deformation at the beginning of the flexible pipe is shown to attenuate the pressure peaks rapidly to about 6 MPa at location P4, 3.81 cm from the flange, and further to about 5 MPa at P5, 15.24 cm from the flange. The pulse shape is also wider than the applied pulse, indicating the dispersion of the pressure pulse caused by the plastic wall deformation.

Again, excellent agreement is indicated between the calculations and the measurements insofar as the incident pulse is concerned. The reflected pulse from the blind flange, however, is consistently higher in the calculation than in the experiments. The reason for this is the modeling of the blind flange as an absolute rigid dead end in the analysis. Thus, the analysis is more conservative than the experiment in the sense that the analysis does not allow any motion of the pipe. Experimentally, although the flanges were limited in their motion by the heavy brackets, which were anchored to the ground, still some of the incident pulse energy was consumed in the axial motion of the pipe as the pulse hit the flange.
Fig. 11. Comparison of Analytical and Experimental Pressure Histories at Location P4 of Flexible Pipe. (a) Test FP-SP-101; and (b) Test FP-SP-102.

Fig. 12. Comparison of Analytical and Experimental Pressure Histories at Location P5 of Flexible Pipe. (a) Test FP-SP-101; and (b) Test FP-SP-102.

Figures 13-16 compare the calculated and measured pressure histories at locations P6-P9 in the middle section of the flexible pipe. The plastic wall deformation of the pipe is shown to further attenuate the incident pressure pulse peaks until this pulse reaches a level slightly higher than the yield pressure of
the pipe (about 3.5 MPa). Thus, the transmitted pressure peak's beyond the
region of plastic wall deformation is about 4 MPa and is in good agreement with
the experimental measurements at gauge P8.

Fig. 13. Comparison of Analytical and Experimental Pressure Histories at Location P6
of Flexible Pipe. (a) Test FP-SP-101; and (b) Test FP-SP-102.

Fig. 14. Comparison of Analytical and Experimental Pressure Histories at Location P7
of Flexible Pipe. (a) Test FP-SP-101; and (b) Test FP-SP-102.
Fig. 15. Comparison of Analytical and Experimental Pressure Histories at Location P8 of Flexible Pipe. (a) Test FP-SP-101; and (b) Test FP-SP-102.

Fig. 16. Comparison of Analytical and Experimental Pressure Histories at Location P9 of Flexible Pipe. (a) Test FP-SP-101; and (b) Test FP-SP-102.

As expected from the discussions of the experimental results, the calculated pressures are higher than the measured ones at gauges P7 and P9 of Figs. 14 and 16, respectively. The reason for this is that both gauges are believed to be in error when recording lower pressures.

Again, the reflected pressure pulse is consistently higher in the calculation than in the experiment. At gauge P9, the calculation briefly shows
the incident pressure pulse indicated by the first plateau in Fig. 16, before
the arrival of the reflected pressure pulse from the blind flange.

In the vicinity of the blind flange, Figs. 17 and 18 compare the calculated
and measured pressure histories at gauges P10 and P11, respectively. Except
for the calculated pressures being slightly higher than the measured ones be-
cause of the conservative modeling of the blind flange in the analysis, the
agreement in pulse shape and arrival time is very good.

Fig. 17. Comparison of Analytical and Experimental Pressure Histories at Location P10
of Flexible Pipe. (a) Test FP-SP-101; and (b) Test FP-SP-102.

Fig. 18. Comparison of Analytical and Experimental Pressure Histories at Location P11
at Blind Flange. (a) Test FP-SP-101; and (b) Test FP-SP-102.
Figures 19 and 20 compare the calculated and measured circumferential strain histories at the four axial locations of the flexible test pipe. As can be seen in Fig. 19, the analytical strains at the first axial strain location, gauges SG₁-SG₅ (3.81 cm from the flange with the thick-walled pipe), match the lower bound of the experimental strain scatter for test FP-SP-102. But the analytical strains are lower than the experimental strain scatter for
test FP-SP-101. At the second axial strain location, gauges SG\textsubscript{6}-SG\textsubscript{10} (15.24 cm from the flange with the thick-walled pipe), the analytical strains fall within the experimental strain scatter but close to the lower bound, as can be seen in Fig. 20. The reason for this is believed to be the relatively low pressure peak recorded at gauge P1, which is used as an input to the analytical model. Both the shape and arrival time are in good agreement.

At the other end of the pipe, near the blind flange, Figs. 21 and 22 show the analytical strains to fall within the experimental strain scatter, but on the contrary, closer to the upper bound. This is to be expected as a consequence of the conservative modeling of the blind flange in the analysis,
resulting in higher reflected pressure pulses, which in turn led to higher strains in this vicinity. The plastic strain at this end of the pipe is caused by the reflected pulse, not the incident one.

All the comparisons of test FP-SP-101 are similar to those of test FP-SP-102, except for the analytical strains for test FP-SP-101 being lower than the experimental strains only at the first axial strain location. The reason for this is believed to be the relatively lower and narrower pressure peak at gauge P1 (shown in Fig. 8). Therefore the effect of increasing the peak input pressure on the ICEPEL calculation is examined by only increasing the peak portion of the pulse at P1 by 25%. The results of the comparison of this run with the experimental results of test FP-SP-101 are shown by the chain-dashed line of part (a) of Figs. 9-22.

Inside the thick-walled pipe, at locations P2 and P3 of Figs. 9 and 10, better agreement with the experimental measurements was obtained. However, the calculated peaks remained below the experimental ones. Also, the effect of the rarefaction wave reflecting from the flexible pipe on the pressure history at location P3 was in better agreement with the experiment.

Insignificant effects were obtained on the analytical pressure histories inside the flexible pipe. Also, the reflected pressure pulse from the blind flange was unaffected, indicating the dependence of the transmitted pressure peaks beyond the region of plastic wall deformation on the yield pressure of the pipe.

The analytical strains were raised by about 45% at the first axial location, 3.81 cm into the flexible pipe, thus falling within the experimental data as shown by the chain-dashed line of Fig. 23. At the other axial locations, the strains were slightly higher, but remained within the experimental scatter, as can be seen in Figs. 19-22.

**B. Single-elbow Loop Tests**

The two plastic single-elbow loop tests, FP-E-101 and -103, are analyzed by the ICEPEL code and the results are compared with the experimental results. Part (a) of each comparison figures is for test FP-E-101, in which the end of the second flexible pipe was a simple open end. Part (b) is for test FP-E-103, in which the second flexible pipe ended with a blind flange.

