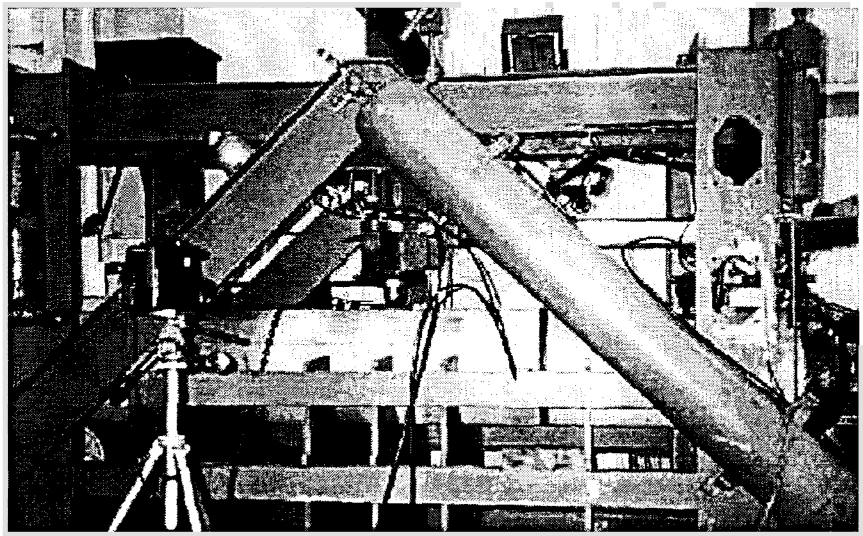
Details on Defect Installation



The defects used in the pull rig and flow loop were installed with a machine that moves a damage tool (indentor) into or along to the pipe wall. In the photo at right, the damage tool is in the center of the photograph, immediately above the pipe. The machine has two hydraulic actuators to press the indentor into the pipe. A vertical actuator applies radial compression, and a horizontal actuator pushes the tool along the pipe axis.

Two methods were used to control the movement of the indentor during defect installation. In the first, the indentor was independently moved down (radially into the pipe), sideways (along the pipe axis), and up (radially out from the pipe). During the sideways movement, the indentor was locked radially so that it could not move up or down (in or out of the pipe). In the second method, a trajectory of the tool was specified. In this case, the indentor could move both radially and axially following a preset path.

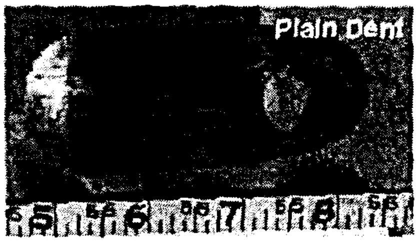
Dent and Gouge Machine Defect Fabrication

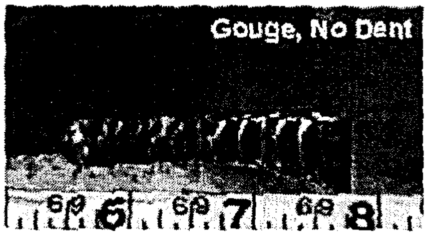
Some difficulties were encountered in installing the defects. These difficulties caused the defects made early in the program to be less repeatable than those made later in the program. For example, machine compliance affected the final dent depth for early defects. When the machine pushed "away" from the pipe, the target dent depth was less than planned because dent depth was controlled by measuring the hydraulic ram displacement. Other difficulties included pipe movement along the axis of the machine, which reduced the defect length relative to the target length, and riding up of the indentor over the pipe wall thickness, which affected gouge depth in early runs.

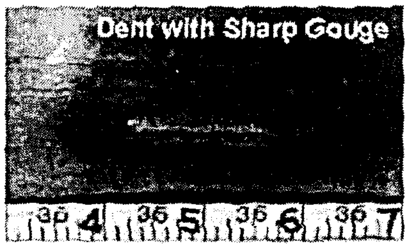
Indentors

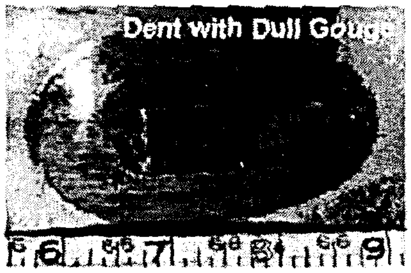
Two indentor shapes were used to create mechanical damage. The first was a 4-inch diameter spherical indentor with a protruding "tooth" that was set to create a gouge with a target depth (in percent wall thickness), as shown at right. Measurements indicate that the target dent depth (in percent of the diameter) was repeatable using this tool, but the actual gouge depth was highly variable and not well correlated with the target depth. Other defect parameters gouge length (in inches) and pressure *at* installation (in percent specified minimum yield stress).

