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CALIBRATION AND ACCURACY OF ELECTRONIC GAUGES USED IN THE HYDROFRACTURING EXPERIMENT, CAJON PASS, CALIFORNIA

By

W.S. Updegrove and J.E. Springer

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ABSTRACT

This report describes the testing and calibration of the electronic pressure gauges and transducers used in the hydraulic fracturing experiment at Cajon Pass, California. Four electronic gauges were connected in parallel to a pressure manifold and tested in the range from atmospheric pressure to 10,000 psi. Two of the gauges had quartz pressure transducers with quartz temperature transducers for temperature compensation. They were certified by Terratek Systems as being traceable to The National Bureau of Standards (NBS). The other two gauges consisted of bonded semiconductor strain gauge transducers.

After adjusting the readings for barometric pressure, the two quartz gauges agreed with each other to within 6.4 psi in 10,000 which was within the manufacturer's specifications. One of these gauges was used as a standard to calibrate the two strain gauge transducers. The results of these calibrations are presented along with recommendations for interpretation of pressure data, a description of the operating principle, and suggestions for future calibration procedures.

INTRODUCTION

This research was in support of the in-situ rock stress study at Cajon Pass, California. The overall purpose of the project is to measure the tectonic stress field at depth along the San Andreas fault using the hydraulic fracturing technique (Hubbard and Willis, 1957; Zoback and Haimson, 1983). This requires monitoring transient fluid flow and pressure during open-hole pump tests. The objective of this paper is to determine the relative accuracy of pressure the transducers to be used in the hydraulic fracturing test.

No measurement is scientific unless its uncertainty is known and no measured value is scientifically stated unless its uncertainty is explicitly stated. For this reason gauges must be calibrated and the calibrations must be understood. Gauge calibrations have two purposes. One is to determine the repeatability and reliability of the instruments being used and the other is to derive the proper function to convert gauge units (volts, frequency, inches, ect.) to pressure units (psi). A laboratory calibration could perform these functions. However, in the field several gauges should also be used simultaneously to check for anomalies in the behavior of the instruments in the working environment.

The hydraulic fracturing operation consists of isolating a section of the borehole with a pair of inflatable rubber packers (fig. 1) and pressuring the interval between them to determine fracture opening and closing pressures. The packer system used in this project is experimental and is designed to operate under differential pressures of up to 10,000 psi and temperatures of up to 230 deg F. Deeper measurements in this hole will require a more durable (20,000 psi/ 700 deg F) system. For the purpose of future design considerations, and to interpret the scientific results correctly, careful monitoring of fluid pressures in various parts of the system are essential. These parts include the packer elements, the test interval, and the open hole outside the packers. Correct procedural desisions require real time indications of both surface pressure, flow rate, and the pressure in the test interval.

Downhole pressures in the packer elements, open-hole, and test interval were measured using Kuster bourdon tube type mechanical pressure recorders. Downhole temperature was measured with a Kuster mechanical temperature recorder (see O'neill and Ader, 1987; in preparation). The real-time pressure measurements were made using two electronic quartz pressure transducers at the surface and two bonded semiconductor strain gauge pressure transducers; one at the surface and one downhole. The surface configuration of recording instruments is given in fig. 2. This report describes a calibration test of these transducers and their associated electronic systems.

APPARATUS

Five pressure gauges were tested and compared on March 6, 1987. Two were quartz pressure gauges, one was an eight-inch bourdon tube dial gauge, and two were electronic strain gauge pressure transducers. All gauges and transducers were connected in parallel via high pressure stainless steel tubing and fittings. This system, along with the control units and readouts is shown in fig. 3.

The visual reference was provided by an eight inch bourdon tube type Heise gauge with a range of 0 to 10,000 psi. It was previously calibrated in the laboratory against a sixteen inch, 0 to 10,000 psi Heise gauge that was traceable to the NBS.

The reference gauge was a Terratek surface gauge system consisting of a Terra Quartz surface transducer, a field interface system (FIS-200) and an IBM Personal Computer. This gauge was chosen because it was the most accurate and had been calibrated throughout its temperature and pressure range by Paroscientific, Inc. using a deadweight tester that was traceable to NBS. It was found in coformance with its rated resolution of $\pm.01$ psi, repeatability of ±0.5 psi, and maximum hysteresis of ±0.5 psi. The transducer in this gauge is based on the principal that a quartz crystal, if cut correctly, will vary its resonant frequency as it is stressed (Busse, 1981; Paros and Wearn, 1986).

