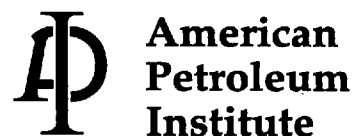


Effects of Smooth and Rock Dents on Liquid Petroleum Pipelines (Phase II)

API PUBLICATION 1156—ADDENDUM
OCTOBER 1999



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**FINAL REPORT
ADDENDUM TO API PUBLICATION 1156**

on

**EFFECTS OF SMOOTH AND ROCK DENTS
ON LIQUID PETROLEUM PIPELINES (PHASE II)**

to

THE AMERICAN PETROLEUM INSTITUTE

September 3, 1999

by

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EXECUTIVE SUMMARY

This report represents an addendum to API Publication 1156⁽¹⁾ which has the same title as this report, "Effects of Smooth and Rock Dents on Liquid Petroleum Pipelines". It presents a description of work which was done after the completion of API Publication 1156. The aim of the second phase of the work remained the same, namely to provide the liquid pipeline industry with information on how to deal with smooth and rock dents in pipelines. On the one hand if these dents pose a threat to pipeline serviceability, they need to be found and removed or repaired. On the other hand, to the extent that they do not pose a threat to pipeline serviceability, the industry can more effectively and justifiably spend maintenance dollars to address other safety-related issues.

As was the case in the first phase, the work of the second phase was largely experimental. Dents were created in actual line pipe materials. The specimens were then subjected to various types of service-simulating stresses. The results were assessed in terms of the effects of dent parameters on the modes of pipe failure and the stress levels or numbers of stress repetitions required to produce failures. The findings of the experimental work were used as the basis for a "field guide" to assist pipeline operators in evaluating the severities of smooth and rock dents in pipelines. The field guide is incorporated into this document as Appendix C.

As a separate issue, the effects of buckles in pipelines were also addressed briefly by means of three pressure cycle experiments. The objective of this work was to determine what degree of buckling if any, can be tolerated without significantly affecting pipeline integrity.

The essential findings of this work (based on both the Phase I and Phase II experiments) are that

- Dents (single unconstrained smooth dents) created by an external smooth object that was pressed into an unpressurized pipe rebounded due to elastic spring back upon release of the load. A substantial amount (up to two-thirds) of the initial indentation was recovered in this process. As internal pressure was applied the unconstrained smooth dents continued to reround and virtually disappeared as the pressure level was taken high enough to significantly exceed the yield strength of the pipe. Such dents had no deleterious effect on the burst pressure of the pipe in a one-time pressurization-to-failure. Similar results were achieved in prior

investigations; the study described herein merely reconfirmed what others had established.

- Single unconstrained smooth dents subjected to simulated operational pressure cycles of a range one-half the maximum operating pressure of most pipelines had fatigue lives greater than the expected life of most pipelines. Stress concentrating features within such dents such as girth welds, seam welds, and manufacturing score marks tended to reduce the fatigue lives of the affected dents, but the lives observed were still quite long, longer than the expected cyclic life of many pipelines.
- The most important parameters controlling fatigue lives were the radii of curvature at the location of the fatigue crack. An enlarged-radius transverse curvature (i.e., a flattened area) was found at all crack locations. The role of curvature in the axial plane was not as clear cut, but relative flattening in that direction appears to contribute to a shorter fatigue life. The relatively flat area between two "overlapping" dents has been the source of fatigue crack leaks on a few occasions in operating pipelines.
- Constrained dents designed to simulate rock dents exhibited a unique mode of failure (a transversely oriented fatigue crack propagating from the ID surface to OD surface) in response to large numbers of pressure cycles. The equivalent fatigue lives in the experiments were much greater than what would be expected for an unconstrained dent. No example of this mode of high cycle fatigue failure in an actual pipeline has been brought to our attention. However, it is entirely possible that rock dents in which the local shear stress is nearly high enough to cause shear failure of the wall thickness will be caused to fail with the application of relatively few cycles of stress.
- Puncture tests in which objects of two different shapes were pressed into a pressurized pipe produced failures in the form of transversely oriented shear cracks, the mode of failure most often associated with leaks at rock dents in actual pipelines.
- Fully-constrained dents containing axially-oriented external notches to simulate rock-contact damage or internal notches to simulate damage from the interference with pig passage exhibited fatigue failures in response to pressure cycles just like those of the constrained dents with no notches. In other words the leaks that developed were at transverse cracks that propagated from the ID surface to the OD surface. The fatigue cracks did not initiate from the notches. In contrast, when the constraint was partly or fully relaxed (i.e. the dent was allowed to flex) fatigue cracks developed quickly at the external notches. No internal notch was tested under these conditions.

- Pressure tests to failure of dents containing actual and simulated external corrosion-caused metal loss showed that corrosion in a shallow to moderate unconstrained dent has no more deleterious effect than the same amount of corrosion in an undented pipe.
- Some types of experiments conducted in this project were similar to experiments conducted in a project on dents sponsored by the Office of Pipeline Safety, U.S. Department of Transportation.⁽²⁾ It is significant that similar results were obtained in both projects in the cases where the experiments were of the same type.

The conclusions reached as a result of this work are as follows.

1. 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. The results were obtained in tests of pipes with diameter/thickness ratios of 68 or more. It is likely that pipe materials with lower diameter/thickness ratios would behave differently exhibiting less rerounding.
2. Pipeline operators need not be concerned about 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, or if it also contains some type of stress riser such as a score mark, a weld crown, a distinct crease or a crack.
3. Flattening of the pipe in conjunction with the area between two smooth dents or two rock dents may facilitate the development of a leak from fatigue crack growth within the useful life of the pipeline that is subjected to significant pressure cycles.
4. It is prudent to repair dents (or replace the pipe) involving a seam weld or a girth weld or score or trim mark if the depth of the dent exceeds 2 percent of the pipe's diameter.
5. Rock dents where the rock remains in place are of concern only to the extent that, if the load is great enough, the pipeline may be punctured. The mode of failure of such a puncture will be a leak not a rupture.
6. The results of this project suggest that aside from issues of corrosion control and monitoring, 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 that exceeds the shear strength of the wall thickness. The results further show that if deep dents exist, they are most likely constrained, and therefore, are most likely rock

*The level of cycles considered aggressive is discussed in the body of the report.

dents. Most people assume that dents found on the bottom half of the pipe are caused by rocks. 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.

7. Leaving "rock" dents in place undisturbed would be preferable to digging them up and removing the rocks, from a fatigue standpoint. It must also be pointed out that leaving rocks in place potentially creates increased risk of corrosion problems for the life of the facility.
8. For pipelines buried in stable soil areas, buckles of 2 percent or less of the pipe's diameter can be considered non-injurious.

It is important to note that before pipeline operators act on these conclusions, they should consider the possibility that some of them, particularly Number 4 and Number 8, may conflict with restrictions in the ASME B31.4 and B31.8 Code and certain parts of the U.S. Code of Federal Regulations, Title 49, Parts 192 and 195. To the extent that field experience continues to bear out the correctness of the data generated in this study and a similar study funded by the U.S. Department of Transportation a rationale may become available for changing the codes and regulations.

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**EFFECTS OF SMOOTH AND ROCK DENTS
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by

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1.0 INTRODUCTION

This report represents an addendum to API Publication 1156⁽¹⁾ which has the same title as that shown above. It presents a description of work which was done after the completion of API Publication 1156. Additional work has been done to address issues confronted but not resolved in the first phase of the work and to address new issues raised by the first-phase work. The aim of the second phase of the work remained the same, namely to provide the liquid pipeline industry with information on how to deal with smooth and rock dents in pipelines. On the one hand if these dents pose a threat to pipeline serviceability, they need to be found and removed or repaired. On the other hand, to the extent that they do not pose a threat to pipeline serviceability, the industry can more effectively and justifiably spend maintenance dollars to address other safety-related issues.

As was the case in the first phase, the work of the second phase was largely experimental. Dents were created in actual line pipe materials. The specimens were then subjected to various types of service-simulating stresses. The results were assessed in terms of the effects of dent parameters on the modes of pipe failure and the stress levels or numbers of stress repetitions required to produce failures. A limited amount of analytical work (finite element analysis) was carried out to clarify some of the experimental observations. The findings of the experimental work were used as the basis for a "field guide" to assist pipeline operators in evaluating the severities of smooth and rock dents in pipelines. The field guide is incorporated into this document as Appendix C.

The test methods and test apparatus used in the Phase II experiments were essentially the same as those used in the Phase I experiments. The descriptions of these items are contained in Section 4 of the Phase I report, and for that reason, they are not provided in this report. On occasion, the test methods for Phase II tests were modified from those of previous tests. When these variations exist, they will be reported for the applicable experiments.

As a separate issue, the effects of buckles in pipelines were also addressed briefly by means of three pressure cycle experiments. The objective of this work was to determine what degree of buckling, if any, can be tolerated without significantly affecting pipeline integrity.

One point should be kept in mind regarding this work and the conclusions. The results are applicable only to materials that can be expected to behave in a ductile manner in the presence of a defect. Most, but not all, line pipe materials fit that description. The implications of non-ductile (i.e. brittle) behavior are discussed in Appendix C.

The authors are grateful for the assistance provided by Mr. Michael J. Rosenfeld of Kiefner and Associates, Inc. in reviewing and critiquing the work. They are also grateful to Colonial Pipeline Company and Southern California Gas Company for contributing pipe materials for some of the tests. The authors would also like to thank the API's Operations Technical Committee for their support of both phases of the project and the members of API's Task Force on Mechanical Damage for their advice and assistance throughout both phases. The members of the Task Force are:

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2.0 BACKGROUND

In the previous work (Phase I) described in API Publication 1156⁽¹⁾ 42 full-scale pipe experiments were conducted to evaluate smooth and rock dents. For the purposes of this work a smooth dent is a region of altered pipe curvature created by an external force in which the changes in curvature are relatively gradual. It is also a region which contains no girth or seam weld, no stress concentrator such as a notch or crack, no mechanical or metallurgical damage, and no corrosion-caused metal loss. A smooth dent is not restrained; it is able to reround under the influence of increasing internal pressure in the pipe. A rock dent is a dent most commonly created by contact between the pipe and a rock, where a portion of the weight of pipe and its contents instead of being uniformly distributed along a bedding of soil is locally supported by the rock. The contact load can be sufficient to indent the pipe. Coating damage is often observed depending on coating type, coating properties, and bearing stress. The rock may or may not also cause local contact damage to the metal. Rock dents formed from the weight of the pipe, contents and overburden are necessarily located on the bottom half of the pipe. Occasionally, rock dents are created on the top half of the pipe by large rocks as the backfill is being pushed into the pipe by heavy equipment. Usually, rock dents are constrained from rerounding with increasing internal pressure. This feature and the possibility of mechanical damage to the pipe or its coating suggest that rock dents can be expected to have effects on the pipe which differ from that produced by smooth dents.

At the completion of the Phase 1 work, it was recognized that many issues concerning the behavior of smooth and rock dents had not been resolved satisfactorily. A second phase of the work was carried out to address these issues. To acquaint the reader with the key issues involved in both phases of the work, the following section of this report presents an overview of the experiments in both phases of the work.

3.0 OVERVIEW OF EXPERIMENTS

The 71 dent experiments* conducted in both Phase I and Phase II are summarized in Table A-1 of Appendix A of this publication. A detailed description of each experiment is available. The first 44 are described in Appendix B of API Publication 1156. The remaining experiments, No. 45 through No. 73 are described in Appendix B in this document. The mechanical properties of all material used in this program are summarized in Appendix B of this document as well. The three buckle experiments are described in this overview section.