Shown at right are four defects made with the spherical indentor. Several features are obvious. First, the contact area between the ball *and* the pipe can be large, often extending several inches on *either* side of the gouge. Second, the socket for the indentor produced a circular mark on the pipe at the start of each defect (this is most clearly seen in the upper left defect). Third, there is same asymmetry to the defects, with the protruding tooth grabbing more on one side than an the other. Finally, there is evidence of slip-stick, which is discussed later.

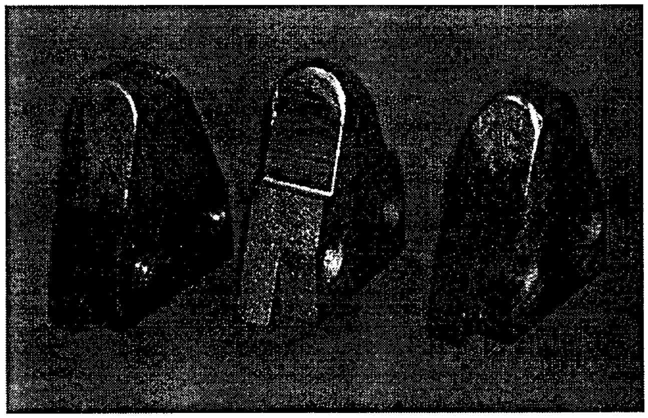




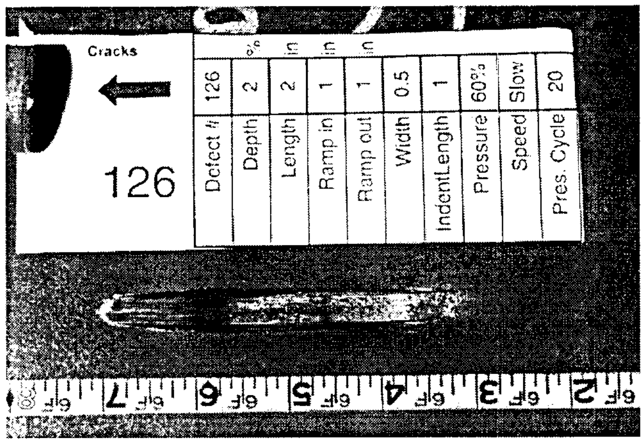




The second type of indentor more closely simulates an actual backhoe tooth, as shown at right. Each tooth had rounded edges and a footprint with a length and width between 0.5 and 1.0 inches. Care was taken to ensure that the supporting frame for the tooth did not contact the pipe.



A typical defect made with the second indentor is shown at right, where various defect parameters are given in the table above the gouge. These parameters represent the variables made with this type of indentor:



- "Depth" is the dent depth in percent of the diameter.
- "Length" is the flat bottom length of the gouge in inches.
- "Ramp in" and "Ramp out" are the distances on either side of the flat bottom used to ramp the indentor into and out of the pipe (thus the total gouge length is the sum of the bottom length and the ramp in and ramp out lengths).
- "Width" and "IndentLength" are the footprint dimensions of the indentor.
- "Pressure" is the internal pipe pressure in percent of specified minimum yield strength.
- "Speed" refers to the rate of axial movement of the indentor (slow is 1 inch per second; fast is 5 inches per second).

In the table "Defect #" is an arbitrary number identifying each defect and "Pres. Cycle" refers to the number of pressure cycles the pipe saw before installation of the defect (discussed below).

Most of the difficulties encountered with the spherical indentor are not present in the defects made with the tooth indentor, with the exception of slip-stick. Slip-stick is a phenomena due to the effects of adhesion occurred in making some of the defects, which leads to chatter marks along the gouges. This slip-stick action occurred primarily near the ends of the defects, whereas the region between the ends was free of such chatter marks. Such chatter marks are not unusual in defects made where the damage involves sliding under significant normal load, and such an effect is compounded at lower pressure levels. Chatter marks have been seen previously as a result of contact with a backhoe(2). They are evident in other simulated damage(3) as well as in some field damage(4).

