Additional Details on the Linear Test Rig Experiments and Defect Sets

The linear test rig was used to take data for a variety of materials and defects. Some edge effects are present when using the linear test rig, but in general, these effects were small. The measurement system used to record data is modeled after that used in the test bed vehicle. So, the resolution and accuracy of measurements from the pull rig should be the same as that from the linear test rig.

For this program, measurements were made at velocities under about 3 miles per hour. Prior results show that such velocities are low enough that they should have negligible effects on the inspection signals. Typically, data were taken at 10 Oersted intervals, ranging from as low as 10 Oersted to as high as 150 Oersted. In addition, remanent measurements were taken using no applied field.

Three types of defects were used in the linear test rig: fifteen defects made under pressure, five natural dent defects in pipe removed from service, and twelve simple mechanical damage defects made in flat plates. The defects consisted of plain dents, cold worked regions, dents with cold worked regions, and cold worked regions with removed metal.

Additional linear test rig defects were made in two pipe steels: the flow loop material and a generic X52 material. The materials used are the same as those used for the pull rig defects.

Linear Test Rig Defect Tables (Partial)

Layout of Defects in One Defect Set

For more information on the linear test rig, refer to GRI Pipeline Simulation Facility Nondestructive Evaluation Laboratory.

Description of the MFL Test Bed Vehicle

The MFL test bed vehicle (TBV) was built as a test platform for use in the Pipeline Simulation Facility. This vehicle eliminates the need to develop a test platform for this research program on mechanical damage. The test bed vehicle makes it easier for research to attain field realism, which is something only vendor laboratories had been able to do previously.

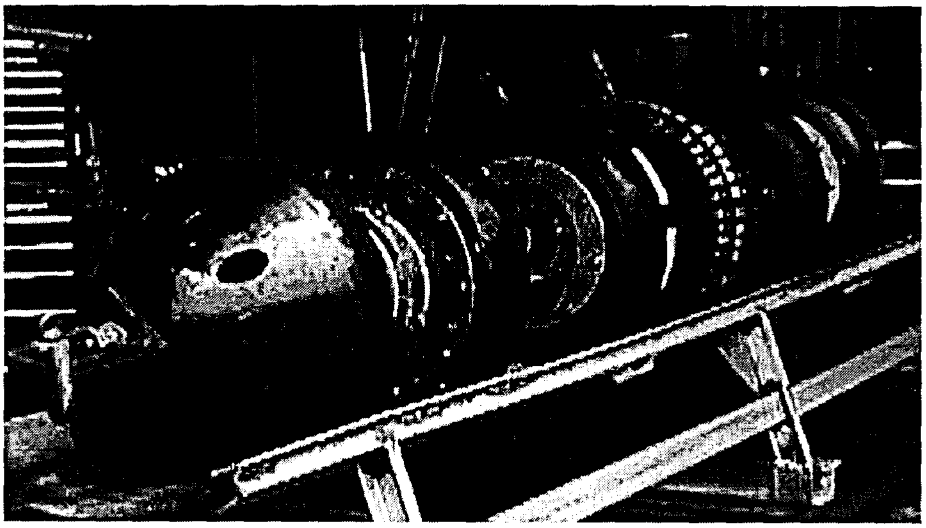
General Description

MFL tools for pipeline inspections are completely self-contained units containing magnets, sensors, data conditioning and recording systems, and power systems. The systems used in most MFL tools include:

- A drive system, which is used to propel the tool through the line. Differential pressure acting on the drive system pulls the tool through the pipeline.
- A power system, which provides battery power for the sensor, data conditioning and recording systems.
- A magnetization system for magnetizing the pipe.
- A sensor system, used to measure a flux-leakage signal.
- A data conditioning and recording system, which amplifies, filters, and stores the measured signals.

The magnetic flux leakage (MFL) test bed vehicle (TBV) was designed to simulate current inspection technology as well advance the state of the art of this technology. Many components were designed so that different configurations could be achieved. A photograph of the three module test bed vehicle is shown below. The overall length is approximately 12 feet and it is configured for 24 inch diameter pipe. The three modules are the

- Propulsion / Battery module
- Magnetizer and sensor module
- Electronics module



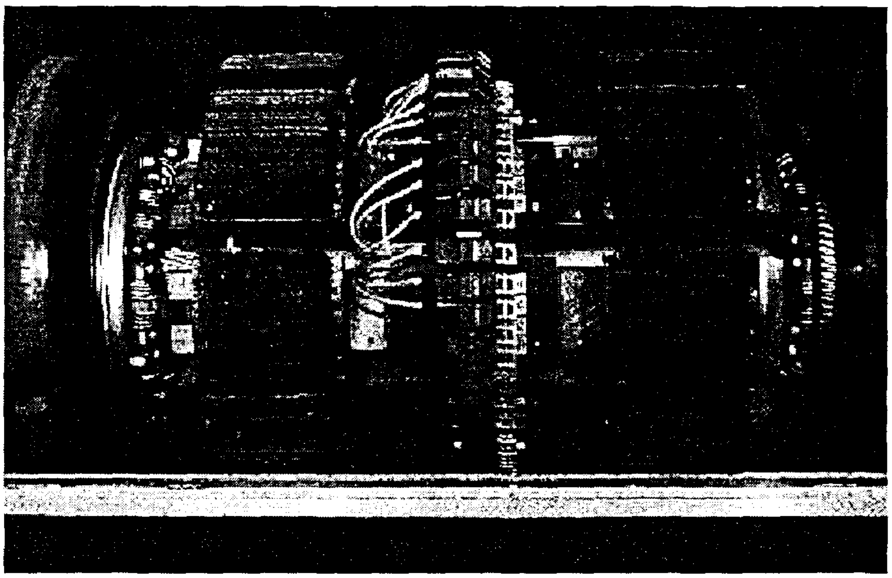
MFL test bed vehicle

For more information on the MFL test bed vehicle, refer to GRI Pipeline Simulation Facility Magnetic Flux Leakage Test Bed Vehicle.

