CONF-970328--1

SPE 37500

SAND96-3026C

Society of Petroleum Engineers

Development of the Downhole Dynamometer Database

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This paper was prepared for presentation at the 1997 SPE Production Operations Symposium, held in Oklahoma City, Oklahoma, 9–11 March 1997.

Abstract

The Downhole Dynamometer Database is a compilation of test data collected with a set of five downhole tools built by Albert Engineering under contract to Sandia National Laboratories. The downhole dynamometer tools are memory tools deployed in the sucker rod string with sensors to measure pressure, temperature, load, and acceleration. The acceleration data is processed to yield position, so that a load vs. position dynagraph can be generated using data collected downhole. With five tools in the hole at one time, all measured data and computed dynagraphs from five different positions in the rod string are available.

The purpose of the Database is to provide industry with a complete and high quality measurement of downhole sucker rod pumping dynamics. To facilitate use of the database, Sandia has developed a Microsoft Windows-based interface that functions as a visualizer and browser to the more than 40 MBytes of data. The interface also includes a data export feature to allow users to extract data from the database for use in their own programs.

This paper includes a description of the downhole dynamometer tools, data collection program, database content, and a few illustrations of the data contained in the downhole dynamometer database.

Introduction

The Downhole Dynamometer Database (DDDB) is a compilation of test data collected by Sandia National Laboratories (SNL) using downhole dynamometer tools built by Albert Engineering (AE). The purpose of the DDDB is to provide industry with a complete and high quality measurement of downhole sucker rod pumping dynamics. To facilitate use of the DDDB, Sandia developed a Microsoft Windows-based interface that functions as a visualizer and browser to the more than 40 MBytes of data. The interface also includes a data export feature to allow users to extract data from the database for use in their own programs.

Database Interface

The DDDB Interface program, DownDyn, is a Microsoft Visual Basic version 3.0 program designed to run on a Microsoft Windows version 3.11 platform. Figure 1 shows DownDyn's main screen. The program includes graphing utilities necessary to generate and display plots. Instructions for installation and how to import user data for viewing, or add user data to the database, are contained in a readme.txt file. Other help information is contained in the help facility built into the program.

The program has been beta tested by over 15 industry experts for six months, resulting in a number of improvements that have been incorporated into the program. Current information about the status of the database and interface can be found at http://www.sandia.gov/apt/.

The DDDB Interface performs four functions: selecting a data file, choosing information from the file, plotting, and importing/exporting information.

Selecting a Data File. Data files are selected by scrolling through lists of the wells in the database and of the tests performed on each well. The list of tests comes from the tool program schedule shown, for example, in Fig. 2.

Choosing Information from the File. If the data file chosen is for a surface dynamometer test, there is no information that must be selected before plotting, Fig. 3. If the data file chosen is a downhole test, there are a number of choices to be made before plotting. First the **Plot Type** must be chosen to be a time dependent plot showing selected **Plot Variables** verses time, Fig 4, or a dynagraph showing load or velocity versus position, Fig. 5. Since the data files contain a number of cycles the **Plot Window** containing the interval of data to be examined must be chosen

Plotting. The plotting function in the DDDB is available through Graph Control version 4.5 by Pinnacle. The advantage of using the DDDB Interface over a spreadsheet to plot downhole data is the ease and speed with which subsets of the data in a file can be chosen and plotted.

Graph Control allows the user to make appearance, textual and scale changes to plots as well as pick off the values of individual data points. A separate help file on the use of Graph Control is included. The title of a plot includes the file name from which it was created. Each plot becomes a new document in a multi-document interface window. This allows the user to recall previous plots or display on the screen more than one plot so they can be visually compared.

Importing/Exporting Information. Once a plot is displayed, it can be printed, copied as an object, or its data can be exported to a file as comma delimited columnar ASCII data. Imported/exported dynagraph data may conform to either Nabla's or Theta Enterprises' dynamometer file format. Downhole time dependent data is stored as comma delimited data and must have the extension ".csv".