3.1 Types of Dent Experiments, Objectives, and Results

3.1.1 Burst Test of Pipes Containing Unconstrained Dents of Various Shapes and Depths

"Burst test" experiments were conducted on five samples of 12.75-inch OD by 0.188-inch w.t. API 5L Grade X52 ERW line pipe into which dents of various shapes and depths were pressed. Details of each test are presented in Appendix B of API Publication 1156. The essential parameters are presented in Table A-1 of Appendix A of this document as well. The relevant experiments are Experiments 6 through 14. Three shapes of indenters were used: a sharply pointed steel pyramid, a smooth 8-inch diameter elliptically-shaped steel end cap, and a long 1-inch-diameter round steel bar. In each case the dent was pressed into an unpressurized pipe sample. In the cases of these burst tests where a round bar indenter was used, the long axis of the bar was aligned with the axis of the pipe. When the target dent depth was reached, the indenter load was released, and the dented pipe was allowed to rebound. Because the pipe samples were not supported laterally, some of their deflection under the indenter was in the form of ovalization. Hence, the elastic rebound consisted of both partial recovery of the circular cross section of the pipe and radially outward deflection of the dent. Four of these dents, located in a single pipe specimen, were first subjected to pressure cycles in the range of 36 percent of SMYS to 72 percent of SMYS, but an accidental overpressurization resulted in the samples bursting at a

* Seventy-three experiments were planned but Experiments 39 and 40 were not carried out. Hence, while 73 experiment numbers were created, only 71 tests were conducted.

pressure level well in excess of the actual yield pressure and in excess of 130 percent of SMYS. The failure originated at an area away from the dents, and the dents themselves were observed to reround with increasing pressure until all but the sharply pointed pyramid dent virtually disappeared. The other four specimens each containing a single dent, were intentionally pressurized to failure, and they too failed after sustaining much plastic strain at stress levels ranging from 150 to 164 percent of SMYS. All four failed at locations away from the dent, and all dents except the one made with the sharp pyramid rerounded completely.

These experiments confirm what has been found by other researchers,^[3,4,5,6] namely, that plain dents containing no significant cracks or stress concentrations have no significant effect on the burst strength of a pipe in a one-time pressurization to failure.

3.1.2 Cyclic Pressure Tests of Pipes Containing Unconstrained Dents of Various Shapes and Depths

Twenty-four experiments were carried out by subjecting samples of pipe containing unconstrained dents to repeated cycles of pressurization to simulate many years of service. The details of these experiments are contained either in Appendix B of the original API Publication 1156 (Phase I tests) or in Appendix B of this document (Phase II tests). The relevant experiments are Experiments 1 through 4, 16, 17, 28 through 38, 45, 46, 49, 50, and 59. Most were carried out on samples of 12.75-inch OD by 0.188-inch w.t. X52 pipe, but two experiments were carried out on 24-inch OD by 0.250-inch w.t. X52 pipe and two were carried out on 32-inch by 0.312-inch w.t. X52 pipe.

The unconstrained dents were created by pressing one of several indenters into an unpressurized sample of pipe to a predetermined depth, releasing the indenter load, and allowing the pipe and the dent to rebound elastically. The pipe in each case was supported opposite the indenter by a saddle which permitted unrestricted ovalization. Most of the ovalization was elastic and was thus recovered upon release of the indenter load. The dents recovered 24 to 67 percent of their target depth upon release of the indenter loads. The indenter shapes included the pyramid indenter (2 cases), the long bar indenter aligned with the axis of the pipe (2 cases), the long bar indenter oriented transverse to the axis of the pipe (1 case), the 8.625-inch-diameter

ellipsoidal cap (17 cases), the 4.5-inch-diameter ellipsoidal cap (1 case), and the 12.75-inch-diameter ellipsoidal cap (1 case).*

Each specimen containing an unconstrained dent was subjected to a single internal pressurization equal to 65 percent of SMYS or 72 percent of SMYS, after which the pressure was released and the amount of pressure-induced rerounding was determined. These dents recovered 57 to 90 percent of their initial target depths as the result of this single cycle of pressure-induced rerounding.

The amount of pressure-induced rerounding was found to depend on the level of internal pressure relative to the pressure corresponding to yielding. For example, the 12-percent initial dents in Experiments 34 and 35 had recovered 39 and 43 percent of their initial depths, respectively, solely from elastic rebound at zero pressure and 77 and 79 percent of their initial depths upon being pressurized to levels corresponding to 72 percent of SMYS. Upon being pressurized further to 101.5 percent of SMYS these same two dents had recovered 90 and 88 percent of their initial depths, respectively. The rerounded axial profiles after various levels of pressurization are shown for Experiment 31 in Figure 1.

The amount of pressure-induced rerounding was also dependent upon the shape of the dent. Those created by the sharp pyramid indenter remained deeper in the center than those made with the smooth profile of a dome-shaped indenter. The long dents made with the round bar rerounded more in the central region than at the ends. Such dents were characterized by relatively deeper "dimples" at their extreme ends. The rerounded shape of the long axial dent of Experiment 17 is shown in Figure 2. All of the above rerounding phenomena observed in these tests agree with the findings of previous researchers.^[2,3,4,5,6]

The specimens with unconstrained dents were subjected to cycles of pressure between 36 percent of SMYS and 72 percent of SMYS** until either a failure occurred or the number of cycles reached approximately 25,000. If no failure had occurred after that many cycles, the pressure range was increased. The larger range extended from 6.5 percent of SMYS to

* For convenience these ellipsoidal cap indenters will be referred to henceforth as the 8 inch dome, the 4 inch dome, and the 12 inch dome.

** In other words, the minimum pressure was 36% SMYS, the maximum was 72% of SMYS, the mean was 54% of SMYS and the range was 36% SMYS.

78 percent of SMYS or about twice the original range. In Appendix E of API Publication 1156 it is shown on the basis of Miner's rule and the DOE-B curve that the one cycle of the latter produces the equivalent fatigue effect of 16 cycles of the 36 to 72 percent of SMYS range. This is due to the assumed half-range S-N curve on a log scale having a slope of 4. This means that the number of "equivalent" half-range cycles is $N_{50} + 16 N_{100}$ where N_{50} is the number of 36 to 72 percent of SMYS cycles and N_{100} is the number of 6.5 to 78 percent of SMYS cycles.

It is noted that the stress range of 36 to 72 percent of SMYS, applied to an operating pipeline at the rate of one a day, would simulate some of the most aggressive cyclic service observed. This was shown by comparing the application of repeated half-range cycles to the effects of actual pipeline operating spectra for pipelines with known fatigue problems. The half-range cycles applied at a rate of one per day produced similar times to failure. (This is equivalent to a full range cycle, 0 to 72 percent of SMYS every 16 days, or 23 full range cycles per year.) It is also noted that 25,000 half-range cycles at one per day represents 68 years. For purposes of assessing the results of the experiments in a conservative manner, it was decided that "severe pressure cycling" would be defined as 2 half-range cycles per day even though calculations suggested that one per day was equivalent to some actual cases where fatigue is known to be a problem. One reason for making this the definition of severe cycling is that it is suspected that "ghost" cycles may occur on liquid pipelines. These cycles arise from surges which travel too fast to be accurately measured by normal pressure recording devices but can be detected by dynamic measurements. Surges occur when valves are closed or opened rapidly and when pumps are started or stopped. Since normal cycles also arise in response to these routine operations, it is conservative to assume that an unrecorded surge may occur for every large measured cycle. Thus, any dent which survived 15,000 of the half-range cycles would have been expected to survive about 20 years of service.

Except for the two "pyramid" dents and one of the shallower dome dents, the unconstrained dents eventually developed fatigue cracks and leaks. Three types of fatigue failures were observed. All resulted in leaks, not ruptures. The more common mode of failure for a smooth dome dent was that shown in Figure 3. This mode of failure consisted of an axially-oriented fatigue crack which initiated on the sloping surface at one end of the dent. In all cases the crack initiated at the OD surface and grew to the ID surface. The slightly less common

mode of failure for a smooth dome dent was that shown in Figure 4. In these cases an axially-oriented fatigue crack initiated in the central, deepest region of the dent. The crack initiated at the OD surface and grew to the ID surface. The third mode of failure, shown in Figure 5, was associated with tests of the long axially dented specimens. In these cases an axially-oriented fatigue crack initiated in one or the other of the dimples on either end of the dent. The location was always on the slope nearer the center of the dent. In all cases, the crack initiated at the OD surface and grew to the ID surface.

The results of the unconstrained dent tests are summarized in Table 1.

Several observations can be made on the basis of these results.

- Not one of the totally smooth dents (those with no weld or score mark) would have been expected to cause a leak in a pipeline within the normally expected life of the pipeline. The shortest life (101,056 cycles in Experiment 28) corresponds to 138 years of service at two cycles per day with a range of half of the MOP.
- Features such as the presence of girth welds and seam welds within the dents produced the shortest fatigue lives (Experiments 16, 17, 20, 21, and 36). These features clearly facilitated fatigue crack initiation. Experiment 20 leaked in 20,220 cycles corresponding to 28 years of service at two half-range cycles per day.
- All of the fatigue cracks were axially oriented, all propagated from the OD surface to the ID surface, all failed as leaks, and all initiated within a dented region.
- There is no consistent relationship between the dent depths (either the initial depths or the depths at the pressurization to 72 percent of SMYS) and the fatigue lives.
- The two specimens which were subjected to a hydrostatic test to 101.5 percent of SMYS prior to being pressure-cycled (Experiments 34 and 35) exhibited relatively long lives in spite of being dents which contained an ERW seam and a girth weld. The additional rerounding associated with the high pre-cycle pressure test apparently reduced the local alternating stress.
- The fatigue cracks tended to initiate in one of two characteristic locations. The majority initiated on the sloping regions toward the flanks of the dents rather than in the deepest parts (centers) of the dents. Some did initiate in the centers, however. The most important factor governing the location of crack initiation appears to be curvature. The role of curvature became better understood following tests conducted later in the project. These latter tests are discussed in the subsequent sections of this report.
- The finding that stress concentrators reduce fatigue lives of otherwise smooth unconstrained dents is consistent with the findings of the Type A dents in work sponsored by DOT.⁽²⁾

Table 1. Results of Unconstrained Dent Tests

Experiment Number	Type of Indenter	Initial Depth, % of Pipe Diam.	Dent Depth After 72% of SMYS, % of Pipe Diam.	Final Depth % of Pipe Diam.	Equivalent Half-Range Cycles to Failure	Figure No. Which Shows Leak Location(s)
1	Pyramid	6	2.6	2.7	1,307,223	no leak
2	8" dome	6	1.5	1.3	1,307,223	no leak
3	8" dome	12	3.8	2.5	684,903	3
4	Pyramid	12	4.4	4.5	1,307,223	no leak
16	8" dome on ERW seam	12	4.2	1.4	22,375	3
17	long bar on ERW seam	12	1.1 ^a	1.6 ^b	62,647	5
20	8" dome on girth weld	12	2.8	1.4	20,220	3&4
21	8" dome near girth weld	12	2.6	1.5	38,972	3
28	8" dome	18	2.6	0.7	101,056	4
29	long bar	18	n.a.	n.a.	148,512	5
30	8" dome on ERW seam	12	2.7	0.7	277,396	4
31	8" dome on girth weld	12	2.7	1.0	213,876	4
32	8" dome ^c	12	3.0	0.8	217,976	3
33	8" dome ^c	12	2.1	0.7	249,816	4
34	8" dome on ERW seam ^d	12	2.8	1.0	451,998	3
35	8" dome on girth weld ^d	12	2.5	0.7	458,590	4
36	8" dome on DSAW seam ^e	12	3.3	2.0	21,603	3
37	8" dome on girth weld ^e	12	3.0	1.6	108,164	3
38	Long bar transverse	12	2.0	1.2	266,567	3
45	4" dome	18	3.5	1.6	168,719	3
46	12" dome	18	1.9	0.3	452,995	3
49	8" dome on ERW seam	18	3.4	1.1	104,766	3
50	8" dome on girth weld	18	3.7	1.7	118,894	4
59	8" dome	18	2.4	n.a.	422,626	3

a Measured at center of dent

b Measured at dimple.

c Planned as double-dent tests but dents too far apart to interact.

d 24-inch OD pipe, pressurized to 101.5% of SMYS before pressure cycling.

e 32-inch OD pipe

3.1.3 Cyclic Pressure Tests of Pipes Containing Constrained Dents of Various Shapes and Depths

Six experiments were carried out by subjecting samples of pipe containing constrained dents to repeated cycles of pressurization to simulate many years of service. The details of these experiments are presented either in Appendix B of API Publication 1156 or in Appendix B of this document. The relevant experiments are Experiments 15, 25, 25, 27, 47, and 48. These are also summarized in Table A-1 of Appendix A of this document. All six experiments were carried out on 12.75-inch OD by 0.188-inch w.t., X52 pipe.

