C..ER 52 (Revised), EFFECTIVE ____ #90

Casing Tests for All Fields

Lea County, New Mexico

The surface casing string shall be tested after drilling plug by bailing the hole dry. The hole shall remain dry for one hour to constitute satisfactory proof of a water shut-off. The surface casing shall stand cemented for 16 hours before releasing pressure and at least 24 hours before drilling plug. The conductor string of one to three joints need not be tested after cementing.

The intermediate string shall stand cemented 24 hours before releasing pressure and not less than 30 hours before testing pipe and cement. Tests of pipe and cement shall consist of building up a pressure of 1,000 pounds, closing valves, and allowing to stand 30 minutes. If the pressure does not drop more than 100 pounds during that period, the test shall be considered satisfactory. This test shall be made both before and after drilling plug.

The production string shall stand cemented 24 hours before releasing pressure and not less than 30 hours before testing casing. This test shall be made by building up a pressure of 1,000 pounds, closing valves, and allowing to stand 30 minutes. If the pressure does not drop more than 100 pounds during that period, the test shall be considered satisfactory.

By the term "releasing pressure" is meant any step or operation which would relieve any pressure at the base of or outside of the casing string being cemented.

All cementing shall be done by the pump and plug method, except that this method shall be optional for a conductor of one to three joints.

Bailing tests may be used on all casing and cement tests and drill stem tests may be used on cement tests, in lieu of pressure tests. In making bailing tests, the well shall be bailed dry and remain approximately dry for 30 minutes.

If any string of casing fails while being tested by pressure or by bailing tests herein required, it shall be recemented and retested, or an additional string of casing shall be run and cemented. If an additional string is used, the same tests shall be made as outlined for the original string. In submitting Form C-101, "Notice of Intention to Drill", the number of sacks of cement to be used on each string of casing shall be stated.

AMERICAN INSTITUTE OF MINING AND METALLURGICAL ENGINEERS
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DISCUSSION OF THIS PAPER IS INVITED. Discussion in writing (2 copies) may be sent to the Secretary, American Institute of Mining and Metallurgical Engineers, 29 West 39th Street, New York 18, N. Y. Unless special arrangement is made, discussion of this paper will close March 30, 1946. Any discussion offered thereafter should preferably be in the form of a new paper.

# Method for Determining Minimum Waiting-on-cement Time

BY R. FLOYD FARRIS*

(Local Fall Meetings, October 1945)

ABSTRACT

A method is presented for determining minimum waiting-on-cement time, which takes into account the differences that exist between types and brands of cements and such individual well conditions as depth, temperature, and pressure.

The basis for the method was determined by laboratory tests. Being a laboratory development, several steps were required to prove its merit. The first step consisted of laboratory tests designed to determine the minimum cement strength required in wells. Basis was found for setting a minimum value of 8 lb. per sq. in. tensile strength. Next, it was shown by laboratory tests that the time to 8 lb. per sq. in. tensile strength may be expressed as a function of consistometer stirring time to 100 "poises," the approximate relation being "the time to 8 lb. per sq. in. tensile strength equals the time to 100 'poises' times three." Next, it was shown that the time of maximum temperature development in cement slurries, due to heat of hydration, is also related to consistometer stirring time to 100 poises, but only by a factor of approximately two. It was shown also that the shut-in casing pressure will build up after cement is placed and register a maximum pressure at approximately the same time the slurry down the hole attains maximum temperature. From this and the relationships listed above, the general rule was established that minimum waiting-on-cement time (time to 8 lb. per sq. in.) after casing cement jobs in any well is equal to the time when the shut-in casing pressure reaches a maximum, as measured from the initial mixing of cement, times a factor of 1.5.

Cement plugs drilled in the field at the time prescribed by this formula were found to drill "firm to hard," thus confirming the laboratory tests.

These tests prove that many of the present regulations for waiting on cement require a longer time than is absolutely necessary. Use of the method herein proposed offers the possibility of a saving of $1200 per well.

## INTRODUCTION

The length of time allowed for cement to set after casing is determined either by state-wide rules, field rules, or self-imposed rules written into drilling contracts. In general, the time is dictated by experience and common practice. However, owing to differences in opinion and in experience of the various groups involved, waiting-on-cement time often varies from one area to the next. For example, an operator in an area where no rules exist may drill out of surface pipe at 24 to 36 hr., while another operator in another area may wait 48 hr. or more to comply with state or field rules, although the depth of the well, hole size, type of cement, and other data are identical. An even greater difference in practices will be found by making similar comparisons with respect to oil-string cement jobs. Differences in waiting-on-cement times of 36 to 48 hr. are common.

Further complicating the picture is the rather common practice of allowing more waiting time for cement to set at the greater depths than is allowed at the shallow depths. This practice has existed for years in spite of the common knowledge[1,2,3] that the temperature of the earth at the usual setting depths of surface

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[1] References are at the end of the paper.