Plots are identified by the name of the file from which they were created. The naming convention for the data files is as follows: #x#a##.csv or #x#a##.dat, where the first number (#) is the tool number (1 - 5), or "s" for surface dynamometer data, the second number (#) is the well number, the letter (a) tells the day of the test, and the last number (##) is the test number of that day. The *.csv files are downhole dynamometer data and the data is comma delimited. The *.dat files are surface dynamometer data and conform to Nabla format. The *.raw files are raw dynamometer data as delivered from AE.

Data files, including all raw data files, can be accessed via standard DOS or Windows File Manager commands. This functionality opens the DDDB for direct access by the user if, for example, the user's plotting needs exceed the capability of the DDDB Interface program. This also allows the user to process the data differently, such as using sophisticated signal processing software to gain insight into the nature of the data recorded, and then filter the data to focus on a particular feature of interest.

The Downhole Dynamometer Tools

The downhole dynamometer tools are high quality, reliable tools used to measure the downhole environment in the sucker rod string. The tools are built, maintained, and serviced by Albert Engineering.

Sensors. The downhole dynamometer tools are memory tools deployed in the sucker rod string with sensors to measure pressure, temperature, load, and acceleration.[1] Load is measured with three full bridge strain gages located at 120° intervals on the ID of the housing. The three load readings average to equal the rod load, and differences between the three load readings gives an indication of rod bending. Acceleration is measured with three separate orthogonal piezoresistive accelerometers with one accelerometer positioned along the axis of the tool. The axial accelerometer data is integrated twice to yield the position of the tool as a function of time, while data from the other two accelerometers gives an indication of the lateral motion of the tool.

Tool Housing. The sensors are housed in an 12" long by 1.75" OD pump barrel with 0.75" API pin couplings on each end. The housing has been pull tested to failure at 39,600 lbf tension.

Data Recording. Data is recorded in memory according to the test schedule programmed in the tool by AE before shipping the tools to the field. Figure 2 shows a sample test schedule consisting of high (50 Hz) and low (5 Hz) rate sampling periods, as well as very low (1 Hz) rate warm-up and ultra-low (1/minute) rate monitoring periods.

The high rate sampling is used to capture high quality data for one minute periods of the pumping cycle. This is generally the most useful information to come from the test. The data is processed by AE to produce axial acceleration, velocity, position, pressure, and three axial loads, all as a function of time. Graphing the average load as a function of position results in the familiar dynagraph. Up to 6 of these high rate sampling periods can be collected in the tool's 512K static memory.

The low rate sampling is used to capture lower quality data during valve check periods. During these intervals, the well technician collects standing valve and traveling valve checks according to his/her established practice. The data is processed by AE to produce pressure and the three axial loads. This data can be compared against the expected static loading as a check of the tool's load calibration or as a check of our understanding of the expected static loading. It is important to note that the standing valve and/or traveling valve loads are NOT used to calibrate the load data that appear in the DDDB. This was the practice with prior versions of the tool, but is not needed with the newer and more accurate generation of tools used in this work.

The very low rate is used to warm the tools sensors and electronics just prior to recording high rate or low rate data. These data are not processed by AE, but appear in the raw data portion of the DDDB.

The ultra-low rate is used to monitor temperature, pressure, and load for all other time periods from the time the tools are shipped to the field to the time the tools are received by AE. These data are not processed by AE, but appear in the raw data portion of the DDDB. Such data have been very useful in documenting certain events that take place in the field. For example, the temperature and load data are a good indication of when a tool is put in, or taken out of, the well, as well as when pumping has stopped. In Test 2, the rods parted during the test (the part was not associated in any way with the tools), and the monitor data was able to tell exactly when the part occurred.

Calibration. The downhole dynamometer tools are calibrated by AE in five separate tests, one each for pressure, load, position, acceleration, and temperature. Each tool has unique calibration constants.