Additional Details on the Test Bed Vehicle Modifications

Magnetizer Modifications

An MFL tool contains a system that magnetizes a length of the pipe wall. Typically, sets of magnets are used to provide coverage around the circumference of a pipe. A permanent-magnet system, shown below, has pairs of magnets that are attached to backing bars and to metal brushes or magnet shoes that rub against the pipe wall. Ferromagnetic brushes are used to efficiently couple the magnetic field to the pipe body. The backing bar is made of a material that is selected to obtain a high flux level in the pipe wall.



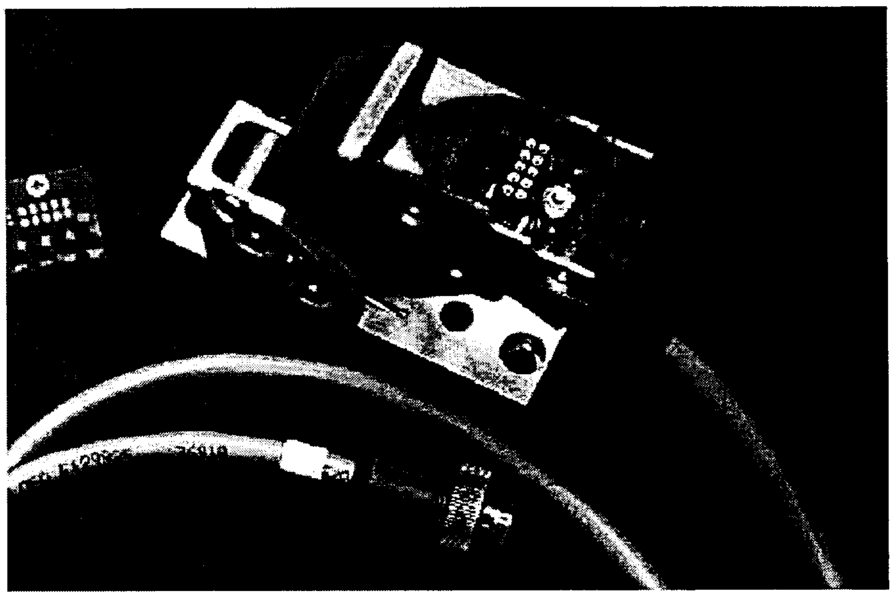
Permanent-magnetic system

The original magnetizer produced field levels in typical wall thickness pipes ranging from 70 Oe to 110 Oe. The magnetizer had 28 megagauss-oersted neodymium-iron-boron magnets in eight magnet assemblies spaced around the circumference. Each assembly had 18 sq. inches of NdBFe magnets and brushes for coupling the magnetic energy into the pipe. (See Background information on magnet strength.)

Linear test rig results showed that two magnetization levels are required: one higher and one lower than the field levels established by the original magnetizer. For optimal characterization, the low field level should be between 50 and 70 Oe, and the high field level should be above 150 Oe. To attain the lower magnetization level in the pipe, some of the magnetic field was coupled directly to the backing bars by shunts. To attain higher magnetization levels in the pipe, the magnet areas were increased by 8 square inches using NdBFe 35 magnets.

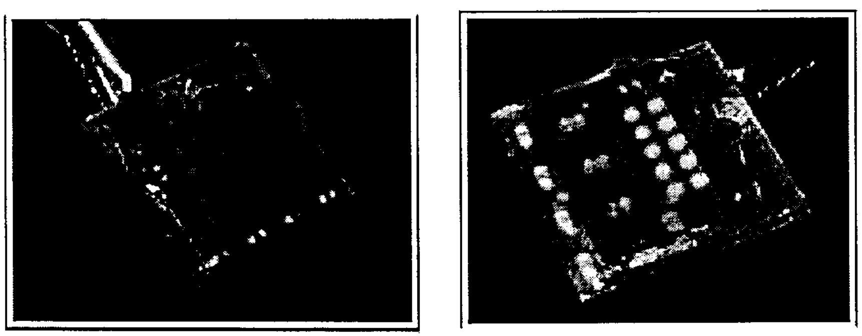
Sensor Modifications

Sensors between the magnet pole pieces measure the flux leakage field. (See Background information on MFL sensors.) The sensor systems convert the flux leakage field into a signal that can be stored and analyzed. The sensor system consists of the sensors themselves, the mounting system used to support the sensors, wear plates between the sensors and the pipe, and cabling between the sensors.



Sensors

The test bed vehicle has **48** sensor heads, six on each magnet bar. Each sensor head has four axial Hall element sensors. The configuration of these sensors is shown below. Sensor spacing is similar to commercial high resolution systems. To minimize noise, some amplification of the signal takes place very near the sensor.



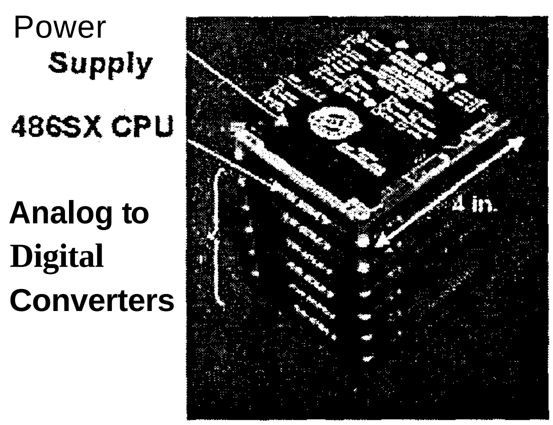
Sensor boards

All sensors on the test bed vehicle were replaced by SS495 Series, solid-state, ratiometric, linear sensors manufactured by Honeywell Micro Switch. These sensors have the necessary characteristics to measure the fields generated by mechanical damage defects. The sensors operate on supply voltages ranging from 4.5 volts to 10.5 volts. Outputs are ratiometric, and are set by the supply voltage. The sensors measure a minimum of +/- 600 Gauss, and they include an amplifier integrated into the circuit. Sensor arrays made up of multiple sensors are constructed using printed wiring boards. These sensor arrays are potted in a sensor housing and mounted in the sensor.

