EFFECTS OF SMOOTH AND ROCK DENTS ON LIQUID PETROLEUM PIPELINES

Christopher R. Alexander
Stress Engineering Services, Inc.
Houston, Texas

John F. Kiefner
Kiefner & Associates, Inc.
Worthington, Ohio

SUMMARY
This paper summarizes the findings of a project sponsored by the American Petroleum Institute (API) to determine the effects of smooth dents and rock dents on the integrity of liquid petroleum pipelines. The incentive for conducting this work is to avoid replacing or repairing pipe affected by such dents if they do not constitute a threat to pipeline serviceability Smooth and rock dents were studied using 12, 24 and 24 inch diameter pipes. The smooth dents were made using either dome-shaped or bar-like indenters.

One of the more significant findings relates to the observed difference in behavior between the unconstrained and constrained dents. Constrained dents, by definition, do not reround; they are prevented from doing so. Unconstrained dents, on the other hand, tend to rebound elastically and reround inelastically in response to increasing internal pressure. The predominant conclusion associated with unconstrained dents of 2 percent or less is that they would not be expected to fail within the useful life of a pipeline, and hence they need not be repaired. Rock dents when they rock remain in place are of concern only to the extent that, if sharp and hard enough, they may puncture the pipeline.

INTRODUCTION
The primary thrust of the work was experimental. Typical line pipe materials, fabricated with smooth dents or simulated rock dents, were subjected to burst tests or service-simulating pressure cycles. The objectives were to determine whether or not these dents of various sizes or shapes would cause failures under normal operating circumstances and to determine the mode of failure.

The experimental work was supplemented with three-dimensional, nonlinear, elastic-plastic finite element analyses. The objectives of this effort were to quantify dent severity in terms of an equivalent local stress concentrator and to provide a method for estimating the fatigue lives of dents not covered by experiments. However, due to time and space constraints, this aspect of the research effort is omitted from this paper.

BACKGROUND
It is well-known that mechanical damage to pipelines in the form of dents and gouges caused by excavating equipment can have adverse effects on pipeline integrity (1-7). That mechanical damage is a serious integrity concern as reflected in the pipeline incident statistics reported to the U.S. DOT. Over the 25 year period for which the reporting requirements have been in effect, mechanical damage defects have accounted for 20 to 40 percent of the serious pipeline incidents in any given year.

In contrast. however, there is no history of significant accidents arising from smooth or rock dents. While in a few cases rock dents have caused leaks, no cases of catastrophic service ruptures are known to have occurred. Likewise, no record of a catastrophic rupture arising from a smooth dent is known to exist. Since numerous rock dents are likely to be found by in-line inspections and since some dents may be found that contain no material damage, pipeline operators would prefer to not cut out or repair these anomalies unless they are indeed a threat to pipeline integrity. Rock dents tend to occur almost entirely on the bottom half of the pipe, whereas serious excavation damage is found most often on the top half of the pipe. Based on this dent-position issue, it may not be necessary to excavate rock dents if it can be shown that they present little or no threat to pipeline integrity.

For reasons cited above, API has funded this research program to determine whether or not smooth dents and rock dents constitute significant threats to pipeline integrity. The information presented herein relates to the resolution of these issues, as well as others encountered in the course of testing and analysis.

DESCRIPTION OF EXPERIMENTAL PROGRAM
General Considerations
A testing program was developed to permit testing of several variables. The variables deemed critical, whether initially or through the course of testing were,

- Dent depth
- Pipe diameter and wall thickness
- Smooth dents and rock dents (unconstrained and constrained)
- Local stress concentrators (corrosion, weld seams, and girth welds)
- Failure mode (fatigue, burst, and puncture)
- Indenter type
- Effects of hydrostatic testing.

The following types of tests were conducted,

- Puncture and dent rerounding tests
- Burst tests
- Fatigue tests.

To develop dents representative of those found in the field based on the experience of the authors and committee members, three classes of dents were agreed upon,

- Round smooth dents
- Long axial smooth dents
- Dents created by a sharp rock.

Ultimately, three types of dents referred to as dome, long bar, and pyramid dents were chosen to simulate these situations. All dents were installed using a large fixture that supports the pipe by means of a saddle and creates the dent by pressing the indenter down into the pipe using a hydraulic ram. The pipe samples were fabricated with end caps prior to indentation.

Most dents were installed with no pressure in the pipe to depths based upon a percentage of the pipe's diameter. The range for most dents was between 6 and 18 percent of the pipe's diameter; however, in a few cases dent depths of 24 or 28 percent were used.

Pipe Sizes and Materials
Table 1 provides a listing of the sample pipe sizes and material properties used in the experimental program.

Stress Concentrators (Corrosion and Welds)
In addition to smooth dents with no stress concentrators, the effects of sharp rocks and the presence of corrosion and pipe welds (seam and girth) in dents were addressed in this study.

Corrosion was simulated by machining a 1" X 9" patch in a pipe having a depth of 50 percent of the wall thickness. Only pipes having nominal diameters of 12 inches were considered in the corrosion study and the effort was confined to evaluating the effects of corrosion on burst strength only (i.e. no fatigue tests on corroded pipe were conducted).

Dents were installed in both seam welds (ERW and SAW) and girth welds. The girth welds were fabricated, examined, and approved with API Standard 1104.

Puncture and Dent Rerounding Testing
The primary aim of the puncture test was to determine the maximum depth of indentation that could be obtained before a leak developed. This information was then used in determining the base dent depth for other dents utilized in the testing program. The first puncture test was conducted on a 12.75" X 0.188", X52 pipe sample. The sample was pressurized to 72% SMYS (1,104 psig) and the indenter was pressed into the sample until a leak occurred. At a dent depth of approximately 12% the pipe's diameter a leak developed in the sample. The dent depth and load required to cause the associated indentation were recorded. Based on the success of this test, similar puncture tests were made on the 24" and 32" pipe sections.