That the chatter marks are prominent at the ends of the damage, but almost nonexistent over the central part of the gouge, suggests that differences in the rate of axial movement - either accelerating or decelerating - may have contributed to their formation. There was usually a drop in axial load near the point where the chatter marks disappear.

Installation Procedures

Prior to making defects, each pipe was pressure tested to between 60 and 65 percent of the actual yield for a leak check. This maximum pressure was typically near 72 percent of the specified minimum yield stress, the maximum allowable operating pressure (MAOP) for Class 1 locations. During installation of each defect, the pressure in the pipe was typically near 60 percent of the specified minimum yield stress, approximately equal to the MAOP for Class 2 locations. When all defects were installed and the pressure in the pipe reduced to ambient, each defect was covered with epoxy-based machinery paint to control rusting.

To avoid possible interaction, the defects were spaced around and along each pipe section. The defects were separated circumferentially by –120-degree increments, at nine to twelve sites staggered axially and separated by about a diameter.

Installing multiple defects in one pipe section necessitates moving the pipe axially and turning it in the dent-and-gouge machine. In general, the pressure in the pipe was reduced to about 25 percent of the specified minimum yield stress each time the pipe was moved to reduce the likelihood of damage growth or an accident. Therefore, defects installed early in the sequence were subjected to a number of pressure cycles of roughly 35 percent of the yield stress.

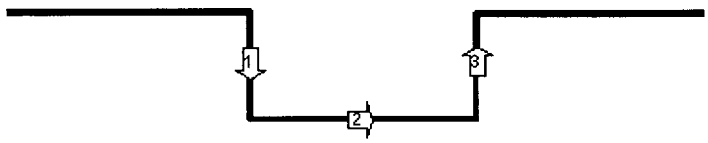
Because the defects were made while there was internal pressure in the pipe, the defect rerounded when the indentor was retracted. This rerounding significantly changes the stress distribution around the defects and can lead to cracking in and around the gouge. Some of the defects may have cracked during one or more of the pressure cycles that occurred during subsequent defect installations - loud "pings" were heard on several occasions.

After all the defects were installed, the pipes were depressurized and inspected using a wet fluorescent magnetic particle technique. Then, the pipes were repressurized. Each sample was pressurized first to the defect-installation pressure and held for 2 hours. Then, the pressure was increased by 10 percent of specified minimum yield pressure every hour until the pressure reached 90 percent or the pipe failed. At this point, the pressure was held for up to one hour, after which the pipe was depressurized and reinspected.

Following the hydrotest, the defect samples were available for MFL measurements. In three cases, a defect set was pressurized once more to a higher pressure after the MFL measurements had been made. The purpose of this repressurization was to change the stress and strain conditions around the defects and, possibly, introduce or extend cracking. In two cases, one of the defects failed. After failure, the damaged section was cut out and **a** patch welded in place. Then, the additional sets of MFL measurements was taken.

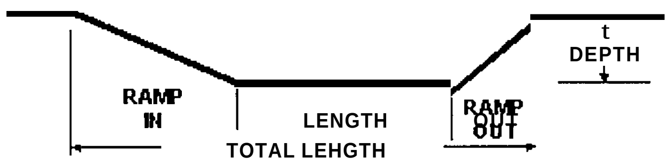
Dent and Gouge Machine Defect Fabrication

During the program, a set of enhancements was made to the dent and gouge machine to allow more control over defect installation parameters. The control-system enhancements enable the fabrication of mechanical damage defects not only with more realistic appearance, but with strain and deformation rates more representative of excavation equipment. Prior to the modification, one hydraulic pump handled indenting and translation. The procedure for making a dent and gouge defects was as follows:



1. The indenting cylinder valve was opened, forcing the tooth into pipe. The indenting cylinder valve was closed when the desired depth was attained as read from a displacement sensor. This part of the denting process required 5 to 10 seconds to complete.
2. The translation cylinder valve was opened, forcing the tooth along pipe. The translation cylinder valve was closed after the desired translation is achieved. This part of the denting process required 5 to 10 seconds to complete. Switching the pump output from the indenting cylinder to the translation cylinder required 10-30 seconds. Switching from the translation cylinder back to the indenting cylinder required an additional 10-30 seconds.
3. The indenting cylinder valve opened, which retracted the tooth from pipe. This step took 5 to 10 seconds to complete.

