Improved Acoustic Liquid Level Surveys by Digital Data Acquisition, Processing and Analysis

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ABSTRACT

A computerized system has been developed for acquisition, processing and analysis of acoustic data used to determine the distance to the liquid level in the casing annulus of a well. The system utilizes a gun-microphone assembly such as has been used in the past. However, the analog signals from the microphone are digitized by a high speed analog to digital converter and stored in a lap-top computer, allowing much greater versatility in signal processing and analysis.

The computerized system processes the acoustic digital data to automatically identify the liquid level reflection pulse and counts the number of collar reflections to the liquid level signal. After acquiring the acoustic data, this system first determines the collar reflection signal rate or frequency. Then, the digital signal data between the initial pulse and the liquid level pulse are filtered with a narrow-band filter centered at the collar reflection frequency, in order to improve the signal to noise ratio. Using this narrow-band filtering, the collar reflections can be distinguished much further down the wellbore. The program uses a cross-correlation technique to automatically count the number of collar reflections to the liquid level. The liquid level depth is calculated utilizing the number of collar reflections and the average tubing joint length.

Digital filtering and signal processing allow the automatic interpretation of the liquid level position in the majority of the field cases, even those where conventional analog recording and broad-band filtering were inadequate for accurate measurements. The system also provides additional processing techniques, under operator control, to obtain accurate results in those wells where conditions are very unfavorable: shallow liquid levels, gaseous liquid columns, noisy well bores, annular constrictions, etc. A number of field cases are presented to illustrate the primary application to optimization of pumping wells.

The system also acquires the casing pressure, determines the casing pressure buildup rate, converts it to an equivalent annular gas flow rate and calculates the effective gradient of the gaseous liquid column in the annulus. The annular liquid level depth and casing pressure distribution determine the producing bottom-hole pressure which is combined with a well data base that contains the production rate, static reservoir pressure and other parameters used in the generation of a well performance analysis for the operator.

INTRODUCTION

Acoustic echo-ranging techniques to generate well soundings have been in effect for over fifty years to aid in the analysis of pumping wells[1]. Early application was limited to determining the presence of liquid in the annulus above the pump. If liquid was found over the pump then the operator knew that additional production was available if a larger pump was installed; or, if the pump were not operating properly, that the pump should be pulled and repaired.

Soon after the development of these instruments, some operators realized that proper interpretation of the records could yield additional information. In particular bottom-hole pressure was calculated from the summation of the surface casing pressure plus the gas column hydrostatic and the liquid column hydrostatic pressures. This presumed some knowledge of the density and distribution of the oil and water in the liquid column especially in the case of shut-in wells where relatively high liquid columns were observed.

Operators also observed that, in those instances where gas was vented from the annulus, the calculated bottom-hole pressure was excessively high. This was attributed to the lowering of the effective liquid gradient by the presence of gas bubbles in the liquid column above the perforations. C. P. Walker[2] patented a method for determining the density of annular liquid columns which are areated by gas bubbling upward through the liquid. Walker presented a technique whereby a back-pressure valve is used to control and increase the casing-head pressure causing the annular liquid level to fall a distance corresponding to the pressure increase. The gradient of the gaseous liquid is calculated by dividing the change in pressure at the top of the gaseous liquid column by the corresponding drop in liquid level. This gradient is then used to calculate the bottom-hole pressure.

If the back-pressure valve setting is further increased until the the top of the gaseous liquid column is stabilized in the vicinity of the pump intake, which generally is near the perforations, then the producing bottom-hole pressure can be estimated quite accurately since the contribution of the hydrostatic pressure from a short gaseous-liquid column is small in relation to the casing-head pressure, and errors in the gradient estimate will not significantly affect the resulting total pressure. In the majority of producing wells in the United States, the liquid level is near the pump inlet and the casing-head pressure plus the gas hydrostatic will yield a very close estimate of the producing bottom-hole pressure. This method which was presented over 50 years ago is still one of the most useful methods of obtaining accurate producing bottom-hole pressure.

Studies by Podio, McCoy, et al.[3] have presented a technique for obtaining the casing annulus gas flow rate by measurement of the casing annulus gas pressure buildup rate. Utilizing the casing annulus pressure buildup rate and the void volume in the annulus, a reasonably accurate casing-head gas flow rate can be obtained. Knowing this flow rate, an estimate of the liquid column gradient is made.using an experimentally determined field data correlation. This permits to calculation of a reasonably accurate producing bottom-hole pressure even when gaseous liquid columns exist above the pump.

Further refinements in obtaining bottom-hole pressures by improvements in determining the gas column pressure and the liquid column pressure along with electronic and mechanical improvements in processing and automation devices resulted in the development of equipment to obtain acoustic liquid level data and casing pressure data automatically without the need of operator assistance.[4]

This battery-operated system was based on automatic measurement of the two-way travel time of the acoustic signal from the wellhead to the gas/liquid interface in the annulus. This was undertaken by starting a time-interval counter at the firing of the acoustic pulse and stopping the counter upon detection of a signal thought to correspond to the liquid level reflection The operator also entered data to calculate the average speed of sound in the casing gas. The distance to the liquid level was then calculated by multiplying the speed of sound times one- half of the measured travel time. Analog filters were included to reduce the interference from signals generated by the pumping unit, or by the reflections at the tubing collars and to insure that the liquid level signal was detected in the majority of cases. Since the principal objective of this system was to obtain data during a pressure buildup test, each measurement was repeated at a pre set time interval. Results (time, depth and casing pressure) were printed on paper tape, for further processing off-site.

Although this system proved very useful in obtaining data for analysis of buildups in pumping wells it suffered from major deficiencies. These included the absence of a record of the acoustic signal for each measurement (only travel time was recorded) and the use of a constant average value for the acoustic velocity in the annular gas. The first made it impossible to verify that the liquid level signal was properly identified and the second introduces significant inaccuracy in the calculation of the depth to the liquid since the acoustic velocity is not a constant and varies as a function of casing pressure during the pressure buildup. Nevertheless this work represented a major contribution to the industry in showing that it was possible to obtain pumping well buildup data which was usable in conventional pressure transient analysis, at a fraction of the cost and effort required by conventional methods.

Computer-based Systems

The advent of small, portable personal computers yielded the opportunity to eliminate the deficiencies of the automatic liquid level monitor and extending its capability through sophisticated data processing. It also provided the possibility to undertake fairly detailed analysis of the data in the field, providing a measure of quality control and information on the progress of the test.

The first application included the use of a note-book computer for calculation of static bottom-hole pressure in high pressure gas wells at the wellsite.This system used the acoustic signal to determine the height of liquid that may be present at the bottom of the tubing. The gas column hydrostatic was integrated by the computer, using an equation of state for the gas, the temperature gradient and the measured surface tubing pressure. The bottom hole pressure was thus obtained by summing the tubing-head pressure the gas column pressure and the liquid hydrostatic. Field tests in deep wells (over 15,000 ft) showed that the calculated values were within the accuracy of conventional bottom hole pressure gages.[5]

The excellent results provided by this system and the development of PC compatible lap-top computers further enhanced the potential for computer-based acoustic measurements for calculation of bottom-hole pressure in wells.

