FIELD MEASUREMENTS OF ANNULAR PRESSURE AND TEMPERATURE DURING PRIMARY CEMENTING

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SUMMARY

To investigate the causes of fluid migration behind the casing after primary cementing, pressure and temperature measurements were made in the annulus of seven wells during cementing operations. Sensors were attached to the outside of the casing as it was run into each well; in this way data were obtained from several depths. A logging cable, also clamped to the casing, was used to bring data from the sensors to the surface. In some of the wells these annular measurements were continued during subsequent completion or workover operations.

The pressure data could be used to determine conditions that either prevented or allowed fluid entry into the wellbore. Generally, pressure in the cement column began to decrease shortly after the cement was pumped. The success of the cementing operation depended on the cement attaining sufficient strength to exclude pore fluids from the cement before the pressure somewhere in the cement column declined to pore pressure at that depth. Pressure in the cement generally appeared to decline to the pore pressure in adjacent formations after the cement had set. In one well, however, pressure in the cement opposite a "tight streak" steadily declined to far less than a water hydrostatic gradient as the cement set.

Fluid did not enter the wellbore and migrate to the surface soon after cementing in any of the wells investigated, but in one well fluid flow between zones behind the casing was indicated when the pressure in the cement decreased to pore pressure before the cement set. Before perforating was performed, annular flow was confirmed by a noise log in this well.

The pressure sensors allowed other observations to be made both during and after cementing, including the effects of annular pressure applied at the surface during curing of the cement, and communication behind the casing during perforating, acidizing, and squeeze cementing.

The temperature measurements in the annulus were used to monitor the setting of the cement, which is accompanied by evolution of heat. The cement generally set from the bottom of the wellbore toward the top.

These field data confirm laboratory data that show a pressure decline in a cement column as the cement cures. Conditions more likely to lead to annular fluid migration before the cement sets and steps that can be taken to decrease the likelihood of these occurrences can be identified from the field results. The pressure loss in a cement column before the cement cures is believed

frequently to be responsible for vertical fluid flow behind the casing. The acronym FILAP is suggested for the phenomenon of "flow induced by loss in annular pressure".

INTRODUCTION

The importance of achieving successful primary cementing of a well is hard to overemphasize. If there is a failure to seal the annulus outside the casing or liner, pressure may appear at the surface of the well from migrating gas (which is called "annular gas flow"), a liner top may leak, or fluids may flow between zones behind the casing in the well. Flow between zones can cause the loss of valuable hydrocarbons, the failure of stimulation treatments, and other problems. Cement repair operations are expensive, particularly in high-cost operating areas, and they are not always successful. Industry long has sought a reliable and practical primary means of sealing the annulus outside casing. Research is continuing on the solution to this very important problem.

Causes proposed in the past to explain failures in sealing an annulus with cement are (1) failure to displace the drilling fluid and fill the annulus with cement, (2) loss of pressure in the cement before it achieves strength, allowing fluid to enter the wellbore, and (3) failure of the cement/pipe bond.

We believe that Causes 1 and 2 are much more important than Cause 3. Cause 1, which was discussed recently by Haut and Crook,[1] was not the primary subject of the investigation reported here. This paper focuses on Cause 2, the loss of pressure in a cement column before the cement has set. In the past, Cause 2 was most often suggested to explain gas pressure observed at the surface of a casing annulus.[2-4] Vertical flow behind the casing below the surface was often ascribed to Cause 1 (lack of complete mud displacement), especially when the flow was to perforations in the casing.[1] In a recent paper on the subject of flow to liner tops, Davies et al.[5] examined both Causes 1 and 2 but did not discuss the relative importance of these causes.

Explanations of the loss of pressure in a cement column (Cause 2) have varied. Carter and Slagle[6] discussed early setting of the cement high in the well, dehydration of the cement across a permeable zone, bridging of particles from a formation or mud filter cake, and gelation of the cement before setting. Later work suggested that fluid-loss control to prevent dehydration of the cement is very important.[7] Recently, Tinsley et al.[3] and Davies et al.[5] suggested that the pressure decline in a cement column is caused by volume reduction of the cement combined with high gel strength. Tinsley et al.[3] and Levine et al.[2] suggested possible solutions to this problem of declining pressure in a cement column.

We believe that the recent theories[3,5] to explain loss of pressure in a cement column are essentially correct and have confirmed in our laboratory the observations that led to these theories. We also believe that factors that cannot be simulated adequately in the laboratory affect the behavior of a cement column thousands of feet in height. Therefore, we have developed techniques to measure annular pressures in wellbores. The only reference we found to annular pressure and temperature measurements during cementing was in the Russian literature.[8] These measurements were narrow in scope.

This paper reports the results of annular pressure and temperature measurements that are relevant to the loss of pressure in a cement column soon after cementing or that indicate the degree of mud displacement by cement. Measurements made during completion and workover operations also are included to show that pressure sensors outside the casing can be used to investigate these operations. To avoid excessive length in the paper, observations related to the loss of returns during cementing, temperatures during cementing, long-term pressures in a mud column, and other effects are discussed in a later publication.[9] Only five of the seven wells in which measurements were made are discussed in this paper.

EQUIPMENT AND PROCEDURES

Fig. 1 shows a schematic of the equipment used to obtain the measurements. The pressure and temperature sensors (shown outside the casing) are contained in a single unit. The sensors were attached to the production casing by special clamps. They extend 1-5/8 in. (4.13 cm) beyond the casing diameter. The logging cable, which was clamped to the casing, contained seven conductors. To attach each sensor to a conductor of the cable, the strands of metal armor were removed from a few inches of the cable. One of the conductors was identified and cut. This conductor was then stripped of insulation on the end and sealed into the top of the sensor. In some of the wells, a very small radioactive source was clamped under the sensor so that its depth could be logged.

The logging cable was stored on a spool and run through a sheave in the derrick. Centralizers were placed over each collar nearest a sensor and were fixed to the casing to prevent rotation.

Casing slips with a bowl containing a slot (to allow a cable or line to pass through) were used. Six sensors spaced at appropriate intervals were used in all the wells. The casing-running operation usually required 6 to 8 hours more than normal.