The constrained dents were designed to simulate rock dents. The idea was to indent the pipe and to hold the dent fixed while the pipe was subjected to pressure cycles. A frame described in API Publication 1156 was designed to hold the dents. Each dent was pressed into the unpressurized pipe* to a target depth, and that depth was held throughout the pressure-cycling. The pressure-cycling was conducted at the range of 36 percent of SMYS to 72 percent of SMYS until either a leak occurred or approximately 25,000 cycles had accumulated. If no leak had occurred by that time the range was changed to 6.5 percent of SMYS to 78 percent of SMYS, and cycling was continued until failure, or until an excessive number of cycles was achieved.

The results of the pressure-cycle tests on the six constrained dents are shown in Table 2.

Table 2. Results of Pressure-Cycle Tests on Constrained Dents

Experiment Number	Type of Indenter	Initial Depth, % of Pipe Diam.	Equivalent Half-Range Cycles to Failure	Type of Failure
15	8" Dome	12	> 426,585	No failure
25	Pyramid	6	> 400,000	No failure
26	8" Dome	24	98,483	See Figure 6
27	8" Dome	18	235,008	See Figure 6
47	4" Dome	24	64,158	See Figure 6
48	12" Dome	24	374,822	See Figure 6

*It is believed that most rock dents are formed when the pipeline is laid empty and that they reach most of their final depth when the pipeline is first filled with hydrostatic test water. Settlement around the rock may occur later while the pipeline is in service, but most of the deformation is believed to occur prior to the hydrostatic test. Hence, the dents were created at zero pressure.

In the four cases where failure occurred, the mode of failure in every case was a leak at a fatigue crack oriented transverse to the axis of the pipe just beyond the point where the indenter and the pipe were in contact. The orientation and location are shown generically in Figure 6. In every case the crack initiated at the ID surface and propagated to the OD surface. The other two tests were terminated before leaks developed because the simulated cyclic pressure service was well beyond the expected useful life of a pipeline. In fact, the shortest life observed for a constrained dent (Experiment 47), 64,358 half-range cycles, is equivalent to 88 years of N_{50} cycles at two cycles per day.

The observations that arise from the tests of constrained dents are as follows.

- The mode of failure of this type of dent is distinctly different from that of the unconstrained dents.
- The numbers of pressure cycles required to cause the failures were greater than the normal expected life of a pipeline.
- The locations of the cracks being just beyond the edge of the indenter suggest that region as exhibiting the highest strain changes in response to pressure changes.
- The first two factors above suggest that this mode of failure may not occur in an actual pipeline. In fact, no such failure has ever been brought to our attention.
- The work sponsored by the DOT⁽²⁾ also showed that restrained dents have long fatigue lives and that one mode of failure of such dents can be a transverse fatigue crack propagating from the ID surface.

3.1.4 Puncture Tests

One mode of failure that has been observed in both gas and liquid pipelines has been that of a leak at a point where the pipeline is bearing on a rock. Examinations of these failures (see field guide section for an example) reveal that they result from the local bearing load exceeding the shear strength of the pipe wall and that the failure mode is that of a transversely-oriented shear, brittle, or mixed-mode failure. To examine the important parameters involved in this type of failure, six puncture tests were carried out. The method of testing in five cases involved slowly pushing a puncturing implement into a sample pressurized to 72 percent of SMYS until a leak occurred. In one case the puncturing implement was pushed into the pipe at zero pressure.

The implement was then held fixed at the target indentation level as the specimen was pressurized to failure. The details of the puncture experiments (Experiments 5, 14, 23, 24, 55, and 58) are presented either in Appendix B of API Publication 1156 or Appendix B of this document. The test parameters are also presented in Table A-1 of Appendix A of this document. The essential results of the puncture tests are presented in Table 3.

Table 3. Results of Puncture Tests

Experiment Number	Type of Indenter	Type of Pipe	Pressure During Puncturing, psig	Indentation at Puncture % of Pipe Diam.	Puncture Load, lb	Ratio of Puncture Load to Wall Thickness ^c X10 ⁻³
5	Pyramid	12.75"x0.188", X52	1100	11.9	26,520	141
14	Pyramid	12.75"x0.188", X52	1100 ^a	12	not determined	
23	Pyramid	24"x0.312", X52	780	3	39,780	159
24	Pyramid	12.75"x0.188", X52	657 ^b	2.7	57,460	184
55	1" ball	12.75"x0.188", X52	1104	12.3	32,340	172
58	1" ball	12.75"x0.375", X52	220	17.3	70,720	189

a An indentation of 12 percent was made at zero pressure and held fixed while the pressure was raised steadily.

b This pressure level corresponds to 65% of SMYS, not 72% of SMYS.

c This comparison makes sense only because the contact area of the punching devices was similar. The grossly simplified concept is that a load applied locally to a small circular contact area will punch through the wall thickness when the shear stress at the edge of the circular area reaches the critical value, S_{cr} , for failure. The ratio of load, P , to wall thickness, t , is $P/t = 2\pi r S_{cr}$, where r is the radius of the contact area.

The mode of failure in every case was a leak. A transversely-oriented shear crack was observed to have formed at the edge of the indenter contact point in every case. The ratios of the puncture load to the wall thickness (ignoring variations in actual thicknesses and yield strengths) range from 141 to 184. This suggests that the failures occurred when the shear stress exceeded the capacity of the wall thickness.

3.1.5 Tests of Notched and Dented Samples

While the focus of this project was on smooth and rock dents, it was recognized that rock dents could involve yielding or crushing at the point of contact and that deep rock dents could

become damaged internally during the passage of pigs. It was also of interest to determine what might happen if some or all of the constraint was lost at a rock dent where external metal damage existed. Six samples were prepared with notches associated with dents. The details of all six are contained entirely within this document (Table A-1 of Appendix A and Appendix B). The experiments are Experiments 51, 57, 53, 59, 57, and 60. All were conducted on samples of 12.75-inch OD by 0.188-inch w.t., X52 material. Five involved pressure-cycle tests and one (Experiment 60) involved a burst test. The latter test exhibited an unexpectedly high burst pressure because of a unique material behavior as explained in Appendix B. Therefore, it offers no useful information regarding possible rock damage in a dent. So, the following discussion is confined to the results of the five pressure-cycle tests.

In four of the five tests 6-inch-long, axially-oriented, 10 percent through-wall V-notches were machined into an undented sample. The unpressurized sample was then indented to a predetermined depth with one of the dome indenters centered on the notch. At that point the dent was held fixed, partly fixed, or it was allowed to reround freely. In Experiment 54 the dent was pressed and held fixed while an internal axial notch was machined into the inward-bulging pipe wall. The maximum depth of this notch was 10 percent of the wall thickness. Because it had to be machined by a linear motion, its depth was deepest at the center of dent, and it became shallower and disappeared within an inch on either side of the center. This specimen was tested in the fully-constrained condition. All five specimens were subjected to pressure cycles of the two ranges described previously. The results are summarized in Table 4.

Table 4. Results of Tests of Notched and Dented Samples

Experiment Number	Type of Indenter	Initial Depth, % of Pipe Diam.	Notch Location	Constraint Condition	Equivalent Cycles to Failure $N_{50} + 16 N_{100}$	Nature of Failure
51	4" Dome	18	External	Full	91,281	Transverse crack
52	12" Dome	18	External	Full	>207,825	No failure
53	4" Dome	18	External	Partial ^a	1146	Leaked at notch
54	8" Dome	18	Internal	Full	153,443	Transverse crack
57	4" Dome	18	External	None	5,324	Leaked at notch

^a Constraint maintained through elastic spring system; see Appendix B for details. The failure initiated in the notch, but the location was in an outward-bulging hump which developed during the test (See Figure 7 for location).

In the cases of the fully-restrained dents, the presence of a notch (external or internal) had no effect on the failure behavior. Two of the specimens (Experiments 51 and 54) developed transverse cracks just beyond the edge of the constraint in the same manner as in the unnotched constrained dent tests (see Figure 6 for location). These cracks initiated at the ID surface and grew to the OD surface just like the cracks in the unnotched constrained dent tests.

The failures in the notched specimens with partially constrained or unconstrained dents were strongly influenced by the presence of an external notch. At a cyclic rate of two per day, the life of the pipe in Experiment 53 would have been just over 1½ years, and the life of the pipe in Experiment 57 would have been about 7 years.

From these results one might reasonably conclude that;

- Metal damage created either externally by a rock or internally by a pig at a rock dent is of no consequence as long as the pipe is fully-constrained from movement in response to pressure cycles. Unless the pipeline is lifted off the rock, the nature of the overburden is changed, or the rock is removed, it is probable that the dent remains fully restrained.
- The situation changes dramatically if the pipe is free or partly free to reround or flex in response to pressure cycles. In that case the time to failure at an area of metal damage within a dent may be quite short. Such situations might be expected to occur if the pipeline is raised, if the overburden is removed or washes away, or if the rock is removed.
- The finding that notches greatly reduce the fatigue life of an unrestrained or partially restrained dent is consistent with the findings of the work sponsored by the DOT.⁽²⁾

3.1.6 Burst Tests of Pipes Containing Corrosion Within a Dent

Recognizing that rock dents and some types of smooth dents may be affected by external corrosion caused metal loss, the task force desired to examine the effects of a dent in combination with metal loss. The purpose of the tests was to determine whether or not a given amount of metal loss would fail at a lower pressure level if located in a dent than it would if the dent were not present. One type of test involved creating machined metal loss, indenting the metal-loss area by centering the indenter over the metal loss area, pressurizing the specimen to

failure, and comparing the burst pressure to the RSTRENG-predicted* burst pressure. In these types of tests one-half of the wall thickness was machined away over a substantial axial length and circumferential width. The other type of test involved accelerated corrosion of a piece of dented pipe (two separate dents) while the pipe was held at a constant level of internal pressure. All corrosion-in-dent tests were carried out on 12.75-inch OD by 0.188-inch w.t. X52 pipe. The detailed results of the first type of test are presented in Appendix B of API Publication 1156 (Experiments 18, 19, and 22). The detailed results of the second type of test (Experiment 56) are presented in Appendix B of this document. The essential parameters of all four tests are presented in Table A-1 of Appendix A of this document. The results are summarized in Table 5.