Automatic Echometer

This system was designed to overcome the deficiencies of the Godbey-Dimon [4] system and to provide transient well test analysis at the well site.

The system consisted of a lap-top PC interfaced with and controlling the operation of a remotely-operated Echometer system.[6] The acoustic signal was monitored by the computer and, at specified time intervals was also recorded on the conventional strip chart. The computer determined the travel time to the liquid level using the broad-band signal to detect the response while simultaneously recording, on a strip chart, the reflections from the tubing collars through appropriate analog filters to enhance their detection as deep as possible in the well. Data from each shot as well as casing pressure, temperature and time was recorded on a floppy disk for subsequent processing. Analysis of the collar chart by the operator, provided a means of determining the acoustic velocity at that particular time and for all subsequent times when a chart was recorded as per computer control. This provided information of changes in acoustic velocity as a function of casing pressure. This function was curve-fitted by the program and used in the conversion of travel time to liquid level depth. Simultaneous measurement of casing pressure as a function of time allowed calculation of annular gas flow rate and of the effective pressure gradient of the gaseous annular fluid column. Thus the system provided direct indication of bottom-hole pressure at the wellsite during the buildup test. The software included the capability of generating conventional plots of the pressure buildup while the data was being recorded. This feature allowed the operator to monitor the progress of the test and to decide when a sufficiently long build-up had been reached and the test could be terminated.

Digital Well Analyzer

Digital signal acquisition, storage and processing combined with powerful lap-top computers offer significant advances and improvements in acoustic well sounding. Four important achievements are possible by utilization of a microcomputer. First, the computer can process the acoustic data digitally to obtain more accurate liquid level depths, automatically. Second, the determination of bottom-hole pressures from the acoustic liquid level measurement, the surface pressure, and properties of the produced fluids is immediately available. Third, the computer offers automatic operation of the equipment in that the computer can be programmed to perform well soundings and obtain casing pressure measurements on command, without operator attention. And fourth, data base management and retrieval are easily implemented to result in timely and accurate record keeping and reporting. These factors were the principal incentives in the development of a fully digital system for acoustic well soundings and acquisition of other data for complete analysis of well performance.[7]

The system's objective is to yield an accurate and timely analysis of well performance for the current operating conditions and to yield information necessary to predict the effect of operational changes . This ability allows the production engineer to evaluate the effect of changes in parameters such as pumping speed, stroke, surface pressure, on/off time, etc. and/or changes in the well configuration such as pump depth, rod sizes, surface unit geometry, well stimulation, etc. on the overall performance of the well. In order to satisfy this objective the system has to include the hardware and software elements illustrated schematically in Figure 1.

- Data Processor

The Well Analyzer is driven by a Toshiba T1000SE computer, but can be configured with other Toshiba lap-top PC-compatible microcomputers. The 16 bit microprocessor (80C86-2) operates at 9.54 MHz and accesses one megabyte of memory with the operating system stored in read-only memory. The 100 pin, expansion port bus connector is used to interface to the Well Analyzer data acquisition and control hardware.

- Interface, signal conditioning and Analog/Digital converter

This sub system consists of a set of hybrid VLSI chips that undertake the necessary communications with the processor, condition the transducer signals and convert the various analog inputs to digital format. Input signals can be digitized at a rate of 1000 samples per second with 16 bit resolution.

- Acoustic Soundings Hardware

Although the Well Analyzer can be utilized with any modern manual acoustic sounding hardware it is designed to be used in conjunction with Echometer's remote-fired wellhead which integrates a noise cancelling microphone, casing pressure transducer, solenoid control valve and the gas volume chamber. The remote fired wellhead generates the acoustic pulse and detects the signals from down-hole reflections. The volume chamber is filled with compressed gas which is released by actuation of the solenoid valve from the computer.

- Dynamometer Hardware

Analysis of beam pumped wells requires acquisition of the load and displacement at the polished rod. Several load cells and displacement indicators can be interfaced to the well analyzer. The preferred configuration includes measurement of acceleration which is then integrated digitally to obtain velocity and displacement thus yielding additional information about the operation of the pumping unit. In electrically driven units, the motor current is measured simultaneously with the polished rod data as a means to analyze the proper counterbalance effect.

- Output devices

Results which are displayed on the screen are also available as printer output, either at the field, by means of a battery-powered jet printer, or off line, using a batch print routine.

- Data storage

All data recorded in the field and all the well data are stored on the high density floppy disk. A data base is thus generated for each well which comprises all the necessary information to evaluate the performance of the well as a function of time. All files are time and date-stamped so that it is possible to compare the performance of the well at the present time to that obtained from earlier tests.

Software

The programs developed for the well analyzer include those required for acquisition of data and control of the hardware and those used for interpretation of the information, analysis of the well's performance and management of the data base. The programs are menu-driven and include operator prompting to insure that the most logical sequence of steps is followed during well testing.

- Acquisition and Control Software

These routines undertake the necessary operations for system set up, transducer calibration, graphics scaling, and sequencing of testing so as to insure the maximum accuracy and quality of the data.

- Application software

These programs provide the tools to analyze the data at the well site so as to give the operator sufficient information regarding the performance of the well to decide whether operations are efficient or they require modification, adjustment or further testing. Specific data files can be stored on diskettes, in formats compatible with other data analysis programs.

A schematic diagram of the well analyzer system as installed to undertake acoustic soundings is shown in Figure 2.

DIGITAL DATA PROCESSING

Automatic Acoustic Analysis

When the acoustic liquid level is determined, the display, shown in Figure 3, is observed by the operator after an acoustic pulse has been generated at the surface of the well and reflected signals are received by the microphone. The top insert shows the raw data. The beginning is at the left. The background noise, the initial acoustic pulse and the reflected signals are shown. Data are recorded past the time at which the liquid level reflection is expected. The dashed vertical line at the liquid level kick indicates the exact time which the software selected as the onset of the liquid level signal. The liquid level kick is at 8.959 seconds.

Automatic selection of the liquid level reflection is undertaken by a pattern recognition scheme that involves the amplitude, polarity, width and slope of the received signals. The software scans the digitized record and selects all the signals that satisfy the pattern requirements, then selects the most probable and presents it to the operator. The arrow keys can be used to scan through the other possible liquid level signals.

The lower right hand inset shows the detail of the liquid level signal selected by the software. When an initial compression pulse is used any reductiobn in annular area results in a negative going signal. Note that for this well, which is typical of many pumping wells with the fluid at or near the perforations, the liquid level signal is preceded by a negative-going signal produced by the tubing anchor (at about 8.7 seconds). The presence of the perforations just above the liquid level is observed as a positive-going signal prior to the large negative spike caused by the liquid reflection.

