REPAIR OF DENTS CONTAINING MINOR SCRATCHES

J. F. Kiefner
Kiefner & Associates, Inc.
P.O. Box 268
Worthington, Ohio 43085

C. R. Alexander and J.R. Fowler
Stress Engineering Services, Inc.
13800 Westfair East Drive
Houston, Texas 77041-1101

(Presented by C. R. Alexander)

REPAIR OF DENTS CONTAINING MINOR SCRATCHES

J. F. Kiefner
Kiefner & Associates, Inc.

C. R. Alexander and J.R. Fowler
Stress Engineering Services, Inc.

ABSTRACT

Presented herein are the results of a research program to demonstrate the feasibility of repairing shallow gouges in dents in pipelines by grinding out the gouge and any associated damaged material. The feasibility of this concept was demonstrated by comparing the burst pressures and cyclic-pressure fatigue lives of pairs of pipe specimens, one of which was tested without being repaired while the other was tested after being repaired. The burst tests and pressure-cycle tests were carried out on samples of 12.75 -inch O.D. line pipe. Simulated longitudinally-oriented gouges were machined into these specimens to depths of 5 to 10 percent of the wall thickness. Indentation of the pre-notched specimens was then carried out with the pipes pressurized to typical operating stress levels. Following indentation each dent was permitted to reround in response to the internal pressure. Maximum indentations ranging from 5% to 20% of the diameter were reached before rerounding was permitted. After depressurizing, one specimen of each pair was repaired by grinding out the notch and any associated cracked material. The specimens were then subjected either to burst testing or pressure-cycle fatigue testing to failure.

The specimens with gouges removed by grinding uniformly exhibited burst pressures in excess of the 100% SMYS pressure. In contrast, the unrepaired specimens exhibited failure pressures which decreased with increasing dent depths to levels as low as 41% SMYS. The specimens with gouges removed by grinding exhibited pressure-cycle fatigue lives at least four times as long as those of the unrepaired specimens. The results show that removal of the gouge by grinding satisfactorily restores the serviceability of the pipe. The viability of this technique depends on being able to remove all of the cracked or otherwise damaged material at the base of the gouge without reducing the remaining wall thickness to the point where the burst pressure based on the net wall thickness is less than 100% SMYS.

INTRODUCTION

The project described herein was aimed at demonstrating the feasibility of repairing a shallow gouge in a dent in a pipeline solely by means of grinding out the gouge and associated cracking or other damage. The amount of grinding to be permitted is limited to the extent that the reduced wall thickness after grinding must be adequate to maintain satisfactory pressure carrying capacity. In terms of existing industry practices this can be interpreted to mean 100 percent of SMYS (the specified minimum yield strength of the pipe material). The basis of this project was the hypothesis that any rerounding of a dent that might occur after the removal of the gouge and associated damage would not seriously reduce the burst pressure of the pipe, nor would it significantly affect the fatigue resistance of the pipe.

The method chosen to test the hypothesis involved testing pairs of initially-identical full-scale pipe specimens. One of each pair was to be tested after the gouge had been removed. To compare the effects of the repair on serviceability, some pairs of the specimens were subjected to burst testing while others were subjected to cyclic-pressure fatigue tests. The results of the tests are presented and discussed herein.

BURST TESTING

The primary objective of the burst testing was to determine whether the removal of gouge-damaged material by grinding restores satisfactory serviceability to gouged and intentionally dented pipe. This objective, it was felt, could best be met by bursting pairs of specimens that were damaged identically. In these pairs one would be tested as-damaged and the other would be tested after the gouge-damaged material had been removed by grinding. Since the severity of damage that could be created by means of notches followed by indenting and rerounding with pressure in the pipe was not known, it was necessary to conduct preliminary testing. Thus, a secondary objective was defined in determining defect parameters that would result in failures of unrepaired specimens with a hoop stress level of at least 60% of the specified minimum yield strength (SMYS). A considerable amount of *preliminary* testing was necessary in order to develop dent/gouge defects which would be realistic and not so severe that their repair would be impractical in field applications. This point can be made more clear when one considers that a dent that is 20% of the pipe diameter will cause a gouge that is 10% of the wall to propagate much deeper than 12.5% of the wall thickness, thus possibly preventing this section from being repaired using conventional grinding techniques. Once the dent/gouge types were adopted based on the *preliminary testing*, fifteen burst tests were conducted to determine the failure pressure for each of the respective defects. The completion of these tests validated the selection of the dents and gouges and a test matrix was developed for the fatigue testing.

Preliminary Work

As discussed previously, the *preliminary* work involved the development of gouges and dents to be used in the fatigue testing. Several steps were involved in this phase of testing, and they are as follows (discussions relating to each will be discussed),

- Selection of pipe based on desired D/t and material grade
- Installation of dents (without gouges) under internal pressure corresponding to 60% SMYS
- Installation of gouges using prescribed geometry and depth relative to pipe wall thickness
- Installation of dents under pressure combined with pre-installed gouges
- Pressurization of all defects after indentation in order to establish the residual dent depths consistent with the typical operating pressure level.

The objective of installing dents without gouges was to determine the initial indentation depth required to obtain residual dent depths that would exist at the operating pressure. The results showed that an initial dent depth of 20% the pipe diameter (d/D=20%) provided a residual dent of 1.58% after the sample had been pressurized to at least 60% of the specified minimum yield strength (SMYS). This observation supported the initial belief that residual dents in thin-walled pipe (wall thickness of 0.188 inches) are unlikely to exceed the 6% value.

The pipe materials selected for this study were parts of two heats of steel. Material testing was done on both heats and the results are provided in **Table 2.1**. Both materials were 12.75 inch O.D. by 0.188 inch w.t. API 5L Grade X52 line pipe with an ERW longitudinal seam.

Table 2.1 Material Properties for Piping Specimens

Heat #	Yield Strength (psi)	Tensile Strength (psi)	Elongation (%)	Charpy V-notch Impact Value (ft.-lbs.) [1]
F83966	53,600	72,100	34.0	17.0
F83967	54,300	74,100	29.5	13.0

Note:
1. These values determined by means of 1/3-size transverse, flattened specimens which exhibited 100 percent shear area on their fractured surfaces.