After the casing was on bottom, mud was circulated and conditioned for several hours before cementing operations began. The temperature of the mud at the suction line and at the return line was measured several times during mud circulation.

Table 1 gives the depth of the casing, the bit and casing sizes, the measured top of cement, and the spacer and cement slurry volumes used in each well discussed in this paper (five of the seven in which annular pressure and temperatures were measured). Table 2 provides information on the densities and classifications of the cement slurries used in each well. Various additives were used in the different wells. The chemistry of the cement slurries will not be discussed in detail, since there was no evidence that the chemistry or chemical properties of the cement slurries had a bearing on the conclusions reached from the physical measurements.

The minimum time interval between the measurements of pressure and temperature at each sensor was 2.5 minutes. This time interval was used for all measurements during a period of significant changes in pressure or temperature. When changes were occurring slowly, the time interval between measurements was increased to as much as 1 hour.

A few hours after cementing, when pressure and temperature were changing slowly, the cable to the sensors was cut at the surface and threaded back down through the blowout preventers (BOP's) and out a valved side outlet on Section A of the wellhead. The cable then was reattached to the surface recording unit, and measurements were continued.

RESULTS

Pressure and temperature changes during cementing are discussed for four wells. Also, pressure responses during the perforating, remedial cementing, or acidizing of three wells is described.

Well A - Annular Pressure and Temperature During Successful Cementing

Results of annular pressure and temperature measurements for Well A are shown in Fig. 2. Time zero was shortly after the last sensor was attached to the casing; results shown began shortly before cement pumping started.

Pressure: Just before cement was started into the well, the mud weight, calculated from the measured pressure at each sensor, varied from 10.0 to 10.3 lbm/gal (1198 to 1234 kg/m^3). This variation of $\pm 1.5\%$ indicates the combined accuracy of the sensors and their calculated depth in this well. Mud weight measured at the surface was 10.2 lbm/gal (1222 kg/m^3) in and 10.1 lbm/gal (1210 kg/m^3) out.

Eleven minutes after cement was started into the well, a pressure increase was noted at the deepest (No. 1) sensor. (The depths of the sensors are shown below the graphs.) This pressure increase was caused by the higher density cement displacing mud above the sensor. As cement, moving upward in the annulus, passed each sensor, pressure began increasing at that sensor. A slight pressure decrease just before the pressure began increasing at some of the sensors was probably caused by the 10-bbl (1.6m^3) water spacer that was pumped ahead of the cement.

It became apparent during the pumping of the cement that the top of the cement was rising faster than expected (because mud was being bypassed). After the cement had passed the top (No. 6) sensor, a decision was made to shut down the cement-pumping operation, because the pressure at the bottom sensor was nearing the breakdown or fracturing value. During shutdown, while the lines were being flushed of cement and the top plug was released [at 840 to 845 minutes (Fig. 2)], pressure decreased slowly or was constant at each sensor. The cement was then displaced, and the pressure increased at all sensors. The maximum pressure was observed at all sensors when pumping (displacement) was completed. The pressure at the bottom sensors declined very rapidly after pumping ended. This decline was much more rapid than during the shutdown to drop the top plug. Possibly, this rapid pressure decline at the bottom sensors was caused by partial loss of returns near the bottom of the well. (Lost returns in this well and in Well B are discussed in a Ref. 9.)

At 890 minutes, which was 24 minutes after pumping was completed, the annular BOP's were closed, and a pressure of 100 psi (689 kPa) was applied to the annulus at the surface. The purpose of this test was to determine whether annular surface pressure would increase pressure in the cement column, as suggested by Levine et al.[2] As can be seen in Fig. 2, none of the sensors detected this pressure increase. This showed that the cement had sufficient gel strength at this time to prevent transmission of this surface pressure even to the top sensor at 3,636 ft (1109 m), about 2,400 ft (732 m) below the top of cement.

The pressure measurements, in conjunction with the known densities of the cement and the mud, enabled the top of cement to be determined. Fig. 3 shows a graphical determination of the top of cement when cement-pumping ended. The maximum pressures at the sensors (measured when the top plug reached bottom) are plotted as points. A line with a slope corresponding to the fluid density of the cement is drawn through the points. A line with a slope corresponding to the density of the mud is drawn from zero depth. The top of cement, determined by the intersection of the two lines, was at approximately 1,200 ft (366 m). (This method was verified by using the same procedure and the pressures from the bottom five sensors to determine the top of cement when cement was passing the top sensor. The top of cement was correctly predicted to be at the top sensor.)

Comparison of the total volume of cement pumped into the well, the hole volume determined by caliper logs, and the top of cement predicted from the pressure measurements allowed a calculation of the volume of mud bypassed by cement. This volume was calculated to be slightly over 200 bbl (31.8 m^3), which was about the volume of the hole in excess of bit size. From this finding we conclude either that mud had not been displaced from the oversize portion of the hole, or that some mud had been displaced from the oversize portion but not from inside the gauge hole.

Since a mud weight of 10.2 lbm/gal (1222 kg/m^3) had prevented influx of fluid during the drilling operations, an equivalent mud weight (EMW) equal to or greater than this value would control influx of fluid after the cement was in place. [EMW is defined as pressure divided by (depth times 0.052), in units of lbm/gal.] The pressure at each sensor decreased with time after the cement was pumped, as shown in Fig. 2, but did not decrease to the mud pressure at any sensor for several hours. The times when this occurred at the sensors are shown in Fig. 2. Wellbore-temperature measurements, discussed later, indicated that the cement began to set before pressures in the cement fell to mud pressures (or later, to pore pressures). Although the strength of the cement at different times and the amount of strength necessary to prevent fluid influx cannot be described precisely, influx of formation fluid before the cement set probably did not occur in this well, because the cement was well advanced toward setting before pressures in the cement fell to mud or pore pressures.