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casing is much less than that at the depths at which oil strings are set, and that increased temperature greatly accelerates the rate of setting and hardening of cement.

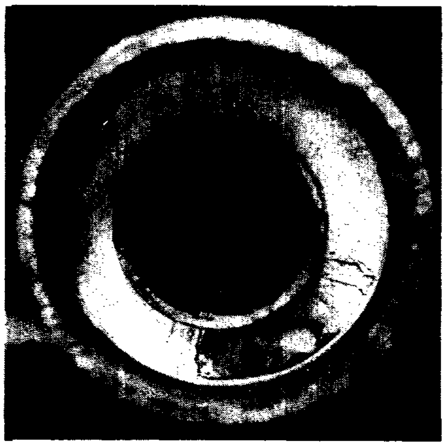

FIG. 1.—CEMENT IN ANNULUS.
End view of 5½-in. o.d. casing inside 9⅝-in. o.d. casing.

The foregoing thoughts suggest lack of a fundamental basis for determining waiting-on-cement time.

The minimum strength cement must develop in a well before it will secure pipe in the hole, exclude undesirable well fluids, and withstand the shock of drilling, and how long cement must stand before it attains that minimum strength, are questions often discussed but never completely answered. The industry has operated to the present time without the answers to these questions, simply by allowing long waiting periods for the cement to set. Thus, since experience has taught that waiting periods ranging from 36 to 72 hr. would give satisfactory results, these periods have become standard practice in many areas; however, it is easy to understand how a practice derived in this manner might include more time than is absolutely necessary.

Experiments conducted in the Stanolind Oil and Gas Co. Research Laboratory suggested that cement in wells may set and gain adequate strength in much less time than normally is allowed for that purpose. This finding led to the development of a simple method for determining the minimum waiting-on-cement time, which will apply to any well condition. The purpose of this paper is to describe the laboratory and field tests that contributed to the development of this method.

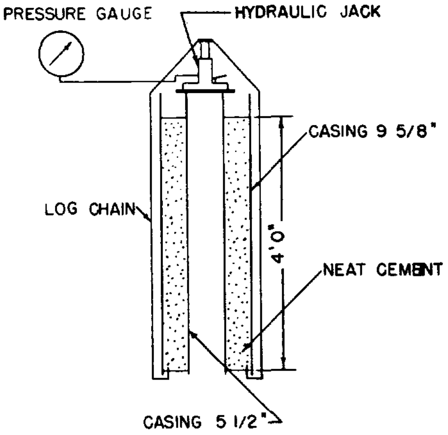


FIG. 2.—APPARATUS FOR MEASURING BONDING STRENGTH OF CEMENT IN ANNULUS.

## BASIS OF METHOD

The expression "waiting-on-cement time," hereinafter referred to as WOC time, simply means the time spent in waiting for the cement to set and gain a given minimum strength. Thus, any logical system for determining WOC time must be based on minimum requirements for cement strength used in wells. Once this has been established, the time to that strength can be reasonably accurately determined.

To obtain information as to what strength cement should develop in wells before it is drilled out, laboratory tests were conducted in which a correlation was made between cement tensile strength and the bonding strength of cement in an annulus. The apparatus consisted of seven pieces of 9⅝-in. o.d. pipe 5 ft. long, into which were centered similar lengths of 5½-in. o.d. pipe. Standard portland cement slurry weighing 15.6 lb. per gal. was poured into the annulus of each unit to a height of 4 ft. Some of the same slurry was placed in briquette molds for tensile-strength tests; also, cement slurry was placed in Vicat molds for determination of initial and final set. The cement was cured at atmospheric temperature, approximately 90°F. An end view of the cement in the annulus between the two sizes of pipe is shown in Fig 1.

The bonding strength of the cement in the annulus was determined by measuring the force that must be applied to the 5½-in. pipe to break the cement bond and move it with respect to the outside (9⅝-in.) pipe. The means of doing this is illustrated by Fig. 2. Each time the bonding strength of cement in the annulus was tested, observations were made of the corresponding cement strength and the progress toward the initial and final set. Table 1 presents a summary of the test results.

TABLE 1.—*Cement Bonding Strength*

| Cement Age, Hr. | Force to Break Bond of 4 Ft. of Cement, Lb. | Cement Tensile Strength, Lb. per Sq. In. | Remarks |
|---|---|---|---|
| 1.83 | 400 | 0 | Soft cement slurry |
| 2.33 | 550 | 0 | Soft cement slurry |
| 3.08 | 1,300 | 0 | Initial set |
| 3.66 | 4,000 | 4 est. | Cement stiffening rapidly |
| 4.42 | 18,200 | 8 est. | Final set |
| 5.50 | 20,000+ | 12 | Could not break bond |
| 6.50 | 20,000+ | 20 | Could not break bond |

The rate of increase in cement bonding strength is better demonstrated when these data are plotted on a graph. Fig. 3 shows that cement has an enormous bonding strength at its final set.