Dent Study (Preliminary)

Figure 2.1 is a photograph showing the equipment used in the dent installation such as the hydraulic cylinder, indenter plate, and displacement transducer. During the denting process the hydraulic cylinder forces the 1-inch diameter round bar indenter into the pipe. The indenter used is shown in **Figure 2.2**. The dent depth was monitored using a displacement transducer. All dents involved in this research were installed with an internal pressure corresponding to 60% SMYS. The process of denting basically involved the following steps,

- Pipe sample placed in the test rig
- Sample filled with water in preparation for pressurization
- Indenter placed between hydraulic cylinder and pipe and positioned to create dent at the specified location on the pipe (all dents installed 90 degrees from pipe weld seam)
- Pipe sample pressurized to 60% SMYS and maintained while dent installed
- Displacement transducer zeroed and dent installed by increasing pressure to hydraulic cylinder (Displacement and Hydraulic Pressure (Load) both monitored)
- Rerounding permitted by releasing hydraulic cylinder pressure (pressure in pipe permitted to drop, but no water from sample released).
- To effect representative rerounding, sample repressurized to 65% SMYS

The pipe diameters at 0° and 90° relative to the defect were measured at each of the dent locations before denting, after denting (internal pressure removed), and after the sample had been repressurized to 65% SMYS (internal pressure removed). **Table 2.2** provides the diameters measured in preliminary (no gouge) test specimens before indentation and the diameters measured as a result of the residual dents. Also included in these tables are the loads required to cause the initial dent depths.

Table 2.2 Measured Dent Depths for Preliminary Testing

Specimen	Before Denting (inches)		Diameters due to Residual dents (inches)		Desired Dent (d/D, %)	Dent Load (lbs.)	Residual Dent (d/D, %)
	0 - 180°	90 - 270°	0 - 180°	90 - 270°			
PD-5	12.728	12.842	12.668	12.826	5	30,940	0.47
PD-6	12.685	12.877	12.587	12.848	10	49,725	0.77
PD-7	12.650	12.902	12.558	12..871	15	72,930	0.73
PD-8	12.712	12.826	12.511	12.917	20	88,400	1.58

As indicated in **Table 2.2**, the dents are substantially removed from the pipe as a result of pressurization. Previous dent data indicate that residual dent depths greater than 5% are unlikely in pipe with D/t ratios as high as 68 for dents installed with no internal pressure.

<u>Gouge Study (Preliminary)</u>
As with the study on dents, the effort in the gouge study was to develop reproducible defects that could be repaired if they were to actually occur in a pipeline. One of the concerns with the gouge study was the possibility that the penetration of the crack extension at the gouge during rerounding would exceed 12.5% of the wall thickness. With this in mind, specific steps were taken to monitor the propagation of the gouge after indentation. The gouge is created by machining a longitudinal notch into the sample with a radius at the base of 0.002 inches. The tasks listed for the denting process were repeated for the gouge specimens; however, a few additional steps were required in order to quantify the change in gouge depths, and they are as follows,

- Installation of gouges prior to indentation
- Once the dents were installed, the dent/gouge sections were cut circumferentially in order to view the gouges in a cross-sectional manner.
- The gouge in one of the pipe halves was ground in a manner similar to the repair method which would actually be used on a pipeline.

The wall thickness was measured prior to grinding. After grinding dye penetrant was used to check for the remaining gouge. Once the gouge had been successfully removed from the pipe wall, the residual wall thickness was measured. **Figure 2.3** and **Figure 2.4** show the gouged region after grinding and after using dye penetrant as a means of detection, respectively. These photographs were taken from the circumferentially-cut pipe segments which were made in the preliminary testing to look at the cross-sectional wall within the defect zone. **Table 2.3** shows the wall thickness measurements before and after grinding.

Table 2.3 Wall Thickness Changes after Grinding for Preliminary Burst Tests

Specimen	Gouge Depth (%, d/t)	Wall Thickness Before Grinding (inches)	Wall Thickness After Grinding (inches)	Percentage of Wall Remaining (%)
PG-1	5	0.194	0.170	87.6
PG-2	5	0.198	0.172	86.9
PG-3	10	0.192	0.166	86.5
PG-4	10	0.194	0.160	82.5
PG-5	15	0.194	(1)	(1)

Note:
1. Specimen failed upon rerounding.

As can be seen the from **Table 2.3**, in order to remove all of the gouge, the grinding may require that more than 12.5% of the wall be removed. This is primarily due to the crack extension which is induced during the process of rerounding.

This procedure of cutting the pipe in half allowed the change in gouge depth as a result of indentation to be examined. Based on the results of this exercise, it was found that the maximum gouge/dent combination which could be tested was one that incorporated a 10% gouge with a 20% dent. It should be noted that when the pipe sample was being pressurized to 65% of SMYS, Defect *PG-5* failed. This was a clear indicator that a 20% dent combined with a 15% gouge was too severe for the existing testing conditions. This information, in conjunction with the other test results, was used in developing the test matrix for the actual burst testing.

Test Matrix for Burst Tests

Once all preliminary testing had been completed, a test matrix was developed for the burst tests which would model a range of defects, including the most severe combination from the preliminary testing. **Table 2.4** shows the test matrix selected for the burst testing. The following nomenclature is used in identifying the specimens,

F2-1N

where: F = Test-type Identifier (*B* for burst and *F* for fatigue)
2 = Material number (in the burst and fatigue tests, this number is a 1 or 2)
1 = Specimen Number
N = Gouge Repair Status (*N* for not ground, *G* for ground, or *D* for dent with no gouge)

All specimens used in the burst (and fatigue) tests utilized 12" nominal size pipe with a wall thickness of 0.188 inches. Although two materials with different heat numbers were obtained for the testing, all fatigue testing involved material from the 2nd lot (refer to **Table 2.1** for the properties of this material).

Table 2.4 Test Matrix for Burst Tests

Specimen	Gouge Depth (d/t)	Dent Depth (d/D)
B1-1N	5%	5%
B1-2G	10%, Ground	20%
B1-3N	10%	5%
B1-4G	10%, Ground	5%
B1-5D	---	5%
B1-6N	10%	10%
B1-7N	15%	15%
B1-8N	10%	12%
B1-9G	10%, Ground	12%
B1-10G	5%, Ground	15%
B1-11N	5%	15%
B2-12G	5%, Ground	10%
B2-13N	5%	10%
B2-14G	5%, Ground	15%
B2-15N	5%	15%

Installation of Dents and Gouges

As with the preliminary testing, the gouges were installed prior to indentation. All dents were installed with the pipe pressurized with water to 60% SMYS.