The two vertical lines shown in the main upper window at 4.5 and 5.5 seconds delimit data which are shown as raw signal on the lower left hand insert. This specific section of the raw signal is processed to accent collar reflections and is displayed immediately above the raw signal. This is done by digitally filtering the data with a band pass filter. The software determines the most appropriate filtering range for a specific signal. The median frequency in this case is 18.2 Hz. An estimate of the total number of collars from the surface to the liquid level is made using the frequency of this processed signal as an average value of collar count per unit time.

Using the PAGE-UP/PAGE-DOWN keys the operator can control the vertical scale for the top presentation of the data. This allows detailed examination of the raw signal as a means of quality control and to insure that the proper kick has been selected for the liquid level response.

Detailed examination of this display allows the operator to visualize the background noise present in the well before the shot, the character of transmitted pulse (amplitude, frequency content and attenuation, the quality of the reflections from the collars and the liquid level kick. In general the software selection of the liquid level will correspond to the correct determination. However, if a tubing anchor, upper perforations, a paraffin ring or other obstructions exist in the annulus, the program may select one of these signals as the liquid level. In these instances the operator can use the arrow keys to displace the liquid level marker to the proper time. After this is done in subsequent tests the software will not accept the earlier signal arrivals. In some extremely difficult conditions, identification of the proper liquid level reflection may necessitate artificially moving the liquid level either by shutting down the well or increasing casing pressure in order to verify that the proper signal has been identified as the liquid level reflection.

After the raw data has been displayed the operator has the choice of a display of the well analysis sheet, a display of the acoustic data which was processed to accent and count the collars, or a display of the raw signal and processed signals from which the operator can count joints and analyze the signals. When the operator acknowledges that the raw data and selected liquid level kick and indicated collars are satisfactory for analysis, the software processes the raw data and counts the number of joints to the liquid level. The operator can display these processed data if desired, so as to visualize the quality of the signal obtained from the well and the accuracy of the count of tubing joints to the liquid level.

Well Performance Analysis

Acceptance of the computer's interpretation of the acoustic data, results in the detailed well analysis screen display shown in Figure 4. The objective of this display is to provide complete visualization of the wellbore conditions at the time of the measurement. The figure is divided in two sections: on the right is a schematic diagram of the wellbore and reservoir configuration, on the left are several blocks containing quantitative information about the well and its past performance.

The quantitative data on the left half of the figure is designed to present vital information about the well. In the upper left hand block, the well name, company, and operator data are shown. Well data are shown in the block immediately below. In the upper right block, the results from the latest production test are included. The central block is used to present the results of well performance analysis based on a Vogel-type IPR relationship. This includes the current producing rate efficiency and the maximum potential production achievable by reducing bottom-hole pressure to a minimum value.

The well schematic is scaled so as to illustrate the wellbore geometry, tubing depth, casing depth and datum depth.. The currently measured casing pressure, casing pressure buildup rate and the calculated casing annulus gas flow rate are printed opposite the gas portion of the well. Just below are printed the depth to the gas-liquid interface and the percentage of liquid present in the gaseous liquid column. At the bottom of the well are printed the calculated producing bottom-hole pressure (PBHP) and the most current value of static reservoir pressure (SBHP).

Every fifteen seconds during the time since the fluid level shot was fired, the computer automatically acquires the casing-head pressure to determine the annular gas flow rate.For this well this is shown in Figure 5, which indicates an increase in pressure of 1 psi in 2.0 minutes. The linearity of this increase is an indication that steady state flow has been established in this well. An erratic pressure profile would indicate that pumping should be continued before steady state is approximated and additional testing can be undertaken. This rate of casing pressure buildup (DP/Dt) is used to calculate the annular gas flow rate in conjunction with the annular geometry and the gas fraction in the fluid column as determined using a correlation which was derived from numerous field measurements.[3]

In this example, the 42-ft fluid column above datum consists of a mixture of oil and gas with about 44% liquid. In the bottom left-hand block is indicated that this 42-ft fluid column is equivalent to 18 ft of gas-free liquid above the perforations.This column's hydrostatic, plus the annular gas hydrostatic and the casing-head pressure result in a producing bottom-hole pressure of 90.3 psia.

Considering that the stabilized formation pressure is 476 psia, and using Vogel's IPR relation, the program determined that this well is being produced at 93% of the maximum producible rate.

Digital Filtering of Acoustic Signals

In some instances the operator may consider that the the first stage automatic interpretation of the liquid level is not accurate enough or the signal may exhibit excessive noise and poor definition. The software provides the capability of filtering the signal in its totality using appropriate filters to accent the collar reflections and give a precise count of number of joints to the liquid level.

The complete acoustic signal record (from the shot to the liquid level reflection) is shown in Figure 6, after digital processing using a narrow-band filter (16.7 to 19.7 Hz. in this case). Superimposed on the signal are a series of unit spikes in phase with the signal's negative cycles, and at a frequency which matches the prevailing frequency of the signal.These frequencies are indicated on the display for each group of ten cycles beginning from 1/2 second after the shot and ending just before the fluid level reflection.The first group frequency is used to extrapolate back to zero time (yielding 9.2 cycles) and the last group frequency is used to extrapolate forward to the fluid level reflection yielding 4.2 cycles. The total number of cycles is summed to yield 163.4 cycles corresponding to an equal number of tubing joints.Using the tubing tally or average tubing joint length the distance to the fluid level is then calculated to be 5179.3 feet. Not that this value is very close to the value obtained previously (5173.1 feet) using the frequency of the signal at the median point of the acoustic record.

Special Processing of Acoustic Data

The Well Analyzer is used in wells throughout the World. Some of these wells will have liners, upper perforations, paraffin, odd length of joints, poor surface connections and other conditions which result in an acoustic record which is difficult to interpret. Normally the software locates the liquid level and then processes collar signals which are midway to the liquid level in order to obtain the average collar signal rate. All the acoustic data is filtered at this median collar rate and the program automatically counts the collars from the initial blast to the liquid level.

The above technique has been successful in over 85% of the wells tested. Interpretation of data in the remaining wells is undertaken using special signal processing methods with computer assistance by prompting of the operator. These methods include entering a known value of acoustic velocity for the annular gas, entering the physical distance between two recognizable acoustic signals, selecting a special section of the acoustic signal to be used to define a filtering frequency or a combination of these.

For example, in wells where the liquid level is very near the surface giving a liquid level time of less than 2 seconds the signal amplitude is affected by the initial blast and reflections from the surface connections. In this case automatic interpretation may be difficult.

The program prompts the operator to locate a movable screen marker on a recognizable collar signal and then locate a second indicator on a deeper collar signal. The program then asks for the number of joints that can be counted between the two signals. From these data the program calculates the average sound velocity for the annular gas and multiplies it times the travel time to the liquid level to obtain its distance.

In noisy wells it is possible that the collar signal frequency at the median position is not truly representative of the overall collar frequency. The operator can select any portion of the signal, in one second intervals, to be analyzed and used to obtain a correct collar frequency.

Some of these and other are illustrated in the following field examples which cover a wide range of conditions.