Table 2 shows the calculated load each foot of cement in an annulus will support at various cement strengths, together with the length of various pipes of equivalent weight.

Returning to the question of how much strength cement should develop in a well before it is drilled out, one can reason that it would not be safe to drill out cement before it reaches the initial set, even though the data in Table 2 indicate that the slurry may support the pipe, because it is not until after the initial set that the slurry passes from the fluid state into that of a solid. In fact, solidification of cement may not be called complete until it has reached the final set. Therefore, since drilling inside of casing before the cement on the outside reaches its final set could possibly reduce it to the fluid or semifluid state, it is obvious that cement should not be drilled out before it reaches the final set, which corresponds to a tensile strength of approximately 8 lb. per sq. inch.

TABLE 2.—*Strength of Cement*

| Cement Age, Hr. | Force to Break 1 Ft. Cement Bond, Lb. | Cement Tensile Strength, Lb. per Sq. In. | Length of Pipe 1 Ft. of Cement Will Support, Ft. | | |
|---|---|---|---|---|---|
| | | | 5½ In., 17 Lb. | 7 In., 24 Lb. | 13⅜ In., 72 Lb. |
| 1.83 | 100 | 0 | 5.8 | 4.1 | 1.3 |
| 2.33 | 137 | 0 | 8.0 | 5.7 | 1.9 |
| 3.08 | 325 | 0 (initial set) | 19.1 | 13.5 | 4.5 |
| 3.66 | 1,000 | 4 est. | 58.8 | 41.6 | 13.8 |
| 4.42 | 4,550 | 8 est. (final set) | 267.5 | 189.6 | 63.1 |
| 5.50 | 5,000+ | 12 | | | |
| 6.50 | 5,000+ | 20 | | | |

If cement should not be drilled out before it attains a tensile strength of 8 lb. per sq. in., the next question is: Would it be safe to drill it out at a tensile strength of 8 lb. per sq. in.? The foregoing data strongly suggest that it would be safe to drill out cement at that strength. At a strength of 8 lb. per sq. in., for example, Table 2 indicates that each foot of cement in the annulus should support 267 ft. of 5½-in. o.d. 17-lb. pipe, and Fig. 3 shows that the rate of bonding-strength development is extremely rapid at that point and probably reaches even greater proportions shortly after that time. These considerations, together with the general feeling that "green" cement may be drilled with less damage to the cement in the annulus, and in view of the fact that the full weight of casing is apt to be set down on cement only when the casing is cemented to the surface, prompted the tentative conclusion that the minimum cement-strength requirement before the plug is drilled out is approximately 8 lb. per sq. inch.

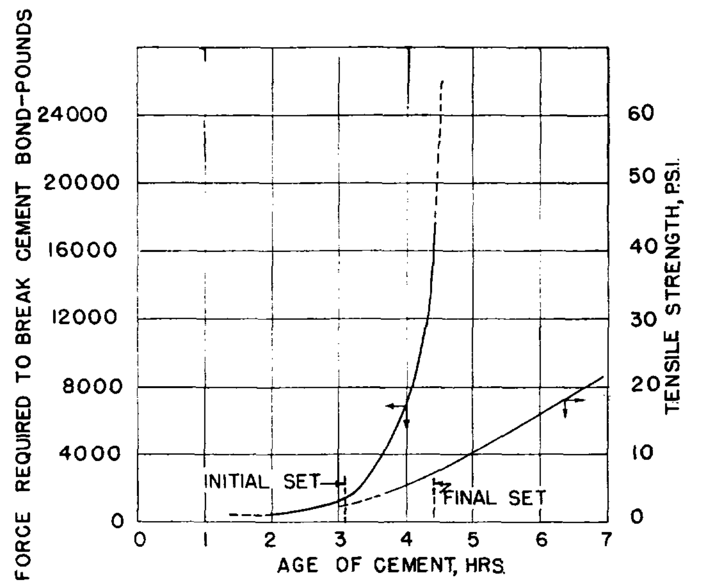


FIG. 3.—DEVELOPMENT OF BONDING STRENGTH.