Figure 23 shows the input pulses for the analytical models of the two tests, as recorded experimentally by gauge P1. The pulse for test FP-E-101 is much weaker than
that of test FP-E-103, even though the same explosive charge of 3.65 g was used in both tests. The same charge consistently produced pressure peaks of the order of 15.8 MPa at location P1 in all the pulse-gun calibration tests.

Figures 24 and 25 compare the analytical and experimental pressure histories at locations P2 and P3 inside the thick-walled pipe. Similar to the straight-flexible-pipe tests, very good agreement is shown with respect to the pulse shape, pulse arrival time, and prediction of cavitation at location P2. Also, the analytical pressure peaks are less than the experimental ones, particularly at location P3. However, the pressure peak at location P3 is higher than that at P1 and P2 upstream from P3 for the same reasons discussed in the straight-flexible-pipe tests.

In test FP-E-103, the reflected pressure pulse from the blind flange at the end of the second flexible pipe is shown by the analysis. No experimental records were obtained at P2 and P3 beyond 3 ms. Also, the analytical results demonstrate the smearing off of the sharp pressure peaks by the implicit finite-difference methods.

Figures 26 and 27 compare the analytical and experimental pressure histories at locations P4 and P5 at the beginning of the first flexible pipe. Plastic pipe wall deformation is shown to reduce the pressure peak rapidly to about half its value at P3 in only 3.81 cm (1.5 in.) and to further reduce the pressure peak at location P5. The analytical pressures are slightly higher than the experimental pressures at gauge P4, especially for the tail part of the incident pulse. The noise in the experimental data at gauge P4 may be attributed to the proximity of the gauge to the heavy flange with thick-walled pipe. At location P5, however, the agreement between the experiment and analysis is better.
Fig. 25. Comparison of Analytical and Experimental Pressure Histories at Location P3 of Thick-walled Pipe of Single-elbow Loop Tests. (a) Test FP-E-101; and (b) Test FP-E-103.

Fig. 26. Comparison of Analytical and Experimental Pressure Histories at Location P4 of First Flexible Pipe of Single-elbow Loop Tests. (a) Test FP-E-101; and (b) Test FP-E-103.
Again, for test FP-E-103, the reflected pressure pulse from the blind flange at the end of the second flexible pipe is slightly higher in the analysis than in the experiment because of the conservative modeling of the blind flange in the analysis.

Figures 28-30 compare the analytical and experimental pressure histories at locations P6, P7, and P8-P10 of the first flexible pipe. Plastic wall deformation has reduced the pressure peaks to a value of about 4 MPa, which is slightly higher than the yield pressure of the pipe (3.5 MPa). Good agreement of all aspects of the pressure pulse is shown.
As expected, at gauge P6, the analytical pressures are slightly higher than the experimental pressures because P6 is believed to have been recording lower pressures when comparing its records with the yield pressure of the pipe and with the pressure peaks at locations P7 and P8-P10 downstream from it.
Figure 30 indicates that the experimental records of gauges P8-P10 showed no variation of pressure around the circumference of the pipe. This confirms the axisymmetry of the flow in the pipe upstream from the elbow, an assumption used in the ICEPEL hydrodynamic coupling of the pipe and elbow models.

Figures 31 and 32 compare the analytical and experimental pressure histories downstream from the elbow, at gauges P14-P16 and P17-P18. Again, the experimental records there affirm the axisymmetry of the flow in the pipe downstream from the elbow, showing no effect of the elbow. At both locations, the analysis has consistently overestimated the pressures. The reason is that experimentally the elbow attenuated the pressure peaks by as much as 18%, while the analysis did not show that much attenuation.

In fact, in test FP-E-103, the analysis showed no drop in peak pressures in its absolute sense. However, a careful investigation of the analytical pressure histories before and after the elbow reveals some kind of loss inside the elbow. Figure 30b shows that the pressure histories before the elbow have an almost flat pressure peak of about 4 MPa that lasted for about 0.75 ms. Figure 31b shows that the pressure history after the elbow rose at the same rate as that at locations P8-P10, before the elbow, until a pressure of about 3.5 MPa was reached; then the pressure continued to increase but at a reduced rate until it reached a peak of 4 MPa, which lasted only for a brief time compared with the peak time before the elbow.

In test FP-E-101, the comparison between the analytical pressure histories before and after the elbow shows a drop in the peak pressure from 4 to 3.75 MPa, a loss of about 6.75% compared to an 18% drop experimentally.

![Fig. 31. Comparison of Analytical and Experimental Pressure Histories at Locations P14-P18 of Second Flexible Pipe of Single-elbow Loop Tests. (a) Test FP-E-101; and (b) Test FP-E-103.](image-url)
However, the experimental records of Figs. 31 and 32 show higher peaks at locations P17 and P18 further away from the elbow, even though the pipe end was open in this test. The experimental drop is only 10.8% if pressure peaks before the elbow are compared with those at locations P17 and P18.

As far as the pressure-peak attenuation along the elbow is concerned, the difference in the analytical results of tests FP-E-101 and -103 can only be attributed to the different boundary conditions of the second flexible pipe, being open in FP-E-101 and closed in FP-E-103.

Another source of the experimental pressure-peak attenuation along the elbow is the geometry of the elbow, which had a slight ovality in section. Also, the elbow had a nominal inside diameter of 7.06 cm and was connected to shore transition pieces that increased the diameter to 7.24 cm, which is less than the inside diameter (7.29 cm) of the connected pipes. This geometry cannot be included in the analytical model.

In the elastic test FP-E-102, all records in the second pipe were lost. Thus, no conclusion could be made about pressure-peak attenuation along the elbow in elastic systems.

Inside the elbow, the analysis showed that the pressures near the outer walls of the elbow are higher than the pressures near the inner walls, whereas the experimental data of tests FP-E-101 and -103 showed no special trend; i.e., there was no significant difference in the pressure inside the elbow. Only in the elastic test FP-E-102, the experimental data showed higher pressures near the outer walls of the elbow than those near the inner walls, agreeing with the analysis. But all pressure records downstream from the elbow were lost in this test.
Figures 33 and 34 compare the analytical and experimental strain histories at the beginning of the first flexible pipe, locations \( SG_1 - SG_5 \) and \( SG_6 - SG_{10} \). For test FP-E-103, the analytical strains are within the rather wide scatter of the experimental strains. For test FP-E-101, the analytical strains at these two locations are well below the experimental strain scatter. The reason is believed to be the rather weak input pulse shown in Fig. 23.

Fig. 33. Comparison of Analytical and Experimental Strain Histories at Location \( SG_1 - SG_5 \) of First Flexible Pipe of Single-elbow Loop Tests. (a) Test FP-E-101; and (b) Test FP-E-103.