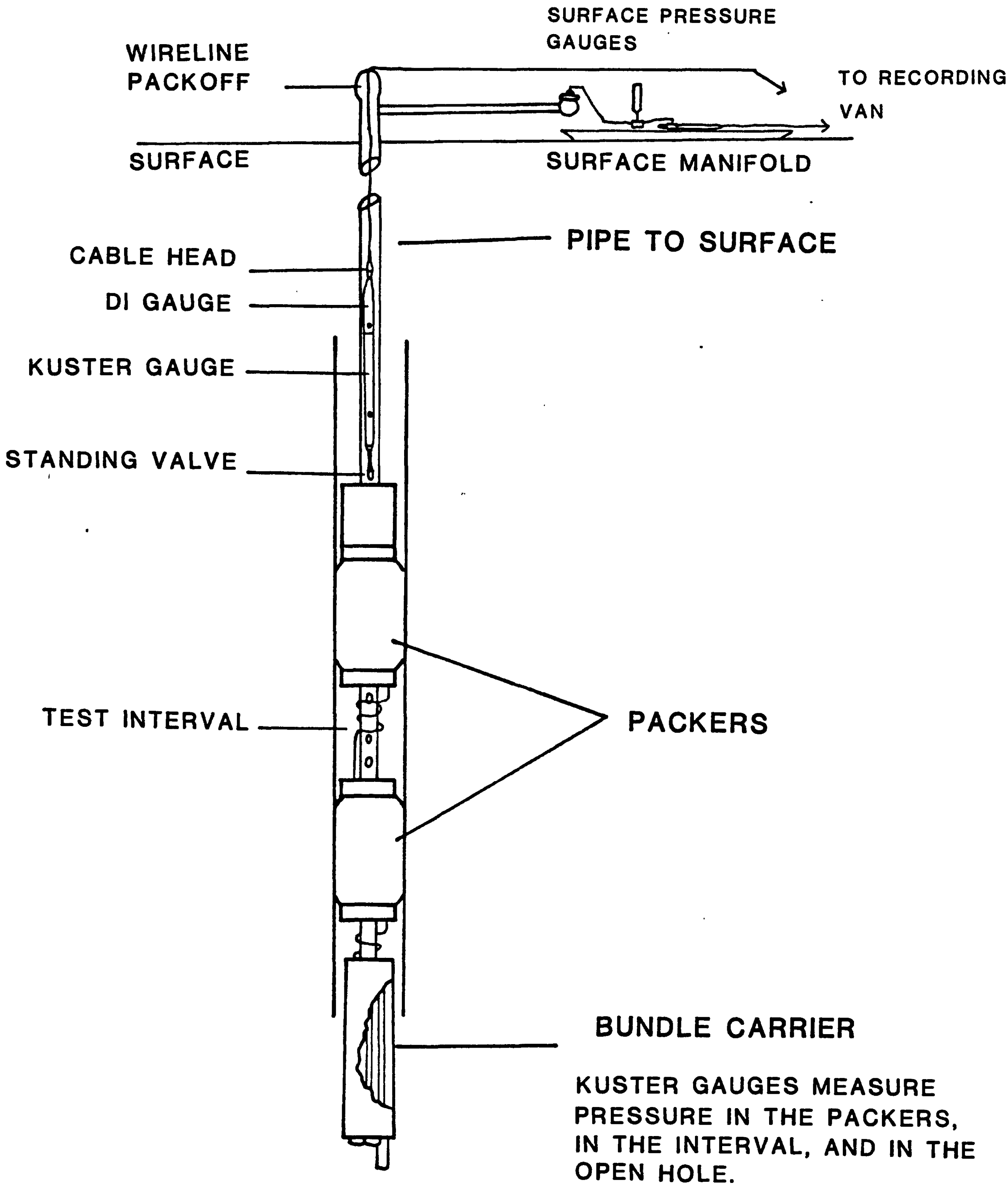

Figure 1. Configuration of the downhole packer system with recording instruments.