The new system uses computer-controlled servo valves to simultaneously control the indenting and translation process. Four parameters are set:



1. Depth - the maximum dent depth in percent of the diameter.
2. Length - the flat bottom length of the gouge or dent in inches.
3. Ramp in - the distance required for the indenting tool to reach maximum dent depth
4. Ramp out - the distance on the exit side of the flat bottom used to ramp the indentor out of the pipe

The total defect length is the sum of the bottom length, the ramp in length, and the ramp out length.

The speed at which the translation cylinder extends can be controlled. Typically, the translation speed ranges between 1 to 5 inches per second. At the slowest and most commonly used setting, an 8-inch defect requires 8 seconds. At the fastest setting, a 6-

inch defect requires just over a second. These rates are similar to backhoe excavation rates.

Defect Set 1
Descriptions and Photographs

Defect sets 1 and 2 are complementary, as described below. The defects in the two sets were chosen to span a range of maximum dent depths from zero to 6 percent of the diameter, gouge depths from zero to 25 percent *of* the wall thickness, and gouge lengths from zero to 6 inches. The individual defect geometries are listed in the tables below. In each table, an identifying number is given if the defect is present in Defect Set 1, and an asterisk (*) represents a defect in Defect Set 2. The values shown below correspond to target geometries.

All defects in Sets 1 and 2 were made with a spherical indentor. The gouge depth was set with a tooth that protruded 5, 10, or 25 percent of the wall thickness from the surface of the sphere. Note that the compliance of the machine used to fabricate the defects was a factor in defining the final defect geometries as was axial movement of the pipe during gouging. When the pipe moved along its axis, the actual defect length was below its target value. When the pipe deformed around the indentor, the actual gouge depth was

different than its target. For details, see the individual defect photos.

Table 1. Gouge Only, No Dent
(Three defects in Set 1. Five defects *in* Set 2)

Gouge length (in.)	Gouge depth (% wall thickness)		
	5	10	25
0.25	*	*	
2.0	#43	*	#28
6.0	#36 *	*	

Table 2. Dent Depths = 3% or 6%; Sharp Cutter
(Nine defects in Set 1. Twelve in Set 2.)

Gouge length (in.)	Gouge depth (% wall thickness)			
		(3%) #29 (6%)	(6%) *	#46 (6%
2.0	#42 (3%) *	* *	#44 (6%) * *	* *
6.0	*	#40 (3%) *	#38 (6%)	

Gouge length (in.)	Gouge depth (% wall thickness)	
	5	10
2.0	#37 (3%) #39 (6%)	#31 (6%) *
6.0	#45 (3%) * *	#30 (3%)

The pipe used for Defect Set 1 was removed from service and appears to be X52 or

X60. Material properties and the layout of the defects are given in the following links:

Pipe specifications.
Layout of Defect Set 1.
Clicking on a defect number in the following tables will bring up a photo of the defect. Note that the file number given in the photograph is *not* the same as the defect number.

Table 4. Defect Set 1

Defect #	Target Values			
	Dent Depth	Gouge Depth	Gouge Length	Cutter Sharpness
28	0	25	2	sharp
29	6	5	0.25	sharp
30	3	10	6	dull
31	6	10	2	dull
33	6	10	0.25	sharp
34	3	5	0.25	sharp
35	6	10	6	sharp
36	0	5	6	sharp
37	3	5	2	dull
39	6	5	2	dull
40	3	5	6	sharp
42	3	0	2	
43	0	5	2	sharp
44	6	10	2	sharp
45	3	5	6	dull
46	6	25	0.25	sharp
48	3	25	0.25	sharp

Defect Set 2
Descriptions and Photographs

Defect sets 1 and 2 are complementary, as described below. The defects in the two sets were chosen to span a range of maximum dent depths from zero to 6 percent of the diameter, gouge depths from zero to 25 percent of the wall thickness, and gouge lengths from zero to 6 inches. The individual defect geometries are listed in the tables below. In each table, an identifying number is given if the defect is present in Defect Set 2, and an asterisk (*) represents a defect in Defect Set 1. The values shown below correspond to target geometries.