Temperature: The lower portion of Fig. 2 shows the results of temperature measurements made over the same time interval as the pressure measurements. Temperatures at the sensors increased rapidly between two and three hours after cement pumping [1,000 to 1,050 minutes (Fig. 2)]. This is the time in which the tail slurry, which covered all the sensors, was setting, in agreement with the laboratory-predicted thickening time of three hours and three minutes. Temperatures increased above geothermal temperatures (noted at the right of the graph).

A temperature log was run in the well 12 hours after cementing. This log indicated a cement top at about 1,500 ft (458 m), in fair agreement with the top of cement predicted from the pressure measurements. A cement bond log run later indicated no bonding of cement above 2,000 ft (610 m). Therefore, the cement top predicted from the cement bond log was approximately 800 ft (244 m) deeper than that determined from the pressure measurements. It was concluded that the cement bond log did not indicate the top of cement reliably in this well.

Well B - Annular Surface Pressure Applied

Results of annular pressure and temperature measurements during the cementing of Well B are shown in Fig. 4. The depths of the sensors are shown on the curves.

Pressure: Before cement-pumping, the pressures at the sensors indicated a mud weight that varied from only 10.44 to 10.64 lbm/gal (1251 to 1275 kg/m^3), which accorded well with the expected value. During cement pumping, a pressure increase was noted at each of the bottom five sensors as spacer or cement passed that sensor. From the method illustrated in Fig. 3 and the pressures when pumping ended, the top of cement was estimated to be at 1,000 ft (305 m).

The pressure at the deepest sensor was about 500 psi (3,445 kPa) higher than expected when pumping was suspended to drop the top cement plug. This apparently was caused by a higher viscosity of the tail slurry, which was present above only the deepest sensor. During displacement of the top plug (beginning at 1,190 minutes), there was a complete loss of returns at the surface. This caused the pressure and temperature data during displacement to be abnormal.

The effects of annular pressure applied at the surface on pressures in the cement, which were investigated only briefly in Well A, were tested extensively in this well. Eleven times during the curing of the cement, annular pressure was applied at the surface. The times at which pressure was applied are shown by arrows on the abscissa of Fig. 4. The pressure chart for the sensor at 979 ft (298 m)(bottom pressure curve), which was above the cement, always showed an increase when surface pressure was increased. The first application of pressure (60 psi)(413 kPa) at 1,243 minutes caused all sensors except the one at 7,412 ft (3359 m) to respond. This indicates that the gel strength of the cement between the sensor at 7,412 ft (2559 m) and the sensor at 5,454 ft (1662 m) was higher than the gel strength above the higher sensors. [In accord with this indication, the tail slurry, which covered only the sensor at 7,412 ft (2559 m), set much earlier than the other two slurries, as discussed later.] A surface pressure of 60 to 100 psi (413 to 689 kPa) did not cause the sensors below 2,904 ft (885 m) to respond at 1,740 and 1,875 minutes. This indicates that the gel strength of the cement was increasing higher in the wellbore at later times.

At 2,100 minutes, surface pressure was increased from 200 psi (1378 kPa) to 570 psi (3927 kPa) and the pressure at 5,454 ft (1662 m) and 4,430 ft (1350 m) suddenly increased by more than 1,000 psi (6895 kPa). The gelled cement above these sensors moved; this movement allowed the downhole pressure in the cement to increase. At the same time, pressure at the surface declined, as will be seen later. When the final application of surface pressure was made, at around 2,300 minutes, a pressure increase was detected only in the mud [at 979 ft (298 m)].

Fig. 5 shows the surface pressure on the annulus during and after the several times that fluid was pumped in at the rate of 0.25 bbl/min (0.04 m^3/min). At the later times, pressure increased more rapidly, and higher pressure could be applied at the surface before a sudden decrease in surface pressure occurred. This higher pressure was possible because the gel strength of the cement was increasing upward in the wellbore and the cement column was more resistant to movement. Note that the surface pressure quickly dropped from 570 psi (3927 kPa) to about 220 psi (1516 kPa) when the downhole cement pressure increased at 2,100 minutes.

The important implication of these results is that pressure at the surface did not increase pressures downhole until the cement column was moved. Fluid movement in the annulus was indicated by sudden pressure declines at the surface.

Temperature: Fig. 4 shows temperature measurements made over the same interval of time as pressure measurements. Temperature data showed that the tail cement around the sensor at 7,412 ft (2259 m) began setting at around 400 minutes after pumping. (This compares to a laboratory-measured thickening time of 205 minutes.) Setting of the lead and filler slurries did not occur until much later than the times shown in the figure. For example, setting of the lead slurry at 2,232 ft (680 m) began at about 3,800 minutes. This degree of retardation of the lead and filler slurries was not expected; however, it explains why surface pressure was transmitted downhole for much longer times after the cement was pumped into this well, compared with Well A.

A temperature log was run in the well during the time that only the tail cement slurry had begun to set. The log indicated the top of the tail slurry to be at the depth calculated volumetrically. A cement bond log was run a few days later. The top of cement measured by pressure data agreed with that indicated by the cement bond log in this well.

After the cement had cured, measured pressures at the bottom four sensors, which were below the surface casing, stabilized near the pore pressure expected at each sensor. The pressure at 3,343 ft (680 m)[35 ft (11 m) above the shoe of the surface casing] declined to an EMW of 7.9 lbm/gal (946 kg/m^3) and then slowly increased to 8.4 lbm/gal (1006 kg/m^3).

Well D - Flow Behind Casing Before Perforating, During Completion

Fig. 6 shows a segment of the SP curve from Well D, the pressure and contents of some of the sands (from wireline tests), the placement of the three lower sensors, and the placement of perforations during completion. Note the high-pressure gas zone at 6,820 ft (2079 m) and the low-pressure gas zone at 6,690 ft (2039 m). Fig. 7 shows the annular pressure and temperature results for this well during cementing.

Pressure: Pressures when pumping was completed indicated that the top of cement was about 4,700 ft (1433 m). The caliper log indicated that the volume of the enlarged portion of the hole below this depth was 56 bbl (8.9 m^3). Volume calculations indicated that 41 bbl (6.5 m^3) of mud had been bypassed by the cement. (No cased-hole logs were run.)