FIELD CASES

Low Production Efficiency Well

Figure 7 shows the acoustic signal in a 4000 ft well with the liquid level at a depth of 1187 ft from the surface. The liquid level signal is very distinct and is selected accurately by the program. The travel time is greater than the minimum of 2 seconds, which permits the software to undertake automatic interpretation. The quality of the median signal, between 1.2 and 2.2 seconds is very good and collar signal can be easily detected both on the raw and the filtered data. Note that the unit spikes in both windows correlate quite well. The collar frequency is calculated at 15.8 Hz which yields a total of 37.5 joints corresponding to a distance of 1187.6 ft to the liquid level.

This well's analysis is presented in Figure 8 which indicates that an annular gas flow of 1.7 MCF/D was calculated from the casing pressure buildup rate of 0.3 psi in 2 minutes. The corresponding percentage of liquid in the annular column is 91%. Thus the 2812 ft of height of fluid column above the datum correspond to a column height of 2558 ft of gas-free liquid. This results in a flowing bottom-hole pressure of 905.5 psia.

From the well's data base, the program has retrieved information regarding the static reservoir pressure and the last production well test data indicating a production of 10 BOPD and 20 BWPD. Combining these parameters with Vogel's inflow performance relation, the program determined that the well is producing at 59% of the maximum producible rate of 17 BOPD. This gives an indication that it would be advisable to analyze the pumping system to identify the cause of the high liquid column which impedes further production. Additional information regarding the efficiency of the pumping system should be obtained from a dynamometer survey and combined with the results of the acoustic liquid level analysis to identify the correct remedial action.

High Gaseous Liquid Column Well

Operators often interpret the existence of a high fluid level as an indication that a well is not being produced as efficiently as possible. Remedies for this situation include increasing pump displacement by varying pump stroke and strokes per minute, lowering the pump and/or replacing the pumping unit with a larger one.

Often however, the desired production increase does not materialize because the well's performance was not accurately analyzed.

Figure 9 shows an example of a well in which it was determined that an annular fluid column of about 3010 feet in height is present above the datum. This well also presents some problems in signal analysis due to the excessive noise caused by gas bubbling up the annulus and unfavorable signal level due to poor connections at the surface. The casing valve was connected to the casing-head through a 1 inch diameter nipple which severely restricted the shot amplitude and unwanted frequency contents. This is easily observed in Figure 9 by noting the high frequency components in the raw signal and the irregular filtered data from the automatic interpretation screen which used the signal from 2.8 to 3.8 seconds. The collar frequency of 14.0 Hz is suspect in view of the poor correlation of the unit spikes with the signal cycles. The alternate digital processing mode was used to select a different portion of the signal, from 1 to 2 seconds to be analyzed. This is shown in Figure 10. Note that in this case the filtered signal correlates very well and a uniform collar frequency of 19.2 Hz yields a total of 108.3 joints to the liquid level for a depth of 3354.7 ft.

The well performance analysis screen indicates that gas is flowing up the annulus at a rate of 50.2 MCF/D resulting in an annular column with only 34% liquid. Therefore the equivalent gas-free liquid above the datum is only 1038 ft, which combined with the casing-head pressure of 46.1 psig yields a flowing bottom-hole pressure of 444.2 psia. The inflow performance analysis indicates that the well is being produced at 94% of the maximum flow rate, and thus it is not likely that much improvement could be achieved by modifying operating parameters. However, since this well produces a significant amount of gas the dynamometer analysis should be studied in detail to determine the possibility of gas interference in the down-hole pump.

Figure 12 is a plot of the casing pressure buildup as a function of time (3.2 psi in 4 minutes). Its linear character is a good indication that the well is producing at stabilized conditions and the calculated annular gas flow rate can be accepted with confidence.

The noisy nature of the acoustic signal is also reflected in the filtered data shown in Figure 13. It can be seen that an anomaly exists between 3 and 4 seconds yielding a collar frequency of 18.4 Hz which is significantly different from the adjacent values. If this value were included in the depth calculation the resulting liquid level would be calculated as 3341 ft or 13 ft higher than it actually is. This demonstrates the advantage of digital filtering which allows control of the filter width used in signal processing.

Liquid Level Below Perforations and Low Casing Pressure

The acoustic signal shown in Figure 14 is an example of a deep well with low casing pressure. When the acoustic was first installed the casing pressure was only about 2 psi. At this low pressure level it was not possible to distinguish a clear reflection from the deep liquid level. After letting the casing pressure build up to the level of 5.6 psi it was possible to detect a low amplitude signal. (Note that the vertical scale corresponds to 1 mv). This signal shows a positive excursion (caused by annular area increase) clearly preceding the negative-going liquid level reflection, indicating the the liquid level is below the perforations. In this case the flowing bottom-hole pressure is calculated,as shown in Figure 15to be 25.4 psia indicating that the maximum drawdown has been achieved.

High Casing Pressure Well

The data in Figure 16 is an example of a well with a gaseous annular liquid column, but with a greater casing-head pressure. The acoustic signal, although somewhat noisy shows clearly that collar reflections can be observed practically all the way to the liquid level which generates a high amplitude signal (vertical scale is 100 mv). Filtering of the data results in a very clean collar reflections. Automatic interpretation yields a liquid level at 2553.6 ft.

The well analysis presented in Figure 17 indicates that the annulus is occupied by a column of 44% liquid which develops a bottom hole pressure of 446.2 psia. This well is being produced at 86% of the maximum producible rate.

No Casing-head Gas Production, No Casing Pressure

This is an example of a well that presents some difficulties for accurate measurement of liquid levels. The low pressure causes attenuation of the signal so that poor definition of collar reflections is observed as shown in Figure 18. The median signal is noisy but the filtered data appears to correlate well with the unit spikes and yields a collar signal frequency of 13.9 Hz.

Digital filtering of the signal with a narrow-band filter (12.4 to 15.4 Hz) shows that in various sections of the record (at about 3 seconds and between 5 and 7 seconds) the signal amplitude is too low to yield a consistent frequency and the signal cycles do not correlate well with the unit spikes as seen in Figure 19. In this case the collar count of 107.2 joints cannot be accepted with confidence. The operator considered that the earlier signal frequency to be a better estimate and used it in obtaining the final well performance analysis shown in Figure 20. The indication is that the annular column consists of 100% liquid and the well is producing at 81% of the maximum rate.

Implosion Signal

In certain cases it may be more convenient to generate the acoustic pulse by releasing the casing-head gas to atmosphere or to the volume chamber, causing a rarefaction pulse. In this case the microphone response is reversed in sign and the liquid would normally appear as a positive going pulse in a conventional analog strip chart recording. This could cause some confusion in interpretation. Digital recording and processing permits automatic reversal of the signal so that the conventional presentation is maintained. This is illustrated in Figure 21 where the same well as shown in Figure 3 was re-tested using an implosion signal. Note that although the amplitude of the liquid level signal is lower, the general character is preserved. This is also true of the raw signal displayed in the median sample.