Fig. 34. Comparison of Analytical and Experimental Strain Histories at Location \( SG_6 - SG_{10} \) of First Flexible Pipe of Single-elbow Loop Tests. (a) Test FP-E-101; and (b) Test FP-E-103.
Figures 35 and 36 compare the analytical and experimental strains at the other end of the pipe, near the elbow. The analytical strains fall within the range of experimental strains. The negative strain before the arrival of the pulse is a result of the precursor effects because the wave speed in the pipe wall is faster than in the fluid.

![Fig. 35. Comparison of Analytical and Experimental Strain Histories at Location SG11-SG15 of First Flexible Pipe of Single-elbow Loop Tests. (a) Test FP-E-101; and (b) Test FP-E-103.](image1)

![Fig. 36. Comparison of Analytical and Experimental Strain Histories at Location SG18-SG20 of First Flexible Pipe of Single-elbow Loop Tests. (a) Test FP-E-101; and (b) Test FP-E-103.](image2)
Careful examination of the analytical strains at this end of the pipe reveals more strains closer to the elbow than farther away from it. This may indicate a pressure pulse reflecting from the rigid elbow back to the pipe. Or it may indicate that the fixing of the pipe ends at their junctions with the elbow led to bulging of the pipe wall in this vicinity, a phenomena observed in a statically pressurized cylinder with fixed ends. Because of the scatter in the experimental strain data, such a phenomenon cannot be ascertained experimentally. This shows the importance of pretest analysis in locating the instrumentations in the experiment.

Similar to the straight-flexible-pipe tests, to investigate the effect of increasing the peak pressure of the input pulse on the ICEPEL predictions, only the peak portion of the input pulse of test FP-E-101 was increased by 25%. The results of this run are shown by the chain-dashed lines of part (a) of Figs 24-36.

Similar results are obtained here, briefly, higher pressure peaks inside the thick-walled pipe, better agreement with experiment on the effect of the rarefaction wave reflecting back from the first flexible pipe on the pressure history at location P3, and insignificant effects on the pressure histories inside the flexible pipes. The strains at the beginning of the first flexible pipe are increased and now fall within the experimental strains, as seen in Figs. 33a and 34a. Also, very insignificant changes in strains were predicted near the elbow.
VII. MODIFICATION OF ICEPEL ELBOW MODEL

The comparison of the analytical and experimental results for the single-elbow loop tests has indicated a discrepancy insofar as the radial pressure distribution inside the elbow is concerned. The experiments showed no significant radial pressure variation inside the elbow; the analysis showed pressures near the outer walls of the elbow to be higher than those near the inner walls. The reason for the radial pressure difference is believed to be the centrifugal-forces effects.

As a consequence, the elbow model is being reinvestigated to resolve the discrepancy and to demonstrate whether or not a radial pressure variation of this magnitude is artificially introduced by the assumptions and approximations made in developing the model. Hence, it was decided to try a simple elbow model that considers a two-dimensional \((r \text{ and } \theta)\) configuration in which the circular cross section of the elbow is replaced by a stack of equivalent strips each of a rectangular cross section as shown in Fig. 37. The width of each rectangular strip is obtained from the area of the corresponding circular strip.

The flow inside each rectangular strip can be described by the standard continuity and Navier-Stokes equations in cylindrical coordinates.

The equations in conservative form, and neglecting gravity forces similar to those used in the ICE technique,\(^2,8\) are as follows:

**Conservation of Mass**

\[
\frac{\partial \rho}{\partial t} + \frac{1}{r} \frac{\partial (r \rho u)}{\partial r} + \frac{1}{r} \frac{\partial (\rho v)}{\partial \theta} = 0. \tag{1}
\]

**Conservation of Momentum**

**Radial Momentum Equation**

\[
\frac{\partial (\rho u)}{\partial t} + \frac{1}{r} \frac{\partial (r^2 \rho u)}{\partial r} + \frac{1}{r} \frac{\partial (\rho uv)}{\partial \theta} - \frac{\rho v^2}{r} = \frac{\partial (P + q)}{\partial r} + \frac{\mu}{r} \frac{\partial}{\partial \theta} \left[ \frac{\partial u}{\partial \theta} - \frac{\partial (rv)}{\partial r} \right]. \tag{2}
\]
Tangential Momentum Equation

$$\frac{\partial(pv)}{\partial t} + \frac{1}{r} \frac{\partial(puv)}{\partial r} + \frac{1}{r} \frac{\partial(pv^2)}{\partial \theta} + \frac{puv}{r} = \frac{1}{r} \frac{\partial(P + q)}{\partial \theta} + \mu \frac{\partial}{\partial r} \left[ \frac{1}{r} \frac{\partial(rv)}{\partial r} - \frac{\partial u}{\partial \theta} \right].$$ (3)

In Eqs. 2 and 3,

$$q = -(\lambda + 2\mu) \left( \frac{1}{r} \frac{\partial u}{\partial r} + \frac{1}{r} \frac{\partial v}{\partial \theta} \right).$$ (4)

In the above equations, $\rho$ is the mass density, $u$ and $v$ are the radial and tangential velocity components, respectively, $P$ is the pressure, $\lambda$ and $\mu$ are the first and second coefficients of viscosity of the fluid, respectively, $t$ is the time, and $r$ and $\theta$ are the radial and tangential coordinates, respectively.

Following the ICE finite-difference scheme, which assigns the density and pressure to the center of the zones and the velocity components to the center of the zone boundaries normal to their directions, the difference forms of Eqs. 2 and 3, the radial and tangential momentum equations, are

$$\frac{(\rho u)_{i+1/2,j}^{n+1} - (\rho u)_{i+1/2,j}^{n}}{\Delta t} = \frac{\varphi}{\Delta r} \left( p_{i+1,j}^{n+1} - p_{i+1,j}^{n} \right) + \frac{1 - \varphi}{\Delta r} \left( p_{i,j+1}^{n+1} - p_{i,j+1}^{n} \right)$$

$$+ CR_{i+1/2,j}^{n+1}$$

(5)

and

$$\frac{(\rho v)_{i,j+1/2}^{n+1} - (\rho v)_{i,j+1/2}^{n}}{\Delta t} = \frac{\varphi}{r_1 \Delta \theta} \left( P_{i,j+1}^{n+1} - P_{i,j+1}^{n} \right) + \frac{1 - \varphi}{r_1 \Delta \theta} \left( P_{i,j}^{n+1} - P_{i,j}^{n} \right)$$

$$+ CS_{i,j+1/2}^{n+1}$$

(6)

where

$$CR_{i+1/2,j}^{n+1} = \frac{u_{i+1/2,j}}{r_{i+1/2,j}} \left[ r_{i+1,j}^{n+1} - r_{i+1,j}^{n} \right] + \frac{1}{r_{i+1/2,j} \Delta \theta} \left[ (\rho uv)_{i+1/2,j+1/2}^{n+1} - (\rho uv)_{i+1/2,j+1/2}^{n} \right]$$

$$+ \frac{1}{r_{i+1/2,j} \Delta \theta} \left[ (\rho v^2)_{i+1/2,j+1/2}^{n+1} - (\rho v^2)_{i+1/2,j+1/2}^{n} \right] + \frac{1}{\Delta r} \left( q_{i,j} - q_{i+1,j} \right)$$