Electronics Module Replacement

The electronics module of the test bed vehicle was designed to collect data during pull rig and flow loop tests. The unit has both sensor electronics and digital computer recording capability. There are approximately 4.3 million square inches of pipe surface in the flow loop. If data are recorded in 0.1 inch (5 mm) intervals in the axial direction and using only the axial sensors, approximately 100 million data points would be taken each lap. The original electronics module was not designed to handle such large amounts of data.

The electronic components were replaced with a personal computer compatible system using PC-104 format cards to minimize size and maximize ruggedness. The computer module shown below has a central processor unit (CPU) card, with six analog-to-digital (A/D) cards, and a power supply module. A mass storage device and cabling complete the data acquisition system.

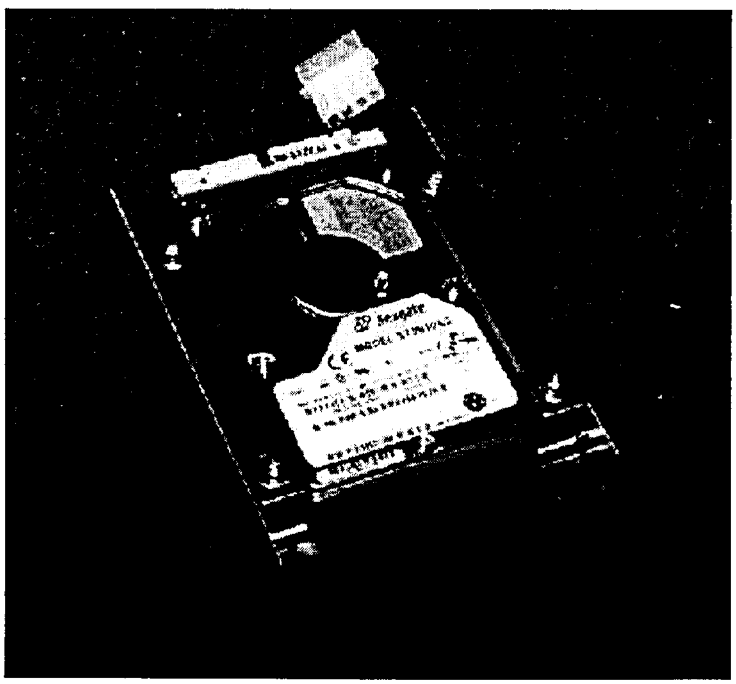


Electronics module

A/D Converters: The AID converter hardware converts the analog signals from the sensors into digital signals that can be stored by the computer. There is one A/D channel for each of the 192 sensors. Sensor voltages are in the range of 0 to 10 volts. Using a 16-bit converter allows 65536 discrete voltage levels to be measured, equating to 0.15 mV per bit. This resolution allows meaningful measurements of magnetic field strength to be recorded for later analysis. The respective AID channel captures the data from 96 sensors, the 96 A/D channels being achieved by using six A/D cards, each with 16 input channels.

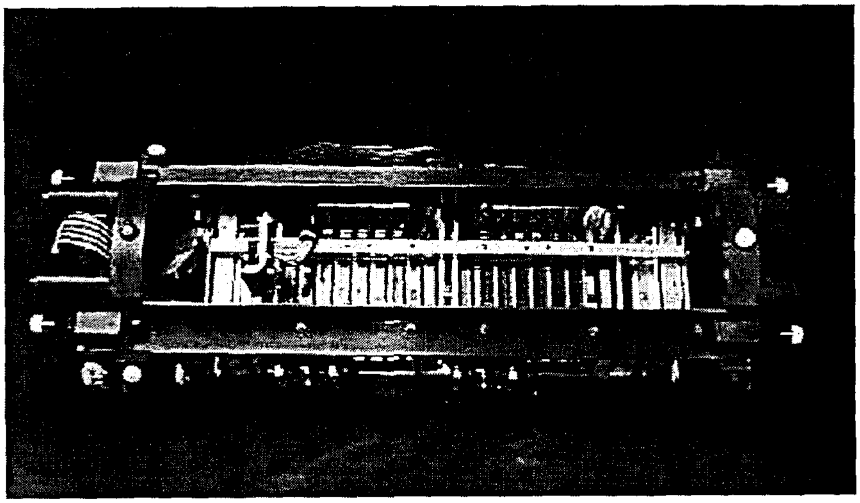
Two separate data recording modules running in parallel are used to record the output of all 192 sensors. The 16 bits of data for each channel is in 2-byte words on the mass storage device. Each storage record, containing one data sample from each sensor, contains 192 bytes of information. Representative 16-channel, 16-bit AID PC104 cards are the PC104-DAS16JR converter boards manufactured by Computer Boards, Inc. The digital sensitivity of the sensor is approximated 0.1 gauss per quantum level.

Mass Storage: Coupled to the CPU is a mass storage device that stores the control software and the acquired data. It is a solid-state disk drive, AT2500-192, manufactured by MemTech, Sunnyvale, CA. This solid-state storage device uses Flash memory as the storage elements, and includes a standard IDE interface. Using non-volatile memory configured to have the standard disk interface results in a rugged storage device with no development of custom hardware.