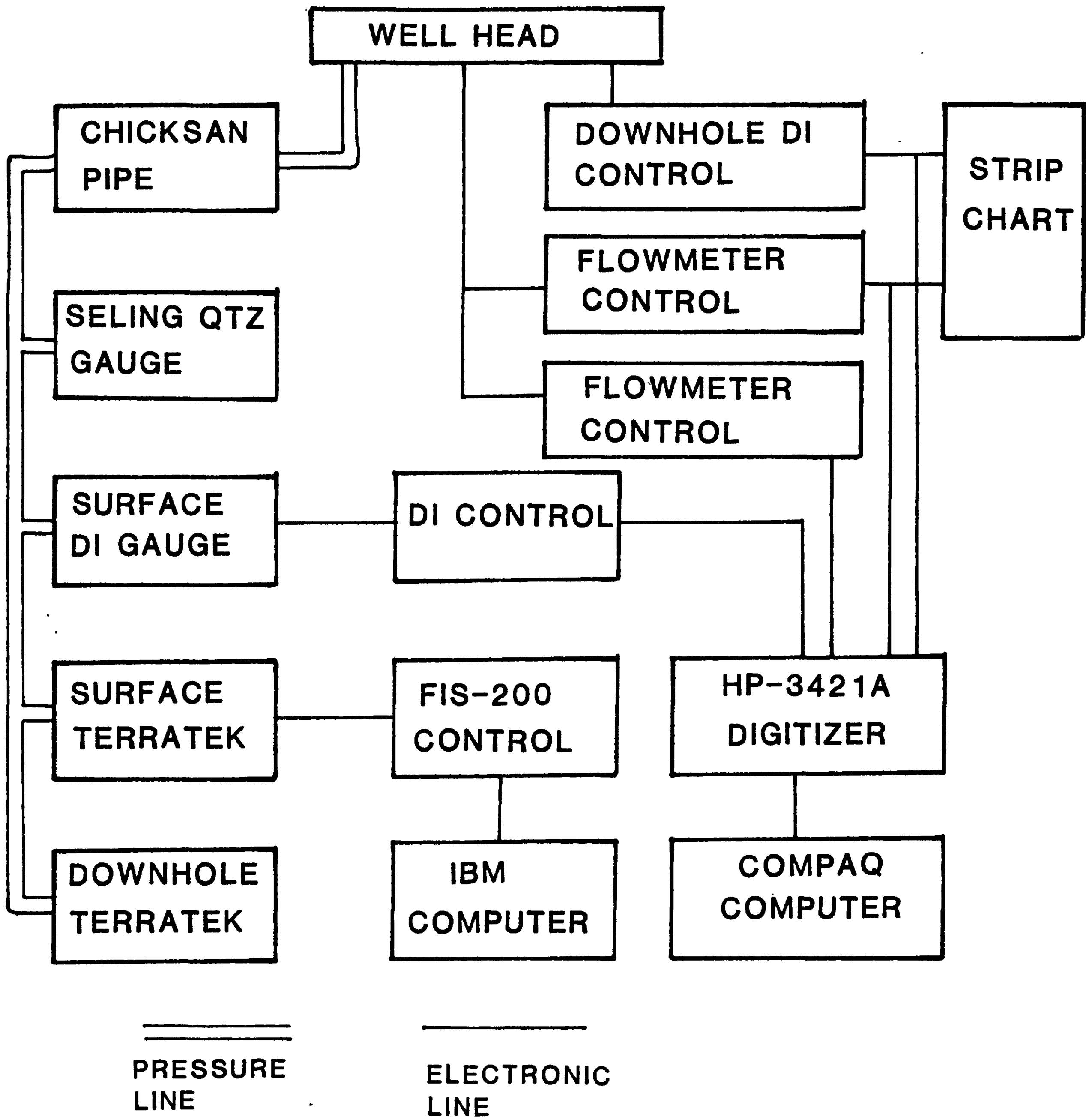

Figure 2. Configuration of the surface instrumentation.