Once all dents had been installed, the specimens were depressurized and the gouges were repaired (i.e. removed by grinding) on those specimens which had been designated to be ground. This was accomplished by means of a hand-held grinder until the gouge was no longer visible using the dye-penetrant detection technique. The grinding was performed with no internal pressure in the pipe. Like the development required for the defect combinations, a similar procedure was required to develop a method for installing dents. Four basic procedures were used and are listed below in addition to those specimens which utilized each procedure. The final procedure to be used was *Procedure B*.

Procedure A (Initial procedure)

Specimens: B1-1N, B1-2G, B1-3N, B1-4G, B1-6N, B1-7N, B1-8N, B1-9G, F2-1N

1. Machine Notch
2. Pressurize to 920 psi
3. Indent/Reround/Pressure Decay
4. Depressurize
5. Measure Dent
6. Grind if Appropriate
7. Pressurize to 994 psi
8. Depressurize
9. Measure Dent

Procedure B (Improved procedure)

Specimens: B1-10G, B1-11N, B2-12G, B2-13N, B2-14G, B2-15N, F2-2G, F2-3N, F2-4G, F2-5N, F2-6G, F2-7N, F2-8G, F2-9N, F2-10G, F2-11N, F2-12G

1. Machine Notch
2. Pressurize to 920 psi
3. Indent/Reround/Pressure Decay
4. Apply Dye Penetrant
5. Repressurize to 920 psi
6. Depressurize
7. Measure Dent
8. Grind if Appropriate
9. Repressurize to 994 psi
10. Depressurize
11. Measure Dent
12. Pressurize to Failure or Apply Pressure Cycles Until Failure

Procedure C (Specimens with no gouges)

Specimens: PD-5, PD-6, PD-7, PD-8, B1-5D

1. Pressurize to 920 psi
2. Indent/Reround/Pressure Decay
3. Depressurize
4. Measure Dent
5. Pressurize to 994 psi
6. Depressurize
7. Measure Dent

Procedure D (Specimens examined by sectioning)

Specimens: PG-1, PG-2, PG-3, PG-4, PG-5

1. Machine Notch
2. Pressurize to 920 psi
3. Indent/Reround/Pressure Decay
4. Depressurize
5. Measure Dent
6. Pressurize to 994 psi
7. Depressurize
8. Measure Dent
9. Cut Circumferentially Through Defect
10. Grind out Crack on Half
11. Examine Depth of Remaining Crack

Testing of the samples was conducted by hydrostatically increasing the internal pressure in the specimen until failure occurred. **Figure 2.5** shows a sample in the test chamber after testing.

Results from Experimental Burst Testing

As with previous testing, the pipe diameters were recorded for each of the specimens before denting, after denting, and after a pressure corresponding to 65% of SMYS had been applied to the specimen. **Table 2.5** provides data relating to these measurements. Also included in this table are the residual dents which remained in the samples as a result of pressurization.

Table 2.5 Geometry Measurements for Burst Test Specimens

Specimen	Gouge Depth (d/t, %)	Interim Dent [Note 1] (d/D, %)	Before Denting (inches)		Diameters due to Residual dents (inches)		Residual Dent [Note 2] (d/D, %)
			0 - 180°	90 - 270°	0 - 180°	90 - 270°	
B1-1N	5	1.48 (5)	12.796	12.779	12.664	12.802	1.03
B1-2G	10 (Ground)	4.09 (20)	12.775	12.811	Failed [Note 3]		---
B1-3N	10	1.71 (5)	12.785	12.784	12.656	21.810	1.01
B1-4G	10 (Ground)	2.25 (5)	12.788	12.802	12.606	12.832	1.42
B1-5D	---	1.65 (5)	12.773	12.787	12.641	12.817	1.03
B1-6N	10	4.14 (10)	12.794	12.796	12.510	12.888	2.22
B1-7N	15	6.45 (15)	12.796	12.771	Failed [Note 3]		---
B1-8N	10	3.70 (12)	12.799	12.771	12.517	12.887	2.20
B1-9G	10 (Ground)	5.00 (12)	12.777	12.779	12.493	12.904	2.22
B1-10G	5 (Ground)	3.46 (15)	12.786	12.790	12.623	12.884	1.27
B1-11N	5	--- (15)	12.800	12.780	Failed [Note 3]		---
B2-12G	5 (Ground)	2.09 (10)	12.767	12.760	12.656	12.784	0.87
B2-13N	5	2.01 (10)	12.770	12.780	12.612	12.766	1.24
B2-14G	5 (Ground)	1.88 (15)	12.688	12.781	12.656	12.932	0.25
B2-15N	5	1.81 (15)	12.730	12.750	12.672	12.873	0.46

Note:
1. The *Interim Dent* value was measured after the dent had been installed in the pipe at 60% SMYS. No pressure was in the pipe at the time of measurement. The value in parentheses was the maximum indentation level at the time of installation.
2. Residual dent measurements made after the specimen had been pressurized to 65% SMYS.
3. These specimens failed in the process of pressurizing the sample to 65% SMYS.

Table 2.6 records the burst test data for each of the specimens. Recorded in this table is information relating to defect configuration and its respective burst pressure.

Initial testing involved Specimens *B1-1N* through *B1-7N*. From this specimen group a range of defects based on burst pressures was developed. As seen from the above table, Specimen *B1-2G* had the most severe defect in this group with a burst pressure of 625 psi. Specimens *B1-8N* and *B1-9G* were designed to validate the original test envelope. Unfortunately, the dent depth of 12% did not lower the burst pressure as expected; however, the upper bound for the burst pressures was confirmed. Specimens *B1-8N* through *B2-15N* were used to fine tune the test matrix and were specifically targeted at developing defect combinations that would be severe enough for fatigue testing.