Burst Testing
The burst tests were conducted to determine the impact of dents on the ultimate pressure-carrying capacity of a pipeline. Dents were installed in the samples as discussed previously and the samples were then filled with water for the purpose of conducting a burst test. The pressure was applied to the sample at a rate of approximately 1 psig/second until failure in the sample occurred. Pressure as a function of time was monitored in the course of testing.

Fatigue Testing
The majority of the tests conducted is this research program utilized the fatigue testing mode. Samples were dented prior to testing and pressurized one to four times to determine the extent of rerounding. These initial pressure levels ranged from 65% of SMYS to 100% SMYS. Although rerounding would have occurred as a result of cyclic operation, knowing the dent level that existed prior to cycling was important to classifying dent severity. After these initial cycles, continuous cyclic pressurization to failure was initiated.

The pressure cycle ranges were based upon a percentage of the MOP for the given pipe sizes. **Table 2** provides the applicable ranges. The procedure used in testing was to cycle the samples until either a failure occurred or 25,000 cycles of the 50% MOP range had accumulated. If the sample did not fail within this period, cycling was continued at the 100% MOP pressure range for an additional 25,000 cycles or until the sample failed. These pressure ranges were selected based on the experience of the authors and developed so that failures would be induced within a reasonable number of applied cycles (typically less than 50,000 cycles).

RESULTS OF EXPERIMENTAL PROGRAM

The results of thirty-eight puncture, burst, and fatigue tests of dented pipes are presented herein. Deformation data for four additional dents which were formed and subjected to a cycle of pressurization, but were not tested to failure, are also presented. The results are presented and discussed in the following groupings.

- **Group 1** — Unconstrained smooth dome-shaped dents
- **Group 2** — Constrained smooth dome-shaped dents
- **Group 3** — Unconstrained smooth bar-shaped dents
- **Group 4** — Pyramid-shaped dents
- **Group 5** — Punctures using pyramid-shaped indenter to simulate a sharp rock
- **Group 6** — Simulated corrosion in unconstrained smooth dents

Unconstrained Smooth Dome-Shaped Dents
This group of 20 tests involved unconstrained smooth dome-shaped dents with the following test characteristics.

- All dents were formed with the 8.625-inch-diameter spherical end cap with no pressure in the pipe.
- Indentations of 6 to 18 percent of pipe's diameter were made prior to release of the indenter load.
- The tests included pressurizing four specimens straight away to failure (i.e., burst tests), pressure cycling fourteen specimens to failure using pressure ranges of ½ MOP or MOP, and forming and pressure-rerounding only of two specimens.

The results of these 20 tests are summarized in **Table 3**. The significant results include, but are not necessarily limited to:

- The amounts of elastic rebound.
- The amounts of total rerounding after pressurization to 65 percent of SMYS.
- The burst test failure stress levels.
- The fatigue lives as influenced by various factors (e.g., dent depth, seam welds, girth welds, hydrostatic test history).

Elastic Rebound
As seen in the fifth column of **Table 3**, the dome-shaped dents recovered anywhere from 24 to 67 percent of the maximum indentation solely from elastic rebound. The average value of elastic recovery was 47 percent with a fairly large standard deviation of 10.6 (a lot of scatter). The finding seems to apply regardless of the D/t value, because the average for the 12.75 inch OD material alone (D/t = 68) was 46.7 with a standard deviation of 11.3. Elastic recovery includes both local rebound at the location of the indenter and rebound of the elastically-induced ovalization. No attempt was made to separate the effects of the two phenomena, but both are believed to have contributed significantly because there was no pressure to stiffen the pipe..

Total Rerounding
As seen in the ninth column of **Table 3**, the dome-shaped dents recovered anywhere from 66 to 86 percent of the maximum indentation after the specimens had been pressurized to 65 percent of SMYS. The average value of total rerounding (elastic and plastic) after pressurization to this level was 76 percent with a standard deviation of 5.4 percent. As in the case of elastic recovery, this result was relatively independent of the D/t ratio. The average for the 12.75 inch OD pipe alone (D/t = 68) was also 76 percent with a standard deviation of 6.0 percent. This result suggests that when one encounters an unconstrained smooth dent in a pipeline which has been formed at zero pressure and which has subsequently been pressurized to 65 percent of SMYS, the present size is probably only about one quarter of the original instantaneous indentation.

Burst Tests
Four of the dome-shaped dents, UD12A-6EW, UD6A-9EW, UD18A-10, and UD12A-11, were pressurized to failure. As seen in **Table 3**, these samples burst at hoop stress levels ranging from 130 to 151 percent of SMYS after undergoing circumferential plastic strains of around 10 percent. The dents were removed by rerounding to a point where they

were barely visible, and the failures initiated elsewhere. Since Specimens UD12A-6EW and UD6A-9EW involved dents on ERW seams, the performance of this ERW bondline was at least as good as the base metal. Clearly, as has been demonstrated on previous occasions (1), plain or smooth dents have no significantly adverse effect on the pressure-carrying capacity of pressurized pipe when not subjected to an excessive number of fatigue cycles.

Pressure-Cycle Tests

The pressure-cycle tests involved subjecting specimens with dome-shaped dents to repeated pressure cycles ranging from 36 to 72 percent of SMYS followed if no failure occurred after about 25,000 cycles by pressure cycles ranging from 6.5 to 78 percent of SMYS until failure. The number of cycles to failure is given in **Table 3** in terms of equivalent numbers of total cycles of the 36 to 72 percent of SMYS range. All failures occurred as leaks rather than ruptures.