### Prediction of Cement-strength Development in Wells

#### *First Method*

Having determined by laboratory tests what appears to be the minimum strength requirement of cement in wells, the next step is to develop a method of determining when cement in wells will attain that strength. Cement slurry, whether in a well or a laboratory apparatus, will remain fluid for a time after the slurry is formed, then it will stiffen, set, and start to develop strength. Also, regardless of whether or not the slurry is in a well or in a laboratory apparatus, the factors that will largely govern the time required for it to stiffen to a given consistency, reach a final set or attain a given strength, will be water-cement ratio, temperature, and pressure. When well conditions or laboratory conditions accelerate the stiffening time of cement to a given consistency, the time to the initial set will be decreased correspondingly. Since both times are affected by the same factors, it appears that it should be possible to express one as a function of the other. If the time for cement stiffening to a given consistency is related to the time of final set (8 lb. per sq. in. tensile strength), and if laboratory tests could be conducted to predict the actual time of stiffening of cement in wells, it would be possible to predict with approximately the same accuracy the time when cement in wells reaches the final set, or a strength of 8 lb. per sq. inch.

In 1941, Stanolind Oil and Gas Co. developed a method[1] of testing cements in which temperatures and pressures are varied to correspond with the increasing temperatures and pressures imposed upon cement slurries as they are pumped from surface to bottom-hole conditions of wells of various depths. The results obtained from these tests are called cement stirring-time tests to 100 poises at simulated well depths. Field tests have shown that this method of evaluating cements describes reasonably accurately the actual performance of cement slurries in wells. Table 3 is a tabulation of cement stirring-time tests to 100 poises at various simulated well depths, the time to 8 lb. per sq. in. tensile strength (assumed to be equivalent to the time of final set), and the ratio of these times.

TABLE 3.—*Cement Stirring-time Tests*

| Type of Cement | Well Depth Simulated, Ft. | Stirring Time to 100 Poises, Hr. | Time to 8 Lb. per Sq. In. Tensile Strength, Hr. | Time to 8 Lb. per Sq. In. / Time to 100 Poises |
|---|---|---|---|---|
| Standard Portland. | 2,000 | 3.5 | 5.4 | 1.54 |
| | 4,000 | 3.0 | 3.8 | 1.27 |
| | 6,000 | 2.5 | 2.9 | 1.16 |
| Slow-set A. | 8,000 | 4.0 | 8.5 | 2.12 |
| | 10,000 | 3.4 | 8.0 | 2.35 |
| | 12,000 | 3.0 | 7.9 | 2.63 |
| Slow-set B. | 6,000 | 3.7 | 10.6 | 2.86 |
| | 8,000 | 3.1 | 9.3 | 3.0 |
| | 10,000 | 2.5 | 7.5 | 3.0 |
| Slow-set C. | 6,000 | 4.0 | 10.1 | 2.52 |
| | 8,000 | 3.1 | 8.8 | 2.84 |
| | 10,000 | 2.6 | 7.8 | 3.00 |
| Slow-set D. | 6,000 | 3.7 | 6.5 | 1.75 |
| | 8,000 | 3.3 | 5.2 | 1.57 |
| | 10,000 | 4.4 | 5.4 | 1.23 |

Data in the fourth column of Table 3 were obtained from time-versus-strength data by extrapolation from actual test points in the neighborhood of 20 to 30 lb. per sq. in. tensile strength. For that reason, and also because the strength tests were made at atmospheric pressure, the data under this heading do not exactly describe the time to 8 lb. per sq. in. tensile strength in a well. The times are a little longer than would be found in actual practice, and thus become an added safety factor to the method herein proposed. But, in spite of the fact that the test data in Table 3 are not perfectly representative, the ratio of the time to 8 lb. per sq. in. strength to the time to 100 poises is surprisingly constant. The average ratio multiplied by the time to 100 poises would quite accurately predict when cement in the average well attains a strength of 8 lb. per sq. in. However, since it is desirable that cement in all wells, not just in the average well, reach a strength of 8 lb. per sq. in. before it is drilled out, the largest ratio, 3, must be used. In general, therefore, cement in wells will attain a tensile strength of at least 8 lb. per sq. in., the minimum strength requirement in wells, at a time corresponding to three times the time required for the cement to reach a consistency of 100 poises at well conditions of temperature and pressure. Or, for practical purposes,

$$\text{Minimum WOC time} = T_{8\text{ lb. per sq. in.}} = T_{100}\text{ poises} \times 3$$

Where:

$T_{8\text{ lb. per sq. in.}}$ = time to a tensile strength of 8 lb. per sq. in.

$T_{100}$ poises $\times 3$ = well simulation stirring-time tests to consistency of 100 poises.

It will be shown later that this method of predicting development of cement strength in wells is actually more accurate than may be believed at this point. However, since the method involves several assumptions, thought was turned to the development of a simpler, more accurate method of determining strength development in wells.