The highest pore pressure measured in the well (by wireline test) was 3,470 psi (23 908 kPa) in the sand at 6,820 ft (2079 m)(Fig. 6). Note in Fig. 7 that the pressures at 6,659 ft (2030 m) and 6,585 ft (2007 m) fell to a value very near this pressure at around 1,600 minutes and remained at this pressure for the duration of the measurements. This pressure was reached before the cement began to set at these depths, as determined from the temperature data. The pressure decline to pore pressure is indicative of gas entering the wellbore at about 1,600 minutes. Gas entered the wellbore because pressure in the cement decreased to pore pressure in a gas zone before the cement had set.

Pressure at 6,885 ft (2099 m), about 60 ft (18 m) below the high-pressure gas zone (Fig. 6), also decreased at a rate approximately paralleling the rate of decline for the two sensors above. The hydrostatic head of the cement between the gas zone at 6,820 ft (2079 m) and at 6,885 ft (2099 m) accounts for the higher pressure at the lower sensor. The gas intering the wellbore from the zone at 6820 ft (2079 m) was apparently leaving the wellbore and entering one or more of the zones below the sensor at 5,969 ft (1819 m), because the pressure at this sensor demonstrated normal pressure decline and therefore no apparent communication with the high pressure zone.

Fortunately, a noise log was run in the well in the period from about 1,400 to 1,580 minutes, before the cement had begun to set. The noise level at a frequency of 2,000 cycles/s (Hz) varied from 15 to 30 mV over the interval from maximum depth [6,930 ft (2082 m)] up to 6,550 ft (1896 m); it then dropped off above 6,500 ft (1981 m). This indicated flow behind the casing in the interval from the high-pressure sand at 6,820 ft (2079 m) up to the lower-pressure sands (Fig. 6). The noise log showed that fluid had entered the wellbore before the cement set; it therefore confirmed the interpretation of the pressure measurements.

Temperature: The temperature rise during the setting of the cement was large in this well (Fig. 7). Setting began at the bottom sensor at about 1,500 minutes and at the two next higher sensors at about 1,900 minutes. About a 40°F (22°C) temperature increase was noted at the bottom four sensors when the cement set. The cement set from the bottom upward. The geothermal temperature at each of the sensors is shown on the right side of the graph. The rapid evolution of heat, indicating final set, did not begin until about 22 hours after mixing. The laboratory-measured thickening time was 4.5 hours.

Completion: The upper right-hand portion of Fig. 7 shows the pressure changes when the well was perforated in the 6,611- to 6,619- ft (2015- to 2017- m) interval (Fig. 6). Pressure at the sensors was constant before the well was perforated (underbalanced). Immediate pressure decreases were observed at 6,659 and 6,595 ft (2040 and 2007 m) after the well was perforated [i.e., 40 ft (12 m) below the bottom of the perforations and 26 ft (8 m) above the top of the perforations]. The sensors showed that pressure communication existed over these distances. The other pressure sensors, farther from the perforations, did not respond when the well was perforated.

Well E - Remedial Cementing

Fig. 8 shows the pressure response at 6,493 ft (1979 m), [49 ft (15 m) above perforations] during remedial cementing operations on Well E. A noise log had shown that flow behind the casing was occurring. The well was first perforated with a tubing gun, and water could be pumped in only at a very low rate at 2,000 psi (13 780 kPa). The well was reperforated with a casing gun, and water could then be pumped at 0.25 bbl/min (0.04 m^3/min) at 2,000 psi (13 780 kPa). The pressure response before the well was reperforated showed that pressure communication existed to the sensor above at that time, although fluid injection rates were very low.

Measurements were discontinued on the first day and resumed again the next day (right-hand side of graph). Again water was injected preparatory to injecting cement. Both the injection of water and that of cement caused a pressure response at the sensor above. A squeeze pressure of 1,800 psi (12 400 kPa) was applied at the surface, but the pressure increase at the sensor was much less. Pressure at the sensor began declining before the squeeze pressure was released and continued to decline after the release of the surface pressure.

These data demonstrate some of the mechanics of remedial cementing that can be studied with pressure sensors in the annulus. The data are not complete enough, however, to draw conclusions regarding remedial cementing.

Well G - Low Pressure in Cement Column, Communication During Acidizing

Fig. 9 shows annular pressures and temperatures in Well G. The production casing was set in a dense barrier between an abnormally pressured (by water flooding) lower porous zone and a normally pressured upper porous zone, both in carbonate. The casing was cemented to the surface.

Pressure: Pressure responses were about as expected during most of the cement-pumping time, but pressure increased more rapidly than expected near the end of this time. The EMW increased to about 14.5 lbm/gal (1737 kg/m^3) at all sensors. A rapid decline in pressure at all sensors when pumping stopped indicated that the EMW had been increased by viscous pressure drop in the annulus. After this rapid decline, pressure continued a slower decline at the sensors.

A point of particular interest is the pressure at 1,900 ft, which dropped steadily to about 250 psi (1723 kPa), or an EMW of 2.5 lbm/gal (300 kg/m^3). This sensor was in a dense anhydrite section. We believe that this very low pressure in the cement was caused by the nonavailability of fluid from the nonporous rock to compensate for the volume reduction during hydration of the cement at that level in the wellbore. Since fluid was not supplied from the rock and the gel strength of the cement column prevented its movement downward to compensate for the lower pressure, very low pressures were possible.

In contrast, the sensor at 2,900 ft (884 m) was opposite a sand formation that, in some areas of the field, can be pressured to about 10 lbm/gal (1120 kg/m^3). The EMW at this sensor approached 10 lbm/gal (1120 kg/m^3) during cement curing. The gradients at the other sensors approached normal values [8 to 9 lbm/gal (958 to 1078 kg/m^3)] - i.e., expected pore pressures.

The results indicate that pressures in cement approach pore pressures when sensors are opposite nonporous zones. (Of course, pressure would likewise be expected to decrease to low values in an annulus between pipe, for the reasons outlined above, if no fluid flowed between the pipe and the cement.)