Various factors influenced the failure results such as the presence of ERW (labeled EW) or SAW seams (labeled SW), girth welds (labeled GW), or adjacent dents (labeled DD). Most of the specimens were tested with prior pressurization only to 65 percent of SMYS. So, the maximum cyclic pressures were the highest levels experienced by the specimens. In four cases, however, the specimens were subjected to an initial cycle simulating a hydrostatic test. Specimens UD12A′-30EW and UD12A′-31GW were subjected to an initial cycle of pressure corresponding to 90 percent of SMYS, and Specimens UD12B-34EW and UD12B-35GW were subjected to an initial cycle of pressure corresponding to 101.5 percent of SMYS. The effect of the initial "hydrostatic test" cycle was to produce additional rerounding. The difference between rerounding for these "pretested" specimens before and after the pretests are listed in **Table 4**.

The beneficial effect of the hydrostatic test cycle can be discerned by the direct comparisons of two pairs of pressure-cycle tests. In these tests each specimen of each pair is identical to the other except for the fact that one was pretested and the other was not. The specimens and the results are listed in **Table 5**. The two in the first pair differed slightly with respect to dent depth after pressurization to 65 percent SMYS, but the effect of the 90 percent test undoubtedly overrode this difference. In the second pair, where the specimens had approximately the same depth, the effect of the 90 percent test was surely the decisive factor in the longer fatigue life.

The fatigue lives of all fourteen unconstrained dome-shaped dents are plotted in **Figure 1**. Data for the ten non-pretested specimens are plotted based on their depths after pressurization to 65 percent SMYS, and those for the four hydrostatically pretested specimens are plotted based on their depths after being hydrostatically tested. Arbitrary upper and lower bounds to these data were drawn on **Figure 1** to establish the rough relationship between dent depth after rerounding at 65 percent SMYS and fatigue life. Clearly, the shallower the dent after rerounding, the longer the life. The effects of ERW seams, SAW seams, and girth welds appear to be overridden by the effect of dent depth. Experiments UD6A-2 and UD12A-3 lie outside the upper bound. This may be because they were inadvertently overpressured at some stage of the pressure cycle testing.

All of the fatigue tests except one were terminated by the development of a leak. The leaks consistently were found to coincide with longitudinally-oriented cracks which initiated at the OD surface and propagated to the ID surface. The cracks tended to be located offset axially from the centers (deepest parts) of the dents. Typically, they were located on the sloping transition regions to one side or the other of the centers.

Final Dent Depth

One parameter which may provide additional insight into the meaning of the results is final dent depth, the depth measured after the test had been completed. This value was consistently less than the depth after pressurization to 65 percent SMYS. This is probably due in large measure to the additional rerounding which took place as the specimens were pressurized to levels of 72 to 78 percent of SMYS. However, some of it may come from cyclic plastic strain during the pressure cycles, and some of it almost certainly comes from the change in compliance introduced by the fatigue crack developing and propagating. An interesting case is that of the double dent specimens. In both cases (UD12A-32DD and UD12A-33DD) the "A" dent was deeper at the outset of testing (i.e., after first pressurization to 65 percent of SMYS). This is assumed to be the reason for the "A" dent in each case becoming cracked whereas the "B" dent did not. After the test, however, the "A" dent in each case is shallower than the "B" dent because its compliance changed due to the crack.

Stress Concentration Factors

Although this work is aimed primarily at studying the behavior of smooth dents, the presence of features such as seam welds and girth welds in some of the dents creates stress concentrating factors in otherwise smooth dents. It seems likely that features such as girth welds and SAW seams would also stiffen the pipe and thus restrain the dent from rerounding as much as a totally smooth pipe. The effects of these features are not easily discerned from the data because the scatter is large. For example, the arbitrarily-defined band of data in **Figure 1** contains both smooth dents and dents with features such as girth welds and seam welds. The genuinely smooth dents (Numbers 28, 32, 33 ignoring Numbers 2 and 3 which may have been overpressured) tend to lie nearer the upper bound while many of the dents with features lie nearer the lower bound. This suggests that the features have some detrimental effect on fatigue life, but that effect appears to be secondary to dent depth. We did observe that the cracks in the "feature" dents tended to initiate at geometric stress concentrations (i.e., girth weld ripples, the toe region of the SAW seam, and slight trim-score marks near the ERW seams). The cracks did not, however, initiate at or propagate in the ERW bondline.

Ram Load Versus Indentation

The relationships between ram loads and dent depths for 15 of the 20 dome-shaped dents are shown in **Figure 2**. The shapes of these curves seem similar over a wide range of conditions. The highest loads were associated with the 32 inch OD by 0.312-inch wall thickness pipe even though this pipe had the highest D/t value (103). This suggests that wall thickness bending may be an important factor in the resistance to indentation.

Constrained Smooth, Dome-Shaped Dents

This group of three tests involved constrained smooth, dome-shaped dents with the following characteristics.

- All three dents were formed with the 8.625-inch-diameter spherical end cap with no pressure in the pipe.
- Indentations of 12, 18, and 24 percent of the pipe's diameter were formed and maintained during testing.
- Elastic recover and rerounding were prevented.
- The three tests consisted of pressure cycles of 36 to 72 percent of SMYS and 6.5 to 78 percent of SMYS until failure.
- All three tests were carried out on 12.75-inch OD by 0.188-inch wall thickness X52 pipe.

The results of these tests are provided in **Table 6**. The dent in Experiment CD12A-15 survived 426,585 cycles without showing any signs of cracking in the dent. The test was terminated because the constraint failed, allowing rerounding probably to the maximum cyclic pressure level (i.e., to 78 percent of SMYS). The other two dents developed leaks unique to the constrained dent configuration. Each one developed a transversely-oriented crack which initiated at the ID surface and propagated to the OD surface. In both experiments the crack was located symmetrically across the longitudinal axis of the dent (transverse), but within and near the edge of the contact area between the constraining end cap and the pipe. In contrast, the unconstrained dents developed longitudinally-oriented cracks which propagated from the OD surface to the ID surface.