### *Second Method*

When water is added to dry cement, chemical reactions occur that give off heat. It is this behavior of cement slurry that permits one to run a recording temperature instrument into a well after a casing cement job and find the location of the top of the cement behind the pipe. It has been found that the temperature of cement behind casing may remain higher than the temperature of the adjacent formation for as long as 60 to 70 hr. after pumping the cement into the well. Field tests have

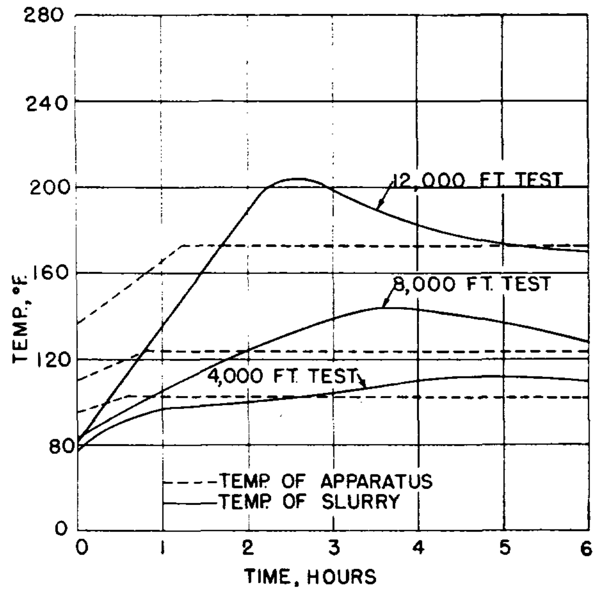


FIG. 4.—TEMPERATURE DEVELOPMENT IN STANDARD PORTLAND CEMENT SLURRY.

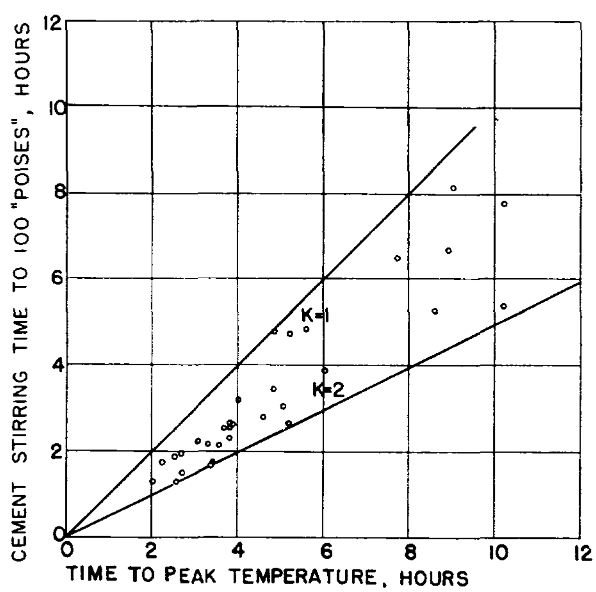


FIG. 5.—STIRRING TIMES OF CEMENTS.

shown also that temperature surveys made at 24 hr. or less after cementing show the tops of cement more distinctly, suggesting that some time after cement is placed on standard portland and slow-set cements, to throw some light on this subject.

A plot of the stirring time of various cements at various conditions of tempera-

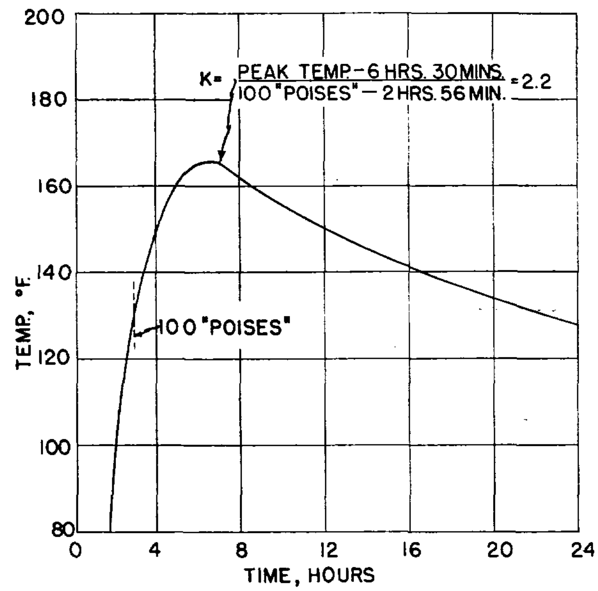


FIG. 6.—PEAK TEMPERATURE IN RELATION TO STIRRING TIME.

in a well the temperature increases to some maximum value above the surrounding strata, then slowly decreases to the normal temperature at that depth. Laboratory tests were made to determine the time of maximum or peak temperature of cement slurries at various pressures and temperatures is simulation of various well depths.