(Contd.)
\[
+ \frac{\mu}{r_i^{(1/2)} \Delta \theta} \left\{ \frac{u_i^{+ (1/2), j+1} - 2u_i^{+ (1/2), j} + u_i^{+ (1/2), j-1}}{\Delta \theta} \right\} \ (\text{Contd.}) \tag{7}
\]

\[
+ \frac{r_i}{\Delta r} \left[ v_{i, j^{(1/2)}} - v_{i, j^{(-1/2)}} \right] - \frac{r_{i+1}}{\Delta r} \left[ v_{i+1, j^{+(1/2)}} - v_{i+1, j^{-(1/2)}} \right]
\]

and

\[
CS_{i, j^{+(1/2)}} = \frac{1}{r_i \Delta r} \left[ r_{i^{-(1/2)}} (\rho uv)_{i^{-(1/2)}, j^{+(1/2)}} - r_{i^{+(1/2)}} (\rho uv)_{i^{+(1/2)}, j^{+(1/2)}} \right]
\]

\[
+ \frac{v_{i, j^{+(1/2)}}}{r_i \Delta \theta} \left[ \rho_{i, j^{+(1/2)}} - \rho_{i, j^{+(1/2)}} \right] - \frac{(\rho uv)_{i, j^{+(1/2)}}}{r_i}
\]

\[
+ \frac{1}{r_i \Delta \theta} (q_{i, j} - q_{i, j+1})
\]

\[
+ \frac{\mu}{\Delta r^2} \left[ \frac{v_{i+1, j^{+(1/2)}} - v_{i, j^{+(1/2)}}}{r_i^{+(1/2)}} + \frac{v_{i, j^{+(1/2)}} - v_{i-1, j^{+(1/2)}}}{r_i^{-(1/2)}} \right]
\]

\[
+ \frac{\mu}{\Delta r \Delta \theta^2} \left[ \frac{u_{i+1, j^{+(1/2)}} - u_{i, j^{+(1/2)}}}{r_i^{+(1/2)}} + \frac{u_{i, j^{+(1/2)}} - u_{i, j^{-(1/2)}}}{r_i^{-(1/2)}} \right]. \tag{8}
\]

In the above equations, i and j are subscripts counting zones in the radial and tangential directions, respectively, n is a superscript counting time cycles, and \( \varphi \) is a time-centering coefficient for the equations of momentum, taking the value between 0 (explicit) and 1 (implicit).

The equation of state in the ICE technique is

\[
P_{i+1,j}^n = P_{i,j}^n + C_{i,j}^n \left( \rho_{i+1,j}^n - \rho_{i,j} \right). \tag{9}
\]

The use of Eqs. 5, 6, and 9 into the difference form of the mass equation results in

\[
P_{i+1,j}^n \left[ \frac{1}{C_{i,j}^n} + 2\varphi \beta \Delta t^2 \left( \frac{1}{\Delta r^2} + \frac{1}{r_i^2 \Delta \theta^2} \right) \right] = C_{i,j}^n
\]

\[
+ \varphi \beta \Delta t^2 \left[ \frac{r_{i+1, j} P_{i+1, j}^n + r_{i-1, j} P_{i-1, j}^n}{r_i \Delta r^2} + \frac{P_{i+1, j}^n + P_{i, j}^n}{r_i^2 \Delta \theta^2} \right]. \tag{10}
\]
where

\[
CG_{i, j} = \frac{P_{i, j}^n}{C_{i, j}^n} + \frac{\beta(1 - \varphi) r_{i+(1/2)} \Delta t^2}{\Delta r^2 r_i} (P_{i+1, j}^n - P_{i, j}^n) \\
- \frac{\beta(1 - \varphi) r_{i-(1/2)} \Delta t^2}{r_i \Delta t^2} (P_{i, j}^n - P_{i-1, j}^n) \\
+ \frac{\beta \Delta t^2}{r_i \Delta r} \left[ r_{i-(1/2)} C R_{i-(1/2)}, j - r_{i+(1/2)} C R_{i+(1/2)}, j \right] \\
+ \frac{\Delta t}{r_i \Delta r} \left[ r_{i-(1/2)} (\rho u)_{i-(1/2)}, j - r_{i+(1/2)} (\rho u)_{i+(1/2)}, j \right] \\
+ \frac{\beta(1 - \varphi) \Delta t^2}{r_i^2 \Delta \theta^2} (P_{i, j+1}^n - P_{i, j}^n) - \frac{\beta(1 - \varphi) \Delta t^2}{r_i^2 \Delta \theta^2} (P_{i, j}^n - P_{i, j-1}^n) \\
+ \frac{\beta \Delta t^2}{r_i \Delta \theta} \left[ C S_{i, j-(1/2)} - C S_{i, j+(1/2)} \right] \\
+ \frac{\Delta t}{r_i \Delta \theta} \left[ (\rho v)_{i, j-(1/2)} - (\rho v)_{i, j+(1/2)} \right].
\] (11)

Equation 10 is a five-point Poisson's equation with only the pressure as an unknown. An iterative solution of Eq. 10 results in the new pressures, which when substituted in Eqs. 9, 5, and 6 result in the new densities and velocities.

The hydrodynamic coupling between the elbow model and the axisymmetric pipe model is achieved by supplying the elbow and the pipe with fictitious zones to represent, respectively, the pipe and the elbow. Since the experimental results confirmed the axisymmetry of the flow in the pipes in the neighborhood of the elbow, the pressures in the fictitious zones of the elbow are simply considered to be one pressure to be obtained from the connected pipe. Such pressure is considered to be an average pressure at a pipe section coincident with the center of the elbow fictitious zones and the midplane of the elbow. Axial linear interpolation between two average pressures in the pipe is performed whenever the center of elbow fictitious zones at the midplane of the elbow does not coincide with the center of a pipe zone where the pressures are defined in the ICE technique.