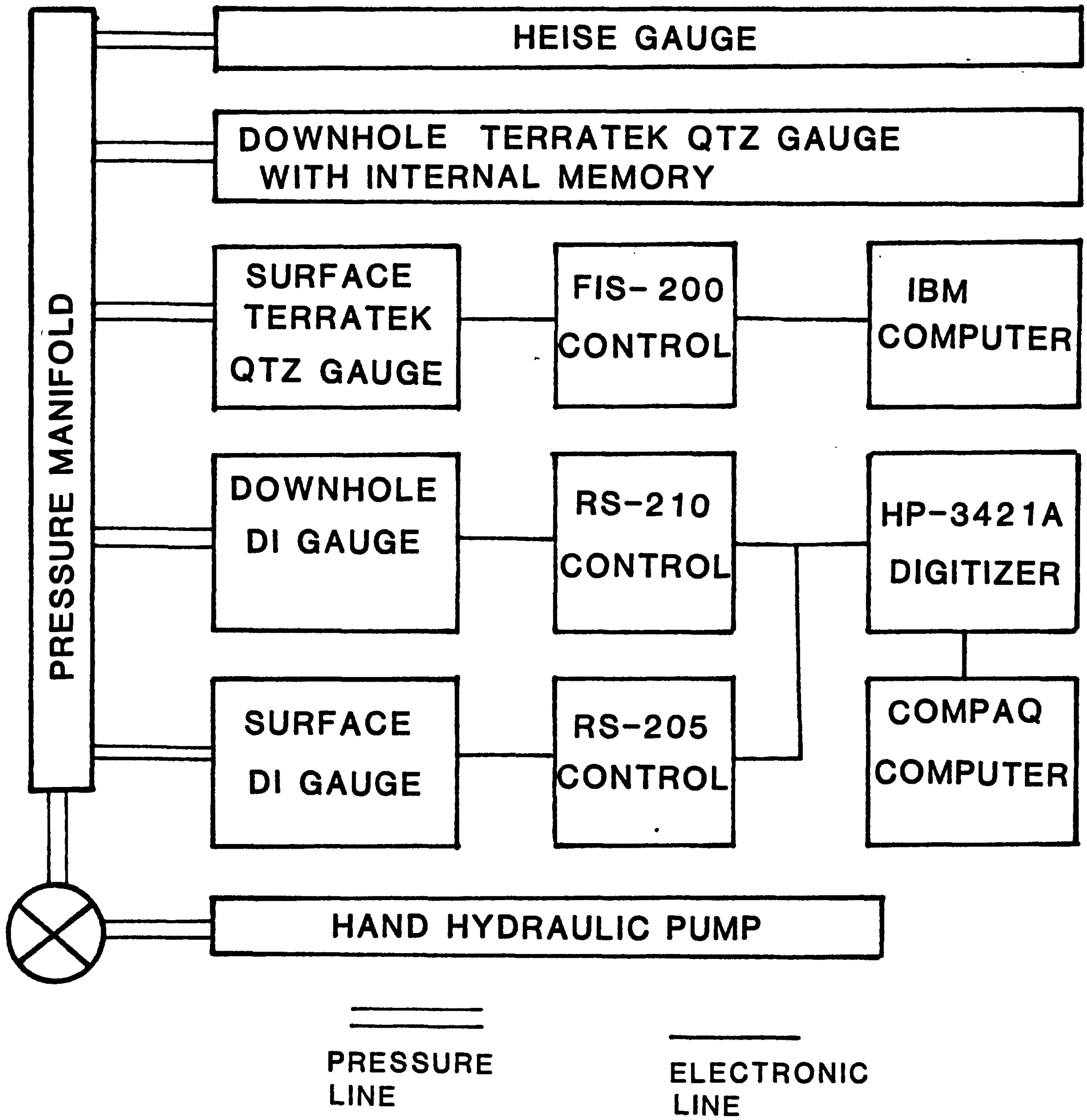

Figure 3. Configuration of the gauge calibration apparatus.

This crystal is connected to a bourdon tube which stresses it as pressure is applied. The crystal resonates circa 34 KHz at "zero" pressure to circa 38 KHz at 15,000 psi. Because this frequency will also vary as a function of temperature, another quartz crystal in the same chamber with a fixed stress serves as a temperature measuring device. This crystal resonates at 172 KHz + 50 ppm/deg C. Both of these fundamental crystal frequencies are divided such that their frequencies may be transfered over a wire line. A reference 10 MHz oscillator serves as a clock and measures the time required for a fixed number of cycles for both crystals. The result is two time measurements. Software is built into the system to correct the pressure sensing crystal for the temperature effect on the bourdon tube - pressure crystal assembly. In addition, software further converts the signals from the respective crystals to pressure in psi and temperature in degrees farenheit. Internal and programmable software packages provide for "zero" adjustments, sample times and elapsed time. The output of the FIS was sent to both the IBM-PC screen and to a floppy disk (fig. 3).

A similar functioning Terratek quartz gauge, designed for downhole measurements, was connected to the system. It was set up with a remote battery pack. The data was stored in an electronic Downhole Memory Recorder (DMR) and later dumped to a floppy disk. This gauge had also been previously calibrated with a deadweight tester traceable to NBS. The manufacturer's rated resolution is ±.02 psi; repeatability is ±1 psi; and maximum hysteresis is ±1 psi. In the actual hydraulic fracturing operation, both of these systems were mounted at the surface. One was used for real-time reference for decision making. The other was used as a back up in case of a computer or power failure.