Pressure Calibration. The tools are placed in a hydrostatic pressure chamber while the tools are recording pressure and load data. The pressure in the chamber is stepped through a range of pressures. The A/D counts (pressure) measured by the tools are compared to the pressure steps to establish the calibration constants used to convert A/D counts to pressure units (psi). In addition, the A/D counts (load) measured by the tools are compared to the pressure steps to establish the calibration constants used to remove the pressure effect from the load measurement.

Load Calibration. The tools are placed in an hydraulic axial tensile load test rig while the tools are recording load data. A calibrated load cell in series with the tools in the load test rig provides accurate load units (lbf) during the stepped load tests. The A/D counts measured by the tools are compared to the load steps to establish the calibration constants used to convert A/D counts to load units (lbf). Each of the three strain gages in a tool has a unique calibration.

For data measured by the tools under load and pressure, the first step is to remove the effect of pressure using the load data measured during the pressure calibration tests. The remaining A/D counts for load are assumed to be the result of axial load, and are converted to load units using the load data measured during the load calibration tests. Positive load values are tensile loads.

Position Calibration. The tools are placed in a motion jig while the tools are recording axial acceleration data. The prescribed motion is similar to a pumping well, and a potentiometer records the position of the tool as a function of time. The acceleration data from the axial accelerometer is integrated twice to give position as a function of time. This position is compared to the potentiometer measured position to establish the calibration between A/D counts and axial acceleration units (in/s/s) that results in the best comparison between positions.

Acceleration Calibration. The tools are rotated in steps while recording lateral acceleration to compare the A/D counts to gravitational acceleration. These accelerometers have good DC response characteristics, so positioning the accelerometer vertically should result in measuring a 1 g acceleration. Turning the accelerometer 90 degrees should result in measuring a 0 g acceleration. These measurements establish the calibration between A/D counts and lateral acceleration units (g).

Temperature Calibration. The tools are placed in an oven while the tools are recording temperature data. The temperature in the oven is stepped through a range of temperatures. The A/D counts (temperature) measured by the tools are compared to the temperature steps to establish the calibration constants used to convert A/D counts to temperature units (°F).

The Data Collection Program

Data for the DDDB was collected in a cooperative effort between SNL and the petroleum industry. For each test, a producing company provided the well and pulling crew, Sandia provided the tools, and, except for the Wyoming test, Nabla provided the surface data collection. The identity of the producing company has been removed from the DDDB to protect their interests, again except for the Wyoming test conducted with the DOE's Rocky Mountain Oilfield Testing Center (RMOTC) near Casper, WY.

In the field, surface activities on the well are carefully coordinated with the programmed test schedule, as indicated in Fig. 2. A watch calibrated to the same time standard as the tools is used to ensure time coordination. To allow for inevitable problems that occur in the field that may result in lost data, redundant recording periods are included in the test schedule.

Database Content

The DDDB contains six (6) tests with the following characteristics:

1) 2700' well at DOE's Rocky Mountain Oilfield Testing Center near Casper, Wyoming.
2) 7600' well with a mixed fiberglass/steel rod string.
3) 9300' well with a Rotaflex pumping unit.
4) 2600' well with varied pump speed and fillage.
5) 5000' well with Echometer's new gas anchor.
6) 2900' well with Axelson's new tension pump.

The database also contains a description file for each test that provides further information including tool locations, pumping unit, rod string taper, and production data. For archival purposes, the database also includes the raw data files delivered by AE for each test, but this information may not be available through the interface program.

Tool Locations. Each test consists of 5 tools located in the sucker rod string, according to the string design and specific needs of the test. The DDDB includes the tool position as part of both the description file and interface display.

Although there are variations among the tests, tools were located, when possible, according to the following criteria:

1) A tool immediately above the downhole pump to best indicate the pump action and other dynamics that may affect pump performance.

2) A tool below the downhole pump to measure pump intake pressure and indicate movement of the tubing string.

3) A tool immediately below the polished rod to both measure stuffing box friction and indicate the quality of the surface dynamometer measurements. Tests on wells with a peak polished rod load greater than 20,000 lbf did not have a tool in this location to prevent damage to the tool if excessive pulling was required to unseat the pump.