Temperature: The temperature data (bottom of Fig. 9) showed that the cement began generating heat at very near the same time (within 10 minutes) at the bottom three sensors. This occurred at about 2 hours after mixing, which is near the measured thickening time of 2.5 hours. These sensors were in the tail slurry. Heat generation began about an hour later at the sensors at 2,900 and 1,900 ft (884 and 571 m), which were in the lead slurry. The data showed that the designed difference in thickening times of the two slurries successfully achieved setting of the cement in two stages from the bottom upward.

Pressure Response During Acidizing: The shoe of the casing of Well G was cemented in a dense zone, and then about 20 ft (6 m) of open hole was drilled below the casing shoe to test deeper porous zones for production. To test these deeper zones in open hole, an acidizing treatment was performed. Hydrochloric acid (15%) was pumped at an initial surface pressure of 1,500 psi (10 680 kPa). Fig. 10 shows the surface pressure during the pumping of the acid over a period of about 33 minutes and the pressure response at the sensors behind the casing. Note that the sensor at 4,432 ft (1351 m), 76 ft (23 m) above the casing shoe, showed a pressure increase beginning about 30 minutes after acid pumping started. This pressure response was likely caused by a hydraulic fracture, since the acid was injected at above the estimated fracturing pressure. The sensor at 4,326 ft (1319 m), 178 ft (54 m) above the casing shoe, did not respond at any time. The sensors showed that pressure communication across the nonporous barrier between the lower and upper zones definitely existed during acidizing.

DISCUSSION

Flow Induced by Loss in Annular Pressure (FILAP)

The wellbore pressure measurements indicate that the pressure drop in a cement column after the cement is in place is generally caused by a combination of volume reduction and gel-strength development in the cement. The volume reduction can have two causes: fluid loss from the slurry and reduction of volume from the hydration chemical reaction. There is evidence in the results from Well B, for example, that in the time interval from 1,340 to 1,400 minutes, the pressure dropped more quickly at the sensors at 5,454 and 4,430 ft (1662 and 1350 m), which were opposite permeable zones. This indicates that fluid loss made a significant contribution to the total volume reduction in the cement in this well. The very low pressure at one sensor in Well G, however, was caused only by the volume reduction accompanying chemical hydration, since fluid loss was not occurring at this sensor. Either or both volume reduction mechanisms can cause a pressure decrease in the cement. The fact that it was necessary to move the cement column to restore pressure in the column (Well B) illustrates the role of gel strength. Higher gel strength made column movement more difficult.

We propose that the term "FILAP" be used to denote the annular flow of fluid after pressure loss in a cement column caused by volume reduction and gel strength of the cement. A term other than annular gas flow is needed to describe this phenomenon. The term annular gas flow should be reserved for instances of pressure at the surface caused by gas migration upward in the wellbore. This is a special type of FILAP. But the fluid flowing in an annulus may also be oil or water, and the flow may not cause pressure at the surface. Therefore, a more general term than annular gas flow is needed.

FILAP vs. Mud Displacement

We can only speculate as to the number of instances of fluid flow behind the casing that are caused by pressure loss in the cement before it cures, compared with the number that are caused by lack of mud displacement. The number caused by pressure loss may be considerably larger than has been recognized. Well D provides support for this statement, since there was no evidence other than the sensor data to show that annular flow was caused by a pressure loss in the cement. But displacement of mud by cement is important, too. Results from several wells showed that significant amounts of mud were bypassed below the top of cement. Later displacement of this bypassed mud, when high vertical pressure gradients exist in a well, can also lead to fluid flow behind the casing. Displacement of the mud by cement should always be beneficial, regardless of the occurrence of pressure loss in cement.

It seems reasonable that FILAP would contribute to cement failure more often in wells when gas flows to the surface within one day after cementing. (i.e., when annular gas flow occurs), fluid flows to a liner top a short time after cementing, or flow occurs behind the casing of a liner where the pipe is not perforated (as in Well D). Lack of mud displacment by the cement would be expected to contribute more often to instances of flow of unwanted fluids from a zone behind the casing to perforations, or to failure of a casing seat or liner top to test at high pressure. Of course, if FILAP occurs shortly after cementing, the resulting channel also could lead to flow to perforations formed later. The mechanism of failure, in this instance, could not be determined unless pressure sensors were used or production logs were run before perforating.

Conditions Conducive to FILAP

Conditions that increase the chance of cement failures because of the pressure-reduction mechanism are believed to be: (1) high pore pressure (any fluid)(a smaller reduction of pressure in the cement will then allow fluid to enter the wellbore), (2) large differences in pore pressure in permeable zones nearby (fluid loss in the pressure-depleted zones will decrease pressure and allow higher pressure fluids to enter), (3) high fluid loss from the cement, (4) long cement columns and high gel strength in the cement before curing, which will decrease the likelihood that the column will move to compensate for volume reduction, and (5) a long period of time before the cement develops strength, which will increase the likelihood of fluid loss causing cement pressure to fall to pore pressure before curing.

The same procedures used to minimize the number of occurrences of annular gas flow should also minimize other types of FILAP.

Practical Steps to Minimize FILAP

Levine et al.[2] listed several procedures that have been used to minimize occurrences of annular gas flow. General guidelines to prevent FILAP are as follows.

1. Maximize the pressure in the cement column when pumping is completed, to the extent allowed by fracture gradients in the surrounding rock.
2. Minimize fluid loss from the cement (a low permeability mud filter cake will help in this regard).
3. Avoid overretardation of cement (long times to cure allowed more pressure reduction in Wells B and D).
4. Pump in fluid at the surface when the fracture gradients in the surrounding rock allow it.
5. Use the shortest cement column that is adequate.
6. Stage the thickening time of the cement if long columns are used.

Guidelines 5 and 6 will be useful only to the degree that movement of the cement column is assisted by these conditions. Since pressure in the cement was not observed to stabilze at the hydrostatic pressure of water, we see no evidence that adding salt to increase density of the mix water could minimize the chances of annular flow, as has been suggested in the past. Higher compressibility of the cement (as from gas bubbles) would tend to decrease the pressure decline. Detailed analysis of the pressure decline for different values of fluid-loss and hydration volume decreases would be necessary to determine the effects of gas on the pressure reduction.