The calibration experiment also utilized two Data Instruments (DI) bonded semiconductor strain gauge pressure transducers. In the actual in-situ stress measurement, one of these transducers is downhole and the other is at the surface in parallel with the quartz gauges. The DI transducers can capture changes in pressure too rapid for the quartz gauge systems. These transducers measure the deflection of a diaphragm by sensing the variations in resistance of a semiconductor bonded to a strain gauge that is connected to the diaphram. The semiconductor is wired as an element in a Wheatstone Bridge which is balanced at no load conditions. An excitation voltage/current applied to the corners of the bridge produces a signal proportional to the deflection of the diaphram. Part of the Wheatstone Bridge and limited temperature compensation are built into the transducer assembly. The bridge is completed and powered from drive electronics in the control panel. Each transducer was connected to an electronic control unit which provided the excitation voltage and direct pressure readout. The output voltage was sent to a strip chart recorder for real time monitoring and to an HP-3421A Data Acquisition/Control Unit for digitization. The digitized numbers were sent to a Compaq II portable computer and stored on a floppy disk.

It must be emphasized that each of these gauges is a complete system and must be treated as such. That is, the transducers, control units, digitizers, computers, and software all work together and each one is critical to the performance and accuracy of that particular transducer.

EXPERIMENTAL PROCEDURE

The entire manifold, pump, and gauge system was set up and the tests carried out in Victorville, California. Because of the high sensitivity and accuracy of the quartz pressure transducers, changes in barometric pressure need to be added or subtracted from the result (Wearn and Larson, 1982). The site elevation is 3,000 +20 ft and the barometric pressure corrected for sea level was slightly less than standard (29.95 in of Hg). Thus an atmospheric pressure on the gauge of 13.2 psi may be assumed to a first approximation. This atmospheric pressure for this time and date was corraborated by the meterological station at George Air Force Base, approximately 10 mi away.

The apparatus was pressured to more than 10,000 psi and leak checked. The system was pressured again to about 10,000 psi and the pump valve was closed. The pressure was reduced in approximately 1,000 psi increments. It took several minutes for the pressure to reach equilibrium at each step because of the elastic response of the aparatus to the pressure change. The pressure would typically show a slight increase as the tubing relaxed. When the pressure stablized, the readings were taken. A set of two to three readings were taken at each pressure. This procedure was repeated again to test the repeatability of the gauges.

RESULTS

The actual readings of the Heise gauge, FIS quartz gauge, and DMR quartz gauge tracked well. These are shown in Table 1. All the readings agreed to within 15 psi. After adjusting the "zero" reading on both gauges to the local atmospheric pressure of 13.2 psi, the readings agreed to within 6.4 psi as shown in table 2. The mean difference between the two gauges was 3.87 psi and the standard deviation was 2.06 psi, indicating that they track well throughout the tested range.

When the pressure was increased to near 10,000 psi and suddenly released, the DMR gauge would give a series of invalid and incorrect readings. It would take up to ten minutes to reach equilibrium and begin reading correctly again. This phenomenon would not happen for smaller 2,000 to 3,000 psi pressure drops or changes that did not go to atmospheric. The problem did not occur with the FIS gauge.

We then compared the two DI gauges against the FIS gauge. These calibrations are shown in tables 3 and 4. The best fit straight line to the voltage is used to convert the values to psi

TABLE 1

Pressure Readings of the Heise, FIS, and DMR Gauges

Heise Reading (psi)	FIS Reading (psi)	DMR Reading (psi)	Difference DMR - FIS
9915	9939	9945	6
9145	9127	9142	15
8085	8075	8088	13
8015	8061	8075	14
7105	7093	7105	12
6100	6086	6097	11
6085	6075	6088	13
5095	5074	5087	13
5095	5074	5088	14
4060	4048	4060	12
4065	4050	4061	11
3040	3025	3038	13
3040	3029	3041	12
2045	2040	2049	9
2050	2049	2059	10
1020	1042	1051	9
1045	1054	1065	11
1055	1057	1068	11
9800	9782	9795	13
9775	9760	9774	14
9765	9749	9763	14
9140	9131	9145	14
9140	9127	9142	15
7960	7953	7968	15
7107	7079	7112	15
7115	7104	7119	15
6085	6078	6093	15
6095	6084	6098	14
5080	5071	5085	14
5080	5071	5085	14
4065	4051	4063	12
4075	4062	4075	13
3050	3043	3056	13
3060	3052	3065	13
2040	2040	2051	11
2045	2050	2062	12
1020	1030	1039	9
1025	1044	1054	10
0	12.4	21	8.6