A comparison of the fatigue lives of constrained dome-shaped dents with those of unconstrained dome-shaped dents is provided in **Figure 3**. This figure suggests that constrained dents of realistic sizes (6 percent or less) would be expected to have much longer lives than unconstrained dents.

Unconstrained Smooth Bar-Shaped Dents

This group of eight tests involved unconstrained longitudinally-oriented smooth, bar-shaped dents with the following characteristics.

- Four of the dents were made by means of the short bar indenter (designated as "bar"). This was a 12-inch-long, 1-inch-diameter bar with rounded ends.
- Four of the dents were made by means of the long bar indenter (designated "long bar"). This was an 18-inch-long, 4-inch-diameter bar with rounded ends.
- All eight dents were created with no pressure in the pipe.
- Initial dent depths ranged from 12 to 28 percent of the pipe's diameter.
- In six of the tests the dent was created by orienting the bar or long bar parallel to the axis of the pipe and pressing it radially inward.
- In two of the tests (designated "T") the dent was created by orienting the long bar transverse to the axis of the pipe and pressing it radially inward.
- Three of the tests were burst tests, three involved pressure cycles to failure, and two involved indentation and rerounding only.

The results of the tests associated with unconstrained bar-dents are presented in **Table 7**.

Elastic Recovery

The degree of elastic recovery of the bar dents based on measurements made at the middle of each dent after removing the indenter ranged from 38 to 61 percent of the diameter. The average amount of recovery, 49 percent, was very close to that of the dome-shaped dents. For the bar dents made parallel to the axis of the pipe the degree of recovery in the center of the dent was slightly more than at the ends but not by more than 5 percent. The amount of recovery did not seem to be dependent on the D/t ratio of the pipe.

Total Rerounding

The bar-shaped dents recovered anywhere from 81 to 91 percent of the maximum indentation after the specimens had been pressurized to 65 percent of SMYS. The average value of total rerounding (elastic and plastic) as measured at the center of the dent after pressurization to this level was 88 percent. This is more than the average rerounding of the dome-shaped dents (76 percent). However, the ends of the longitudinally-oriented bar dents did not reround quite as much as the centers. The average rerounding of the ends was 82 percent, more like that of the dome-shaped dents. This left "dimples" at the ends of the longitudinally-oriented dents that were 3 to 4 times the depth at the center.

Burst Tests

Three specimens with longitudinally-oriented bar dents, UB12A-8EW, UB28A-12, and UB12A-13 were subjected to burst tests including one with the dent centered along the ERW seam. All three failed at hoop stress levels in the range of 130 to 151 percent of SMYS after having undergone gross plastic circumferential strains approaching or exceeding 10 percent. The failures did not initiate in the areas of the dents. The indentations, including the dimples at the ends, virtually disappeared.

Pressure-Cycle Tests

Two of the three pressure cycle tests involved longitudinally-oriented bar-shaped dents. Both developed leaks in the form of longitudinally-oriented cracks that developed at the OD surface of the pipe in the vicinity of the dimples. The cracks were located in the sloping transition regions between the bottom of one of the two dimples and the central, uniform-depth regions of the dents. The representative *dimple* depths at the beginning of the pressure cycles were probably at least twice the central depths given in **Table 7**. For Specimen UB12A-17EW this means that the starting depth was about 2.2 percent and for Specimen UL18A'-29 the depth was probably at least 2.0 percent. The results of these two tests which failed after 62,647 and 148,512 equivalent cycles, respectively, are plotted on **Figure 1** along with the results of the dome-shaped dents. It is seen that these results fit well within the band of dome-shaped dent data suggesting that the end dimples of the longitudinally-oriented bar dents behaved much like the dome-shaped dents.

The pressure cycle test of Specimen UL12A-38T with its transverse bar dent developed a leak after 266,567 equivalent cycles. The crack was longitudinally-oriented and initiated at the OD surface as did all other cracks in unconstrained dents. This result also fits well within the band of data shown in **Figure 1**. This is not surprising because the longitudinal profile of the transverse bar dent is very similar to that of a dome-shaped dent.

Other Findings

The final dent depths of the bar dents, as in the case of the dome dents, represent substantial additional rerounding beyond that created by the pressurization to 65 percent of SMYS. Much of this is undoubtedly the result of the fact that the dents were subjected to stress levels as high as 78 percent of SMYS during the pressure cycles. Some of it could also be the result of additional rerounding during the pressure cycles. Since the cracks were not in the center where these measurements were made, the final dent depths are probably not affected by the changing compliance in the vicinity of the crack.

Pyramid-Shaped Dents

This group of four tests involved three unconstrained and one constrained pyramid-shaped dents. The characteristics of these tests were as follows.

- All dents were formed by pressing the pyramid-shaped indenter into an unpressurized pipe.
- All four specimens involved 12.75-inch OD by 0.188-inch wall thickness X52 pipe.
- Two sizes of dents, 6 and 12 percent of the pipe's diameter, were created.
- Three of the specimens were subjected to pressure cycle tests and one was subjected to a burst test.

Elastic Recovery and Rerounding

For the three unconstrained dents, UP6A-1, UP12A-4, and UP12A-7EW, the amounts of elastic recovery upon removal of the indenter were 18, 44, and 23 percent, respectively. These values are, on the average, lower than the average values for the dome and bar dents (these dents averaged about 48 percent recovery). Similarly, the pyramid dents exhibited less total rerounding (elastic and plastic) after being pressurized to 65 percent of SMYS than the other types of dents. The three pyramid dents exhibited rerounded depths of 57, 63, and 67 percent at zero pressure after having been pressurized to 65 percent of SMYS. By comparison the average amounts of rerounding under the same conditions for the dome and bar dents were 76 and 88 percent, respectively. The relatively sharp profile of the pyramid dent undoubtably accounts for these differences. The pyramid dents cannot respond to the same degree as the smoother dome and bar dents to the restoring forces.