Future Research Needed

More data on annular pressures and temperatures during primary cementing under a wide range of conditions would be useful, of course. It is apparent from the measurements taken at Wells D, E, and G during completion, and from remedial cementing and acidizing that various other processes can be studied using external casing sensors.

The strength of cement necessary to prevent fluid from entering a wellbore is undefined. The failure mechanism of the cement that allows fluid to enter also is not defined. We have assumed here that if the cement is evolving heat at a high rate, it has developed sufficient strength to prevent fluid entry, and we have no field data to indicate that that assumption is not correct. But very careful investigation will be necessary to determine the required properties of the cement and the time at which a particular cement slurry wil provide a seal in a given wellbore condition.

Conclusions

From the investigations discussed in the paper, the following conclusions were made.

1. Pressure and temperature sensors in the annulus can furnish a large amount of information on the physical phenomena occurring during primary cementing.

2. Pressure in a cement column in a well normally begins to decline shortly after the pumping of the cement is completed. The pressure decline can be explained in terms of a volume reduction of the cement accompanied by sufficient gel strength of the cement to prevent downward movement of the column.

3. The effectiveness of applied surface pressure to prevent the pressure decline in cement depends on the rate at which the gel strength of the cement develops. Surface pressure can compensate for the volume reduction, but fluid must be pumped in for the technique to be effective. This means that a surface pressure sufficient to break the gel strength of the cement column must be applied. Whether this is possible depends on pressure limitations in the well and the degree of gel strength development in the cement.

4. Annular pressure measurements indicate fluid entering the wellbore when the cement pressure drops to pore pressure in a zone and stabilizes at this value before the cement sets. Sensors above the point of fluid entry can establish a limit on the extent of vertical movement of the fluid that has entered the wellbore.

5. Pressure sensors can detect fluid communication in the annulus when the well is perforated, squeeze cemented, or acidized and can be used to investigate completion or workover operations in the well.

6. The top of cement at the completion of pumping can be estimated from pressure data. This value may not agree with the top of cement indicated by a cement bond log.

7. The volume of mud bypassed by the cement can approximate the volume of the hole in excess of bit size.

8. The time of the final setting of the cement at different depths in a well can be detected by annular temperature measurements.

9. Cement generally sets from the bottom of the wellbore upward, because of the higher temperatures at lower depths or because of the shorter thickening times of tail slurries.

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SI METRIC CONVERSION FACTORS

ft	X 3.048*	E-01	= m
°F	(°F-32)/1.8		= °C
gal	X 3.785 412	E-03	= m^3
lbm	X 4.535 924	E-01	= kg
psi	X 6.894 757	E+00	= kPa

*Conversion factor is exact.

Table 1
Description of Wells and Cementing

Well	Cased Depth (ft)	Cased Depth (m)	Bit Size (in.)	Bit Size (cm)	Casing Size (in.)	Casing Size (cm)	Top of Cement (ft)	Top of Cement (m)	Spacer Volume (bbl)	Spacer Volume (m^3)	Slurry	Volume (bbl)	Volume (m^3)
A	8,900	2712	7-7/8	20.0	2-7/8	7.3	1,200	366	10	1.6	lead	89	14.1
											tail	302	47.8
B	7,580	2310	7-7/8	20.0	2-7/8	7.3	1,000	305	25	4.0	lead	200	31.8
											filler	60	9.5
											tail	100	15.9
D	7,030	2142	7-7/8	20.0	2-7/8	7.3	4,600	1402	25	4.0		140	22.2
E	6,710	2045	8-3/4	22.2	5-1/2	14.0	5,000	1524	30	4.8		75	11.9
G	4,505	1386	8-3/4	22.2	5-1/2	14.0	0	0	120	19.1	lead	367	58.3
											tail	80	12.7

Table 2
Cement Properties

Well	Slurry	Density (lbm/gal)	Density (kg/m^3)	Classification
A	lead	16.6	1983	H(+sand)
	tail	16.6	1983	H(+sand)
B	lead	14.0	1673	(TLW)
	filler	16.6	1983	H(+sand)
	tail	16.6	1983	H(+sand)
D		16.6	1983	H(+sand)
E		13.5	1613	H(+extenders)
G	lead	13.4	1601	C(+extenders)
	tail	15.0	1793	H