Table 2.6 Burst Test Information

Specimen	Gouge Depth (d/t)	Dent Depth (d/D)	P_{burst} (psi)	% SMYS (P_{burst}/SMYS)
B1-1N	5%	5%	2,165	141
B1-2G	10%, Ground	20%	625	41
B1-3N	10%	5%	1,985	129
B1-4G (3)	10%, Ground	5%	2,138	139
B1-5D	---	5%	2,160	141
B1-6N	10%	10%	1,479	96
B1-7N	15%	15%	820	53
B1-8N	10%	12%	1,517	99
B1-9G (3)	10%, Ground	12%	1,928	126
B1-10G	5%, Ground	15%	1,820	119
B1-11N	5%	15%	775	51
B2-12G	5%, Ground	10%	1,887	123
B2-13N	5%	10%	1,354	88
B2-14G	5%, Ground	15%	2,153	140
B2-15N	5%	15%	920	60

Note:
1. Pipe dimensions: 12.75" O.D. by 0.188" wall
2. SMYS for this pipe calculated to be 1,533 psi (assuming X52)
3. Results for this specimen not entirely valid because grinding was done after only partial rerounding.

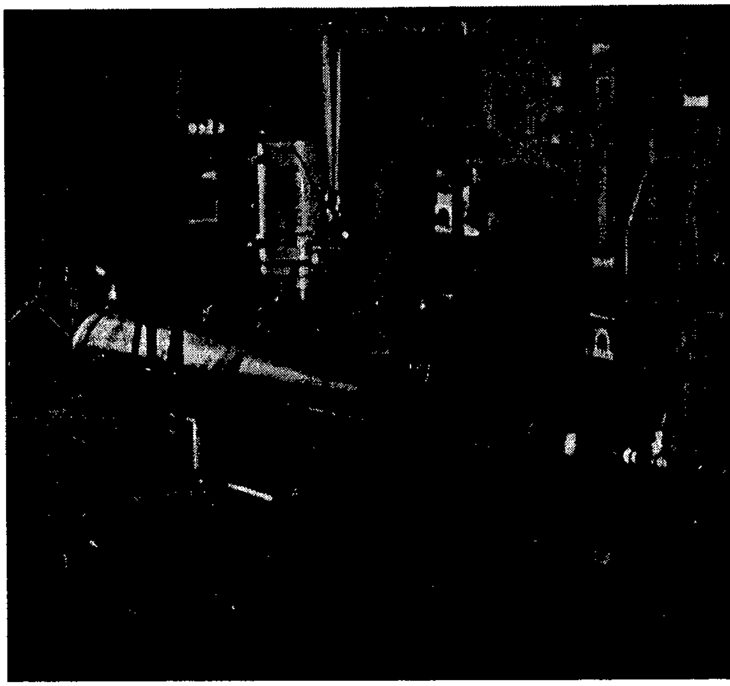

Figure 2.1 Pipe Specimen in Dent Installation Rig

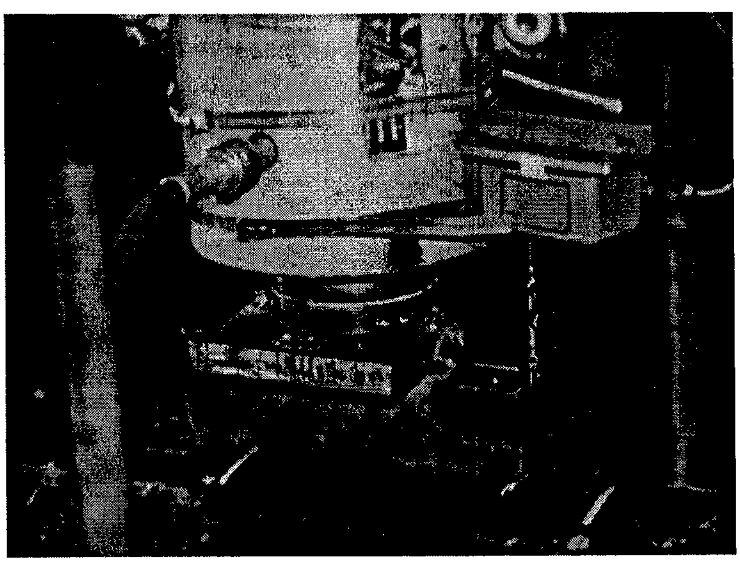

Figure 2.2 Close-up View of Denting Set-up

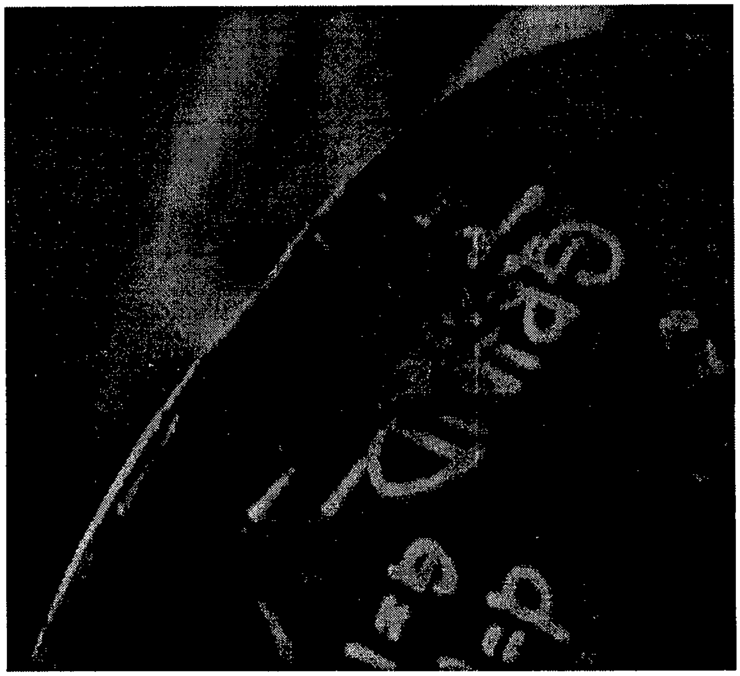

Figure 2.3 Grinding of Gouge

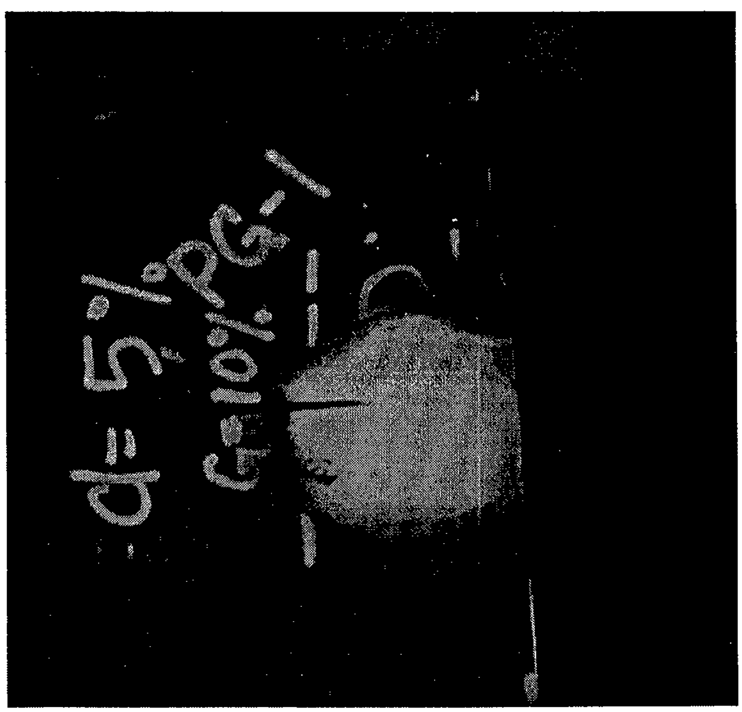

Figure 2.4 Dye Penetrant Check

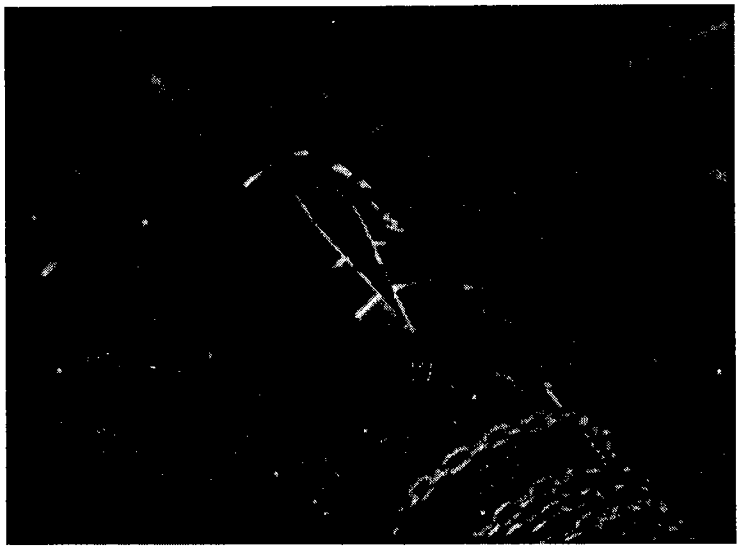

Figure 2.5 Failure in Pipe Specimen

Discussion of Burst Test Results

As stated previously, the primary objective of the burst testing was to determine whether the removal of gouge-damaged material by grinding restores satisfactory serviceability to gouged and dented pipe. The range of repairable defects was also an issue. The ideal defect combinations were those which produced failures between 72% and 100% of SMYS. **Figure 2.6** presents a plot of the burst test data in the form of their respective burst pressures as functions of dent and gouge depths.

The subsequent remarks are made based on the results from the burst tests ,

- The linear curve fit for the results involving specimens repaired by grinding indicates that when a defect was repaired in this manner, the burst strength of the pipe exceeded 100% SMYS for the defect combinations studied.
- In considering the defects which were not ground, it is clear that the failure pressures decreased with increasing initial dent depth to levels well below 100% SMYS.
- From this one can readily conclude that removal of the gouges by grinding effectively restored the serviceability of the pipe as long as 80% of the nominal wall thickness remains after the removal of the damaged material.