An example of maximum temperature development in a standard portland cement slurry at three stimulated well depths is shown in Fig. 4, which shows that the greater the depth, the more quickly the cement reaches the maximum temperature. Viewing this behavior brings to mind the fact that the greater the depth, the more quickly cement stiffens and sets. That thought, in turn, suggests that the time to maximum temperature development in a well may be related to stirring time to 100 poises. A number of tests were made ture and pressure, corresponding to wells of various depths, versus the time to the peak or maximum temperature development (Fig. 5) suggests that these factors may be reasonably closely related to each other. In other words, knowing the stirring time to 100 poises, one can multiply that time by a factor ($K$), which is more than one but less than two, and predict the approximate time when cement in wells will reach the peak temperature. Fig. 5 indicates that the average $K$ factor is somewhere between 1.5 and 2.0.

Field tests were then made to determine when cements in wells actually reach peak temperature and to determine how it is related to laboratory tests of stirring time to 100 poises. The first test was run in a well in North Cowden field, Ector County, Texas, where 5½-in. o.d. casing was set at 4624 ft. and cemented with 125 sacks of a standard portland cement.

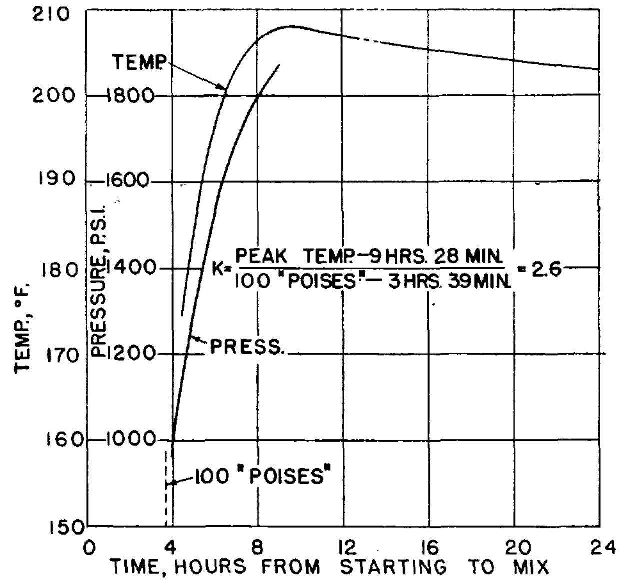


FIG. 7.—RELATION OF PRESSURE AND TEMPERATURE.

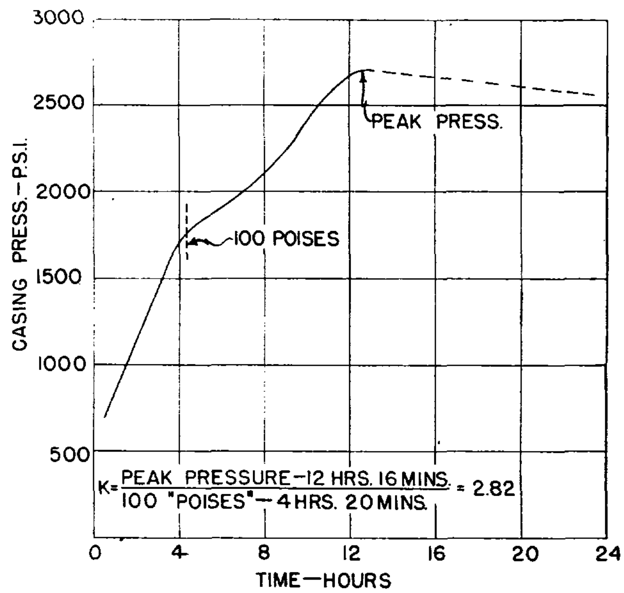


FIG. 8.—PRESSURE BUILD-UP ON CASING.

Immediately after the cement was pumped down, a recording temperature element was lowered into the casing to a point well below the estimated top of the cement and was left at that point for approximately 24 hr. The temperature recorded during that time is plotted on Fig. 6. The ratio of the time to the peak temperature in this well to the stirring time to 100 poises, as determined by a laboratory well-simulation test on the same cement, is 2.2, or slightly higher than the *K* factor indicated by previous laboratory tests.

Since the maximum temperature recorded in this well was so very much greater than the normal static formation temperature, approximately 94°F., at that depth, the thought occurred that perhaps if the casing being cemented is closed in after the cement is pumped down, expansion of the fluid in the casing should cause an increase in the shut-in casing pressure, which would reach a maximum at approximately the same time that the cement down the hole reaches its maximum temperature. This thought was investigated in the next field test.

In the next field tests, the test procedure used on the previous well was followed, except that hourly readings of the shut-in casing pressure were taken. This well was drilled in Tri-Cities field, Texas, where 5½-in. o.d. casing was set at 7681 ft. and cemented with 600 sacks of a slow-set cement. Fig. 7 shows the results of these tests. The pressure built up with temperature to approximately the peak, but, unfortunately, the pressure on the casing was bled off at that time. Ratio of the time to peak temperature to the time to 100 poises was found to be 2.6.