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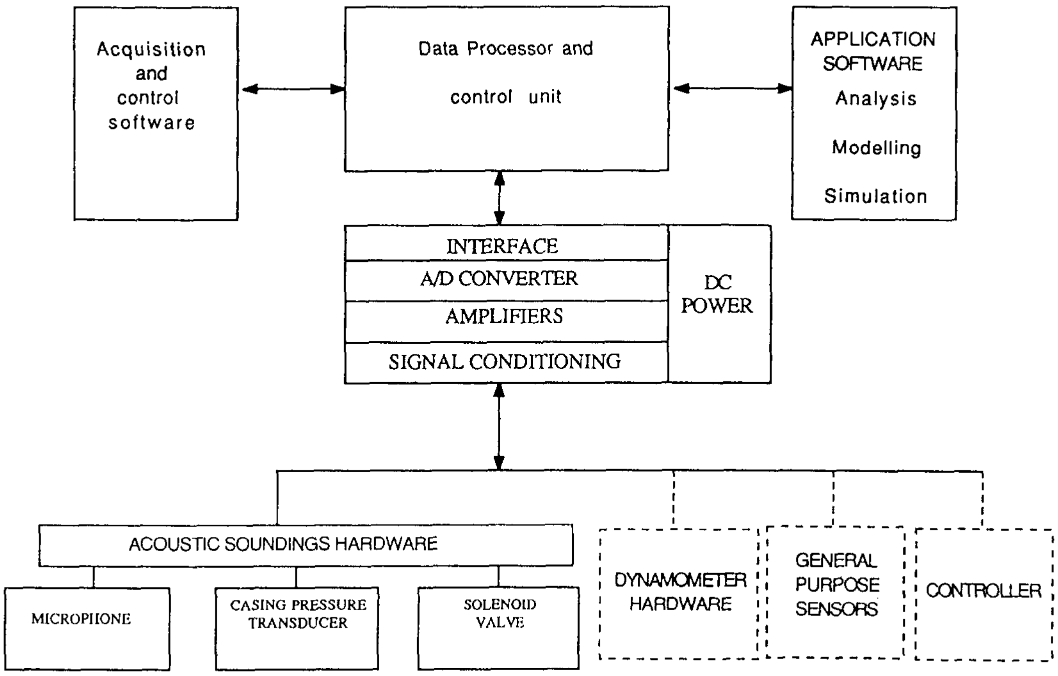