TABLE 2

Comparison of FIS and DMR Gauge
after Correcting for Atmospheric Pressure

FIS (psi)	DMR (psi)	Difference DMR - FIS
9939.8	9937.2	-2.6
9127.8	9134.2	6.4
8075.8	8080.2	4.4
8061.8	8067.2	5.4
7093.8	7097.2	3.4
6086.8	6089.2	2.4
6075.8	6080.2	4.4
5074.8	5079.2	4.4
5074.8	5080.2	5.4
4048.8	4052.2	3.4
4050.8	4053.2	2.4
3025.8	3030.2	4.4
3029.8	3033 2	3.4
2040.8	2041.2	0.4
2049.8	2051.2	1.4
1042.8	1043.2	0.4
1054.8	1057.2	2.4
1057.8	1060.2	2.4
9782.8	9787.2	4.4
9760.8	9766.2	5.4
9749.8	9755.2	5.4
9131.8	9137.2	5.4
9127.8	9134.2	6.4
7953.8	7960.2	6.4
7097.8	7104.2	6.4
7104.8	7111.2	6.4
6078.8	6085.2	6.4
6084.8	6090.2	5.4
5071.8	5077.2	5.4
5071.8	5077.2	5.4
4051.8	4055.2	3.4
4062.8	4067.2	4.4
3043.8	3048.2	4.4
3052.8	3057.2	4.4
2040.8	2043.2	2.4
2050.8	2054.2	3.4
1030.8	1031.2	0.4
1044.8	1046.2	1.4

Mean Error = 3.87
Standard Deviation = 2.06

TABLE 3

Calibration of Downhole DI Transducer S/N 93388 with Control Panel S/N 96669

FIS Gauge (psi)	DI (volts)	DI psi * Calculated	Residual (psi)
9782.8	4.831	9785.1	2.26
9131.8	4.506	9127.8	-4.01
9127.8	4.506	9127.8	-0.01
7104.8	3.503	7099.3	-5.50
6084.8	3.002	6086.1	1.26
4062.8	2.007	4073.8	10.96
3052.8	1.503	3054.5	1.66
2050.8	1.009	2055.4	4.58
1044.8	0.503	1032.0	-12.76
13.2	0	14.8	1.56

* Based on: PSI = DI Voltw * 2022.419 + 14.8
Correlation Coefficient = 0.999996

TABLE 4

Calibration of Surface DI Transducer S/N 89510 with Control Panel S/N 96668

FIS Gauge (psi)	DI (volts)	DI psi* Calculated	Residual
9782.8	6.994	9805.6	22.84
9131.8	6.536	9137.1	5.33
9127.8	6.536	9137.1	9.33
7104.8	5.127	7080.5	-24.28
6084.8	4.427	6058.8	-26.02
4062.8	3.058	4060.6	-2.24
3052.8	2.363	3046.1	6.69
2050.8	1.685	2056.5	5.68
1044.8	0.984	1033.3	-11.51
13.2	.304	40.7	27.54

* Based on: PSI = DI Volts * 1459.627 - 402.988
Correlation Coefficient = 0.999975

for each gauge. The values for the downhole DI showed good linearity (correlation coefficient = 0.999996). The maximum residual was -12.8 psi, or 0.13% of full scale. The residuals are plotted as a function of pressure in fig. 4, showing that they are well within the manufacturer's specification of ±0.2% of full scale.

The surface DI gauge showed less linearity than the downhole gauge (correlation coefficient = 0.999975) and the residuals were higher. The maximum residual was 27.5 psi or 0.25% of full scale. These residuals, plotted in fig. 5, exceed the manufacturer's specifications. This is not surprising because a pathological malfunction in the control unit caused the voltage range to be 0.3 volts to 7 volts instead of the specified 0 to 5 volts. Nevertheless, this calibration is still good enough to use the gauge as an indicator to help correlate the timing of events recorded on other gauges.

CONCLUSIONS

Without compensation for zero offset or barometric pressure at the time and location of the test, the two quartz gauges correlated to within 15 psi of each other over the range of 0 to 10,000 psi. After adjusting the zero offsets on both gauges for barometric pressure on that day (13.2 psi), the gauges correlated to within 6.4 psi. The typical cause of failure or drift in quartz transducers is loss of vacuum. This is usually caused by exposure to high temperature. If, in the event this occurred between the time of shipment from the vendor ande the time the transducer was put into service, it could account for the zero offset on the down hole unit. Once the unit is reset or rezeroed, accuracy may be restored more or less permanently (Wearn and Larson, 1982).