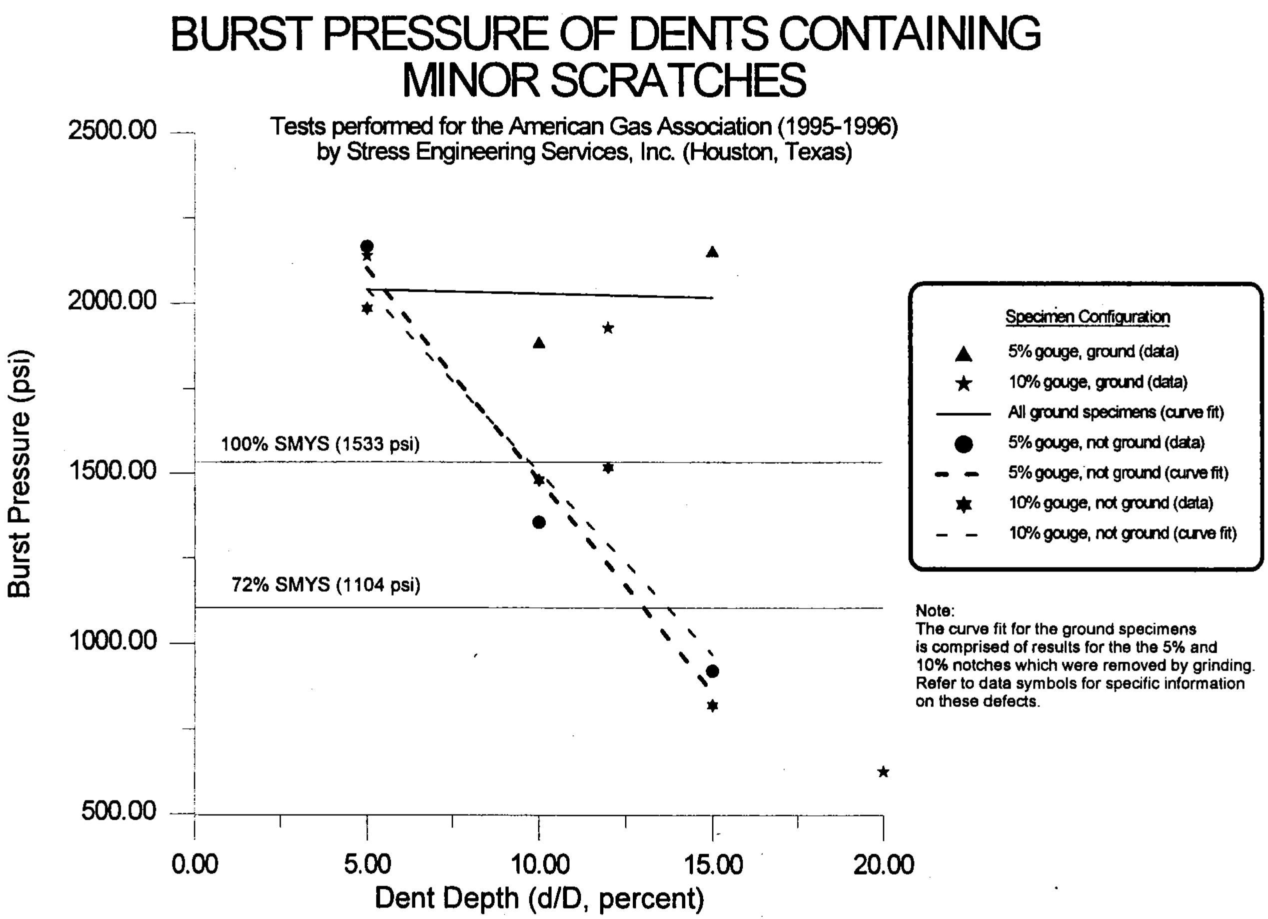

Figure 2.6 Burst Pressure of Dents Containing Minor Scratches

FATIGUE TESTING

While the issue of pressure-cycle fatigue is a greater concern with liquid lines than gas lines, pressure cycling provides a very effective means to quantify the effects that dents with minor scratches have on the lives of pipelines. There were two primary aims in conducting the fatigue tests. The first was to quantify the degree of benefit to be derived from repair by grinding in terms of the fatigue lives of pipes subjected to cyclic internal pressure variations. The second was to show that the lives after grinding would be longer than the useful life of the pipeline.

Development of the Fatigue Test Matrix

As with the burst tests, a fatigue testing matrix was developed in order to meet the research objectives. **Table 3.1** provides the specimens used in this phase of testing with their respective defective combinations. As before, dent depths listed are before rerounding.

Table 3.1 Specimens Used in Fatigue Testing

Specimen	Dent Depth, d/D (%)	Gouge Depth, d/t (%)
F2-1N	15	10
F2-2G	15	10
F2-3G	15	5
F2-4N	15	5
F2-5G	10	10
F2-6N	10	10
F2-7G	10	5
F2-8N	10	5
F2-9G	10	5
F2-10N	10	5
F2-11G	10	5
F2-12N	10	5

The selection of the defects used in the fatigue testing is based upon results from the burst tests. For example, the high burst pressure for the 5% dents and 5% gouges indicated that the severity of this defect was not sufficient enough to consider its use in fatigue testing.

The fabrication of the samples was identical to the procedure used in the burst testing. All fatigue samples used Procedure B in their indenting process, except sample *F2-1N* which was not tested due to failure during indentation. For review, the steps in *Procedure B* are outlined below,

1. Have notch machined in sample to specified depth
2. Measure diameter of pipe at 0° and 90° and wall thickness at 0° relative to gouge
3. Pressurize sample to 920 psi (60% SMYS)
4. Indent sample with selected indenter (pressure in sample allowed to decrease as indenter is released)
5. Remove indenter and repressurize sample to 920 psi (60% SMYS), holding for 2 minutes
6. Take pressure off sample

7. Apply dye penetrant to gouge region
8. Measure dent
9. Grind out gouge if appropriate
10. Repressurize sample to 994 psi (65% SMYS)
11. Depressurize sample
12. Measure dent (this value becomes the residual dent)
13. Perform either burst or fatigue testing.

Fatigue Testing Experimental Procedures

In conducting the fatigue tests, cyclic internal pressures were applied to the pipes with the pressure range based on a percentage of MAOP. Water was used as the testing medium. **Figure 3.1** shows a schematic diagram of the fatigue testing facility.

The selection of the pressure range was based on previous research which involved samples with reasonable pressure variations, but at the same time had sufficient amplitudes to induce failures within 50,000 cycles of operation. Based on these requirements, the following pressures were applied,

1. 25,000 cycles (or until failure) with ΔP = 50% - 100% MAOP
2. 25,000 cycles (or until failure) with ΔP = 0% - 100% MAOP

This selection of pressures was well-suited for the given defects when it is considered that all samples failed before 50,000 cycles were reached. An additional benefit in selecting pressure variations based on percentages of MAOP is that direct comparison of results from pipe samples with different pipe geometries (D/t) and defect characteristics (gouge and dent depths) can be made. Under normal circumstances, comparison of the fatigue lives for defects having different applied cyclic pressures is difficult; however, usage of MAOP provides normalization to the results. The presentation of results in Section 3.3 discusses the mathematical method used to determine an equivalent number of cycles for samples cycled with different pressure differentials.

Results from Experimental Fatigue Testing

All fatigue samples listed in **Table 3.1** were tested until failure, except samples *F2-1N* and *F2-1G* which were aborted when the gouged sample failed during the installation process. Although the failures in the burst tests typically involved ruptures (as shown in **Figure 3.2**), most but not all of the fatigue failures resulted in leaks. A typical leak due to fatigue testing is shown in **Figure 3.3**.

Table 3.2 provides a listing of the fatigue specimens and the number of cycles at which they failed. Because all samples had the same pipe geometries and material properties, the applied pressures were identical for each.

Table 3.2 Fatigue Test Results

Sample Number	Number of Cycles 50% Differential (ΔP = 550 - 1100 psi)	Number of Cycles 100% Differential (ΔP = 100 - 1200 psi) (2)	Equivalent Number of Cycles with ΔP = 50% MAOP (3)
F2-1N (1)	---	---	---
F2-2G(1)	----	---	---
F2-3G	25,427	3,747	85,379
F2-4N	7,267	---	7,267
F2-5G	25,427	---	25,427
F2-6N	6,582	---	6,582
F2-7G	27,789	8,928	170,637
F2-8N	18,093	---	18,093
F2-9G	24,970	5,338	110,378
F2-10N	24,970	---	24,970
F2-11G	27,479	4,594	100,983
F2-12N	16,316	---	16,316

Note:
(1) Testing of these two samples was aborted when the ground sample failed during installation.
(2) The minimum reasonable pressure achieved in cycling for the pump system was 100 psi; therefore, the cycle range was 100 - 1,200 psi as opposed to 0 - 1,100 psi.
(3) The Equivalent Number of Cycles is based upon a combination of Miner's Rule and the DOE-B Curve. See explanation in this section of the report for further details.