Figure 1 - Hardware and software configuration

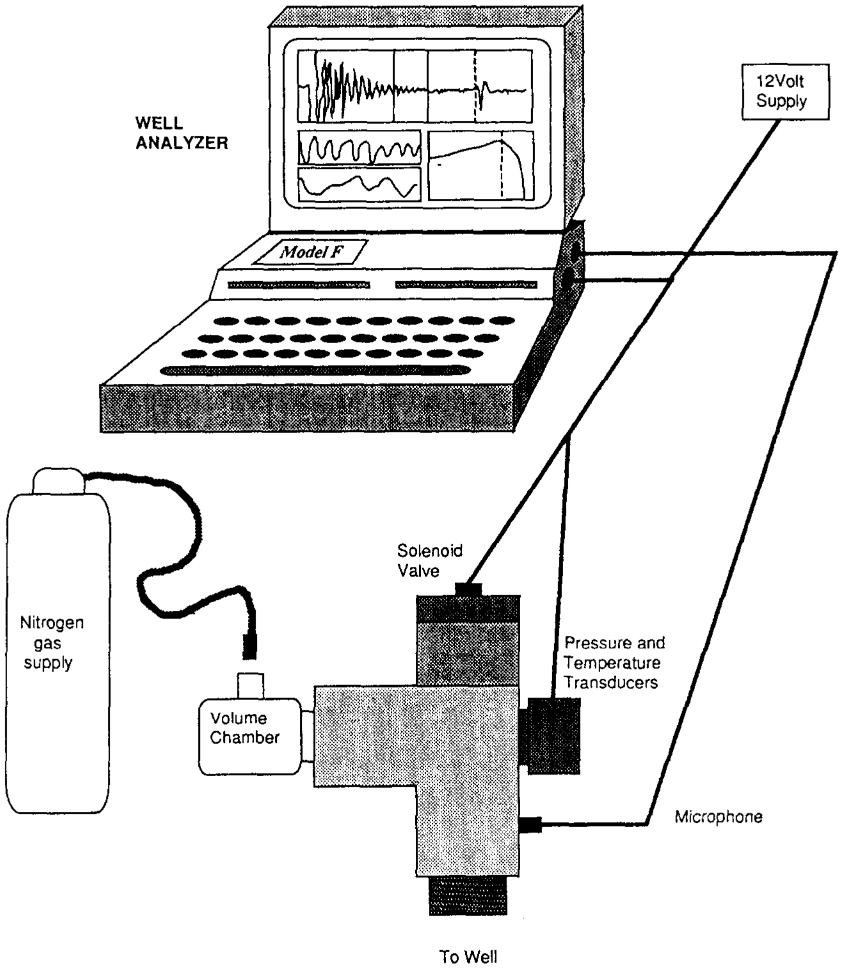


Figure 2 - Well analyzer system

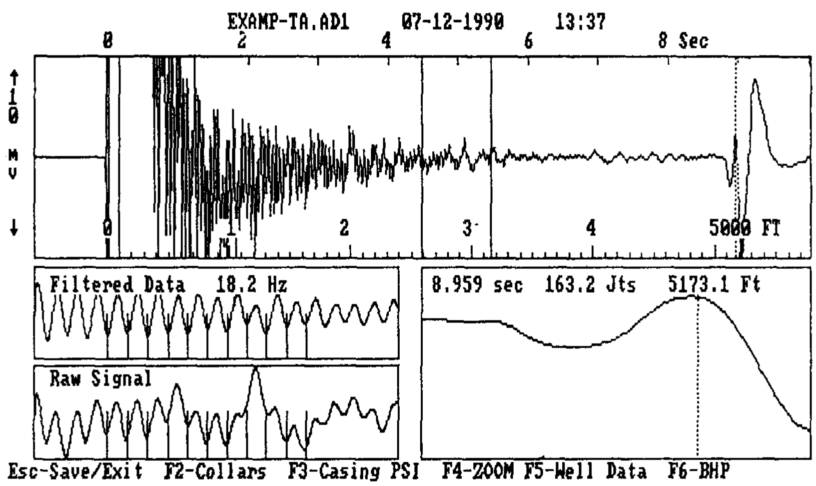


Figure 3

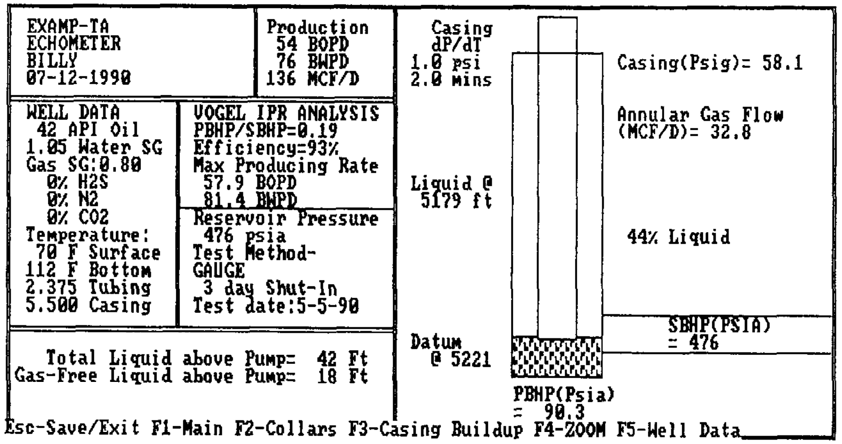


Figure 4

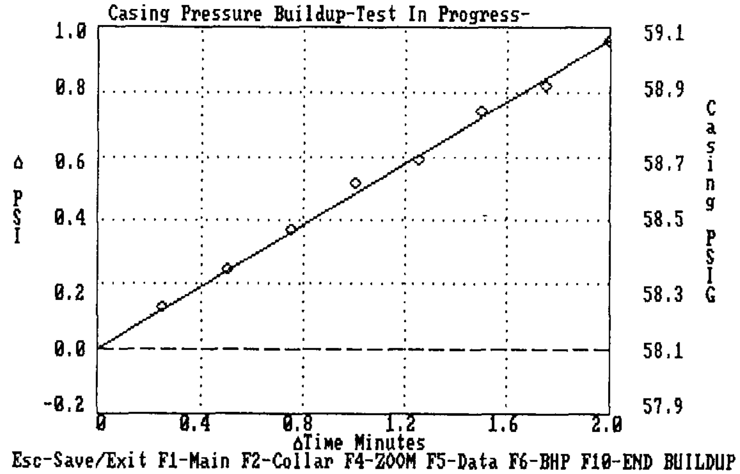


Figure 5

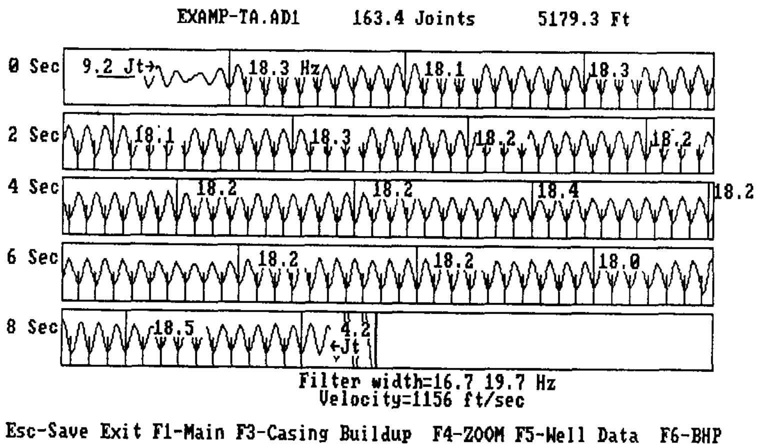
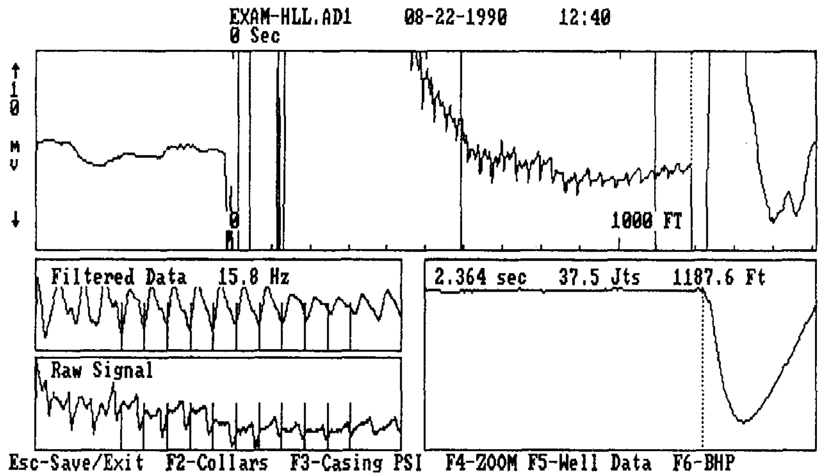


Figure 6



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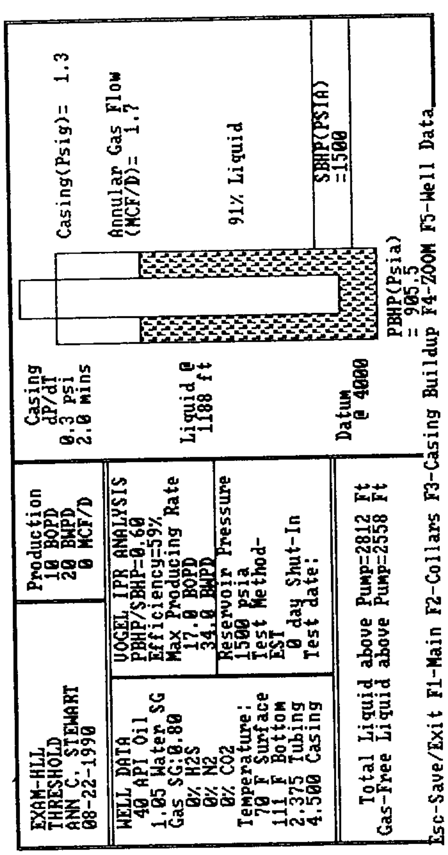

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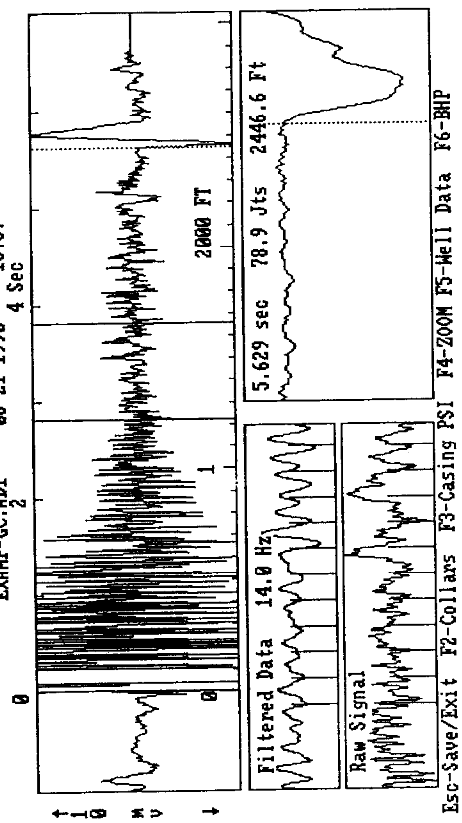