Table 5. Results of Burst Tests of Pipes Containing Corrosion Within a Dent

Experiment Number	Type of Indenter	Initial Depth, % of Pipe Diameter	RSTRENG-Predicted Failure Pressure, psig	Actual Burst Pressure, psig	Actual Exceeded RSTRENG-Predicted
18	8" dome	12	1136	1365	Yes
19	Long Bar	12	1136	1358	Yes
22	Long Bar	18	1071	881	No
56 ^a	8" Dome	18	669	1100	Yes
56 ^b	8" Dome	18	1339	1762	Yes

^a Dent A failed during holding at 1100 psig. Dent B was then pressurized to failure.

In four cases the actual burst strengths exceeded the RSTRENG-predicted values. In the case of Experiment 22, the burst pressure was significantly lower than the RSTRENG-predicted value. The reason for the latter result being quite different from the others is not fully understood. The principal difference between it and the others is the depth of the dent. Perhaps during the indentation to 18 percent, the remaining thickness in the machined area was severely damaged. Except for this one extreme example, it appears that corrosion in a dent behaves like corrosion that is not in a dent.

* RSTRENG^[7] is a well-known method of evaluating the remaining pressure-carrying capacity of a pipe which has sustained corrosion-caused metal loss. The method is based on tests of non-indented corroded pipe.

3.1.7 Pressure-Cycle Tests of Two Interacting Dents

One type of leak observed on occasion in a liquid petroleum pipeline is caused by axially-oriented fatigue cracks which develop in a region of altered curvature between two dents separated along the axis of the pipe. The generic configuration of the crack in relation to the dents is shown in Figure 8. It is believed that these situations arise when two rock dents exist in close proximity. It is also believed that the rock dent regions probably were restrained, but the "flattened" area between the rocks was free to flex in response to pressure variations. A special test apparatus was designed to produce simulated double constrained dents, and eight such specimens were tested. These experiments, Experiments 61 through 68, are described in detail in Appendix B of this document, and their essential parameters are summarized in Table A-1 of Appendix A of this document. All of the experiments were carried out on 12.75-inch OD by 0.188-inch w.t. X52 pipe. The indenter in each case consisted of either two 4-inch domes separated by $\frac{1}{2}$, 1, 2, or 3 dome diameters or two 8-inch domes separated by 1, 2, or 3 dome diameters. The dents separated by $\frac{1}{2}$ -dome-diameter had to be altered by cutting away some of each dome in order to achieve the desired spacing. The latter arrangement was used only after it was discovered that the desired behavior could not be achieved with the larger spacings. Each test was conducted by first pressing the double dent into the unpressurized specimen to a depth of 6 percent of the pipe's diameter. Then, pressure cycling of the two ranges discussed previously was carried out until a leak developed. Because of the development of leaks from transverse cracks, an unintended result, the constraint was released at some dents and pressure cycling was resumed with the dents unconstrained. Some cracks of the type shown in Figure 3 then developed. It was only when the cracks appeared at the location shown in Figure 8 that the tests were considered successful in terms of reproducing failures of the type exhibited by double dents in actual pipelines.

Table 6. Results of Pressure-Cycle Tests on Double Dents

Experiment Number	Type of Indenter	Spacing of Dents, inches	Equivalent Half-Range Pressure Cycles to Failure Constrained	Equivalent Half-Range Pressure Cycles to Failure Unconstrained	Applicable Figure Showing Crack Location
61	4" dome	4	92,910	—	Figure 6
62	4" dome	8	92,910	—	Figure 6
63	4" dome	12	92,910 (no failure)	193,152	Figure 3
64	8" dome	8	371,594 (no failure)	51,952	Figure 3
65	8" dome	16	371,594	—	Figure 6
66	8" dome	24	371,594 (no failure)	62,576	Figure 3
67	4" dome	2¼	1,600 (no failure)	346,435	Figure 8
68	4" dome	2¼	—	227,600	Figure 8

The transverse fatigue cracks which propagated from the ID surface to the OD surface at one of the dents in Experiments 61, 62, and 65 were identical to those that were observed in four of the constrained dent experiments (Experiments 26, 27, 47, and 48). The axial fatigue cracks which propagated from the OD surface to the ID surface at one of the dents in Experiments 63, 64, and 66 were identical to those that were observed in numerous unconstrained dent experiments (see Table 1). Neither of these modes of failure duplicated the mode of failure observed in several double-dent service failures. However, the axial cracks which propagated from the OD surface to the ID surface in Experiments 67 and 68 were located in the outward curving area between the two dents as shown in Figures 9 and 10. The numbers of half-range cycles required to produce the leaks in Experiments 67 and 68 (346,435 and 227,600) are much too high to represent the pressure-cycle/strain-range conditions which must have caused the observed service failures. Nevertheless, our ability to reproduce the mode of failure suggests that the interacting double dent situation in a pipeline is potentially injurious. The difference in the case of the service failures may be the degree of strain range severity associated with the particular curvatures involved. This hints at the possibility that curvature and not dent depth, per se, is the primary factor which controls the fatigue life of a smooth dent.

3.1.8 Special Pressure-Cycle Tests of Dents to Study the Effects of Curvature

The last series of dent tests involved pressure-cycle tests of special dents designed to produce deep dents with smooth curvatures that would not reround as readily as had other smooth dents. In this manner, it was felt that if dent depth is really the important parameter, these dents would have shorter fatigue lives than some of the unconstrained smooth dents previously examined. On the other hand if curvature is the important parameter, it was hoped that a trend with variations in curvature could be established.

All five tests in this series (Experiments 69 through 73) were conducted on 12.75-inch OD by 0.188-inch w.t. X52 material. The detailed descriptions of these experiments are provided in Appendix B of this document and the essential parameters are presented in Table A-1 of Appendix A. The dent-fabrication procedure consisted of indenting an unpressurized pipe to the target dent depth level, holding the dent constrained while pressurizing the specimen to a level corresponding to 72 percent of SMYS, and then releasing the constraint so that the dent could reround. The dents created in this manner usually did not reround to the extent of those which were rerounded without first being subjected to pressure while constrained. Table 7 provides representative comparisons.

**Table 7. Comparisons Between Depths of
Rerounded Unconstrained Dents and Those
of Dents Created by Pressurizing with Constraint**

Target Dent Depth, % of Pipe Diam.	Depths after Pressurization with No Constraint, % of Pipe Diameter	Depths After Pressurization with Constraint, % of Pipe Diameter
6	1.6 (8" dome—Experiment 2)	1.8 (4" dome—Experiment 69)
12	2.0 to 3.0 (8" dome—Experiments 32, 33)	3.5 (4" dome—Experiment 70)
12	2.0 to 3.0 (8" dome—Experiments 32, 33)	1.5 (8" dome—Experiment 73)
18	3.6 (4" dome—Experiment 45)	6.9 (4" dome—Experiment 71)
24	N.A.	7.2 (4" dome—Experiment 72)

In 3 to 5 cases the constraint during pressurization resulted in deeper dents after rerounding, one other did not and one is not known. But, at least in the case of Experiments 71 and 72 the dents

were deeper than any others in the program that had sustained pressurization to 72 percent of SMYS.

It is useful to refer to the dents created by constraint during initial pressurization as "special" dents not only because of the way in which they were created. They are special also in the sense that at least four of the five (the ones created with the 4 inch dome) rerounded to visibly unusual shapes. Instead of rerounding in proportion to their initial depths at each point, these special dents appeared to reround nonuniformly with some central portion of each dent rerounding somewhat like a rigid body. The result was the formation in each case of a concentric "hump" of the shape portrayed by Figure 7. In other words, the severe plastic deformation and cold work produced a center section having a shape resistant to rerounding. Internal pressure caused this more-rigid center section to push out as a unit while the more-flexible pipe wall adjacent to it responded by yielded and deforming. The humps were formed on the first cycle and were easily visible for the dents of Experiments 71 and 72 (the 18 and 24 percent dents, respectively). They appeared at the dents in Experiments 69 and 70 (the 6 and 12 percent dents) after the specimens and had been pressure cycled to the point of leakage. The hump in Experiment 73 (indented with the 8 inch dome) was barely visible but was detected by careful measurement. Detailed axial profiles through each of these dents are presented in Appendix B of this document.

The results of the pressure-cycle tests of the special dent samples are presented in Table 8 along with a few selected smooth unconstrained dents formed at zero internal pressure.

Table 8. Results of Pressure-Cycle Tests of Special Dents and Selected Unconstrained Dents

Experiment Number	Type of Indenter	Initial Dent Depth, % of Pipe Diam.	Dent Depths After 72% SMYS, % of Pipe Diam.	Final Depth, % of Pipe Diam.	Equivalent Cycles to Failure	Figure No. Which Shows Leak Location(s)
69 ^(a)	4" dome	6	1.8	0.7	359,350	4
70 ^(a)	4" dome	12	3.5	2.3	263,910	7
71 ^(a)	4" dome	18	6.9	4.9	204,246	7
72 ^(a)	4" dome	24	7.2	5.0	234,934	7
73 ^(a)	8" dome	12	1.5	1.0	263,382	4
2	8" dome	6	1.5	1.3	1,307,223	no leak
3	8" dome	12	3.8	2.5	684,903	3
28	8" dome	18	2.6	0.7	101,056	4
32	8" dome	12	3.0	0.8	217,976	3
33	8" dome	12	2.1	0.7	249,816	4
45	4" dome	18	3.5	1.6	168,719	3
46	12" dome	18	1.9	0.3	452,995	3
59	8" dome	18	2.4	n.a.	422,626	3

(a) Special dent created by pressurizing once to 72% SMYS while constrained.

One thing these results show is that the fatigue life is not related to dent depth. The best clue to the parameter most likely to control fatigue life was provided by curvature measurements made on the special dents after they had developed leaks. The curvatures were measured as described in Appendix B and the results are as shown in Table 9.

Table 9. Curvatures at Key Locations in the Special Dents

Experiment Number	Equivalent Half-Range Cycles to Failure	Minimum Radius of Curvature, in. ^b			
		Axial Profile at Center of Dent	Axial Profile at Leak	Transverse Profile at Center of Dent	Transverse Profile at Leak
69 ^a	359,350	-4.5	-4.5	>> 12	>>12
70	263,910	-3.4	+2.0	-4.4	+12.3
71	204,246	-2.8	+2.0	-7.7	+17.2
72	234,934	-2.3	+2.4	-6.9	+21.4
73 ^(a)	263,382	-13.7	-13.7	+11.5	+11.5

a Location of leak coincides with center of dent.

b Positive sign on radius of curvature means outward curvature (same as the pipe). Negative sign on radius of curvature means inward curvature (opposite pipe curvature). Undeformed radius of curvature = +6.375 inch.

Prior to making these curvature measurements, it was already known from the unconstrained dent experiments that the center of the dent is not always the place that a fatigue crack develops. In fact, while some dents did exhibit cracks at their centers (as shown in Figure 4) the majority exhibited cracks in the location shown in Figure 3. The curvature measurements tend to explain why cracks might occur in these particular areas. The data in Table 9, especially the transverse curvatures show that the cracks occurred in the locations having a radius of outward curvature larger than the radius of the pipe, in other words a large degree of flattening. The transverse curvatures in the centers of the dents of Experiments 69 and 73 were very large and the cracks initiated in the centers of those dents. In contrast, the curvatures in the centers of the dents in Experiments 70, 71, and 72 (in fact, the deepest dents) were smaller and inward-curving. The cracks in these experiments initiated in areas where the transverse curvatures were large.

The next logical step was to examine the axial curvature at the crack. For the cases where the cracks initiated at the centers of the dents (Experiments 69 and 73), the one with the more flattened axial curvature (Experiment 73) had the shortest fatigue life of the two. For the cases

where the cracks initiated in the "humped" areas (Experiments 70, 71, and 72), the axial curvatures were nearly the same, the transverse curvatures were all large, and the fatigue lives were similar.