Storage drive

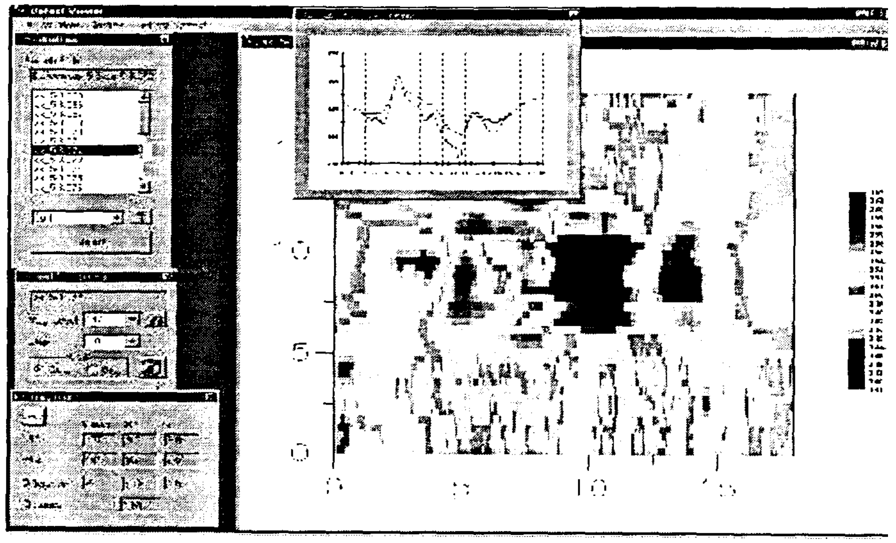
The CPU, A/D converters, power converters and mass storage devices are mounted in a rugged frame. The assembled test bed vehicle data recorder is shown below. Testing has shown that data from all 192 sensors can be recorded in 0.1 inch increments at speeds up to 8 miles per hour.



Overall system

Data Display Software

The data recorded by the MFL test bed vehicle can be displayed using a proprietary Windows@based viewer. The following figure shows test bed vehicle data recorded in the pull rig with the mechanical damage defect set. In a typical display, both image data and a particular sensor output are displayed. For the image display, axial distance along the pipe is on the horizontal axis, Each horizontal line represents one sensor with color corresponding to flux leakage amplitude.



Display software

Background Information on Magnet Strength

Various permanent magnet strengths are available. A magnet's strength is categorized by its maximum energy product, which is a measure of the magnet's force of attraction. Many older inspection systems used ceramic permanent magnets, which have an energy product of 1 to 4 megagauss-oersted.(10) Other systems used Alnico (aluminum-nickel-cobalt) magnets, which have energy products from 5 to 12 megagauss-oersted. Rare earth magnets, such as neodymium-iron-boron magnets and samarium-cobalt, became available in 1984. These magnets have energy products from 18 to 45 megagauss-oersted. Thus, the newer magnets have dramatically increased the magnet power available. They are also mechanically stronger than the other magnet types, which tend to be brittle, and they are significantly more expensive.

Background Information on MFL Sensors

The two types of sensors commonly used in MFL tools are induction coils and Hall elements (field sensor). Coils measure the rate of change of a magnetic field, while Hall elements measure the actual magnetic field strength. Historically, induction coils have been the most commonly used type of sensor on MFL inspection tools because they do not require a power source. Instead, a voltage is generated in a passive coil of wire or printed circuit as it passes through a changing magnetic field. A recording device measures this voltage, which is proportional to the change in flux density. Since a coil responds to a change in flux density, the output of a coil is a function of the speed at which it is moving. Integration techniques can be used to convert coil measurements to flux density measurements, but the constant component is lost. The constant component is needed to determine the applied magnetic field strength.

The MFL test bed vehicle uses Hall elements. In a Hall element, an electrical current is distorted by the presence of a magnetic field. A recording device measures the change, which is proportional to the strength of the magnetic field and the amount of current. Although electrical power is required to generate the current, Hall elements are not sensitive to speed, which makes them attractive for research applications. Also, the constant field component that is related to the applied flux density in the pipe is available.

Sensors are spring-loaded against the pipe surface. The test bed vehicle has a spring-loaded four-bar linkage system. Spring loading allows the sensors to ride over weld beads, dents, and other intrusions. The stiffness of the mounting system and the mass of the sensors affect how closely the sensors follow the wall. Stiff systems closely follow the wall, but they also increase wear on the sensors. Low-mass sensors follow the wall better than high-mass sensors, but there is often a trade-off between sensor mass and sensor ruggedness.

Test Details

MFL inspection signals were taken from Defect Sets **4** and 5 in the pull rig and from Defect Set 6 in the flow loop. Defect Sets **4** and **5** were welded together to form an 80-foot test section. Defect Set 6 was flanged for installation in the loop. Both pull rig and flow loop tests were conducted at high and low magnetization levels at various speeds.

The pull rig also offered the opportunity to test the effects of magnetization direction on the inspection signals. For these tests, the defect section was periodically swapped end for end before pulling. Swapping the test section provided a different remanent magnetization level. Gouge-type defects are inherently asymmetric. Swapping the pipe allowed the effects of magnetizer orientation (direction) relative to the defect to be assessed.

For each magnetization level and velocity, at least five pulls were completed to allow the remanent magnetization levels to stabilize. The results were analyzed and compared to prior results to ensure flow loop tests would be meaningful. There was good correlation with prior results, though some differences were noticed. (These differences are discussed later in this report). In addition, pull rig tests were conducted just prior to the flow loop tests to ensure the data acquisition system was performing to specification.