Burst Test

Specimen UP12A-7EW, although it was initially intended to be a pressure cycle test, was subjected to a burst test when the overpressure protection system malfunctioned. This dent survived without failing to a pressure level in excess of 130 percent of SMYS and a level of circumferential strain exceeding 7 percent. Thus, even with the cold work that was created by the tip of the pyramid, the pyramid dent had no effect on the burst strength of the pipe. The failure of the pipe took place in the undamaged body of the pipe away from this dent. However, unlike the smooth dents, the pyramid dent was not entirely removed by pressurization to the ultimate burst pressure level, and of course, the cold work created by the tip of the pyramid was irreversible.

Pressure Cycles

The pyramid dents in Specimens UP6A-1 and UP12A-4 were subjected to more than 1,000,000 equivalent cycles of the 36 to 72 percent of SMYS stress range, yet neither specimen exhibited any sign of developing a leak. The tests were terminated in the interest of time and the dents were examined by metallographic sectioning. No sign of cracking was discovered.

One additional pyramid dent was subjected to pressure cycles. It was the constrained pyramid dent CP6A-25. The testing of this specimen was terminated after more than 400,000 equivalent cycles of the 36 to 72 percent of SMYS stress range although no leak had developed and no sign of cracking was evident.

The results of both the burst test and the pressure cycle tests on the unconfined pyramid dents and at the pressure cycle test on the constrained pyramid dent strongly suggest that the effects of this dent configuration on pipeline integrity are not significant. Reasons for this may be that the relative sharpness of the dent's profile minimizes the strain range during cyclic pressurization and/or that its restricted ability to reround lowers its effective stress intensity factor below that of the smoother dents.

Punctures Using the Pyramid-Shaped Indenter

This group of four tests involved punctures using the pyramid-shaped indenter. The characteristics of the tests were as follows.

- Three tests were conduced by pressing the indenter into pressurized samples until a puncture occurred.
- One test was conducted by pressing the indenter into an unpressurized pipe to a fixed indentation of 12 percent of the pipe's diameter. While the dent was held at that displacement, the specimen was pressurized until a failure occurred.

The results of the puncture tests of pressurized specimens are listed in **Table 8.**

All of the punctures occurred as transverse shear cracks through the remaining ligaments. The wall thicknesses had been reduced as much as 50 percent from their initial nominal value by cold work from the tip of the indenter. This is a mechanism associated with rock dent punctures of operating pipelines. The results indicate the significance of wall thickness to puncture resistance. As has been shown by others (4), puncture load resistance definitely increases with wall thickness. These prior studies have assessed puncture resistance from the standpoint of excavating equipment where the puncturing ability of the equipment is load-controlled. The data from the current test could have the opposite implication for rock dents because the displacement required for puncturing goes down with increasing wall thickness. It would depend on how much pipeline and over-burden weight is forcing the pipeline onto a rock.

The fourth specimen, CP12A-14, failed at a pressure level of 1100 psig. It involved the pressurization of a 12.75-inch OD by 0.188-inch wall thickness specimen in which a 12 percent constrained pyramid dent existed. The mode of failure was the same as that of the previously mentioned puncture tests. Its behavior closely paralleled that of CP12A-5.

Simulated Corrosion in Unconstrained Dents

This group of three tests involved pressurization to failure of specimens containing machined areas of metal loss which were subsequently indented. The characteristics of these tests were as follows.

- Corrosion-simulating defects were created by machining away ½ of the wall thickness from the outside surface over an area 9 to 10 inches in axial length by 1-inch in circumferential extent. The thickness was reduced uniformly over the entire machined area.
- All three tests involved the 12.75-inch OD by 0.188-inch wall thickness X52 material.
- Either a smooth dome-shaped indenter or a smooth bar-shaped indenter oriented longitudinally was used to indent the corroded area of the unpressurized pipe to a dent depth of 12 or 18 percent of the pipe's diameter.
- The indenter was removed permitting elastic rebound.
- The specimens were pressurized to failure.

Listed in **Table 9** are the results of these tests. In the cases of the first two samples, their failure pressures exceeded the values predicted by RSTRENG (8). This suggests that there was no adverse synergistic effect of the corrosion and the dents. In contrast, in the case of the third sample, the failure pressure was less than the value predicted by RSTRENG. In this case the dent and corrosion combined seemed to be worse than corrosion alone. The only thing that can explain these results is the difference in dent depths. The 12 percent dents seemed to produce no adverse results whereas the 18 percent dent seemed to produce an adverse effect.

FINDINGS OF EXPERIMENTAL WORK

The key findings suggested by the results of the experiments are expressed as follows.

- As has been demonstrated in several investigations, the smooth dents with no stress concentrators had no effect on the ultimate pressure carrying capacity of the pressurized pipes.
- When the indenting loads were removed, the smooth dents rebounded elastically to an extent in the range of 24 to 67 percent of the maximum indentations made without the pipe being pressurized. Some of this recovery came from spring back at the point of contact but an appreciable amount also arose from elastic recovery of the cross section of the pipe which was initially ovalized by the indenting force.
- The unconstrained, smooth dents rerounded to an ever-increasing degree with increasing internal pressure until they virtually disappeared as the pressure approached the burst pressure of the pipe. At pressure levels of 65 percent of

SMYS, the rerounding resulted in 66 to 88 percent recovery of the initial maximum indentations.