The coupling problem now reduces to finding a pressure in the fictitious zones of the pipe from the elbow. This is obtained in such a way that guarantees the continuity of the mass flow rate between the pipe and the elbow. In other words, the mass flow rate that leaves the pipe should enter the elbow, and vice versa.
Figure 38 shows the junction between a pipe $k$ and an elbow $m$ in a pipe system. Let $\text{JJUN}(k)$ refer to the $j$th index of the zones inside pipe $k$ and next to the elbow junction, and $\text{KJUN}(k)$ refer to the $j$th index of the pipe junction with the elbow. Similarly, let $\text{JJUN}(m)$ refer to the $j$th index of the zones inside elbow $m$ and next to its junction with pipe $k$, and $\text{KJUN}(m)$ refer to the $j$th index of the elbow junction with the pipe. $P_e$ is the pressure in the fictitious zones of the elbow as obtained from the pressures inside the pipe $k$. $P_p$ is the pressure in the fictitious zones of the pipe, which is to be determined by satisfying the mass flow continuity between the pipe and the elbow.

The mass flow rate into the elbow can be expressed as

$$\text{mass}_e = \sum_{i=1}^{IE} A_{e_i} (\rho_e v_e)^{n+1} \left( \text{JJUN}(m), \text{KJUN}(m) \right)$$  \hspace{1cm} (12)

where $A_{e_i}$ is the area of the $i$th strip of the elbow cross section, and $IE$ is the number of radial zones in the elbow.

Using the $\theta$-momentum equation (Eq. 6) in the above equation yields

$$\text{mass}_e = \sum_{i=1}^{IE} \left[ A_{e_i} \left( \rho_e v_e \right)_{i, \text{KJUN}(m)} + \frac{\varphi}{r_i \delta \theta} \left( P_e^{n+1} - P_{e_i}^{n+1} \right) \right]$$

$$+ \frac{1 - \varphi}{r_i \delta \theta} \left[ P^n_e - P^n_e_{i, \text{KJUN}(m)} + CS_i, \text{KJUN}(m) \right] \right].$$ \hspace{1cm} (13)

The mass flow rate leaving pipe $k$ can be expressed as

$$\text{mass}_p = \sum_{i=1}^{IP} A_{p_i} (\rho_p v_p)^{n+1} \left( \text{JJUN}(k) \right) \right] \right].$$ \hspace{1cm} (14)

where $A_{p_i}$ is the area of the $i$th ring in the pipe cross section and $IP$ is the number of axisymmetric zones in the pipe cross section.
Using the z-momentum equation for the axisymmetric pipe model in Eq. 14 results in

\[
\text{mass}_p = \sum_{i=1}^{IP} \left[ A_{p_i} \left( \rho_{p_i} v_{p_i} \right)^n_{i, KJUN(k)} + \delta t \left\{ \frac{\varphi}{\Delta Z_k} \left[ P_{P_i, KJUN(k)}^n - P_{P_i}^n \right] + \frac{1}{\Delta Z_k} \left[ P_{P_i, JUN(k)}^n - P_{P_i}^n \right] + S_{i, KJUN(k)} \right\} \right].
\]

Equating Eqs. 13 and 15 and solving for \( P_{P_i}^{n+1} \) results in

\[
P_{P_i}^{n+1} = \frac{\Delta Z_k}{\delta t \varphi A_{P_i}} \left( \sum_{i=1}^{IP} M_{p_i} - \sum_{i=1}^{IE} M_{e_i} \right),
\]

where \( A_p \) is the cross-sectional area of the pipe,

\[
M_{p_i} = A_{p_i} \left( \rho_{p_i} v_{p_i} \right)^n_{i, KJUN(k)} + \delta t \left\{ \frac{\varphi}{\Delta Z_k} \left[ P_{P_i, KJUN(k)}^n - P_{P_i}^n \right] + \frac{1}{\Delta Z_k} \left[ P_{P_i, JUN(k)}^n - P_{P_i}^n \right] + S_{i, KJUN(k)} \right\},
\]

and

\[
M_{e_i} = A_{e_i} \left( \rho_{e_i} v_{e_i} \right)^n_{i, KJUN(m)} + \delta t \left\{ \frac{\varphi}{r_i \delta \theta} \left[ P_{e_i, KJUN(m)}^n - P_{e_i}^n \right] + \frac{1}{r_i \delta \theta} \left[ P_{e_i, JUN(m)}^n - P_{e_i}^n \right] + C_{S_i, KJUN(m)} \right\}.
\]

For \( \varphi = 0 \), the explicit scheme, the pressure in the fictitious zones of the pipe is

\[
P_{P_i}^{n+1} = \frac{\Delta Z_k}{\delta t A_{P_i}} \left( \sum_{i=1}^{IP} M_{p_i} - \sum_{i=1}^{IE} M_{e_i} \right),
\]

where

\[
M_{p_i} = A_{p_i} \left( \rho_{p_i} v_{p_i} \right)^n_{i, KJUN(k)} + \delta t \left\{ \frac{1}{\Delta Z_k} P_{P_i, KJUN(k)}^n + S_{i, KJUN(k)} \right\}.
\]
and

\[ \text{Ms} = A_{e_i} \left( \rho e v_i, KJUN(m) + \delta t \left\{ \frac{1}{r_i} \phi \left[ P^0 - P^e, KJUN(m) \right] + C_{Si}, KJUN(m) \right\} \right). \]  

(21)

Equations 13 and 15 are written with respect to the junction local coordinates which assume the positive direction of the flow to be from the pipe to the elbow. Hence for the other junction, where the flow goes from the elbow to the pipe, the signs of \( v_{Pi}, KJUN(k) \), \( S_i, KJUN(k) \), \( v_{ei}, KJUN(m) \), and \( C_{Si}, KJUN(m) \) should be reversed.

Equations 16 and 19 indicate that the pressure in the fictitious zones of the pipe can be obtained explicitly from the values of the field variable inside the pipe and the elbow. This is done in each iteration with the new pressure calculation.

This modified elbow model has been incorporated in a modified version of ICEPEL, which was then used to analyze test FP-E-103 for a single-elbow loop. The same 1-in. zone model was used to analyze the test.

The results of the new analysis showed insignificant quantitative changes in the pressure and strain histories inside the two pipes connected to the elbow. Consequently, the comparison between the analytical and experimental results of pressures and strains in the straight pipes is practically the same as in the earlier analysis.