All defects in Sets 1 and 2 were made with a spherical indentor. The gouge depth was set with a tooth that protruded 5, 10, or 25 percent of the wall thickness from the surface of the sphere. Note that the compliance of the machine used to fabricate the defects was a factor in defining the final defect geometries as was axial movement of the pipe during gouging. When the pipe moved along its axis, the actual defect length was below its target value. When the pipe deformed around the indentor, the actual gouge depth was different than its target. For details, see the individual defect photos.

Table 1. Gouge Only, No Dent
(Three defects in Set 1. Five defects in Set 2)

Gouge length (in.)	Gouge depth (% wall thickness)		
	5	10	25
0.25	#9	#18	
2.0	*	#25	*
6.0	#1 *	#16	

Table 2. Dent Depths = 3% or 6%; Sharp Cutter
(Nine defects in Set 1. Twelve in Set 2.)

(in.)	Gouge depth (% wall thickness)			
	0	5	10	25
0.0-0.25	#15 (3%) #13 (6%)	* *	#2 (3%) *	* *
2.0	#6 (6%) *	#10 (3%) #20 (6%)	#4 (3%) #27 (3%) *	#3 (3%) #8 (6%)
6.0	#24 (3%)	#2 (6%) *	#38 (6%)	

Table 3. Dent Depths = 3% or 6%; Rounded Cutter
(Five defects in Set 1. Four defects in Set 2.

Gouge length (in.)	Gouge depth (% wall thickness)	
	5	10
2.0	* *	#19 (3%) *
6.0	#21 (3%) #7 (6%)	#12 (6%) *

The pipe used for Defect Set 2 was removed from service and appears to be X52 or

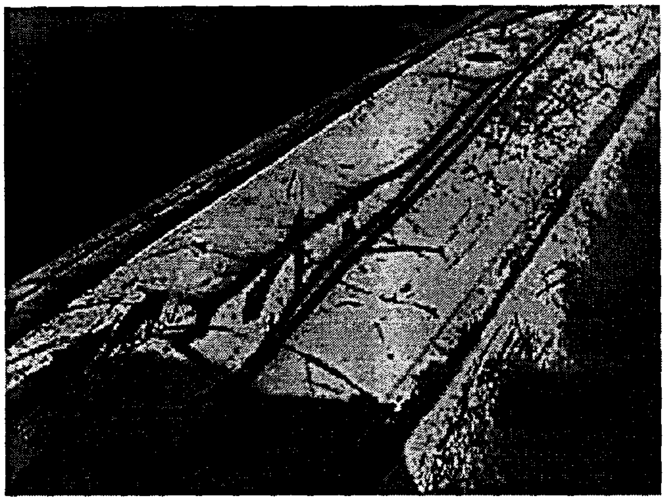
X60. Material properties and the layout of the defects are given in the following links:

Pipe specifications.
Layout of Defect Set 2.
Clicking on a defect number in the following tables will bring up a photo of the defect.
Note that the file number given *in* the photograph *is not* the same as the defect number

Table 4. Defect Set 2

Defect #	Target Values			
	Dent Depth	Gouge Depth	Gouge Length	Cutter Sharpness
1	0	5	6	sharp
2	6	5	6	sharp
3	3	25	2	sharp
4	3	10	2	sharp
6	6	0	2	
7	6	5	6	dull
8	6	25	2	sharp
9	0	5	0.25	sharp
10	3	5	2	sharp
12	6	10	6	dull
13	6	0	0.25	
15	3	0	0.25	
16	0	10	6	sharp
18	0	10	0.25	sharp
19	3	10	2	dull
20	6	5	2	sharp
21	3	5	6	dull
22	3	10	0.25	sharp
24	3	0	6	
25	0	10	2	sharp
27	3	10	2	sharp

Defect Set 3 - Backhoe Defects
Descriptions and Photographs



Defect Set 3 consists of mechanical damage defects that had been made by a backhoe in a Gas Research Institute project on real-time monitoring. This pipe sample includes the following defect classes:

- Vertical hits on crown of pipe
- Hits and scrapes on crown of pipe
- Scrapes on crown of pipe
- Hits and scrapes on side of pipe
- Scrapes on side of pipe
- Scrape perpendicular to pipe axis.

These defects were made by striking the pipe with a rubber-tired 3000 series John Deere backhoe. Two internal pressures were used during impact, 150 psi and 250 psi.