- For unconstrained smooth dents the deeper the dent at the start of cycling, the shorter its fatigue life in terms of pressure cycles required to create a leak.
- The smooth dents with depths not exceeding 2 percent of the pipe's diameter did not adversely affect the serviceability of the pipes tested within a simulated useful life span of a liquid pipeline. For this purpose we assumed that the worst case pressure cycle service would not be more aggressive than the equivalent of 40,000 ½MOP to MOP cycles (1000 cycles per year for 40 years). The shortest life for a smooth dent tested in this program exceeded 20,000 ½MOP to MOP cycles. That particular dent contained an ERW seam, and its depth after being pressurized to 65 percent of SMYS was 4.2 percent of the pipe's diameter.
- The presence of minor stress concentrators such as girth weld ripples in an otherwise smooth dent appeared to reduce the fatigue lives of smooth dents somewhat but the effect was not nearly as significant as that of dent depth at the start of cycling.
- Significantly, no fatigue failures were observed to initiate at any location other than within an indented location. Thus, for all samples subjected to pressure cycles the dents studied herein had at least some adverse effect on the pipe.
- The two unconstrained smooth dents which were sufficiently close to partially overlap lengthwise appear to have had a more detrimental affect on fatigue life than the two that did not overlap.
- Hydrostatic testing had a beneficial effect on the fatigue lives of the unconstrained smooth dents most likely because of the additional rerounding associated with testing to pressure levels in the range of 90 to 102 percent of SMYS.
- Dents created by the sharply pointed pyramid indenter rebounded elastically and rerounded significantly with increasing pressure, but they did not reround fully like the smooth dents even when the pressure level reached the burst pressure level of the pipe. They seemed to reach a point at which neither further pressure increases nor pressure cycles had much effect on the dent. Failures were not achieved in these samples either with increasing pressure or with the application of hundreds of thousands of pressure cycles.
- The constrained smooth dents, even though much deeper than unconstrained smooth dents, appeared to have had no more detrimental effect on fatigue life than the unconstrained smooth dents that were initially of the same depth before rerounding.
- The mode of failure of smooth dents from pressure cycles was a leak in every case, not a rupture. For unconstrained dents the leaks were associated with longitudinally-oriented cracks which initiated at the OD surface and propagated to the ID surface. In most cases these cracks were located in the sloping transition regions between the deepest part of the dent and the undented pipe. For constrained dents the leaks were associated with transversely-oriented cracks which initiated at the ID surface and propagated to the OD surface. For the cases considered which involved leaks, not ruptures, the materials exhibited ductile fracture initiation. It is possible that similar cracks in materials which might tend to exhibit brittle fracture initiation would fail as ruptures.
- The sharply pointed pyramid indenter was capable of puncturing the pressurized pipe. The thicker the pipe, the higher the load and the less the total deformation required to puncture the pipe. The mode of failure in a puncture consisted of both crushing the wall thickness and shear failure.
- The tests involving indenting of pipes containing machined corrosion-simulating metal loss produced results that showed a strong influence of initial indentation depth on remaining pressure carrying capacity. For the 12 percent initial dents, the failures occurred at levels that suggested no worse behavior than might be expected from the same amount of metal loss with no indentation. For the 18 percent initial dent, however, the failure occurred at a level significantly below what one would have expected for the same amount of metal loss with no indentation.

DISCUSSION AND CONCLUSIONS

The experimental and analytical results of this project lead to conclusions or tentative conclusions on a number of damage issues.

Rerounding

The experiments have shown that dents reround significantly upon removal of the indenting force or object. This phenomenon was well known prior to this research project, but this research provided an enhanced understanding of the phenomenon. In particular, this work showed that very deep indentations, 6 to 28 percent of the pipe's diameter are not retained once the indenting force or object is removed. For smooth dents elastic recovery both from rerounding of the initially ovalized cross-section of the pipe and from local spring back at the point of contact can account for as much as 50 percent of the rerounding for the D/t range studied (i.e., 68 to 102). Again for smooth dents, by the time the internal pressure level has reached 65 percent of SMYS, total rerounding in the range of 60 to 90 percent of the maximum indentation can be anticipated. The finite element analyses tended to confirm the expectations of rerounding and showed the nature of the residual stresses which result from rerounding. It is necessary to keep in mind that the ovalization behavior observed in these tests, which involved a saddle for support, is not the same as one would expect in a buried or partly buried pipeline. Because buried pipe is effectively stiffer, one might expect that impacts from encroachment are more damaging than in the case of a saddle-supported pipe sample.

Conclusion: Because of the potential for rerounding, it is highly unlikely that unconstrained dents with depths exceeding 5 percent of the pipe's diameter will exist in areas of a pipeline which have been pressurized to levels of 72 percent of SMYS or more.

A significant implication of this finding is that dents indicated by caliper tools to be deeper than 5 percent are likely to be constrained (i.e., rock) dents. It should also be noted that prior work by others (1-5) identified additional significance attached to the phenomenon of rerounding with increasing internal pressure, namely, that dents created by encroachment of excavating equipment where a gouge or cold work was created have a high potential to be cracked solely as the result of rerounding and that dents caused by excavator encroachment do not have to be deep to be a serious threat to pipeline integrity.

Static Strength of Smoothly Dented Pipe

The experiments showed that smooth dents have no significant effect on the ultimate pressure-carrying capacity of the pipe in a one-time loading situation. This finding is in agreement with the results of previous studies. The results of the current work appear to validate this situation for the case of a dent on a sound ERW seam as well.

Conclusion: Pipeline operators need not be concerned about the short-term consequences of truly smooth, unconstrained dents. Concern arises, if and only if, the dent will be subjected to aggressive service pressure cycles over a long period of time.

Implications:
1) When an in-line tool becomes available that can detect both the presence and accurate dimensions of a dent and the presence or absence of mechanical damage in the dent, pipeline operators will be able to prioritize their responses based on the knowledge that smooth dents are of little concern.
2) When a pipeline operator exposes a dent and can check for the presence or absence of mechanical damage, it will now be possible to justify leaving smooth dents as they are subject, of course, to the pressure-cycle considerations discussed below.

Fatigue Resistance of Smoothly Dented Pipe
The experimental work established, for both long and round dents, a clear relationship between dent depth and the resistance of the dent to fatigue cracking when subjected to pressure cycles. The mode of failure from pressure cycles in these ductile materials was consistently a leak because the cracks grew through the thickness without being nearly long enough to cause a rupture.