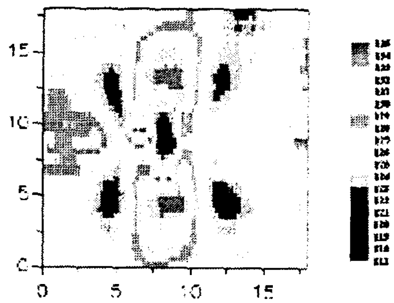
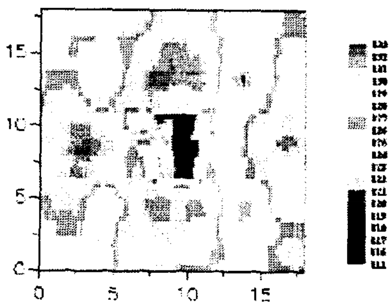
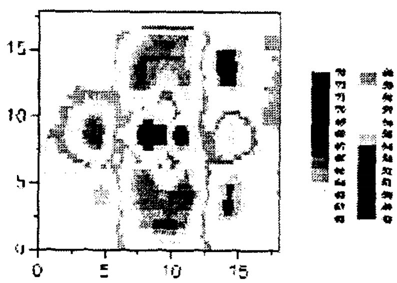
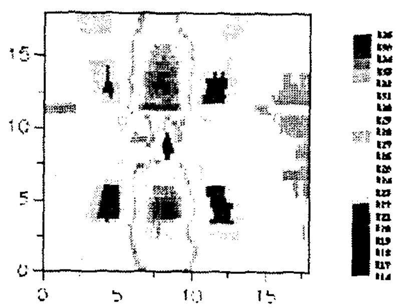
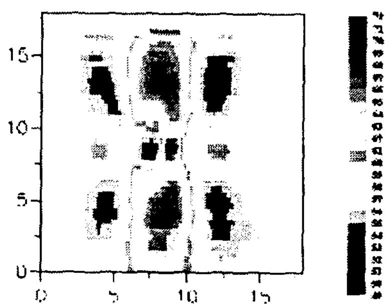
Date	Mag Level	Pressure (psi)	Comments
17-Sep-99	High	None	Pipe in forward direction
19-Sep-99	Low	None	Pipe in forward direction
12-Oct-99	Low	None	Pipe in reverse direction
19-Oct-99	High	None	Pipe in reverse direction

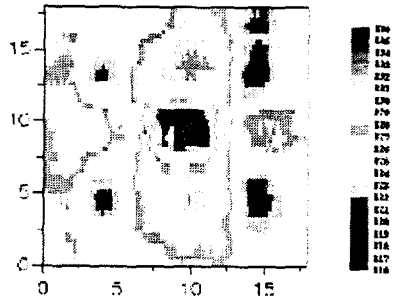
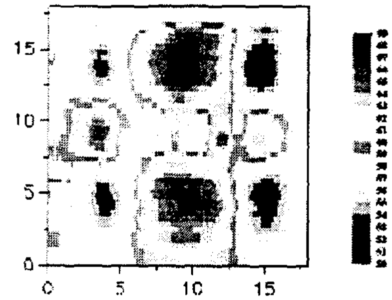
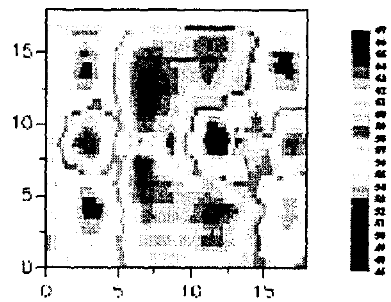
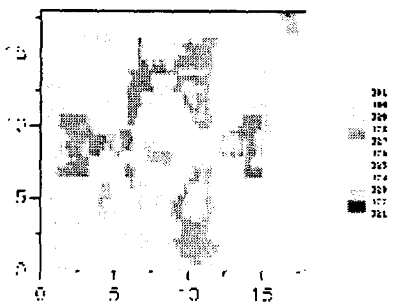
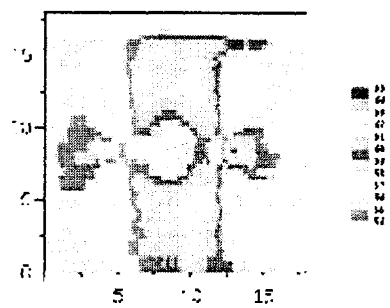
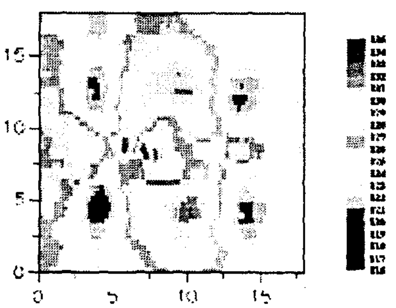
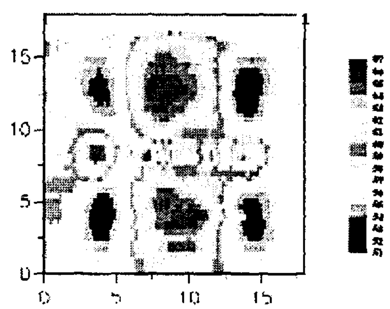
For flow loop testing, high pressure were at nominally 600 psi. After both high and low magnetization was acquired, the pressure was dropped to nominally 400 psi. The flow loop data collection plan included:

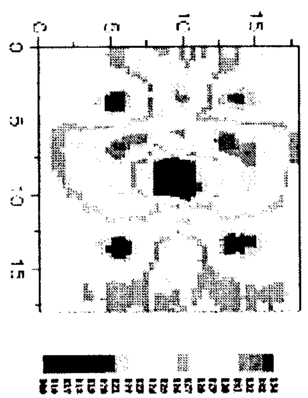
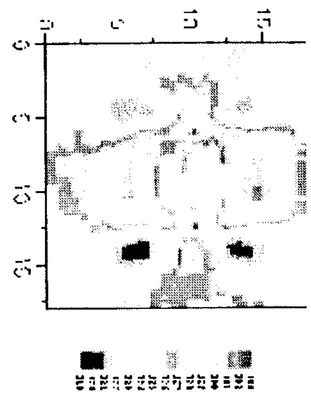
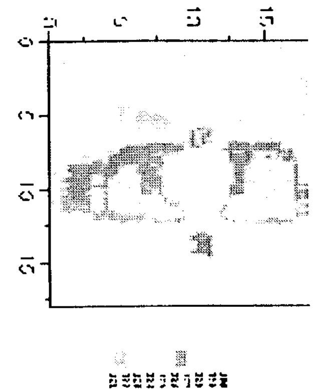
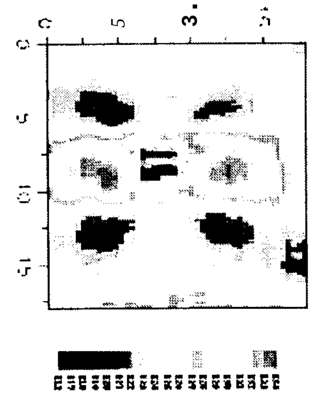
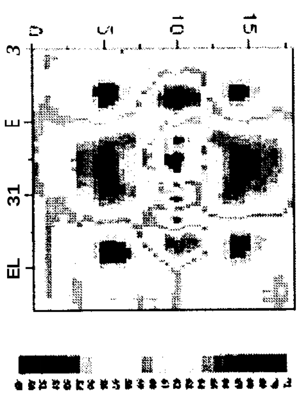
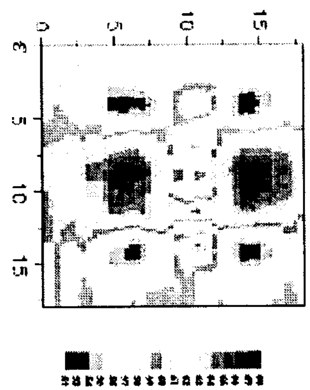
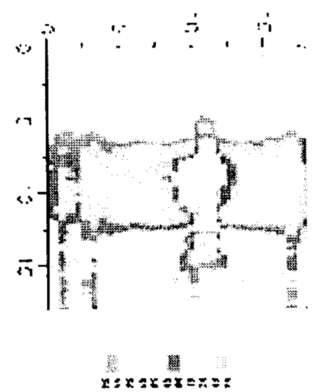
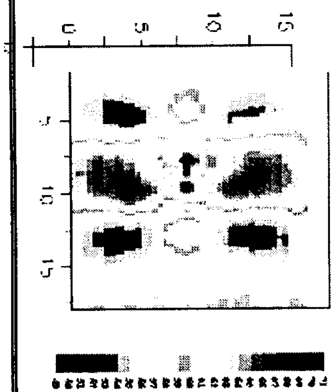
Date	Mag Level	Pressure (psi)	Comments
14-Oct-99	Low	620	One lap, flow control problem
15-Oct-99	Low	618	One lap, flow control problem
20-Oct-99	High	612	Five laps, resolved flow problem
21-Oct-99	High	416	Five laps
25-Oct-99	Low	416	Five laps

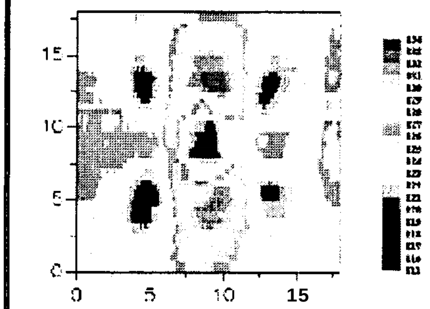
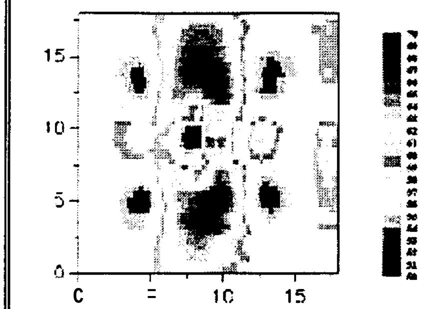
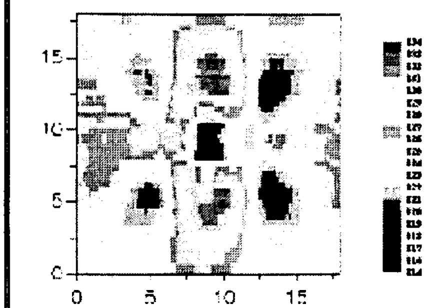
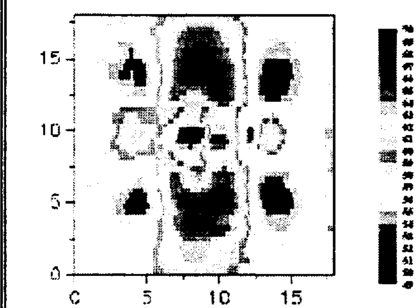
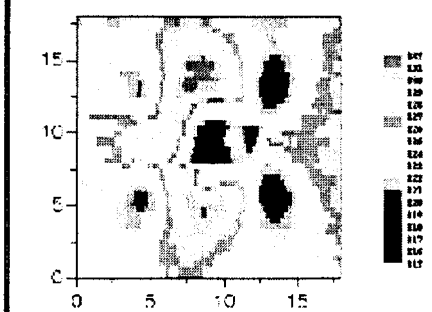
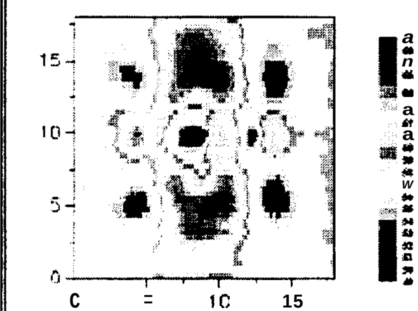
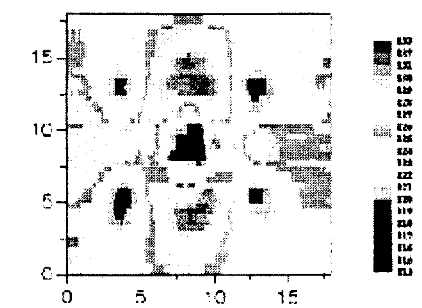
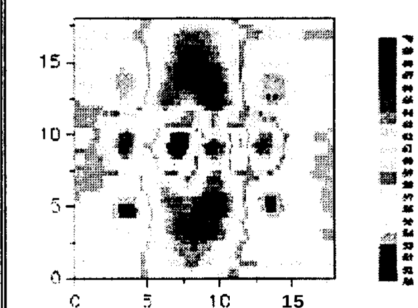
Defect Set 4 - Practice Defects
MFL Data