4) A tool at the tapers to provide a comparison with calculated results. When there are more tapers than tools, the tapers lower in the string will get a tool. Simulation codes usually output some results at the tapers, so it is easier to compare results at the tapers than it is at non-taper positions in the string.

5) A tool three joints (one triple) above another tool to compare closely spaced dynamic information. Modeling what occurs between closely spaced positions in the string requires few assumptions, so the effects of friction, for example, can be estimated much more accurately.

In addition to data collected with the downhole tools, the DDDB contains surface data collected by Nabla, except for the first test in Wyoming where the surface data was collected by RMOTC using Delta-X equipment. By including the surface data in the DDDB, users are able to download this information into their own diagnostic software and compare the results with data measured downhole. This comparison is beyond the scope and intent of this project and is not included in the DDDB.

Insights

The primary intent of the project was to provide a tool that the industry could use to gain insight into the downhole dynamics of sucker rod pumping. As such, little effort has been made at Sandia to analyze the data. However, presented here are some interesting features of the data as noted while assembling the DDDB. Any significance attributed to these features will need to be assigned by industry.

To conserve space, these examples are all taken from the dataset acquired at the Rocky Mountain Oilfield Testing Center. The 2700 ft. well has a 0.75 in. API Grade 'C' steel rod string with a 1.5 in. RWA pump in 2.875 in. tubing. The well produces about 4 barrels of 38 degree API oil per day, 130 barrels of water per day, and no gas, while pumping at about 11 strokes per minute with an 86 in. surface stroke. This test represents a "normal" well with no unusual operational or failure conditions noted.

Pump Stroke. Figure 4 shows the acceleration, velocity and position for the case described above from the tool located above the pump. At this position, the dynamic behavior of the tool is a very good indicator of the dynamics in the pump stroke. While the position curve appears smooth, the acceleration and velocity curves show that the plunger is continuously accelerating and decelerating in response to the propagation of stress waves in the string. This same behavior is observed in all tests.

Compressive Loading. All tools located just above the pump show considerable compressive loading. For example, Fig. 5 shows nearly 700 lbf compressive load in the tool above the pump, suggesting the possibility of bending or buckling in the rods in the lower portion of the string. Other indicators of buckling, such as lateral acceleration and differences between the loads, support this conclusion. Figure 6 shows lateral acceleration and the three loads over the same time period as the dynagraph in Fig. 5. The lateral acceleration deviates from zero, indicating lateral motion, when the load first becomes compressive. Later, when the loads separate, indicating bending, the lateral motion stops. One scenario that might show this behavior is buckling, where the rods initially move laterally, or shake, until the rods buckle up against the wall of the tubing. As mentioned earlier, however, this scenario is not proven, and other scenarios may produce the same observed behavior.

Incomplete Fillage. Two hours after the dynagraph shown in Fig. 5, the dynagraph in Fig. 7 shows that the pump is only about 75% full. The peak compressive load is now nearly 850 lbf, but the lateral acceleration and load graph, Fig. 8, does not show increased buckling as might be expected. It is not shown here, but Test 4 includes cases of incomplete fillage at different stroke rates. Understanding what happens at the pump is critical to both developing the production strategy of a well and defining an acceptable pumped off criteria to use in pump-off controllers.

Conclusions

1. The downhole dynamometer is a valuable tool in accurately diagnosing downhole sucker rod behavior.

2. The downhole dynamometer database contains data that will allow industry to improve predictive and diagnostic codes, and develop improved field practices.

Acknowledgments

The authors gratefully acknowledge the support of Nabla, RMOTC, and the producing companies that participated in these field tests. In addition, the guidance of the Sucker Rod Working Group, including beta testing by some of the members, is appreciated. This work was funded at Sandia by the US Department of Energy through the Natural Gas and Oil Technology Partnership, and performed under DOE contract DE-AC04-76DB00789.

References

1. Albert, G.: "Downhole Dynamometer Tool," Proceedings of the Forty-First Annual Meeting of the Southwestern Petroleum Short Course, Lubbock, TX, April 20-21, 1994.