The pattern that emerges suggests that the more flat the transverse curvature, the shorter will be the fatigue life. The role of axial curvature is not clearcut, but the behaviors observed at double dents where service failures have arisen from cracks in the flattened area between the dents strongly suggests that increased flatness in both directions leads to shorter fatigue life. This possibility is believable because a flat plate offers the least resistance to internal pressure of any shape in terms of strain response.

3.2 Buckle Experiments

With the emergence of curvature as possibly the most significant factor in the fatigue life of a dent, it was felt that another curvature-affecting phenomenon, buckles should be addressed. Currently, buckles which occur in liquid petroleum pipelines must be repaired irrespective of size under current ASME B31.4 requirements. However, it appears from what we have learned about dents, that small buckles might not pose a significant threat to pipeline integrity. A brief experimental program was designed around three intentionally-induced buckles in pieces of 36-inch OD by 0.281-inch w.t. API 5L Grade X52 line pipe (SAW longitudinal seams). Each sample was buckled by means of cold bending an unpressurized pipe with no internal mandrel. The intent was to obtain buckles of 2, 4, and 6 percent buckle height (peak-to-trough) as a percent of pipe diameter. These buckles were typical but more extreme than the somewhat common ripples that can occur during cold field bending. It has long been felt that these ripples are non-injurious. The experiments were intended to confirm that observation. The nature of these buckles is shown in Figures 11, 12, and 13. As can be seen, each buckle consists of several circumferential nodes. The dimensions of these buckles, at least, the worst case axial profiles, are shown in Figure 14. The maximum peak-to-trough heights prior to pressurization were 1.7, 3.7, and 6.9 percent of the pipe diameter, for Buckles 1, 2, and 3, respectively.

Caps were welded on the ends of each buckled sample, and each sample was subjected to pressure cycles until failure. The pressure cycle range in each case was 100 psig (12 percent of

SMYS) to 684 psig (84 percent of SMYS). The results of the pressure cycle tests were as follows.

Buckle Number	Depth of Buckle	Cycles to Failure	Failure Location
3	6.9%	1086	See Figure 11
2	3.7%	2791	See Figure 12
1	1.7%	44,541*	No failure

In the cases of those buckles which did exhibit leaks (Buckles 2 and 3) the leaks developed as diagonally oriented cracks at the locations shown in Figures 11 and 12. The radii of curvatures of these two regions were determined roughly to be 26 inches and 28 inches, respectively. The locations and orientations of the cracks appear to be unique to the buckled geometry and are not easily related to the dent results. Both cracks initiated at the OD surface.

4.0 FINDINGS OF EXPERIMENTAL WORK

The findings for the entire program (Phase I and Phase II) are presented below. In a few cases the Phase II results cause the Phase I findings stated in API Publication 1156 to be viewed in a different light. In these cases the revised view of the findings is indicated. Readers are reminded that these results are applicable to materials which can be expected to behave in a ductile manner in the presence of a defect. It is possible that materials which have a tendency to fail in a brittle manner in the presence of a defect would fail at lower pressure levels and have a greater tendency to exhibit ruptures than the materials considered in this work.

- As has been demonstrated in several investigations, unconstrained smooth dents with no stress concentrators had no effect on the ultimate pressure carrying capacity of pressurized pipe in a one-cyclic pressurization to failure. This finding

* Test terminated, no evidence of cracking. The two samples which leaked exhibited diagonally-oriented cracks. These cracks initiated at the OD surface at the locations shown in Figures 11 and 12. The third specimen (Buckle No. 1) showed no signs of developing a leak at 44,541 cycles, so the test was terminated. The maximum transverse radii of curvature for the three specimens were 26, 28, and ---- inches for Buckles 3, 2, and 1, respectively.

remains unchanged from Phase I. No new tests of the type were conducted in Phase II.

- When the indenting loads were removed, the unconstrained smooth dents made with no pressure in the pipe rebounded elastically to an extent in the range of 24 to 67 percent of the maximum indentation. The unconstrained smooth dents rerounded to an ever-increasing degree with increasing internal pressure until they virtually disappeared as the pressure level approached the burst pressure of the pipe. At pressure levels of 65 to 72 percent of SMYS, the rerounding resulted in 57 to 90 percent recovery of the maximum indentations. Similar rerounding takes place at a constrained dent if the constraint is removed. This rerounding behavior has been clearly described by prior investigators, so it came as no surprise. The Phase II results added additional confirmation of this behavior
- In the Phase I work it was observed that for unconstrained smooth dents the deeper the rerounded dent at the start of pressure-cycling, the shorter the fatigue life. This finding was based on one uniform shape of dent (all made with the 8 inch dome). The Phase II work showed that when dents of different shapes are involved, the parameter of dent depth by itself is not a reliable indicator of fatigue life.
- Taken together, the results of Phase I and Phase II strongly suggest that the local circumferential curvature within the area affected by a single smooth dent controls the location where an axially-oriented fatigue crack will initiate and influences the number of pressure cycles of a given range required to cause a leak. In terms of circumferential curvature, the locations most likely to develop fatigue cracks were those with large convex (outward bulging) radii of curvature (two or more times the normal radius of the pipe). In single smooth dents cracks were observed to initiate in both areas of convex axial curvature (outward bulging, see Figure 3) and concave (inward bulging, see Figure 4) curvature, but whatever axial location, the location of crack development was always a location with a large convex, circumferential radius of curvature.
- The pressure cycle range of 36 percent of SMYS to 72 percent of SMYS was compared to actual operating spectra for aggressively-cycled pipelines (where material defects and mechanical damage have produced service failures after exhibiting fatigue crack growth). A spectrum of the 36-percent-of-SMYS-to-72-percent-of-SMYS (i.e., equivalent) cycles applied twice per day is thought to produce comparable fatigue crack growth. Therefore, 15,000 cycles of this magnitude is equivalent to about 20 years of severe pressure-cycle service.
- The least number of equivalent half-range cycles observed to produce a fatigue failure at a single smooth dent exceeded 100,000. This is equivalent to about 137 years of aggressive service.

- For single smooth dents containing seam welds or girth welds, the numbers of equivalent cycles to failure ranged from as low as 20,220 (equal to 28 years of service) to as high as 458,590. In the five shortest-life cases the numbers ranged from 20,220 to 62,647. The surface anomalies associated with these welds, reinforcement, geometric ripples, and trim marks served as origins of fatigue cracks.
- All fatigue cracks which developed in unconstrained single smooth dents were axial-oriented and were leaks, not ruptures. All such cracks initiated at the outside surface of the pipe within the area affected by the dent.
- Of the ten experiments designed to simulate interacting double dents, two experiments resulted in failures from cracks which clearly initiated between the dents as the result of mutual interaction. The numbers of equivalent cycles to failure in these two represented much longer lives than the lives of double dents which have caused service failures in pipelines. The regions between the pairs of interacting dents were characterized by large radii of circumferential curvature, greater than that of the original pipe radius. In the cases of the pairs of dents which did not interact, the radii of circumferential curvature between the dents were not larger than the original pipe radius.
- In the Phase I work comparisons of similar single unconstrained smooth dent experiments showed that the specimens with the highest degree of rerounding prior to the start of pressure-cycling, everything else being equal, exhibited the longest fatigue lives. Nothing observed in the Phase II work contradicted this finding. In fact, the curvature studies of Phase II suggest that the benefit of additional rerounding from a higher preload occurs from a reduction in radius of curvature, i.e., radius of curvature approaches that of original pipe.
- In the Phase I work unconstrained dents created by the pyramid indenter tended to reround less completely than more smoothly shaped dents. The pyramid dents also exhibited very long fatigue lives; in fact, none was observed to fail from fatigue in over one million equivalent half-range pressure cycles. The curvature studies of Phase II suggest that the results associated with the pyramid dents arose because there were no regions of large radii of curvature in the pyramid dents.
- The consistent mode of failure of a fully constrained dent was the development of a circumferentially-oriented fatigue crack which initiated at the ID surface just beyond the edge of the constraining indenter. The numbers of pressure cycles required to cause such failures correspond to fatigue lives which are much greater than the expected useful life of a pipeline. Also, the mode of failure was the same (i.e., a circumferential fatigue crack) even when an axially oriented notch was present at the ID or the OD surface. Whether or not this mode of failure has ever occurred in an operating pipeline is unknown, but no such failure has been brought to our attention.

- Dents containing axially-oriented external notches exhibited short lives (3 to 15 years of equivalent pressure cycles) in cases where the dent was only partially constrained or not constrained at all.
- Both the sharply pointed pyramid indenter and a blunt small-radius indenter were 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. This type of experiment produced transverse cracks much like those observed in well-documented rock-dent failures in service.
- 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.
- Two tests involving the actual removal of metal by external corrosion in 2 percent smooth dents resulted in failures at pressure levels well above the levels that one would have predicted on the basis of RSTRENG assessments of the metal loss if that metal loss had been present in similar pipes without the dents.
- Pressure-cycle tests of buckled pipes caused larger buckles (peak-to-trough heights of 4 and 6 percent of the pipe's diameter) to develop leaks from fatigue crack initiation after relatively few ($< 2,500$) large cycles of pressure (range equal to MOP). In contrast, a similar pipe containing a buckle of only 1.6 percent of the pipe's diameter survived more than 44,000 pressure cycles of (range equal to MOP) without developing a leak.

5.0 DISCUSSION AND CONCLUSIONS

The results of this project lead to conclusions on a number of dent and buckle issues.

5.1 Rerounding (Essentially Unchanged from API Publication 1156)

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 to 72 percent of SMYS total rerounding in the range of 60 to 90 percent of the maximum indentation can be anticipated. The finite element analysis tended to confirm the expectations of rerounding and showed the nature of the residual stresses which result from rerounding.

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 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.

5.2 Static and Fatigue Strength of Smoothly Dented Pipe (Altered Somewhat from API Publication 1156)

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 in a sound ERW seam as well. The experiments showed that the mode of failure of a smooth dent subjected to significant pressure cycles is the development

* It is necessary to keep in mind that the ovalization behavior observed in these tests where a saddle was used to support the pipe is probably not the same as the ovalization behavior of a buried or partly buried pipeline. Because a buried pipe is effectively stiffer, one might expect that impacts from encroachment would be more damaging than in the case of a saddle-supported specimen.

of an axially-oriented fatigue crack. However, the number of and severity of pressure cycles required to cause a leak in every case exceeded the pressure-cycle service that one would expect to occur within the useful life of most pipelines.

Conclusion: Pipeline operators need to be concerned about smooth, single unconstrained dents, if and only if, the dent will be subjected to aggressive service pressure cycles over a long period of time, or if it also contains some type of stress riser such as a score mark, a weld crown, a distinct crease or a crack.

Implications of this conclusion are:

- (9) 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 cracks or 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.
- (10) When a pipeline operator exposes a dent and can check for the presence or absence of cracks or mechanical damage, it may be possible to justify leaving smooth dents as they are.
- (11) The current limit in ASME B31.4 and ASME B31.8 of 6 percent on smooth dents is sound, but the dent must be free of other stress concentrating features and operators of pipelines with large numbers of pressure cycles should evaluate each case carefully.