The two DI pressure transducers showed good linearity across their ranges. In general, the calibrations of these gauges are within the manufacturers' specifications, despite the problem with the surface DI gauge's control unit. While the calibration of the downhole DI gauge was excellent, the calibration function derived in this experiment will not be valid in the downhole environment. This is because the temperature compensation of the strain gauge is only good through the range of 0 deg to 130 deg F and the downhole temperatures at the depths of the first stage of the experiment (6000 ft to 6940 ft) are 175 deg to 195 deg F. Effective use of this gauge requires compensating for the downhole temperatures. This can be done by either 1) comparing the output voltages with the Terratek gauge, adding the hydrostatic head, and deriving a new calibration function for the downhole temperature, and/or 2) using a Kuster mechanical pressure recorder, which has been calibrated at high temperatures, as downhole calibrators for deriving a calibration function. In future experiments, calibration of all the gauges together at various temperatures is recommended.

The principal advantage of the DI transducers is their time

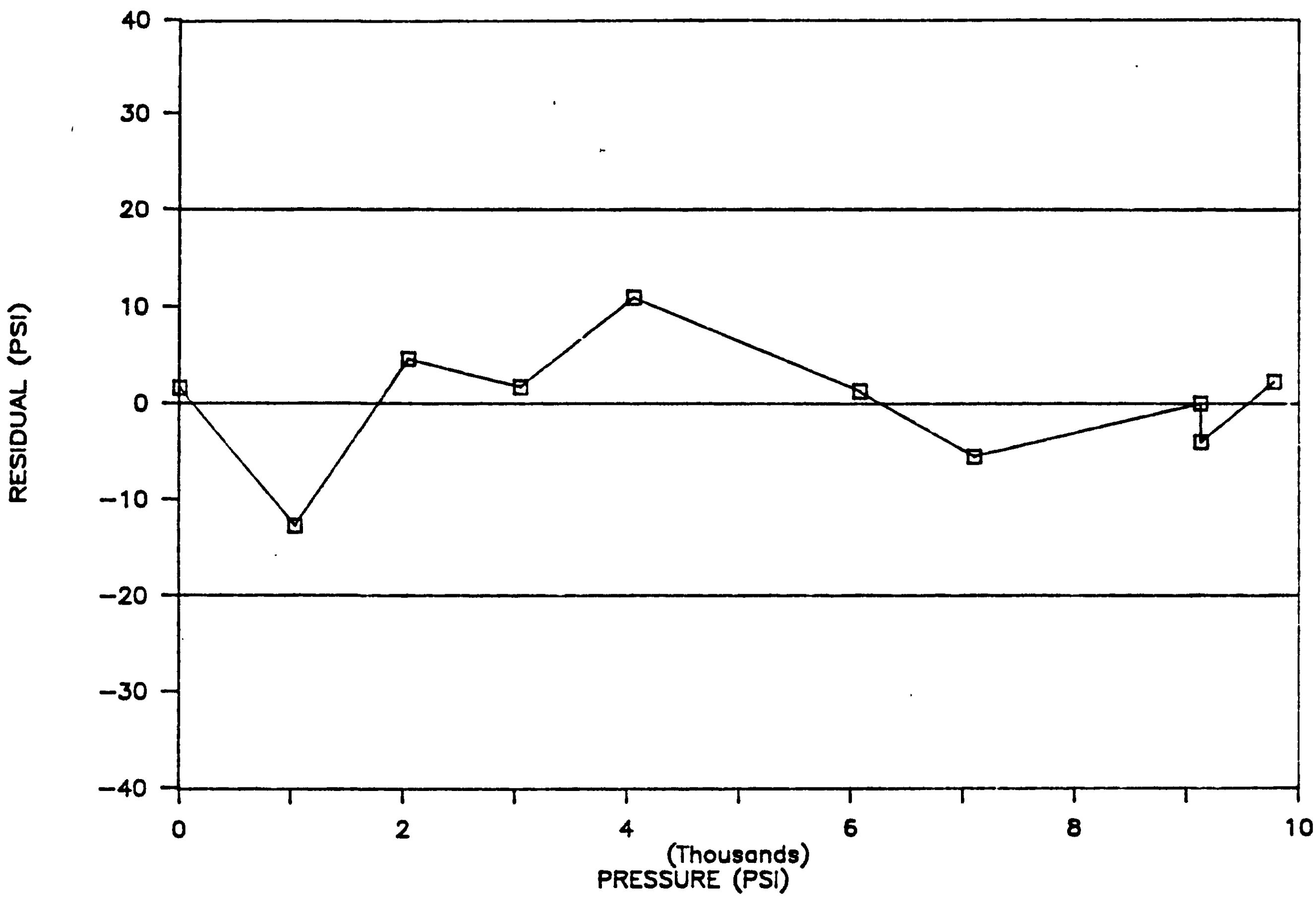

Figure 4. Measured residuals on DI gauge 93388. This gauge is used downhole.