The Equivalent Number of Cycles is used to normalize the data so that the cumulative damage imposed by the multiple pressure cycles (two in these tests) can be incorporated into one value. The Equivalent Number of Cycles is calculated using an equation based on a combination of Miner's Rule and the DOE-B curve. This method calculates an equivalent number of cycles at a specified pressure for a pipe which was pressure cycled at other pressure ratios. This equation is presented in addition to an example problem.

$$N_{B_{eq}} = N_{B_1}\left(\frac{\Delta P}{\Delta P_{B_1}}\right)^{-4} + N_{B_2}\left(\frac{\Delta P}{\Delta P_{B_2}}\right)^{-4}$$

where:

N_{Beq} = Equivalent number of cycles for Sample B at the specified pressure differential, ΔP
ΔP = Base pressure differential
N_{B1} = Number of cycles obtained for Sample B at ΔP_{B1}
ΔP_1 = First pressure differential for Sample B
N_{B2} = Number of cycles obtained for Sample B at ΔP_{B2}
ΔP_2 = First pressure differential for Sample B

Example Problem

Assume that Sample B had the following fatigue data,

25,000 cycles at ΔP = 500 psi

13,000 cycles at ΔP = 1200 psi

Determine the equivalent number of cycles for ΔP = 1000 psi,

$$N_{1000} = 25000\left(\frac{1000}{500}\right)^{-4} + 13000\left(\frac{1000}{1200}\right)^{-4} = 28{,}519\ cycles.$$

This procedure was done for all data found in **Table 3.3**. In addition to the tabulated values, a graphical presentation of these results is presented in **Figure 3.4**. The information in this graph plots gouge depth as a function of cycles to failure for various dent depths.

Discussion of Fatigue Results

From the fatigue tests, the following important observations can be made,

- The contribution of grinding to the fatigue life for pipes cannot be over-emphasized. The fatigue life for ground specimens is approximately five times that of their unground counterparts.
- As would be expected, both increasing dent depth and gouge depth act to reduce fatigue life. Based on the data, it is not apparent which of these contributes most to this reduction. Previous research indicates that by themselves, minor gouges and dents are not severe; however, combinations of the two can be significant. The reason for their severity is the development of microcracks that occur at the base of the gouge when the rerounding occurs.