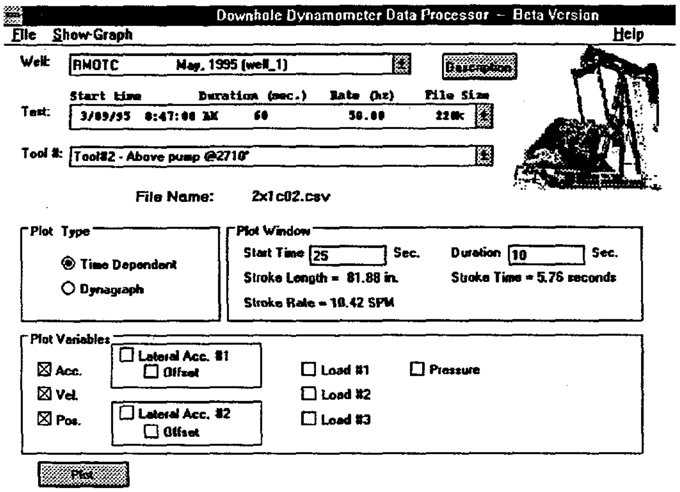

Fig. 1 — Main screen of the DDDB Interface program, DownDyn.

	Field Operations Schedule	Start Time (CST)	Duration (sec)	Rate (Hz)	#	T	P	L1	L2	L3	AX	A2	A3	Memory Rqd.
Day 1	Friday	07:00:00 AM	262800	0.02	3	•	•	•						26280
	AE will ship tools to field.													
Day 4	Monday													
	•Crew will place tools in string and trip in.	08:00:00 AM	81900	0.02	8	•	•	•	•	•	•	•	•	21840
Day 5	Tuesday	06:45:00 AM	60	1.00	8	•	•	•	•	•	•	•	•	960
	•Nabla install load cell by 9AM with	06:46:00 AM	60	50.0	7		•	•	•	•	•	•	•	42000
	minimal well downtime.	06:47:00 AM	9720	0.02	8	•	•	•	•	•	•	•	•	2592
	*Nabla cut card before 9:30 AM.													
		09:29:00 AM	60	1.00	8	•	•	•	•	•	•	•	•	960
	•Nabla conduct Standing and Traveling	09:30:00 AM	300	5.00	5		•	•	•	•	•			15000
	valve checks starting at 9:30 AM.	09:35:00 AM	1440	0.02	8	•	•	•	•	•	•	•	•	384
		09:59:00 AM	60	1.00	8	•	•	•	•	•	•	•	•	960
	•Nabla cut card at 10:00 AM	10:00:00 AM	60	50.0	7		•	•	•	•	•	•	•	42000
		10:01:00 AM	3480	0.02	8	•	•	•	•	•	•	•	•	928
	•Change pumping condition													
		10:59:00 AM	60	1.00	8	•	•	•	•	•	•	•	•	960
	•Nabla cut card at 11:00AM	11:00:00 AM	60	50.0	7		•	•	•	•	•	•	•	42000
		11:01:00 AM	3480	0.02	8	•	•	•	•	•	•	•	•	928
	•Change pumping condition													
		11:59:00 AM	60	1.00	8	•	•	•	•	•	•	•	•	960
	•Nabla cut card at 12:00PM Noon	12:00:00 PM	60	50.0	7		•	•	•	•	•	•	•	42000
		12:01:00 PM	780	0.02	8	•	•	•	•	•	•	•	•	208
		12:14:00 PM	60	1.00	8	•	•	•	•	•	•	•	•	960
	•Nabla conduct Standing and Traveling	12:15:00 PM	300	5.00	5		•	•	•	•	•			15000
	valve checks starting at 12:15 PM.	12:20:00 PM	76140	0.02	8	•	•	•	•	•	•	•	•	20304
	•Change pumping condition													
Day 6	Wednesday													
	•Nabla install load cell by 9AM.													
		09:29:00 AM	60	1.00	8	•	•	•	•	•	•	•	•	960
	•Nabla conduct Standing and Traveling	09:30:00 AM	300	5.00	5		•	•	•	•	•			15000
	valve checks starting at 9:30 AM.	09:35:00 AM	1440	0.02	8	•	•	•	•	•	•	•	•	384
		09:59:00 AM	60	1.00	8	•	•	•	•	•	•	•	•	960
	•Nabla cut card at 10:00 AM	10:00:00 AM	60	50.0	7		•	•	•	•	•	•	•	42000
		10:01:00 AM	3480	0.02	8	•	•	•	•	•	•	•	•	928
	•Change pumping condition													
		10:59:00 AM	60	1.00	8	•	•	•	•	•	•	•	•	960
	•Nabla cut card at 11:00AM	11:00:00 AM	60	50.0	7		•	•	•	•	•	•	•	42000
		11:01:00 AM	780	0.02	8	•	•	•	•	•	•	•	•	208
		11:14:00 AM	60	1.00	8	•	•	•	•	•	•	•	•	960
	•Nabla conduct Standing and Traveling	11:15:00 AM	300	5.00	5		•	•	•	•	•			15000
	valve checks starting at 11:15 AM.	11:20:00 AM	84300	0.02	8	•	•	•	•	•	•	•	•	22480
	•Ship tools back to AE													
Day 8	Friday	10:45:00 AM											Total ->	419064