However, inside the elbow, the new model showed no radial variation in the pressure. This agrees with the experimental results, as can be seen in Fig. 39, which compares the analytical results of the pressure history and the experimental results of gauges P11, P12, and P13 at the midsection of the elbow. The results of the new model also showed a radial variation in the tangential velocity inside the elbow, being higher near the inner walls of the elbow than near the outer walls. This tangential velocity distribution is similar to that of a free vortex in which \( v_r \) is approximately equal to a constant.

Thus, the new elbow model, which uses the standard governing equations in cylindrical coordinates, shows that, in an elbow connecting two pipes, in which the flow axisymmetry is maintained, radial pressure variation due to centrifugal forces is not dominant during the short time of the fluid transient.
VIII. CONCLUSIONS AND RECOMMENDATIONS

The physical phenomenon of pressure-pulse propagation along pipes is well understood. Plastic pipe wall deformation attenuates pressure peaks until only peaks of slightly higher magnitudes than the yield pressure of the pipe are transmitted beyond the region of plastic wall deformation. However, the subsequent interaction of the transmitted pulse with the different piping components and with other pulses in the system can produce pressure pulses of higher magnitudes that cause plastic wall deformation to occur anywhere in the pipe system. Cavitation is also a possible result of the interaction between the different pulses in the pipe system.

The sensitivity of the calculated results to the material-properties representation was demonstrated in the dependence of the transmitted pressure peaks beyond the region of plastic wall deformation on the yield pressure of the pipe. Higher yield stress results in higher transmitted pressure peaks. The subsequent interaction of these transmitted pressures is thus bound to be overestimated.

Through the ICEPEL analysis of the five piping tests, it can be concluded that, considering the accuracy of the experimental measurements, the ICEPEL calculations have agreed generally well with the experimental measurements of pressures and strains. Of particular importance here is the accuracy of the pressure records at P1 which were used as an input to the analytical models. The pressure records at P2 are not recommended for use as an input source to the analytical models because of the proximity of P2 to the junction with the flexible test pipe. The pressure record there involved both the incident pulse and its interaction with the reflected pulses from the flexible pipe. It is to be recommended in this respect that for future experiments, records to be used as input to the analytical model should be measured by at least two different gauges.

The modified ICEPEL elbow model, which used the standard Navier-Stokes equations in r and θ coordinates, has shown no radial pressure distribution inside the elbow, in agreement with the experimental results. This indicates that the centrifugal-forces effects are not dominant within the short transients of the tests. It also indicates that the assumptions and simplifications in the original ICEPEL elbow model have artificially introduced the radial pressure distribution inside the elbow. Both models have shown, however, that the flow inside the elbow is localized and has no noticeable effect on the results in the rest of the piping system.

One discrepancy that remains to be resolved is the attenuation of the pressure-pulse peaks as the pulses propagate along the elbow. The experimental results showed much more attenuation than the analysis. The geometry of the elbow and the short transition pieces at the ends of the elbow may have contributed to the bigger attenuation in the experiments. For this, a precision elbow test is recommended.
The analysis has shown some indications of pressure pulses reflecting from the rigid elbow back to the first flexible pipe. Experimentally, because of insufficient dynamic strain measurement close to the elbow, such a conclusion cannot be made. This indicates the importance of pretest analysis in locating the instrumentation.

The variation of strain measurements around the circumference of the pipe cannot be totally due to the nonuniformity of the pipe-wall thickness around the circumference. Because of imperfections in the commercial off-the-shelf pipe used and because of the existence of the elbow, bending of the pipes cannot be ruled out. Thus, it is important to include the flexural stresses in the structural analysis of piping systems. Also, the preexisting stresses due to normal operation pressurization, creep, and thermal phenomena need to be included in the analysis so that the integrity of reactor piping systems can be ensured.
APPENDIX A

Effect of Pipe-wall Thickness on Circumferential Strains

The experimental strain measurements at one axial location of a pipe showed a wide scatter around the circumference of the pipe. The scatter was attributed to the variation of pipe-wall thickness around the circumference. The wall thickness was measured before and after the tests at the strain-gauge locations and varied within ±5%. However, the scatter in the strain measurements was nowhere close to that. In some instances, a whole order-of-magnitude difference between the largest and smallest strains was recorded.

An analytical investigation on the effect of pipe-wall-thickness variation on the calculated strains is reported here. The ICEPEL code, however, cannot handle thickness variations around the pipe circumference since it uses an axisymmetric thin-shell model of the pipe walls.

Therefore, the code can only be run twice, once using the smallest measured thickness of the pipe walls (0.1575 cm, 0.062 in.) as a uniform thickness of the flexible pipe of test FP-SP-102 (as an example), and once using the largest measured thickness (0.1727 cm, 0.068 in.). The calculated strains for both cases are then compared. The layout and the ICEPEL model of test FP-SP-102 were described earlier.

Figure A.1 compares the calculated strains for both cases at the beginning of the flexible pipe (3.81 cm into flexible pipe, location SG1-SG5). The figure indicates that the variation in strains is only 15% as a result of thickness variation of 9.25%. As expected, the thinner walls have predicted higher strains than the thicker-wall case.

Because of the higher yield pressure of the thicker pipe, the effect on the pressure histories in the deformable pipe was found to have the expected trend, higher pressure peaks for the thicker pipe. Figure A.2 shows that the increase in the transmitted peak pressure has about the same ratio, 9.25%, as that of the thickness variation.

At the other end of the flexible pipe, near the blind flange, the effect of the thickness variation on the calculated strains is opposite that at the beginning of the pipe, i.e., higher strains for the thicker pipe than for
the thinner pipe, as shown in Fig. A.3, which shows the calculated strains at location \( \text{SG}_{16}-\text{SG}_{20} \) (3.81 cm from the blind flange). This is due to higher reflected pressure pulse in the thicker-pipe case, a result of the higher yield pressure of the pipe.

As shown in Fig. A.2, the transmitted pressure peak beyond the plastic-wall-deformation region is about 9.25% higher in the thicker-pipe case than in the thinner-pipe case. Consequently, the reflected pressure pulse from the blind flange is about 18.5% higher in the thicker-pipe case. This resulted in only about 5% more strain near the flange in the thicker-pipe case, as shown in Fig. A.3.

This study, however, does not show the effect of the thickness variation around the circumference of the pipe on the calculated strains. To analytically investigate this effect, a pipe section in which the wall thickness varies gradually between the smallest and the largest measured thickness is analyzed by the STRAW\(^7\) structural code, which uses a similar finite-element structural analysis to that used in the structural part of the ICEPEL code.
Because of symmetry, only half the pipe section is modeled, as shown in Fig. A.4. Thirty-six beam elements are used to model the circumference of the pipe. The heights of the beam element (representing the pipe-wall thickness) are varied in seven equal steps between 0.1575 and 0.1727 cm (0.062 and 0.068 in.), according to Table A.1. The pipe whose radius is 3.65 cm was uniformly subjected to a simple triangular pulse of 9.0-MPa peak pressure and 50-μs rise and fall times.