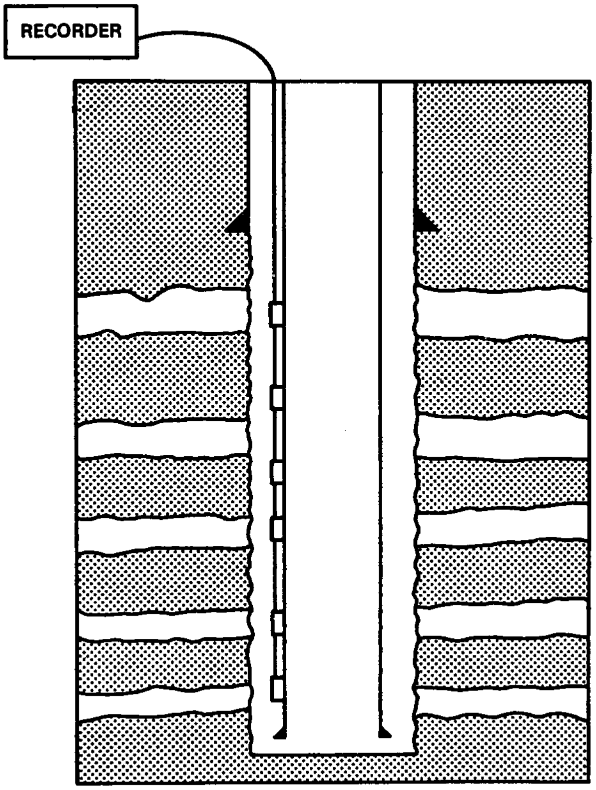

Figure 1 - Wellbore with sensors on casing

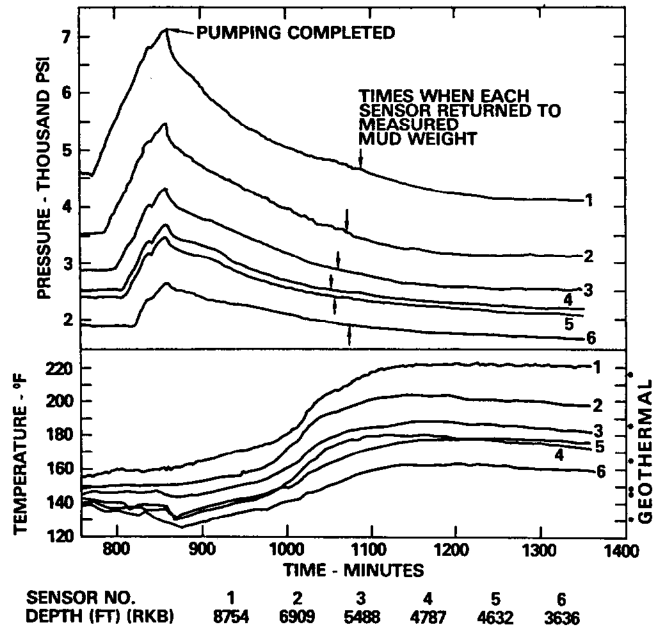

Figure 2 - Annular pressure and temperature - Well A

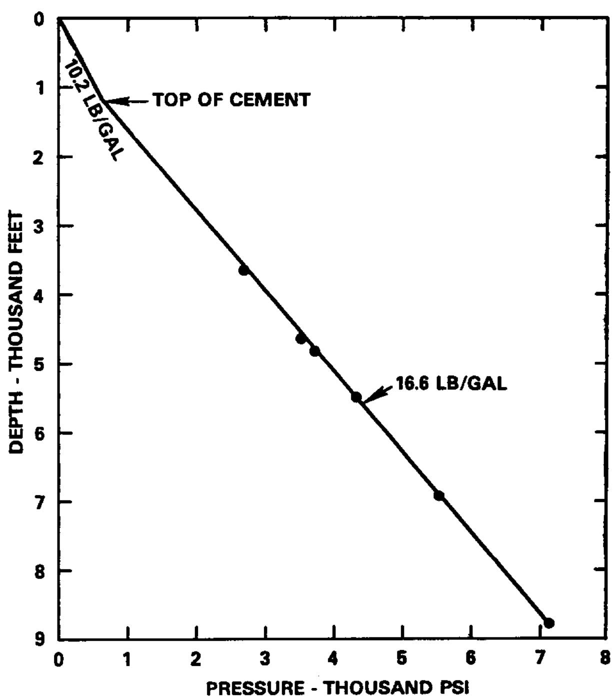

Figure 3 - Pressure vs. depth when cement pumping ended - Well A

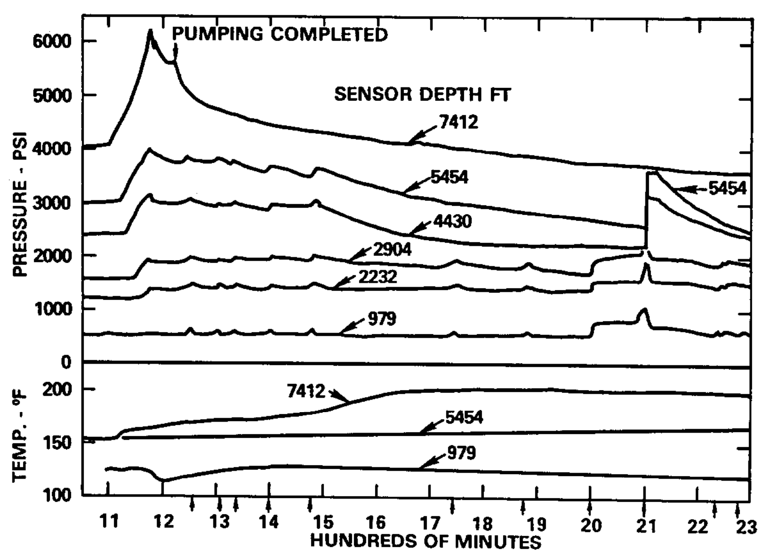

Figure 4 - Annular pressure and temperature - Well B

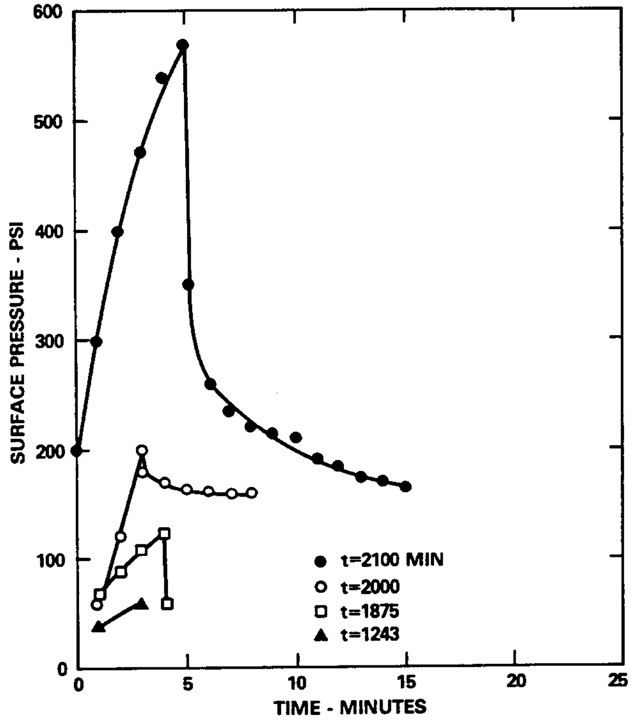

Figure 5 - Surface pressure on annulus during and after times that fluid was pumped in - Well B