Figure 9

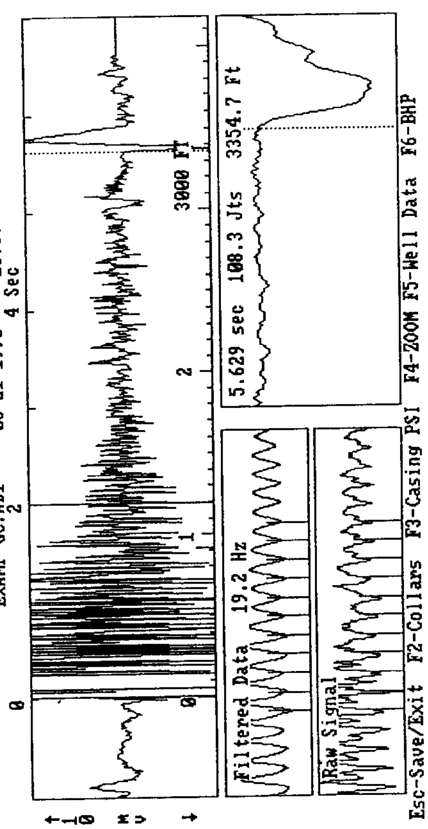

Figure 10

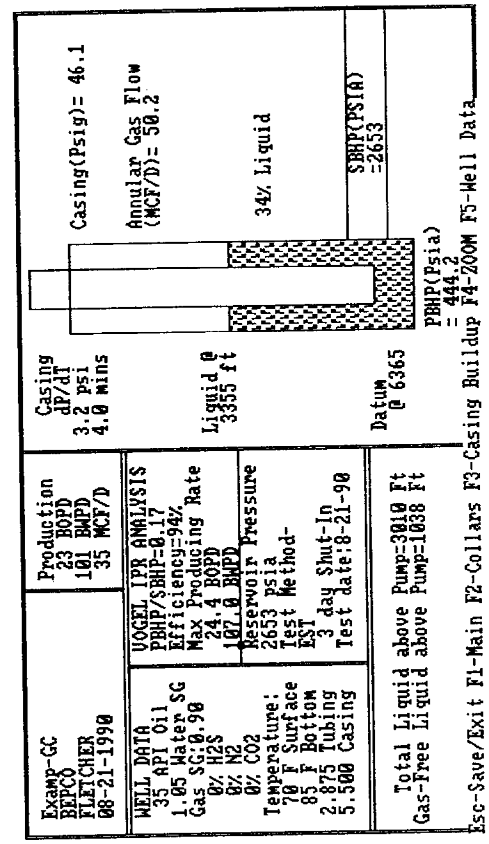

Figure 11

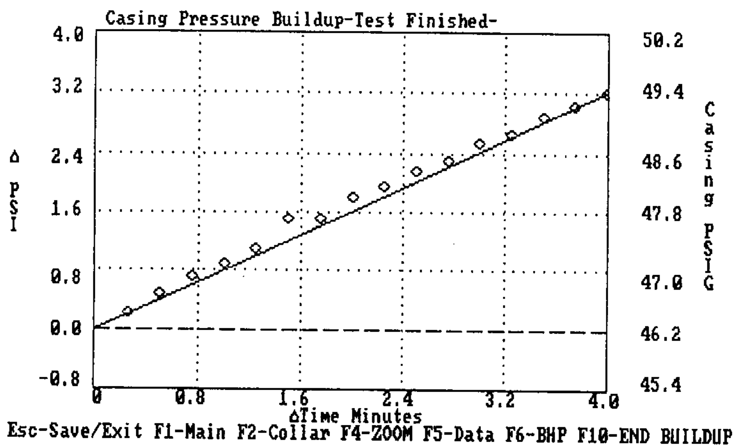

Figure 12

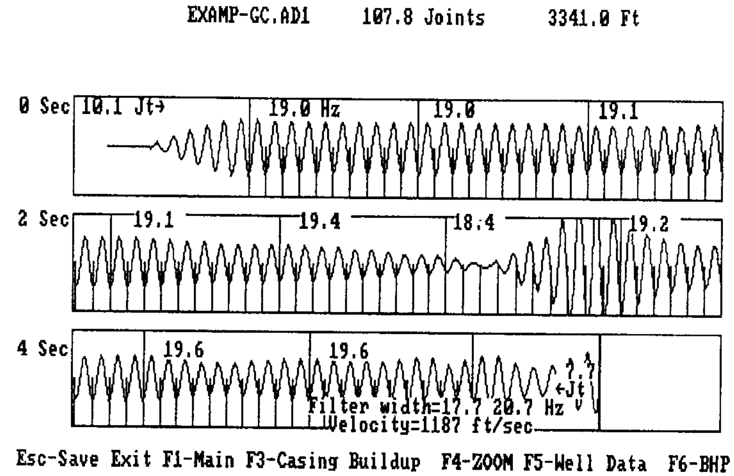

Figure 13

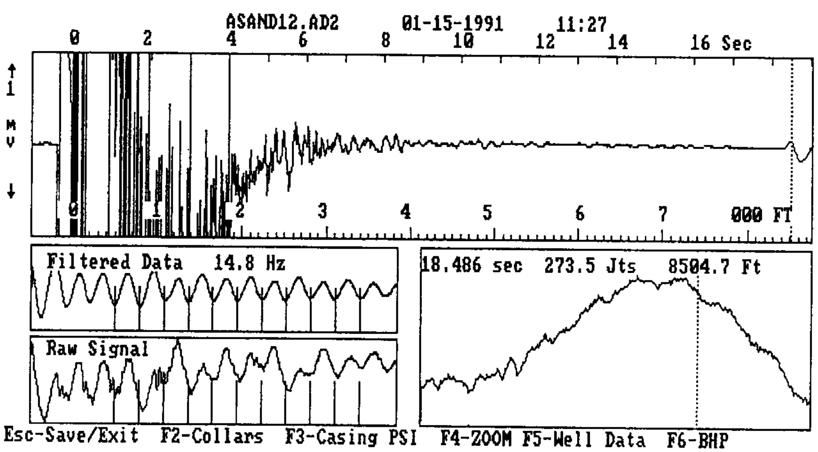

Figure 14

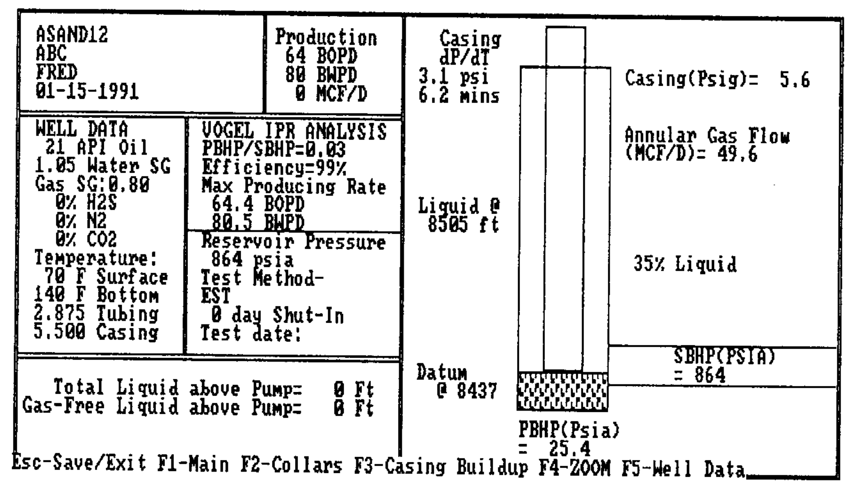