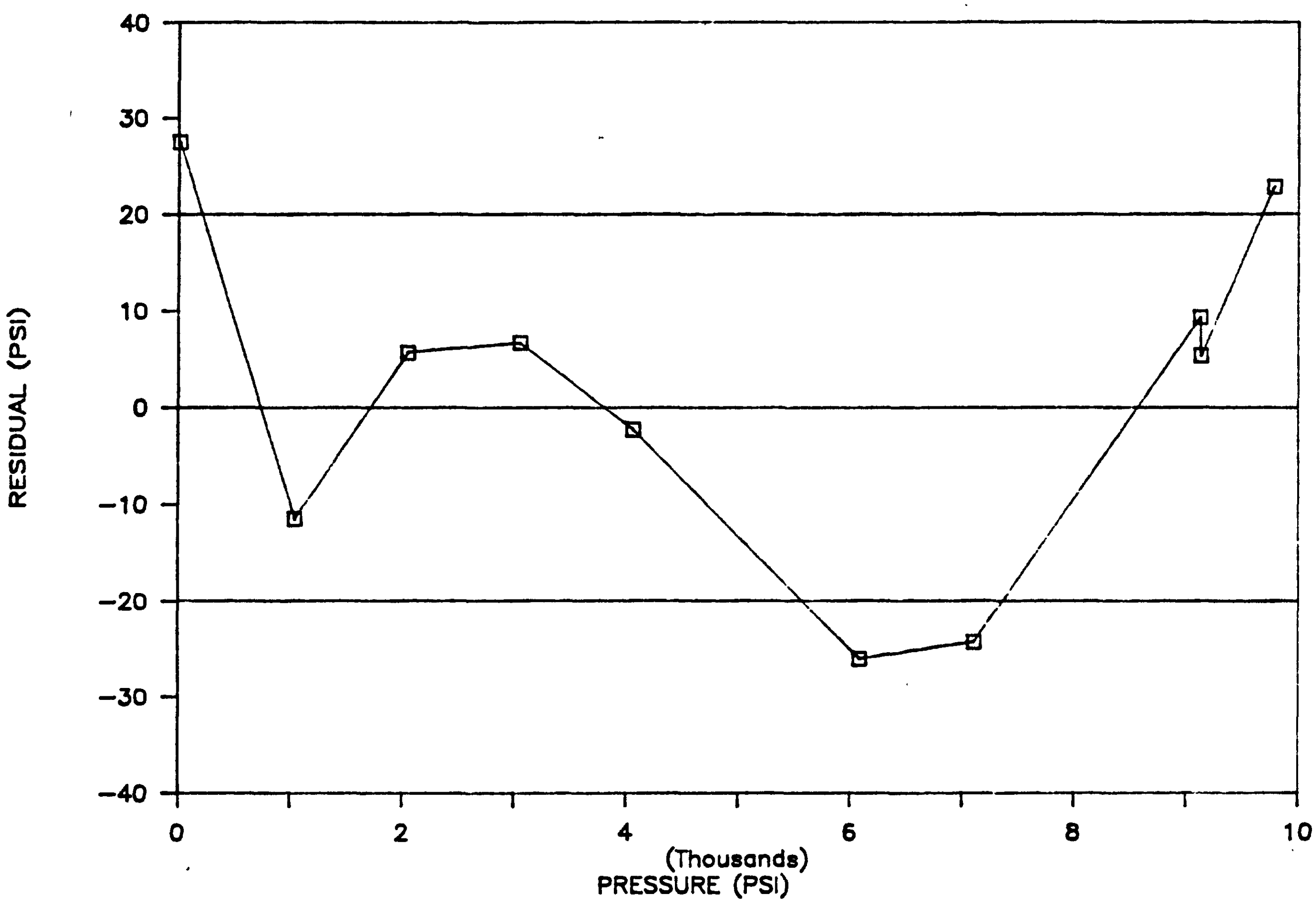

Figure 5. Measured residuals on DI gauge 89510. This gauge is used at the surface.

response. These transducers have a natural frequency of 25 KHz and are down 3 db at 3 KHz. Thus, although their accuracy is less than the quartz gauges, they do show rapid changes in pressure and should track better with the Kuster gauges.

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