Conclusion: Smooth, unconstrained dents of depths greater than 2 percent can safely be left unrepaired if an analysis of the pressure cycles shows that the dent would not come close to failing within the useful life of the pipeline.

Implication: One implication is that the former limit in ASME B31.4 and B31.8 of 2 percent on smooth dents was sound. This does not mean that the current limit of 6 percent is unsound, but it does suggest that perhaps a warning about pressure cycles is justified particularly in the case of B31.4.

Fatigue Resistance When Minor Stress Concentrators Exist in Smooth Dents
The experimental work showed that minor stress risers including the toes of weld reinforcements, and the ripples in girth welds tend to serve as origins of fatigue cracks and to facilitate the initiation of fatigue cracks in unconstrained smooth dents in pipes subjected to large numbers of significant-size pressure cycles. The results suggest that the effects of these types of stress concentrators are not as great as the effect of dent depth.

Tentative Conclusion: It is prudent to repair (or replace the dented pipe) dents involving a seam weld or a girth weld if the depth of the dent exceeds 2 percent of the pipe's diameter.

Implication: The implication of this is that the current provisions in B31.4 which require repairs to any dent involving a weld are over-restrictive except for the case of an older-low-frequency-welded ERW material. In view of the findings so far, it would appear that such situations are not critical unless the dent is more than 2 percent of the pipe's diameter when the pressure service is cyclic and typical of most liquid pipelines.

Constrained Dents
The experiments have shown that constrained dents pose only one kind of threat to pipeline integrity, namely the threat of puncturing if the constraining object is hard enough and sharp enough to penetrate into the wall thickness. This behavior is consistent with a number of well-documented leaks caused by rock dents. The results do not preclude the possibility that pressure cycles will make such a situation worse, but they do suggest that the role of fatigue is not prominent. No fatigue-related failure was produced at the sharp constrained dents that were included in the study. And certainly, the results show that a fatigue failure is not possible within the useful life of a pipeline if the rock creates no localized damage in the form of wall-thickness penetration.

Conclusion: Rock dents where the rock remains in place are of concern only to the extent that, if sharp enough, they may puncture the pipeline. The mode of failure of such a puncture will be a leak not a rupture.

Practical Considerations
Currently, many pipeline operators remove rocks from under pipelines after they are discovered and excavated. Actual experience and the tests conducted in this program show that the removal of a rock will be followed by rerounding to some extent immediately and certainly to greater extent later if the pressure is subsequently raised. There are merits to removing rocks in this context. Punctures can be prevented, coating can be repaired, and the pipe can be inspected. However, the occurrence of rerounding is not to be taken lightly. The results of this work suggest that immediate rerounding would not be a concern unless some sort of mechanical damage existed or another type of severe stress concentration were present. Since one cannot currently assess these conditions before a rock is removed, it would seem prudent in such a situation to:

1) lower the operating pressure at the location of the rock to the lowest feasible level.
2) After removal of the rock, carefully inspect the surface of the pipe in the contact area for the presence of damage and/or cracks.
3) Repair the dent or replace the pipe if damage (that cannot be removed by superficial grinding) or cracks are found.
4) Record the depth and extent of the dent and repair the coating if no repair to the pipe is deemed necessary.
5) Consider whether or not the remaining dent will be subjected to significant pressure cycles.

From the standpoint of current in-line inspection capabilities, pipeline operators can locate and, to a limited extent, characterize dents in operating pipelines. Most people assume that dents found on the bottom half of the pipe are caused by rocks. The results of this project suggest that rock dents will at worst cause punctures and that such punctures will occur only if the rock is sharp enough to produce a concentrated load and/or penetration of the wall thickness. The results further show that deep dents are most likely constrained, and therefore, are most likely rock dents. In view of these findings, it is prudent for pipeline operators to focus their first responses to excavating dents that appear on the top or sides of the pipe.

ACKNOWLEDGMENTS
The authors are grateful for the support of this project received from API and the guidance received from the members of the API's Task Force on Mechanical Damage. The complete report which presents the detailed results of this project is available from the API. It is titled *Effects of Smooth and Rock Dents on Liquid Petroleum Pipelines*, API Publication 1156, First Edition, November 1997.

REFERENCES

1. McClure, G.M., Eiber, R.J., Hahn, G.T., Boulger, F.W., *Research on the Properties of Line Pipe*, A.G.A. Catalog No. L00290, 1962.
2. Jeglic, F.S., *Mechanical Damage and its Effect on Fracture Initiation in Line Pipe*, Physical Metallurgical Research Laboratories Report MRP/PMRL-76-5(J), CANMET, March 1976.
3. Jones, D.G., *The Significance of Mechanical Damage in Pipelines*, 3R, July 1982.
4. Maxey, W.A., *Outside Force Defect Behavior*, NG-18 Report No. 162, A.G.A. Catalog No. L51518, 1986.
5. Hopkins, P., Jones, D.G., and Clyne, A.J., *The Significance of Dents and Defects in Transmission Pipelines*, BG ERS Report E.634, Second Conference on Pipework, Engineering and Operation, Institute of Mechanical Engineers, London, February 1989.
6. Fowler, J. R., C. R. Alexander, P.J. Kovach, and L.M. Connelly, *Cyclic Pressure Fatigue Life of Pipelines with Plain Dents, Dents with Gouges, and Dents with Welds*, Prepared by SES for the Offshore and Onshore Applications Supervisory Committee of the Pipeline Research Committee, PR-201-9324, 1995.
7. Kiefner, J. F., C. R. Alexander, and J. R. Fowler, *Repair of Dents Containing Minor Scratches*, Proceedings from Ninth Symposium on Pipeline Research, Houston, Texas, October, 1996.
8. Kiefner, J. F., and Veith, P. H., *A Modified Criterion for Evaluating the Remaining Strength of Corroded Pipe*, Project PR 3-805, Pipeline Research Committee, American Gas Association, December 22, 1989.