![Fig. A.4. STRAW Model of Variable-thickness Pipe](image)

<table>
<thead>
<tr>
<th>Element No.</th>
<th>Height of Beam Element, cm (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-5</td>
<td>0.1575 (0.062)</td>
</tr>
<tr>
<td>6-10</td>
<td>0.1600 (0.063)</td>
</tr>
<tr>
<td>11-15</td>
<td>0.1626 (0.064)</td>
</tr>
<tr>
<td>16-20</td>
<td>0.1651 (0.065)</td>
</tr>
<tr>
<td>21-25</td>
<td>0.1676 (0.066)</td>
</tr>
<tr>
<td>26-30</td>
<td>0.1702 (0.067)</td>
</tr>
<tr>
<td>31-36</td>
<td>0.1727 (0.068)</td>
</tr>
</tbody>
</table>

Table A.2 shows the variation in the calculated strains between the thinnest and the thickest elements at different times. The results indicate that variation in strains did not exceed 45% for a thickness variation of 9.25%.
TABLE A.2. Calculated Strains of Thinnest and Thickest Elements at Various Times

<table>
<thead>
<tr>
<th>Time, (\mu s)</th>
<th>Smallest Strain, %</th>
<th>Largest Strain, %</th>
<th>Percentage Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>0.0147</td>
<td>0.0162</td>
<td>9.1</td>
</tr>
<tr>
<td>30</td>
<td>0.0644</td>
<td>0.0749</td>
<td>15.1</td>
</tr>
<tr>
<td>45</td>
<td>0.147</td>
<td>0.197</td>
<td>29.1</td>
</tr>
<tr>
<td>60</td>
<td>0.339</td>
<td>0.459</td>
<td>30.1</td>
</tr>
<tr>
<td>75</td>
<td>0.579</td>
<td>0.784</td>
<td>30.1</td>
</tr>
<tr>
<td>90</td>
<td>0.739</td>
<td>1.06</td>
<td>35.7</td>
</tr>
<tr>
<td>105</td>
<td>0.704</td>
<td>1.11</td>
<td>44.8</td>
</tr>
<tr>
<td>120</td>
<td>0.69</td>
<td>0.972</td>
<td>33.9</td>
</tr>
<tr>
<td>135</td>
<td>0.695</td>
<td>1.06</td>
<td>41.6</td>
</tr>
<tr>
<td>150</td>
<td>0.719</td>
<td>1.08</td>
<td>40.1</td>
</tr>
</tbody>
</table>

Table A.3 summarizes the SRI strain and thickness measurements for the four plastic piping tests performed. The strain variation is seen to be mostly more than those resulted analytically. Also, no consistency is observed between the thickness variation and the strain variation. Widely different strain variations were recorded for the same thickness variation.

TABLE A.3. Summary of Measured Thicknesses and Variations in Recorded Maximum Dynamic Strain in SRI Piping Tests

<table>
<thead>
<tr>
<th>Test</th>
<th>(SG_1-SG_5) Strain Variation, %</th>
<th>(SG_4-SG_{10}) Strain Variation, %</th>
<th>(SG_5-SG_{15}) Strain Variation, %</th>
<th>(SG_{14}-SG_{20}) Strain Variation, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP-101</td>
<td>4.7</td>
<td>6.2</td>
<td>4.7</td>
<td>4.5</td>
</tr>
<tr>
<td></td>
<td>43.2</td>
<td>96.6</td>
<td>133.3</td>
<td>79.2</td>
</tr>
<tr>
<td>SP-102</td>
<td>9.2</td>
<td>10.7</td>
<td>7.8</td>
<td>10.7</td>
</tr>
<tr>
<td></td>
<td>31.0</td>
<td>30.8</td>
<td>120.0</td>
<td>108.8</td>
</tr>
<tr>
<td>E-101</td>
<td>6.3</td>
<td>4.6</td>
<td>7.6</td>
<td>9.2</td>
</tr>
<tr>
<td></td>
<td>42.6</td>
<td>57.8</td>
<td>76.9</td>
<td>123.8</td>
</tr>
<tr>
<td>E-103</td>
<td>7.6</td>
<td>3.0</td>
<td>7.6</td>
<td>6.2</td>
</tr>
<tr>
<td></td>
<td>140.6</td>
<td>176.0</td>
<td>169.2</td>
<td>200.0</td>
</tr>
</tbody>
</table>

Thus, it can be concluded that the thickness variation is not the only major source of strain variations around the circumference. Another source is the bending effects that are superimposed on the stresses due to internal pressurization and that result from possible imperfections in the test pipes and changes in flow direction due to the elbow. Such effects are not included in the ICEPEL code analysis of piping systems. However, such effects are planned in the near future.
APPENDIX B

Effect of Pipe Material-properties Representation on ICEPEL Calculations

As discussed in Sec. V of this report, it is important to represent the stress-strain relationship for the pipe-wall material by the correct yield stress in order to correctly predict the consequences of the interaction of the transmitted pressure pulses with the different piping component and with other pulses. The study that led to this conclusion is presented here.

If we use the straight-flexible-pipe test FP-SP-102 as an example and its model as described in Sec. IV of this report, the stress-strain relationship for nickel-200 is described by the relations shown in Fig. B.1. The solid line represents a bilinear relation with a high yield stress of 96.5 MPa (14,000 psi), the dashed line is a bilinear relation with a lower yield stress of 86.2 MPa (12,500 psi), and the dotted line is a trilinear relation with an even lower yield stress of 75.8 MPa (11,000 psi).

The results of the three different runs are summarized in Fig. B.2, which shows the deformed pipe configuration of the three runs. The transmitted pressure beyond the region of plastic deformation is reduced by reducing the yield stress. Consequently, the strains at the blind flange of the pipe are also reduced, since they result from the reflected pressure pulse. However, the strains at the beginning of the pipe are not significantly affected by the changes in the yield stress of the material.
APPENDIX C

Effect of Zone Size and Time Step on ICEPEL Calculations

The straight-flexible-pipe test FP-SP-102 is used here to investigate the effects of different analytical models on the performance of the ICEPEL code. The changes among models involve the axial zone size and the time step.