5.3 Fatigue Resistance in Relation to the Curvature of Smoothly Dented Pipe (Significantly Different from API Publication 1156)

The experimental work indicated, for both single and multiple dents, a relationship between pipe curvature and the resistance of the pipe to fatigue cracking when subjected to pressure cycles. The locations of failures from pressure cycles in smoothly dented pipes were consistently in one of three places: the center of the dent, the flank of the dent, or the area between two dents separated axially but spaced closely enough to alter the normal pipe curvature between them. All such cracks were axially oriented and initiated at the OD surface. The one consistent feature of the three typical origin regions was a circumferential radius of curvature that exceeded the normal radius of the pipe. In other words, the typical origin area was characterized by a flattened region. While no experiment involving a smooth single or double dent resulted in a failure within the useful life of a pipeline, service failures (leaks) have been observed arising

from axial fatigue cracks which initiated at the OD surface in a relatively flattened area between the dents.

Conclusion: Flattening of the pipe in conjunction with the area between two smooth dents or two rock dents may facilitate the development of a leak from fatigue crack growth within the useful life of the pipeline that is subjected to significant pressure cycles.

The implication is that double dents that have overlapping influence should be repaired or removed.

5.4 Fatigue Resistance When Minor Stress Concentrators Exist in Smooth Dents (Altered Somewhat from API Publication 1156)

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.

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

The implication of this is that the current provisions in ASME B31.4 which require repairs to any dent involving a weld are overly restrictive except for the case of an older low-frequency-welded ERW material. In view of the findings, 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.

5.5 Constrained Dents (Altered Somewhat from API Publication 1156)

The experiments have shown that fully constrained dents pose only one kind of threat to pipeline integrity, namely the threat of puncturing if the force applied by the constraining object is enough to cause the shear strength of the wall thickness to be exceeded. The mode of failure from puncturing is a circumferentially-oriented shear crack. 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. The results of pressure-cycle tests on fully-constrained dents show that a fatigue failure is not possible within the useful life of a pipeline.

Conclusion: Corrosion control and monitoring considerations aside, rock dents where the rock remains in place are of concern only to the extent that, if the load is great enough, the pipeline may be punctured. The mode of failure of such a puncture will be a leak not a rupture.

5.6 Practical Considerations Regarding Rock Dents (Altered Somewhat from API Publication 1156)

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 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) If possible, examine the affected area using angle-beam ultrasonics to crack for the possible presence of cracks at the ID surface.
- 4) Repair the dent or replace the pipe if damage (that cannot be removed by superficial grinding) or cracks are found.
- 5) Record the depth and extent of the dent and repair the coating if no repair to the pipe is deemed necessary.

- 6) Leave most rock dents alone unless the dent is so deep that it interferes with the passage of pigs or is so deep and short that the risk of a puncture is judged to be significant.
- 7) Repair region or replace the pipe if the dent has two or more nodes and a region or regions of altered pipe curvature between the dent nodes.

Conclusion: 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 that exceeds the shear strength of the wall thickness. The results further show that deep dents are most likely constrained, and therefore, are most likely rock dents. It is most often assumed that dents found on the bottom half of the pipe are caused by rocks. 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.

5.7 Buckles

The limited amount of testing conducted on buckles in this project suggests that even large buckles have a reasonable resistance to failure from pressure cycles. The failure of the largest buckle at 1086 cycles ranging from 12 to 84 percent of SMYS is equivalent to 17,376 cycles of 36 to 72 percent of SMYS or more than 23 years of service. The testing did not address the effects of secondary loads, but for pipelines buried in stable soils, the displacements would be limited to non-injurious amounts.

Conclusion: For pipelines buried in stable soil areas, buckles of 2 percent or less of the pipe's diameter can be considered non-injurious.

REFERENCES

1. Alexander, C. R., and Kiefner, J. F., "Effects of Smooth and Rock Dents on Liquid Petroleum Pipelines", to the American Petroleum Institute, API Publication 1156, First Edition, November 1997.

2. Keating, P. B., and Huffman, R. L., "Fatigue Behavior of Dented Petroleum Pipelines", A Report of the Texas Transportation Institute, Texas A&M University System, for the Office of Pipeline Safety, U.S. Department of Transportation, Contract No. DTRS 56-95-C-0003, May, 1997.
3. Eiber, R. D., Maxey, W. A., and McClure, G. M., "The Effects of Dents on the Failure Characteristics on Line Pipe", American Gas Association, Catalog No. L51403, May 8, 1981.
4. Maxey, W. A., "Outside Force Defect Behavior", Seventh Symposium on Line Pipe Research held in Houston, Texas, Catalog No. L51495, October 14-16, 1986.
5. Hopkins, P., Jones, D. G., and Clyne, A. J., "The Significance of Dents and Defects in Transmission Pipelines", Conference on Pipework Engineering and Operations, I Mech E, London, Paper C376/049, February, 1989
6. Fowler, J. R., "Criteria for Dent Acceptability of Offshore Pipelines", Stress Engineering Services, American Gas Association, Catalog No. L51671, July, 1992
7. Kiefner, J. F., and Vieth, P. H., "A Modified Criterion for Evaluating the Remaining Strength of Corroded Pipe", Project PR-3-805, Pipeline Research Committee, American Gas Association, Catalog No. L51609.
8. Kiefner, J. F., and Alexander, C. R., "Repair of Pipeline Dents Containing Minor Scratches", to Line Pipe Research Supervisory Committee, PRC International, Contract No. PR 218-9508, Catalog No. L51788, May 18, 1999.

DENT PROFILE FOR SAMPLE 31

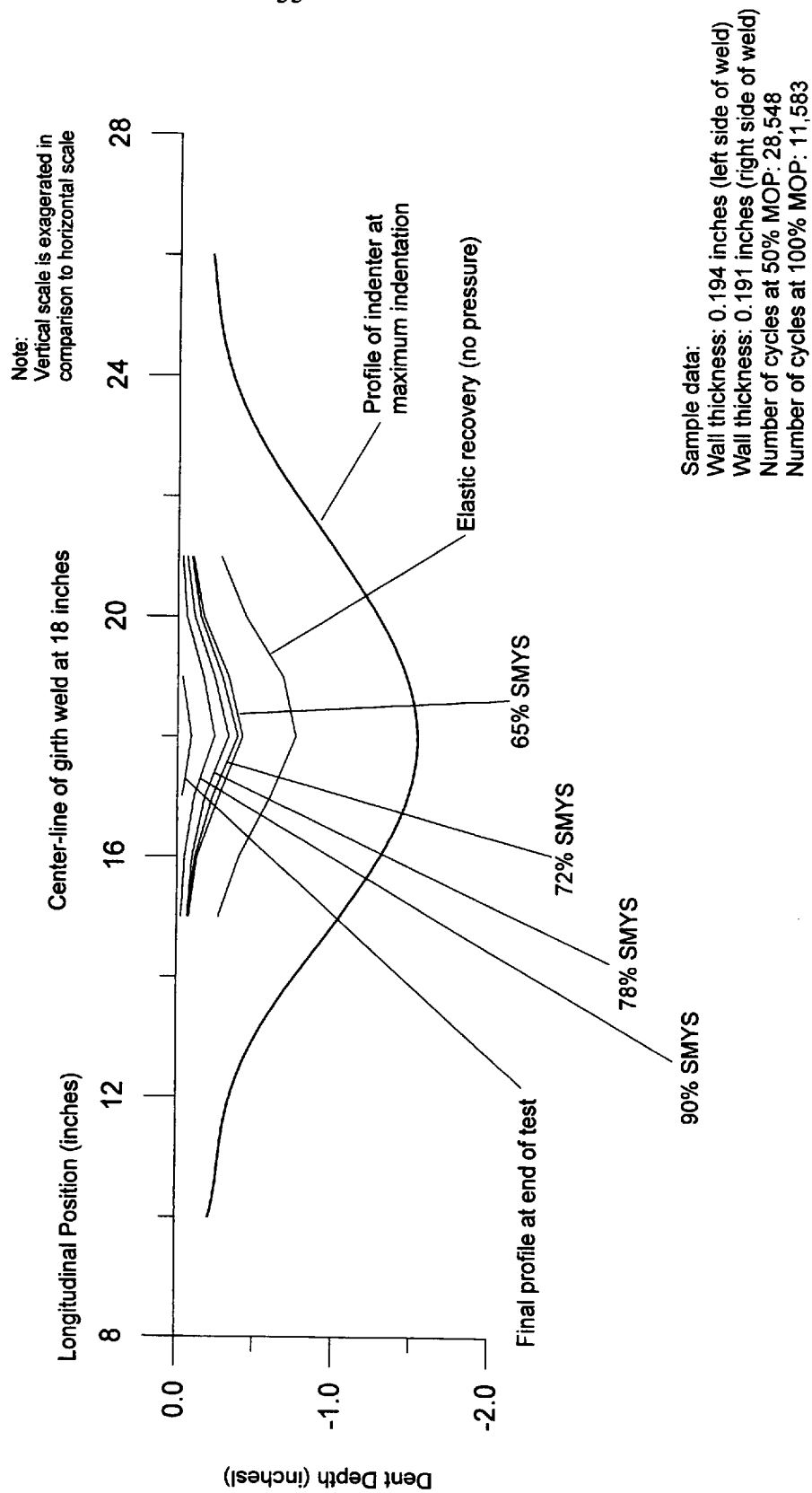


Figure 1. Longitudinal Profiles of Dent After Various Stages of Pressurization for Experiment 31.