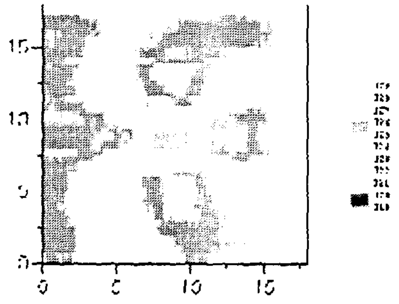
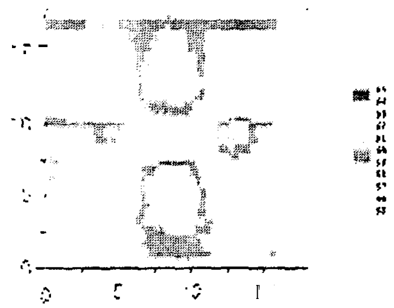
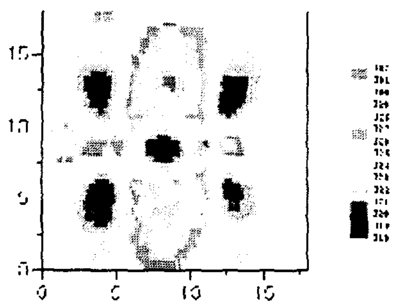
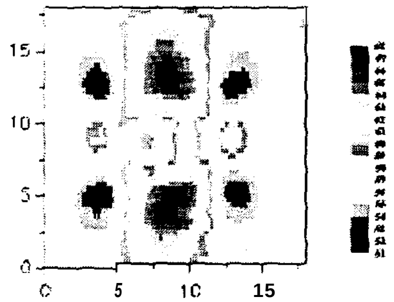
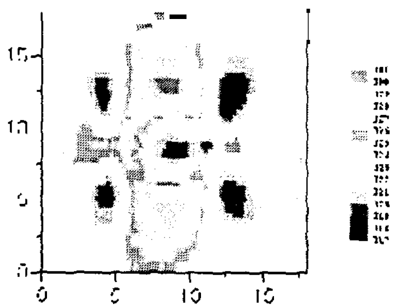
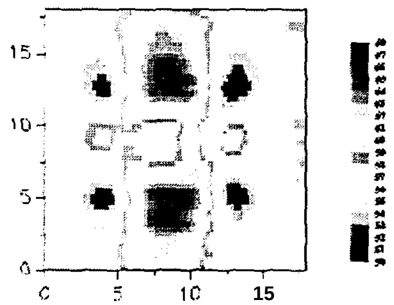
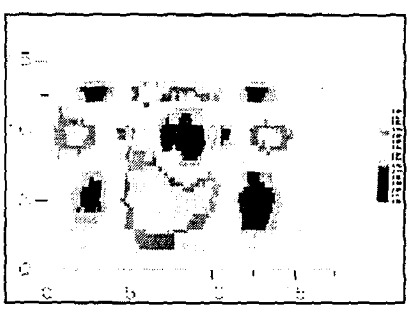
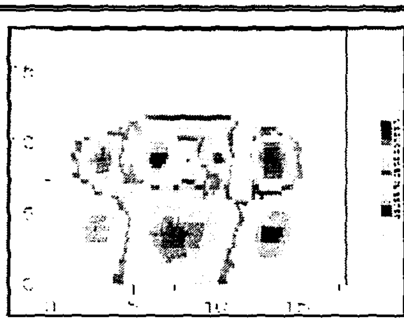
This defect set was used in the pull rig. For a layout map of the defects, click here. For a description of the variables included in this table, see the legend at the bottom of this page.