In all different models to be discussed, the pressure pulse as recorded by the pressure transducer at location P1, 76.2 cm (30 in.) from the pulse gun, is considered as an input pulse applied to the pipe downstream from location P1. Table C.1 summarizes the different input parameters of the five models.

<table>
<thead>
<tr>
<th>TABLE C.1. Summary of Input Parameters for the Five Models</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>Number of Radial Zones</td>
</tr>
<tr>
<td>Number of Axial Zones</td>
</tr>
<tr>
<td>Total Number of Zones</td>
</tr>
<tr>
<td>Axial Zone Size, cm (in.)</td>
</tr>
<tr>
<td>Hydrodynamical Time Step, μs</td>
</tr>
<tr>
<td>Structural Time Step, μs</td>
</tr>
<tr>
<td>Number of Hydrodynamic Cycles</td>
</tr>
<tr>
<td>Number of Structural Cycles</td>
</tr>
</tbody>
</table>

Table C.1 indicates that, in the first three models, the hydrodynamic and structural time steps were chosen so that two structural calculational cycles are performed within each hydrodynamic calculational cycle. In the last two models, one structural calculational cycle is performed within each hydrodynamic calculational cycle.

The stress-strain relationship for Nickel-200 is approximated by a three-straight-line segmented curve described in Table C.2.

<table>
<thead>
<tr>
<th>TABLE C.2. Stress-Strain Approximation for Nickel-200</th>
</tr>
</thead>
<tbody>
<tr>
<td>Segment</td>
</tr>
<tr>
<td>---------</td>
</tr>
<tr>
<td>Segment 1</td>
</tr>
<tr>
<td>Segment 2</td>
</tr>
<tr>
<td>Segment 3</td>
</tr>
</tbody>
</table>
Figure C.1 shows the configuration of the flexible pipe wall at about 8 ms as obtained by all models. At this time, the pressure pulse had almost died in the system; thus, it represents the final wall configuration of the flexible pipe.

The figure reveals that the first four models have generally predicted the same results. At the beginning of the flexible pipe, however, comparison of the results of the first three models shows that the longer the length of the wall segment, the stiffer the structure becomes, which is to be expected. This generally leads to slightly higher pressures transmitted downstream, which in turn results in higher deformation.

This is more clearly shown in Table C.3, which compares the pressure peaks at three locations in the flexible pipe for models 4 and 5. The difference diminishes as the distance along the pipe increases.

A comparison of models 3 and 4 shows that decreasing the hydrodynamic time step led to higher pressure peaks in the rigid pipe: 10.8 MPa for model 4, compared to 9.45 MPa for model 3. This confirms that in finite-difference solutions, increasing the time step reduces the resolutions of pressure pulses.

The reflected pressure pulse from the blind rigid flange caused more plastic deformations to occur in this vicinity. However, the first four models consistently showed that the point of maximum wall deformation is somewhat between 2.54 and 5.08 cm (1 and 2 in.) from the flange. This bulge is caused by the fixed-end condition used at the flange. The same behavior was observed in a statically loaded cylinder with fixed ends.\textsuperscript{6}

Unfortunately, strain gauges SG\textsubscript{16}-SG\textsubscript{20} were located in the same region with no other gauges nearby. This signals the importance of pretest analysis for the experimentalist in locating instrumentation.

Table C.4 summarizes some of the code performance parameters for all models. For models 1-3, in which two structural calculational cycles were performed within each hydrodynamic calculational cycle, the CPU (central processing unit) times per cycle per zone were almost equal. Thus, the total CPU time is directly proportional to the total number of zones (including fictitious zones) and the number of hydrodynamic cycles.

Thus, it is in the best interest of economy to use a smaller number of zones and larger time steps, as long as there is no significant effect on the accuracy of the results. As regards numerical stability for the structural calculations, the smaller the zones the smaller the time step needed.
Fig. C.1. Wall Configuration of Flexible Pipe at 8 ms. ANL Neg. No. 900-77-744.
TABLE C.3. Peak Pressures for Models 4 and 5

<table>
<thead>
<tr>
<th>Distance into Flexible Pipe, cm (in.)</th>
<th>Model 4 Pressure, MPa</th>
<th>Model 5 Pressure, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.81 (1.5)</td>
<td>5.51</td>
<td>6.27</td>
</tr>
<tr>
<td>15.24 (6)</td>
<td>4.93</td>
<td>5.15</td>
</tr>
<tr>
<td>121.9 (48)</td>
<td>5.0</td>
<td>5.05</td>
</tr>
</tbody>
</table>

TABLE C.4. Summary of Some Performance Parameters for ICEPEL Code

<table>
<thead>
<tr>
<th></th>
<th>Model 1</th>
<th>Model 2</th>
<th>Model 3</th>
<th>Model 4</th>
<th>Model 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Number of Hydrodynamic Iterations</td>
<td>19,106</td>
<td>15,042</td>
<td>11,686</td>
<td>16,328</td>
<td>16,652</td>
</tr>
<tr>
<td>Average Number of Iterations per Hydrodynamic Cycle</td>
<td>9.55</td>
<td>9.37</td>
<td>11.69</td>
<td>8.16</td>
<td>7.826</td>
</tr>
<tr>
<td>Total CPU Time, s</td>
<td>1626</td>
<td>966</td>
<td>417</td>
<td>517</td>
<td>247</td>
</tr>
<tr>
<td>CPU Time per Cycle per Zone, ms</td>
<td>1.006</td>
<td>0.997</td>
<td>1.022</td>
<td>0.633</td>
<td>0.593</td>
</tr>
</tbody>
</table>

A comparison of results for models 3 and 4, in which the total numbers of zones were the same, shows that the reduction of the hydrodynamic time step led to better results, insofar as the pressure-peak resolution and strain are concerned, and reduced the CPU time per cycle per zone by about 37%, while increasing the total CPU time only by about 24%.

Code economy can be further improved by increasing the safety factor used in calculating the maximum structural time step from 50 to 80%. This was tried on model 2 and resulted in about 25% savings in the total CPU time.

Although the ICEPEL code is two-dimensional, it can be used for one-dimensional modeling of pipes by using only one radial zone in the pipe.

The conventional one-dimensional methods, which consider the wall deformation only from the fluid viewpoint by adjusting the compressibility accordingly, do not perform a fluid-structure-interaction coupling calculation or structural calculation for the walls. Thus, the bending effects between wall segments are not accounted for, and the precursor effect due to the different wave speeds in the wall and in the fluid is ignored; i.e., the stress wave traveling through the wall is ignored. However, the above phenomena are automatically included in the ICEPEL one-dimensional calculation without undue penalty in running time.
ACKNOWLEDGMENTS

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