Fig. 2 — Sample test schedule for one of the DDDB tests. Field operations (left side) are coordinated with the tool program (right side) to measure desired data with a downhole dynamometer tool.

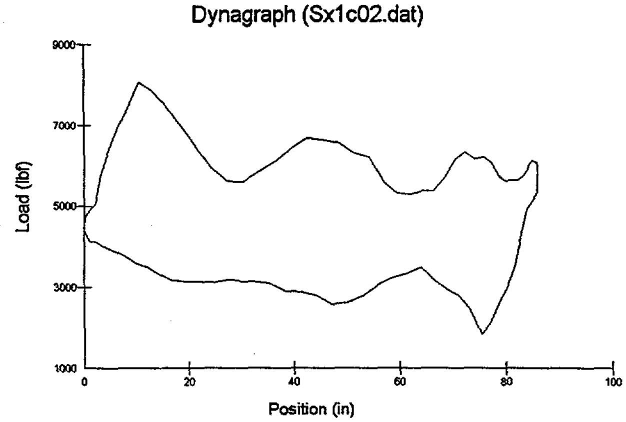

Fig. 3 — Surface dynagraph from the RMOTC test at 8:47 AM.

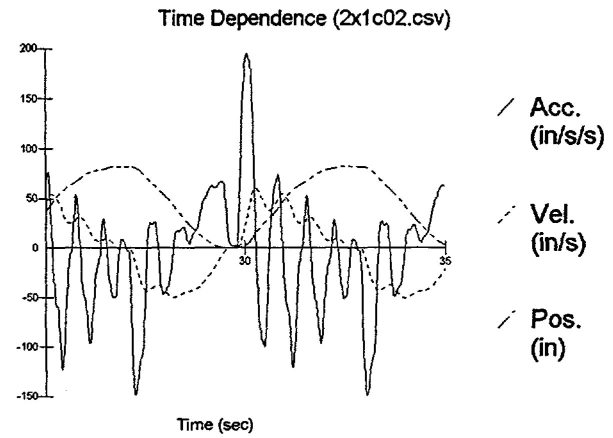

Fig. 4 — Plot of acceleration, velocity and position versus time just above the pump from the RMOTC test at 8:47 AM.

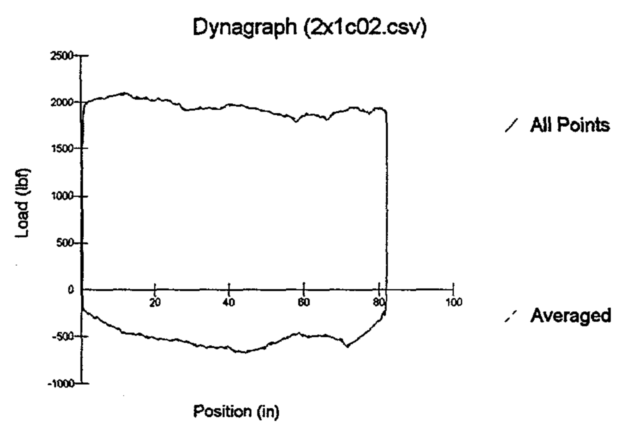

Fig. 5 — Downhole load dynagraph just above the pump from the RMOTC test at 8:47 AM.