Figure 15

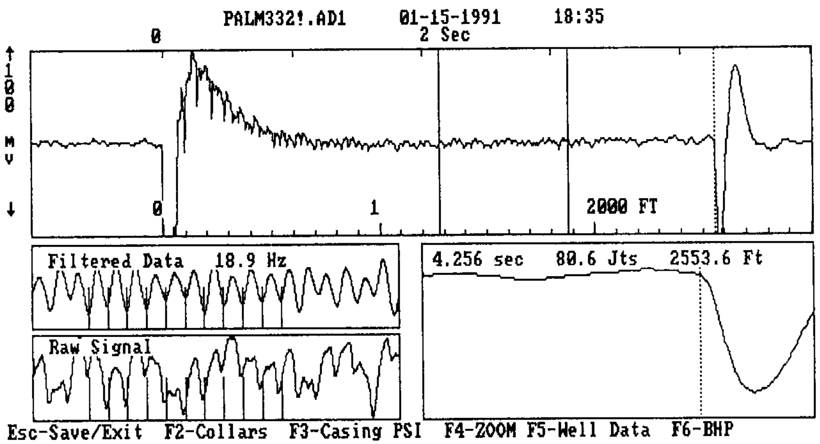

Figure 16

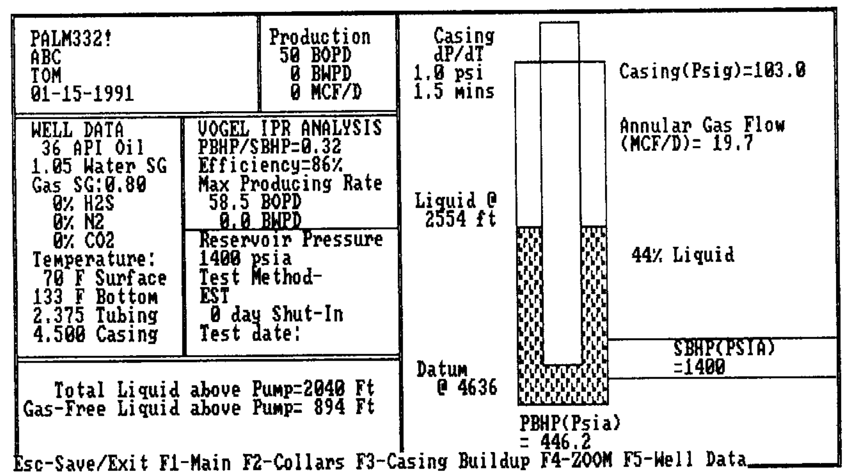

Figure 17

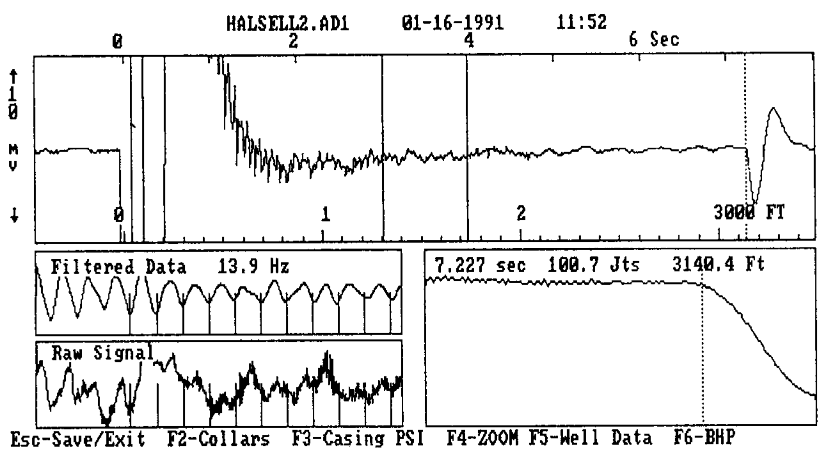

Figure 18

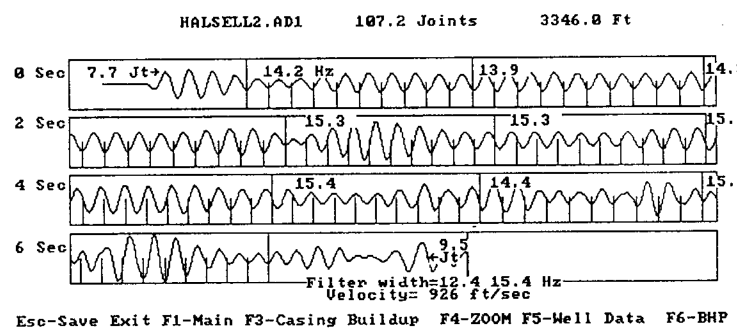

Figure 19

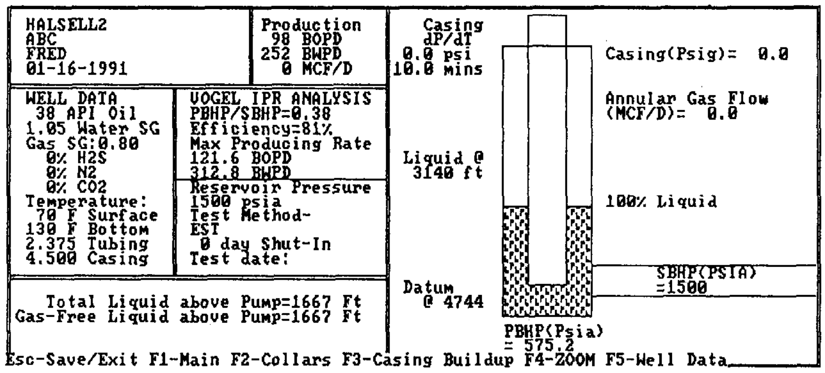

Figure 20

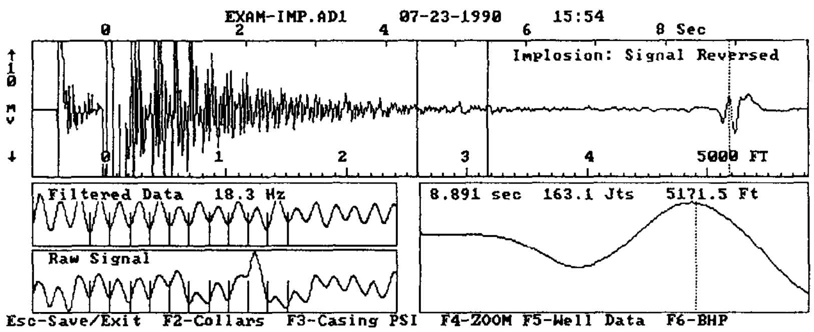

Figure 21