Another test was run in Tri-Cities field to obtain a record of the pressure build-up on the casing, since readings were not taken to the maximum pressure on the previous well. In this test, 5½-in. o.d. casing was set at 7612 ft. and was cemented with the same type and amount of cement. The results (Fig. 8) confirmed the thought that pressure on the casing after cement is placed reflects heat of hydration of cement in a well. The ratio of time to peak pressure to stirring time to 100 poises was 2.82 in this case. Why the peak temperature occurred in one well at 9 hr. and 28 min. and the peak pressure occurred at 12 hr. and 16 min. in another well of approximately the same depth is understandable in view of the fact that the cement showed different setting-time characteristics, although the same brand was used in both cases. Also, another possible difference between these wells is the fact that the latter was cemented during a season of the year when the atmospheric temperature was probably less than that at the time of cementing the first well. It is a well-known fact that mud-pit temperatures are affected by atmospheric temperature, which, in turn, affect the bottom-hole temperatures and, therefore, the setting time of cement placed therein.

A pressure build-up test was made on a well in West Edmond field, Oklahoma, where 7-in. o.d. casing was set at 7028 ft. and cemented with 700 sacks of a special experimental oil-well cement. Fig. 9 shows that the ratio of peak pressure to 100 poises was 2.4.

Surface pipe, 10¾ in., was set at 649 ft. in a well in Sour Lake field, Texas, and cemented to the surface with 500 sacks of a standard portland cement. Fig. 10 shows that the ratio of peak pressure to 100 poises was 2.1. Pressure was bled down once, to permit installation of a recording pressure gauge. Pressure was bled down at first to avoid subsequent high pressure on the casing. When the peak pressure was reached, a transit was set up some distance from the well and trained to a mark on the pipe to observe any settling of the pipe when the strain was released. The weight of the pipe was set down on the cement. but no movement was observed.

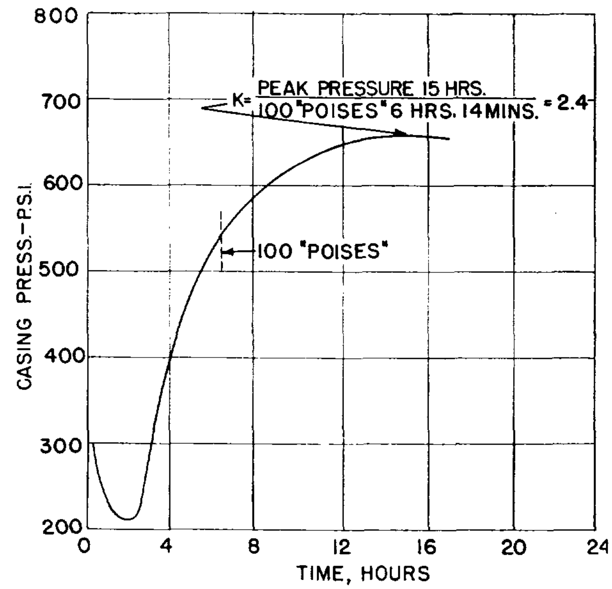


FIG. 9.—PRESSURE BUILD-UP ON CASING.

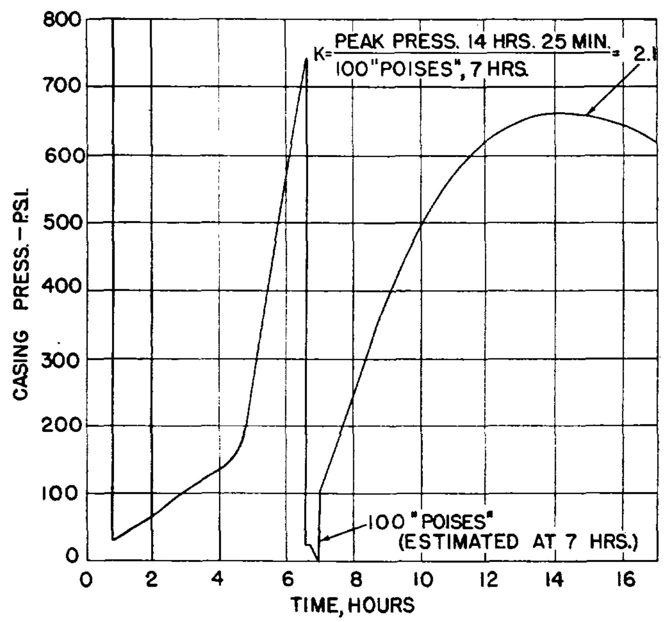


FIG. 10.—PRESSURE BUILD-UP ON CASING.