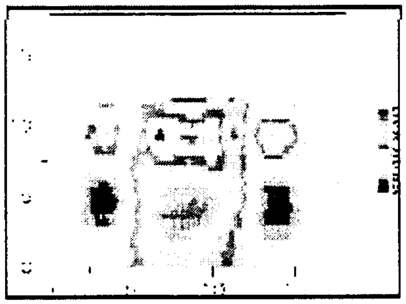
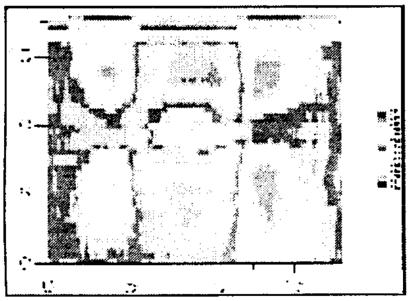
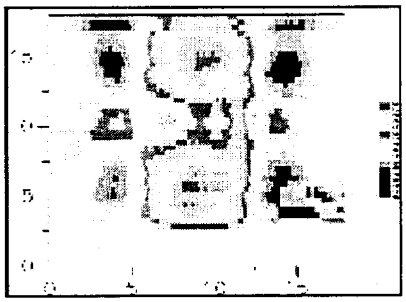
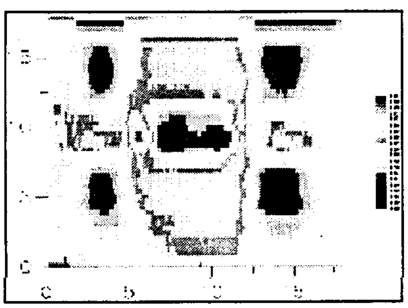
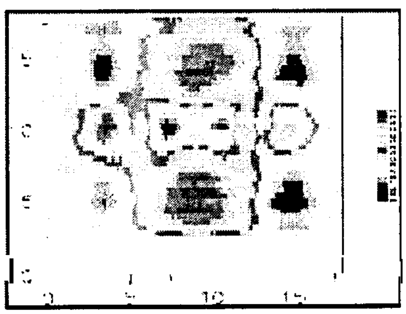
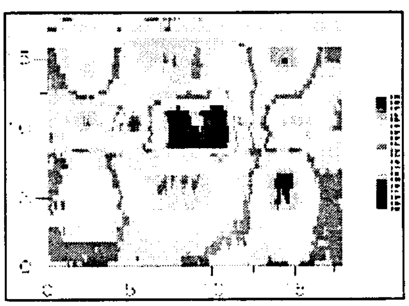
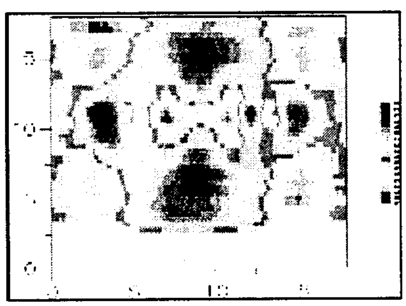
#	High Level MFL Signal	Low Level MFL Signal	D	L	FB	RI	RO	IW	IL	P	S
P01			3	3	0	1	2	0%	0%	60%	S
P02			6	3	0	1	2	0%	0%	60%	S
P03			3	3	0	1	2	1	0.5	60%	S

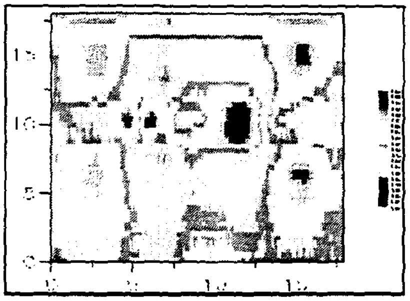
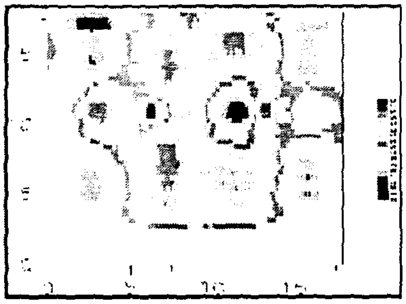
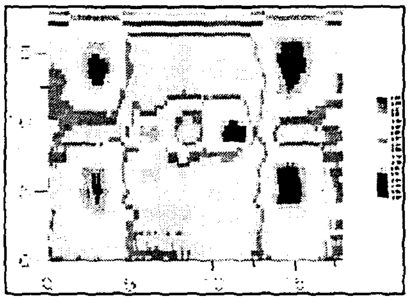
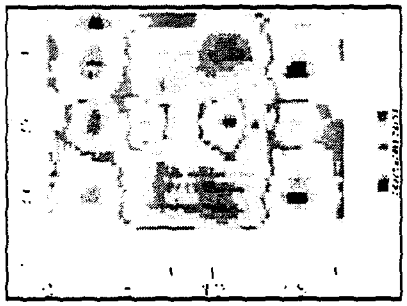
P04			3	7	4	1	2	0% w/10%	0% w/10%	60%	S
P04R			3	7	4	1	2	0% w/10%	0% w/10%	60%	S
P05			1	8	4	2	2	1	0.5	60%	S
P06			2	8	4	2	2	1	0.5	60%	S

P13	P09	P08	P07
			
			
3	2	1	1
8	8	8	8
4	4	4	3
2	2	2	3
2	2	2	2
1	1	1	1
1	1	1	0.5
60%	60%	60%	60%
S	S	S	S

P11			3	8	0	d	4	1	1	60%	S
P12			3	8	0	d	4	1	1	60%	S
P13			3	8	0	4	4	1	1	60%	S
P14			3	8	2	3	3	1	1	60%	S

P15			1	8	2	3	3	1	1	60%	Not F
P16			2	8	2	3	3	1	1	60%	Not F
P17			3	8	2	3	3	1	1	60%	F
P18			3	8	4	2	2	1	1	60%	S

P19			2	8	4	2	2	0%	0%	60%	S
P20			2	8	4	2	2	0%	0%	60%	S
P21			3	8	4	2	2	0%	0%	60%	S
P22			4	8	4	2	2	0%	0%	60%	S

P23			3	10	w	2	2	0%	0%	60%	S
P24			3	10	w	2	2	0%	0%	60%	F

Legend:

- # = Defect # is an arbitrary number identifying each defect
- D = Depth is the dent depth in percent of the diameter.
- L = Overall Length is the total length of the gouge in inches.
- **FB** = Flat Bottom Length is the length of the flat bottom portion of the gouge in inches.
- RI = Ramp In and RO = Ramp Out are the distances **on** either side *of* the flat bottom used to ramp the indentor into and out of the pipe (the overall gouge length is the sum of the flat bottom length and the ramp in **and** ramp out lengths).
- IW = Indentor Width and IL = Indentor **Length** are the footprint dimensions of the indentor in inches; where x% is shown, the indentor was a 4-inch sphere with a sharp protruding cutter that extended x% of the wall thickness.
- **P** = Pressure is the internal pipe pressure in percent of specified minimum yield strength.
- S = Speed refers to the rate of axial movement of the indentor (S is 1 inch per second; F is 5 inches per second).