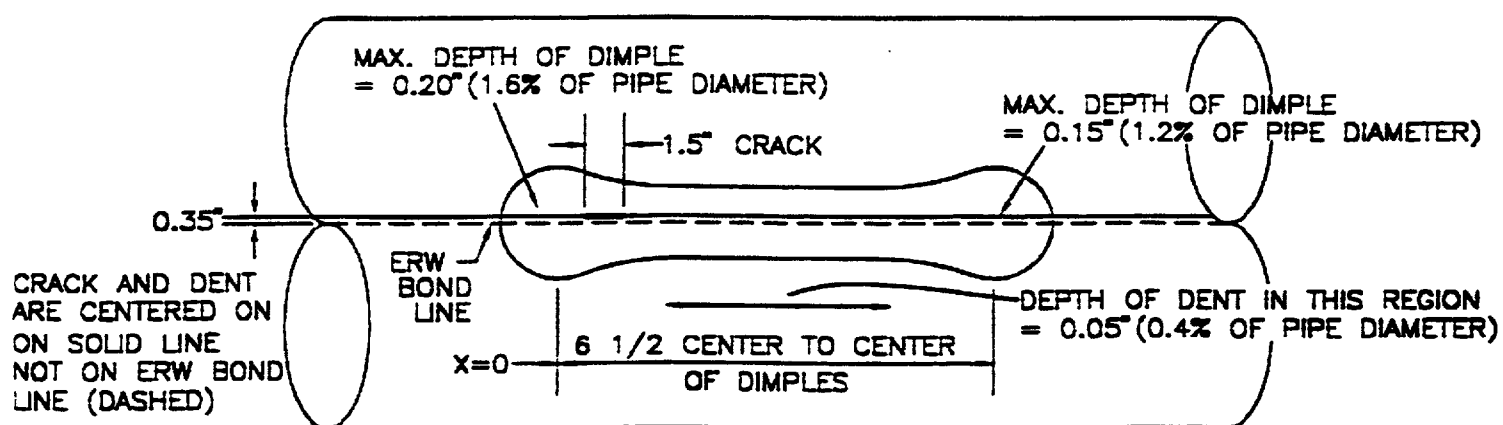


Figure 2. Experiment 17 after test

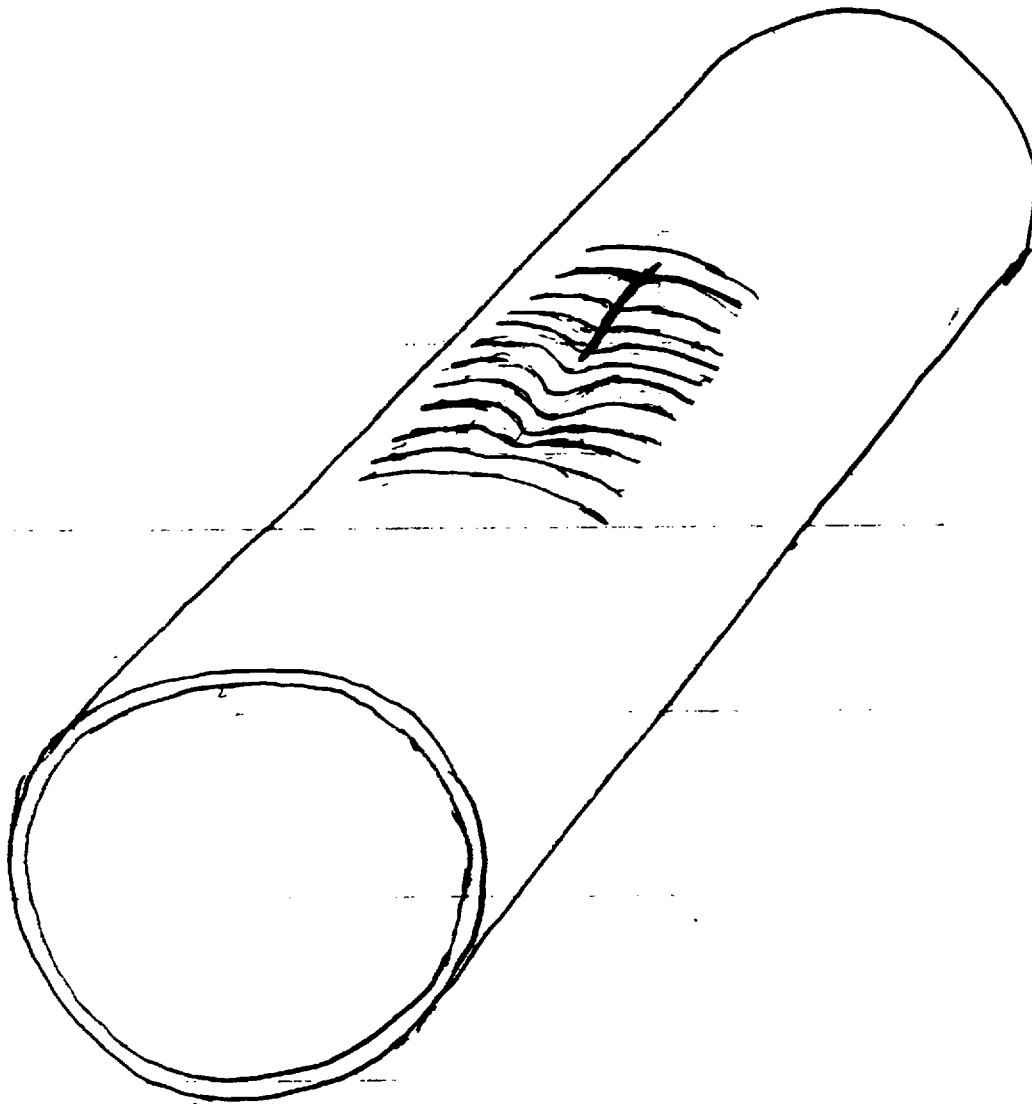


Figure 3. Single unconstrained dome-shaped dent showing more common location of fatigue-crack initiation. Crack starts at OD surface and grows to ID surface.

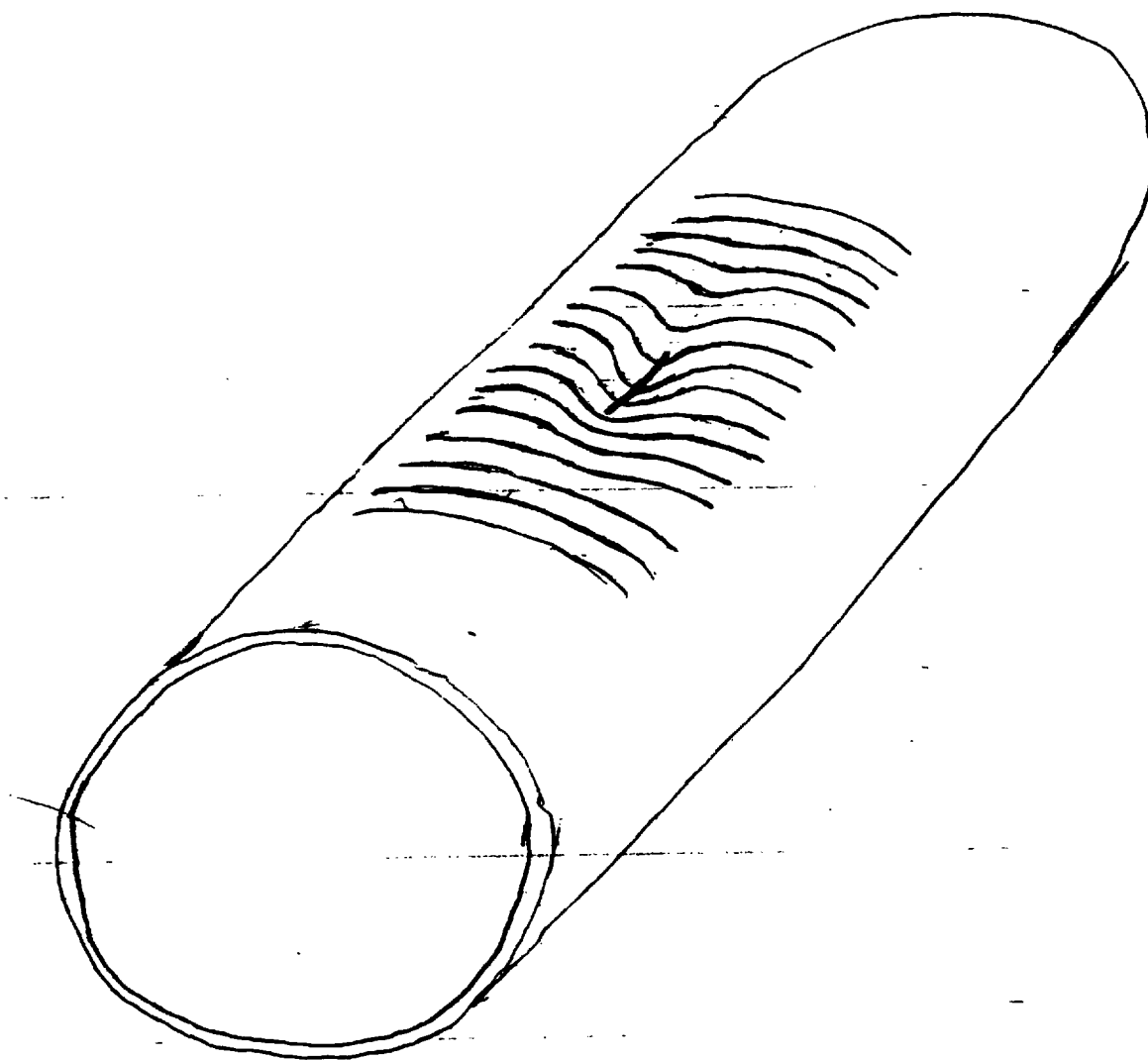


Figure 4. Single unconstrained dome-dent showing less common location of fatigue-crack initiation. Crack starts at OD surface and grows to ID surface.

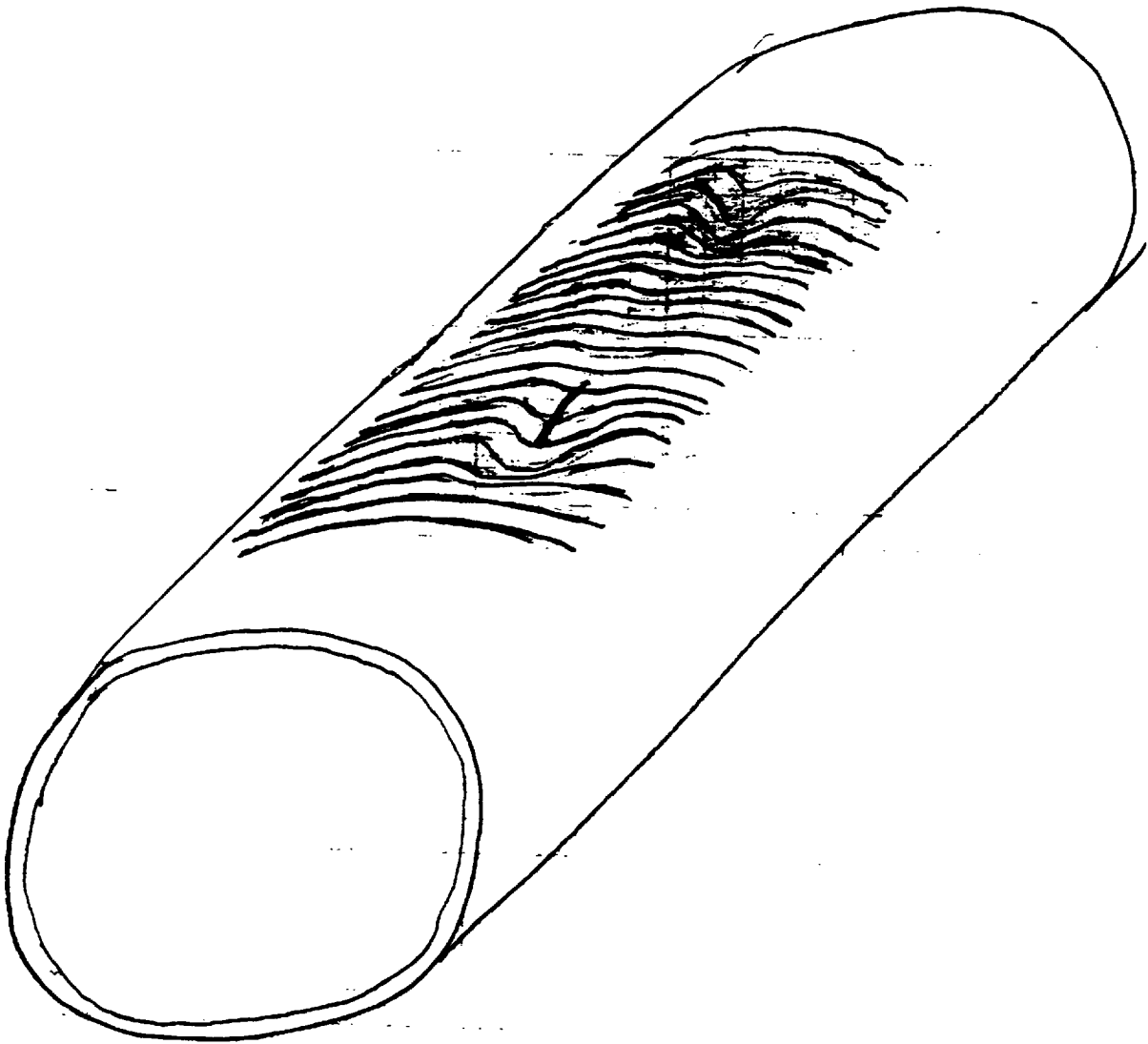


Figure 5. Unconstrained axial round-bar dent showing most common location of fatigue-crack initiation. Crack starts at OD surface and grows to ID surface.