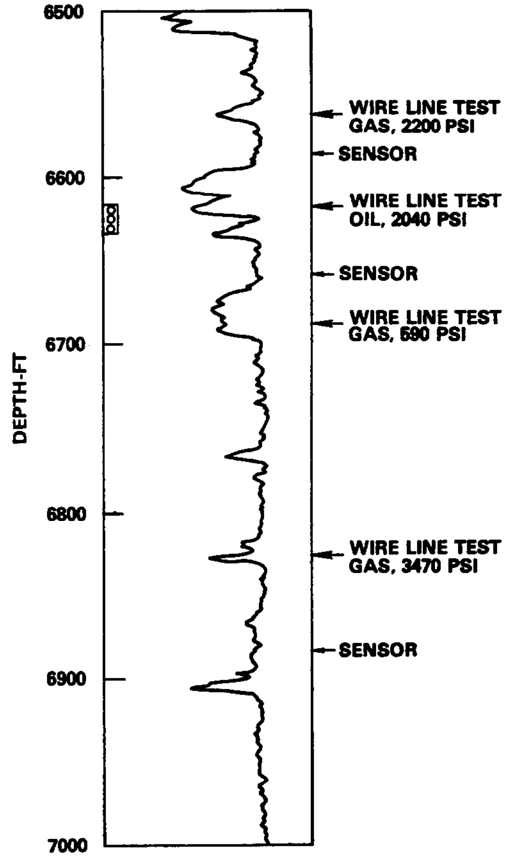

Figure 6 - Log, pore pressures, perforations, and sensor locations - Well D

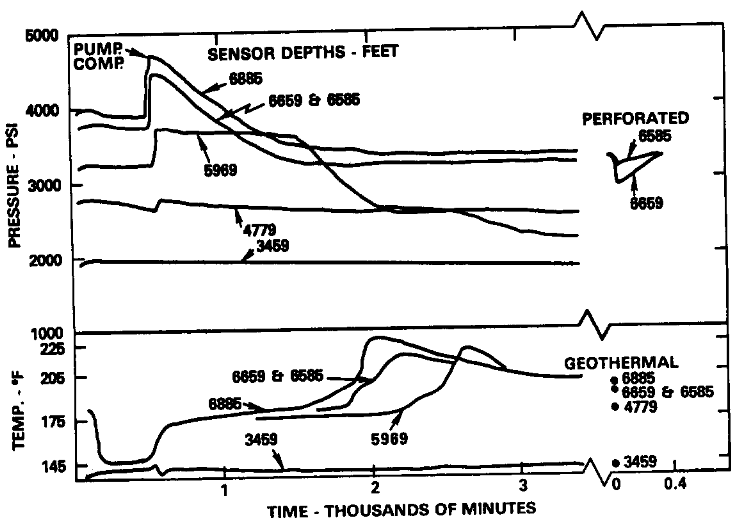

Figure 7 - Annular pressure and temperature - Well D

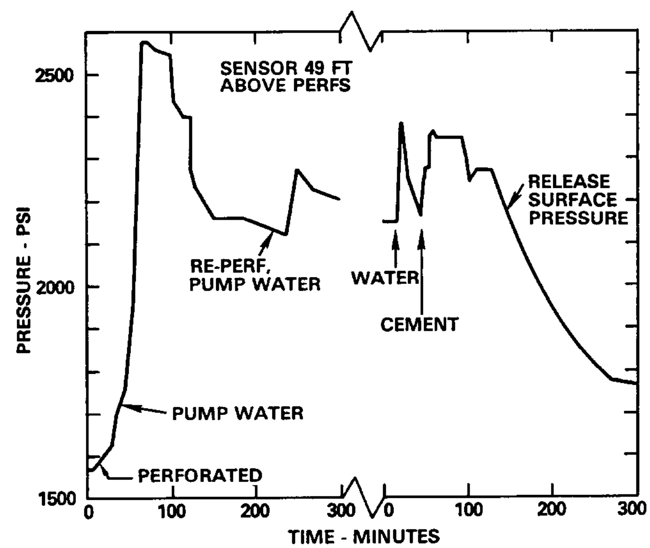

Figure 8 - Pressure response during remedial cementing - Well E

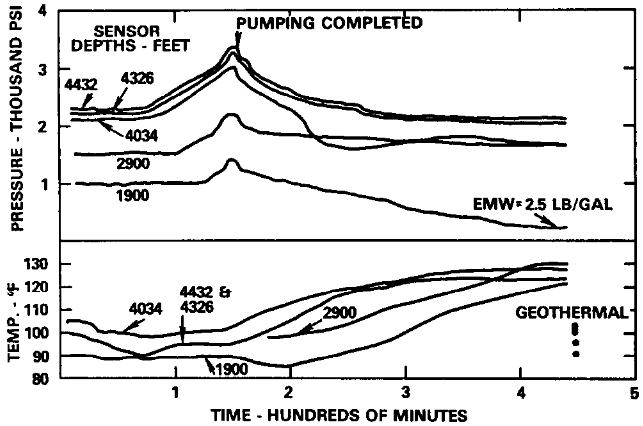

Figure 9 - Annular pressure and temperature - Well G

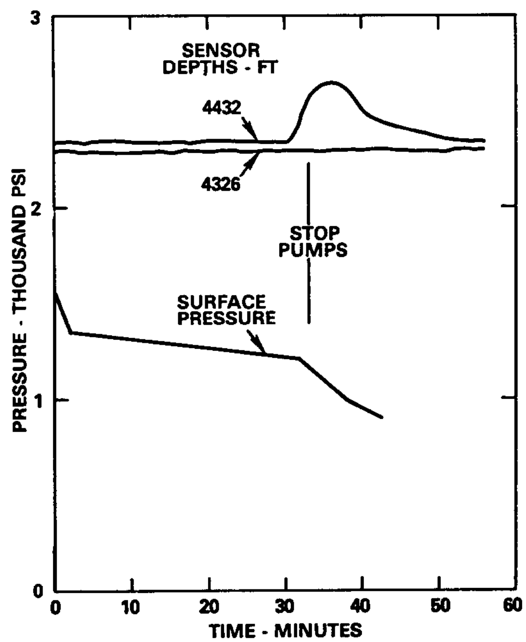

Figure 10 - Pressure response during acidizing - Well G