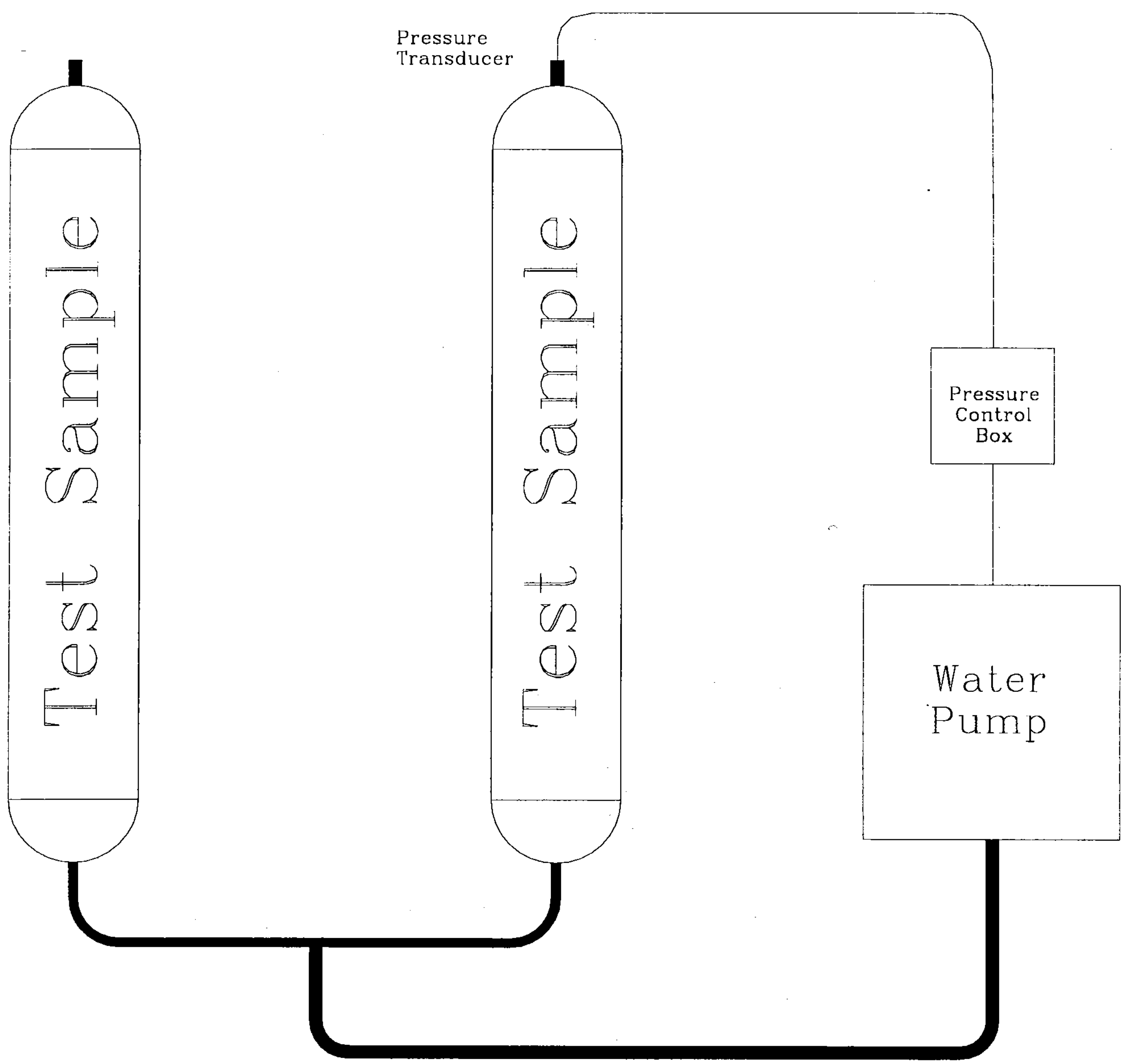

Figure 3.1 Schematic Diagram of Fatigue Test Set-up

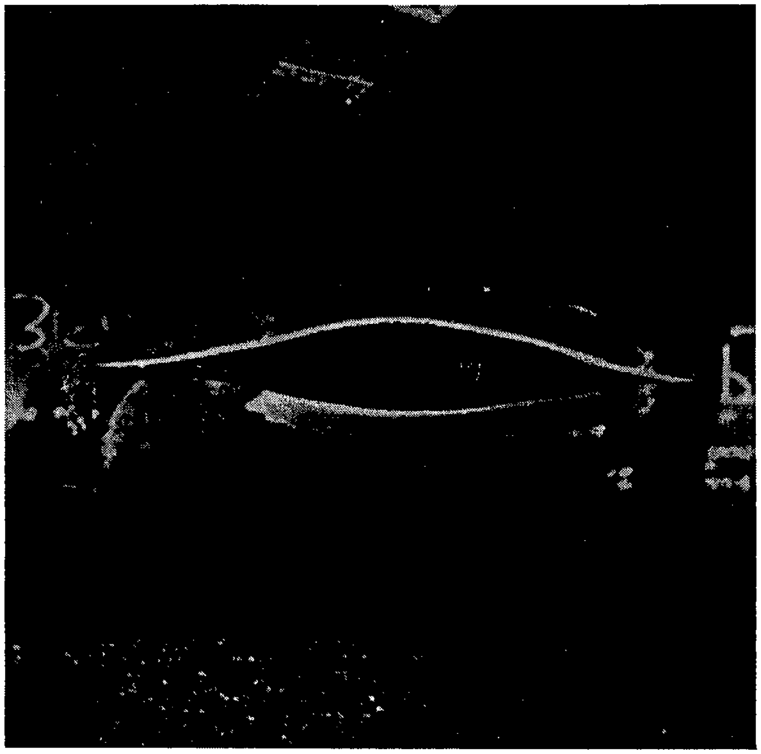

Figure 3.2 Photograph of a Typical Failure in a Burst Specimen

Figure 3.3 Photograph of a Typical Failure in a Fatigue Specimen

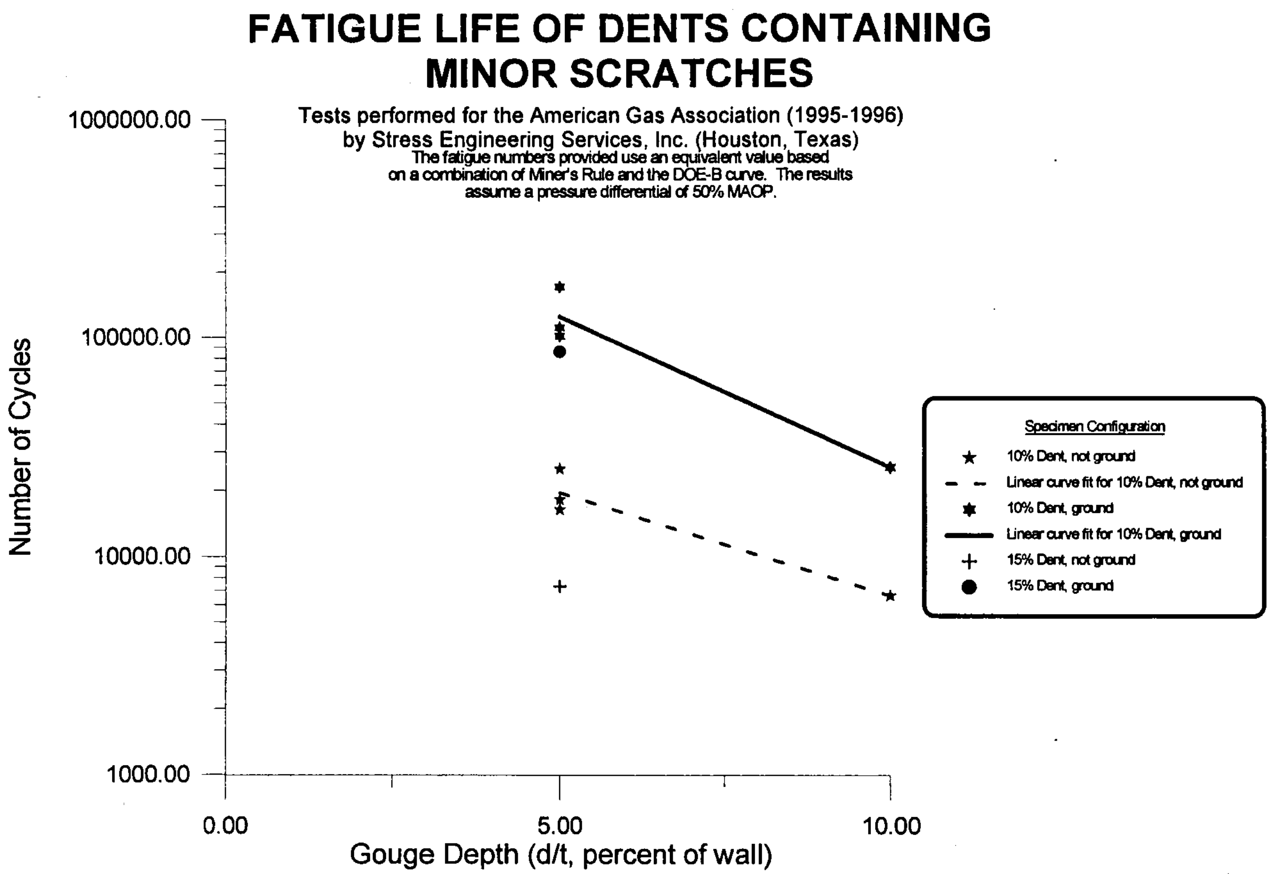

Figure 3.4 Fatigue Life as a Function of Gouge Depth

CONCLUSIONS

One of the primary motivations for conducting this research is to provide pipeline operators with a means for repairing mechanical damage in a simple and effective manner. The results of this study indicate that the repair of gouges in dents by grinding can restore adequate serviceability to a pipeline that has been damaged in a manner which does not involve extremely deep penetration of cracking or associated material damage.

In addition, the burst testing provided several important observations regarding the impact that gouges combined with dents have on the burst strength for a given pipe section.

- Gouges in dents that are repaired by grinding can be expected to have burst strengths that exceed 100% SMYS as long as at least 80% of the nominal wall thickness remains after removal of the damaged material.
- The burst strengths for shallow gouges combined with dents are directly related to the maximum level of indentation and the subsequent rerounding that takes place because of the internal pressure.
- The indentation and rerounding of a pressurized notched pipe as was done herein appears to adequately simulate the effects of real mechanical damage based on the experience of the authors.

The results of the fatigue tests indicate that grinding is an effective means for restoring the pressure-cycle fatigue resistance of a mechanically-damaged pipe.