Table 1 Pipe Geometries and Material Properties

Pipe Designation	Pipe O.D. (Inches)	Pipe Thickness (inches)	Yield (ksi)	Ultimate (ksi)	Elongation (%)	Charpy [(1)] (ft-lbs)
A	12.75	0.188	53.9	76.8	35.0	47.0
A'	12.75	0.188	54.9	78.0	36.0	42.0
B	24	0.25	60.4	70.9	36.0	78.0
C	32	0.312	68.0	77.2	34.5	98.0

Notes:
1. Upper shelf energy as determined by means of Charpy V-notch impact specimens. All values are full-size equivalents

Table 2 Pressure Ranges for Fatigue Samples

Pipe Designation	Pressure for 100% SMYS (psi)	MOP (psi)	Upper Pressure Range, 50% MOP (psi)	Full Pressure Range, 100% MOP (psi)
A	1,533	1,104	550 - 1,100	100 - 1,100
A'	1,533	1,104	550 - 1,100	100 - 1,100
B	1,083	780	390 - 780	100 - 880
C	1,014	730	365 - 730	100 - 830

Table 3 Results of Tests on Unconstrained Dome-Shaped Dents

Experiment Number	Pipe Diameter & actual w.t. (inches)	Initial Dent Depth (%, d/D)	Elastic Rebound (%, d/D)	Elastic Recovery (%) (note *a*)	Number of Equivalent Cycles	Burst Pressure (psi) (%SMYS)	Residual Dent Depth (%,d/D) (note *b*)	Total Rerounding (%) (note *c*)	Post-failure Dent depth (%, d/D) (note *d*)
UD6A-2	12.75 X 0.191	6	4.55	24	1,307,223		1.55	74	4.25
UD12A-3	12.75 X 0.191	12	6.8	43	684,903		3.8	68	2.5
UD12A-6EW	12.75	12	6.3	48	24,701	>2000 (130)	3.8	68	
UD6A-9EW	12.75	6	2.6	57	24,701	>2000 (130)	1.4	77	
UD18A-10	12.75	18	10.7	41	N/A	2294 (150)			
UD12A-11	12.75	12	7.9	34	N/A	2314 (151)			
UD12A-16EW	12.75 X 0.191	12	7.7	36	22,375		4.2	65	1.4
UD12A-20GW	12.75 X 0.190	12	7.6	37	20,220		2.8	77	1.4
UD12A-21GW	12.75 X 0.191	12	6.8	43	38,972		2.6	78	1.5
UD18A'-28	12.75 X 0.194	18	11.3	43	101,056		2.6 [(e)]	86 [(e)]	0.7
UD12A-30EW	12.75 X 0.191	12	5.9	51	277,396		2.7	78	0.7
UD12A'-31GW	12.75 X 0.194	12	6.0	50	213,876		2.7	78	1.0
UD12A-32DD (double dent)	12.75 X 0.191	12	5.2 5.6	57 53	217,976		3.0 2.5	75 79	0.8 1.2
UD12A-33D (double dent)	12.75 X 0.188	12	4.4 4.0	63 67	249,816		2.1 2.0	83 83	0.7 1.0
UD12B-34EW	24 X 0.250	12	7.3	37	451,998		2.8	77	1.0
UD12B-35GW	24 X 0.251	12	6.8	43	458,590		2.5	79	1.0
UD12C-36SW	32 X 0.326	12	5.4	55	21,603		3.3	73	0.7
UD12C-37GW	32 X 0.330	12	4.5	63	108,164		3.0	75	2.0
UD18B-42	24 X 0.253	18	8.7	52	N/A				1.6
UD18C-44	32 X 0.320	18	9.2	49	N/A				3.8

Notes

(a) Quantity of maximum indentation minus elastically rebounded depth divided by maximum indentation

(b) At zero pressure after pressurization to 65% SMYS

(c) Quantity of maximum indentation minus total dent depth after 65% SMYS divided by maximum indentation

(d) After completion of all testing

(e) Estimated from the first dent made for this test that was pressurized to 65% SMYS, but had to be discarded due to another flaw in the specimen.

Table 4 Variations in Dent Depth for Unconstrained Dents Combined with Welds as a Function of Pressure

Experiment Number	D/t	Maximum Indentation	Dent Depths Measured at Zero Pressure		
			After 65% SMYS	After 90% SMYS	After 101.5% SMYS
UD12A'-30EW	68	12%	2.7%	1.3%	—
UD12A'-31GW	68	12%	2.7%	1.3%	—
UD12B-34EW	96	12%	2.8%	—	1.2%
UD12B-35GW	96	12%	2.5%	—	1.4%

Table 5 Unconstrained Dents and Effects of Hydrotesting

Experiment Number	Maximum Indentation	Dent Depth after 65% SMYS	Condition	Cycles to Failure
First Pair				
UD12A-16EW	12%	4.2	Not pretested	22,375
UD12A'-30EW	12%	2.7	pretested to 90% SMYS	277,396
Second Pair				
UD12A-20GW	12%	2.8	Not pretested	20,220
UD12A-31GW	12%	2.7	Pretested to 90% SMYS	213,876

Table 6 Test Results for Constrained, Smooth Dome-Shaped Dents

Experiment Number	Maximum Indentation, % of Diameter	Number of Equivalent Cycles	Final Dent Depth, % of Diameter
CD12A-15	12	426,585[(a)]	2.0[(b)]
CD24A'-26	24	98,483	15.1[©]
CD24A'-27	18	235,008	8.9[©]

[(a)] Test terminated before failure because constraint was lost.
[(b)] Includes rerounding under pressure when constraint lost.
[©] Result of elastic recovery at zero pressure upon release of constraint.