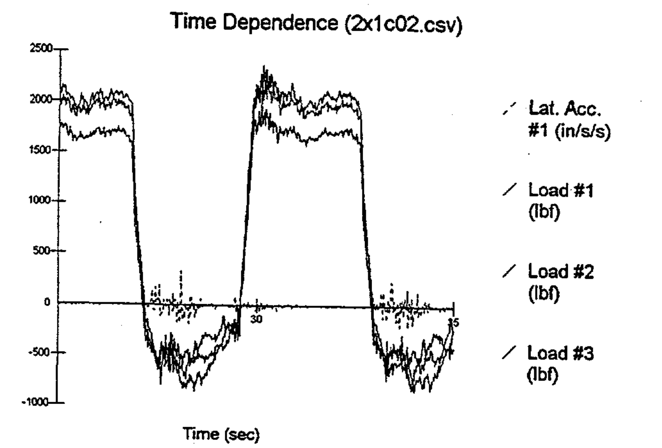

Fig. 6 — Plot of lateral acceleration and three loads versus time just above the pump from the RMOTC test at 8:47 AM.

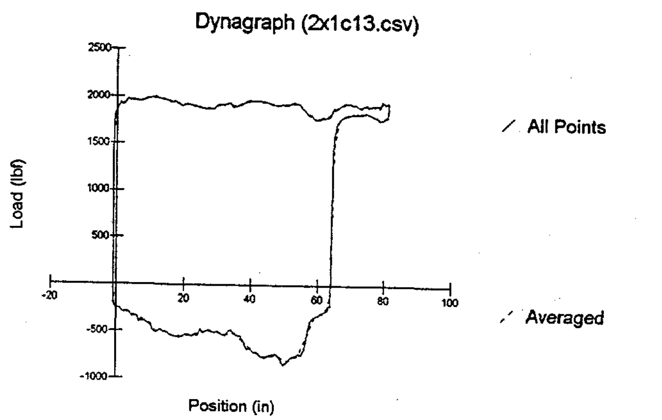

Fig. 7 — Downhole load dynagraph just above the pump from the RMOTC test at 10:47 AM.

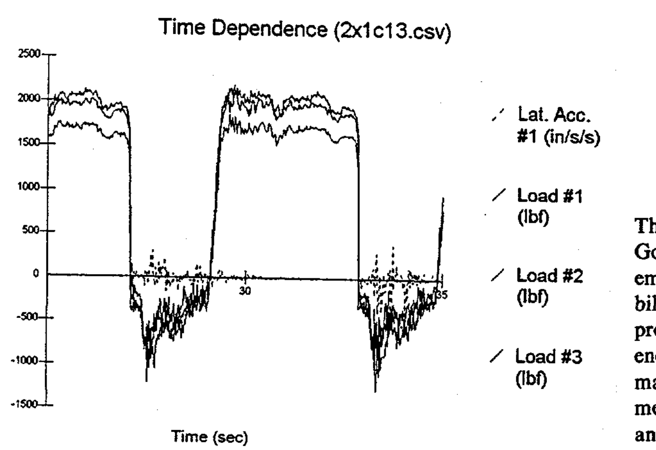

Fig. 8 — Plot of lateral acceleration and three loads versus time just above the pump from the RMOTC test at 10:47 AM.

SI Metric Conversion Factors

ft x 3.048*	E-01	= m
in. x 2.54*	E+00	= cm
lbf x 4.448 222	E+00	= N
psi x 6.894 757	E+00	= kPa

*Conversion factor is exact.