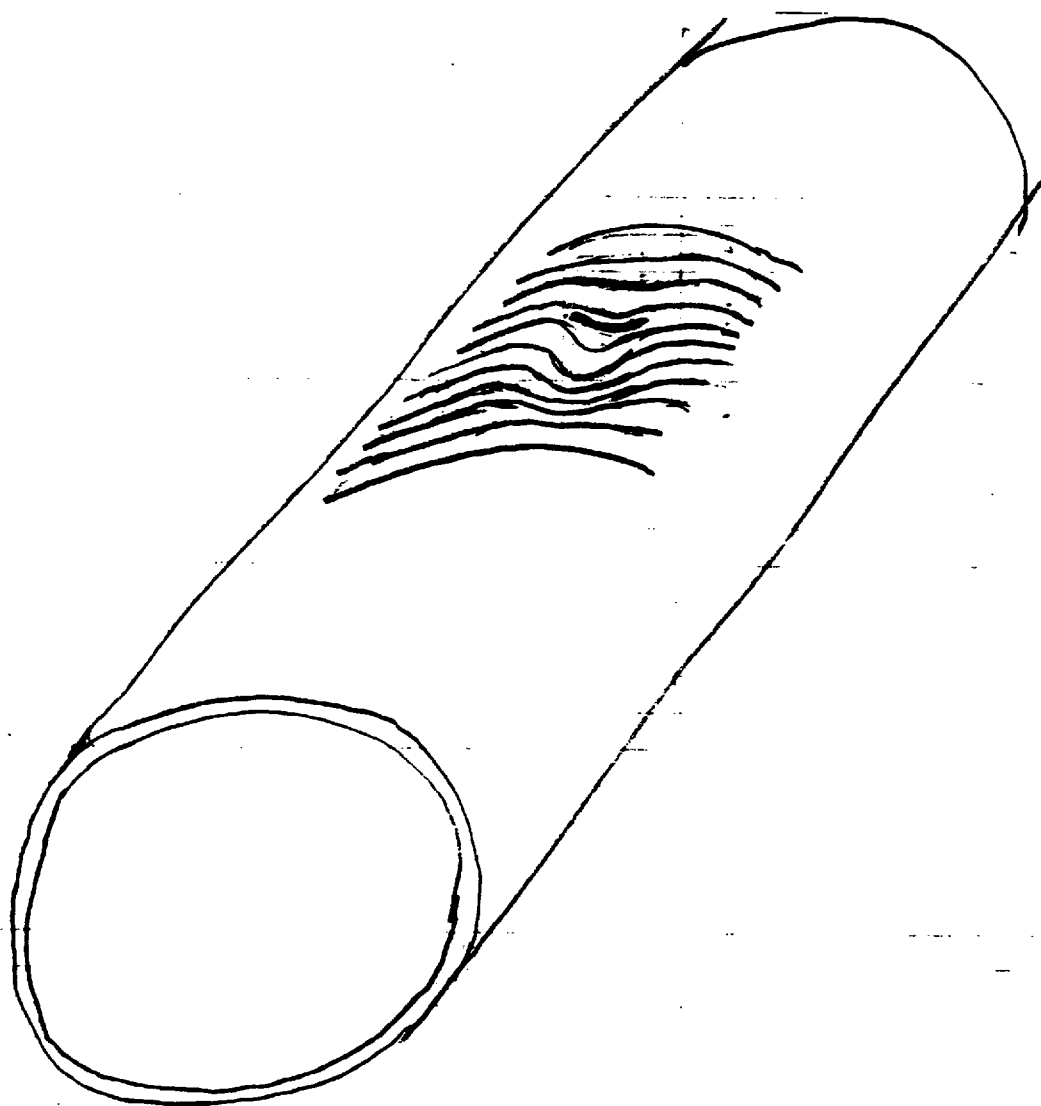


Figure 6. Single constrained dome-shaped dent showing location and transverse orientation of typical fatigue crack. Crack starts at ID surface and grows to OD surface. Location and orientation of crack is also typical of location and orientation of punching shear failure.

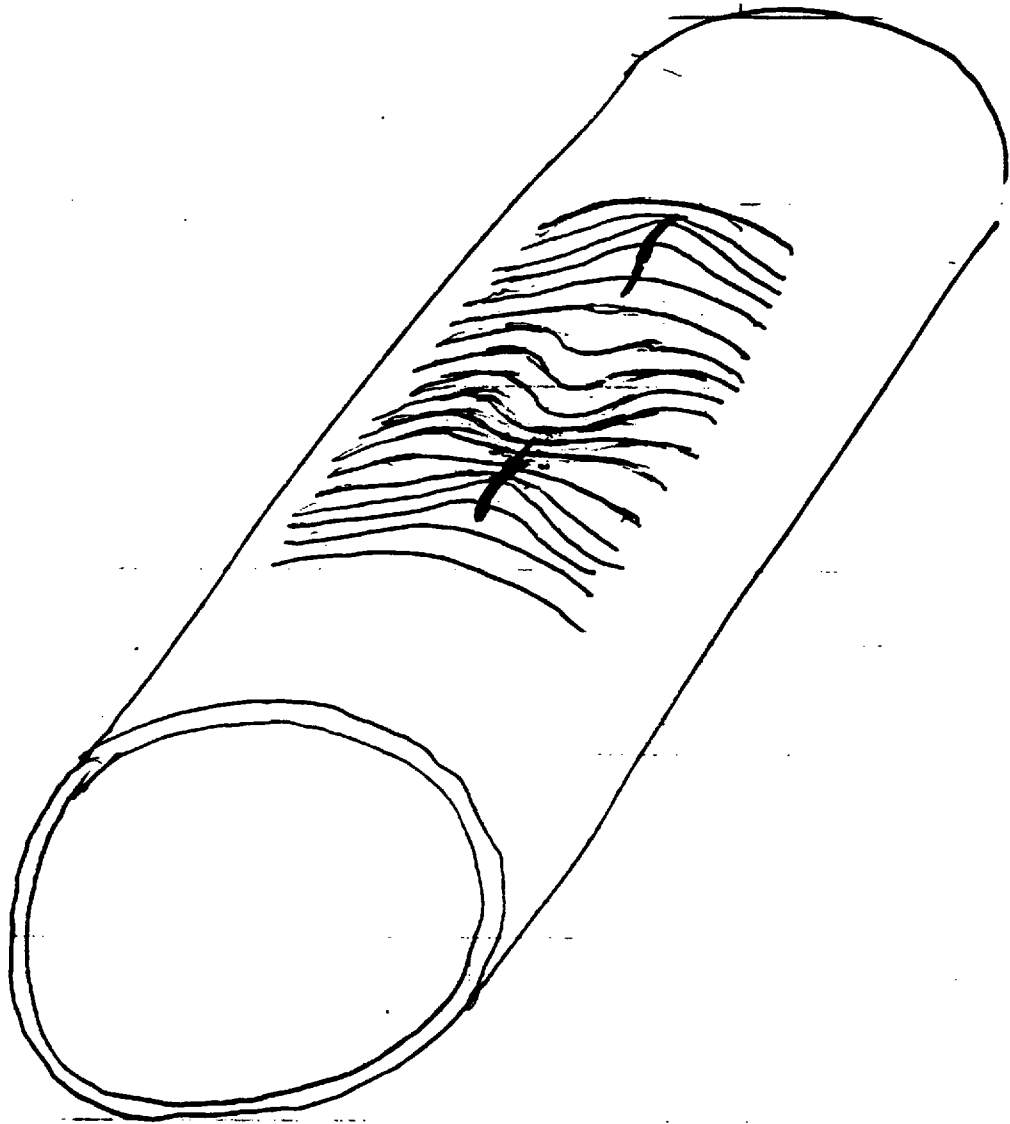


Figure 7. Single dome-shaped dent pressurized while initially constrained but subsequently tested unconstrained. Typical fatigue crack locations are shown. Cracks start at OD surface and grow to ID surface. Crack sometimes appeared at only one side. In other cases cracks were found on both sides as shown above.

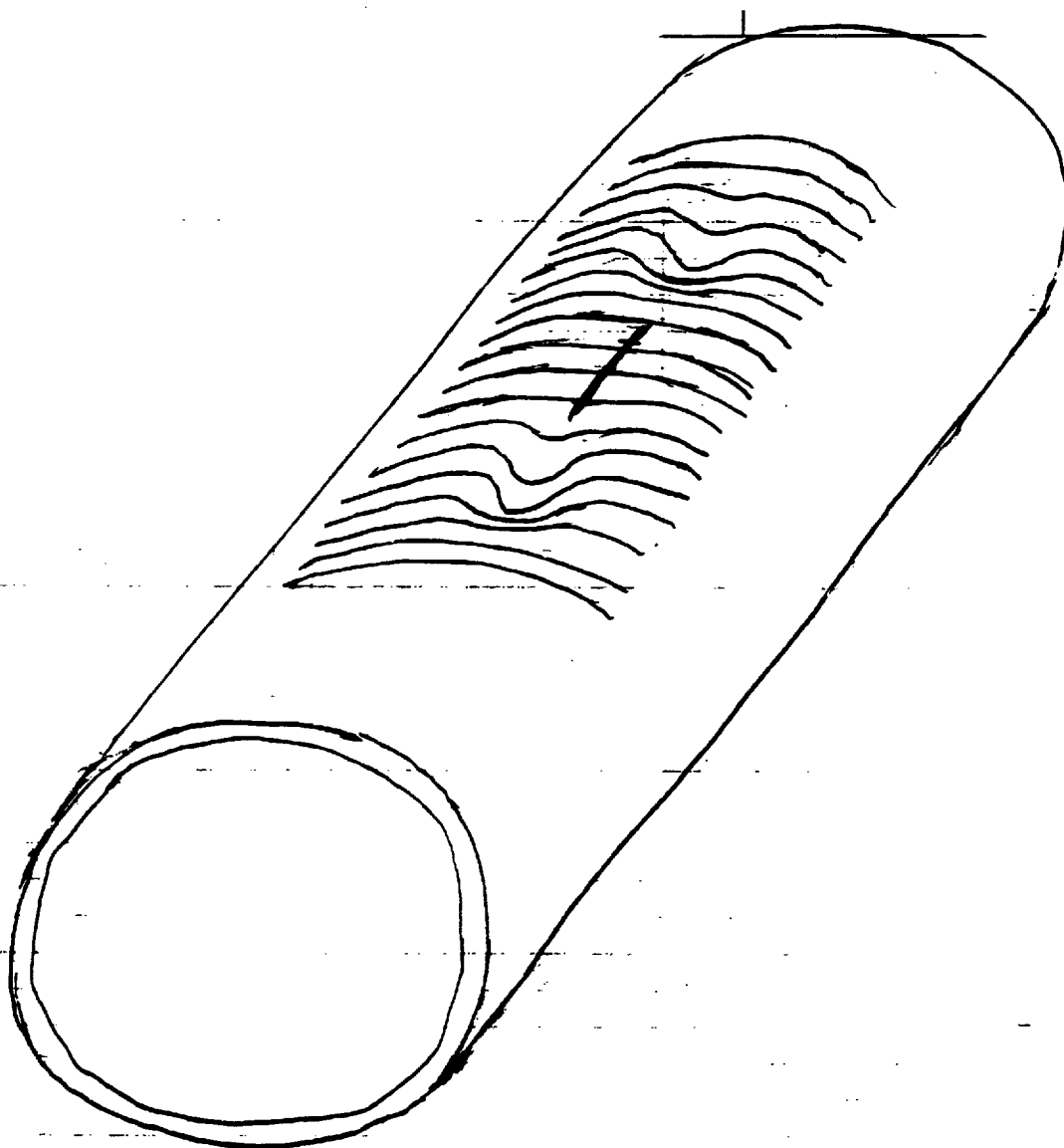


Figure 8. Interacting dome-shaped dents showing location of fatigue crack. Crack starts at OD surface and grows to ID surface.