Earlier in the discussion it was shown by laboratory tests, that the ratio of the time to maximum temperature development in cement to the stirring time to 100 poises is equal to a factor ($K$) slightly less than 2 but more than 1.5. All field tests show that the ratio is slightly more than 2 but less than 3. Since the difference between laboratory tests and field tests is small, one might strike a compromise with the statement or conclusion that cements in wells reach peak or maximum temperatures at a time corresponding to approximately twice the time required for the cement to attain a consistency of 100 poises, under the particular laboratory consistometer test conditions used in this case. This relationship, with others pointed to throughout the discussion, may be written as equations as follows:

$$T_{8\text{ lb. per sq. in.}} = T_{\text{min.}}\text{ WOC} \quad [1]$$

$$T_{\text{min. WOC}} = T_{100}\text{ poises} \times 3 \quad [2]$$

$$T_{\text{max. temp.}} = T_{\text{max. csg. press.}} \quad [3]$$

$$T_{\text{max. cgs. press.}} = T_{100\text{ poises}} \times 2 \quad [4]$$

Therefore,

$$T_{\text{min. WOC}} = T_{\text{max. csg. press.}} \times 1.5 \quad [5]$$

where:

$T_{8\text{ lb. per sq. in.}}$ = time from mixing of the cement to a tensile strength of 8 lb. per sq. in.

$T_{\text{min. WOC}}$ = minimum waiting-on-cement time.

$T_{100\text{ poises}}$ = cement well simulation stirring-time test to 100 poises (pressure consistometer; Stanolind test procedure).

$T_{\text{max. temp.}}$ = time to maximum temperature development in cement.

$T_{\text{max. csg. press.}}$ = time to maximum shut-in pressure on casing.

Eq. 5, which expresses the second method for predicting development of cement strength in wells, simply means that all one has to do to determine the minimum WOC time in any well is to read the shut-in casing pressure after landing the cement until it reaches a maximum, then multiply the time to that point, as measured from the time of mixing the first sack of cement, by a factor of 1.5. This method is much simpler than the first method and is much more accurate, as it will reflect differences in well conditions and differences in cement behavior.

The foregoing equations describe relationships that laboratory tests indicate to be true, or approximately true, in wells with respect to minimum strength requirements and minimum WOC times. Whether or not the laboratory predictions hold true in field practice is quite another matter. Field tests were made to check the correctness of these hypotheses.

## Field Tests

If the trends indicated by laboratory tests are fundamentally correct, the equation for predicting minimum WOC time will apply to all portland-type cements in any well at any depth. Therefore, exceptions to field rules were obtained where necessary to permit drilling out of cement as early as might be required to check laboratory tests. Wells were selected in various areas and at various stages of drilling in order to obtain data on jobs at various depths and with different types and brands of cements. Each job differed from normal practice only in the time of drilling out of the plug. Field men were instructed to take hourly readings of the shut-in casing pressure until it reached a maximum, release pressure at that point, run the bit into the hole, and start drilling the plug at a time equal to the time to the maximum pressure times 1.5. Incidentally, field men were advised to bleed off the pressure at intervals if it reached dangerous proportions. The criterion is not necessarily the magnitude of the pressure, but, rather, is the point when the fluids inside the casing stop expanding as a result of an increase in temperature. that releasing the pressure after it reaches the maximum is a more critical test than

TABLE 4.—*WOC Field Tests*

| Field | Casing | | Cement | | Elapsed Time, Hr., to | | | Plug Drilled at, Hr. | Time to Maximum Casing Pressure × 1.5, Hr. | Drilling Rate, Min. per Ft. | Wt. on Bit M#s | Rev. per Min. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Size, In. | Depth, Ft. | Type | Sacks | Maximum Casing Pressure | Stirring Time, 100 Poises × 2 | Release of Casing Pressure | | | | | |
| Fullerton, Tex. | 7⅝ | 3,771 | Common | 2,000 | [a] | 6.16 | 7.38 | 12.25 | 9.24[c] | 5 | 5 | 55 |
| Fullerton, Tex. | 7⅝ | 3,805 | Common | 1,800 | 7.25 | 7.23 | 8.0 | 16.0 | 10.87 | 5 | 2 | 50 |
| Fullerton, Tex. | 7⅝ | 3,785 | Common | 1,900 | 7.05 | 6.16 | 7.20 | 11.2 | 10.57 | 2.4 | 2 | 50 |
| Fullerton, Tex. | 5½ | 6,765 | Slow-set | 350 | [a] | 8.0 | 7.07 | 26.2 | 12.0[c] | 2.0 | 3 | 50 |
| Sittner, Kans. | 5½ | 3,612 | Common | 150 | [a] | 8.5 | 9.53 | 16.2 | 12.75[c] | 3 | 3 | 50 |
| W. Edmond, Okla. | 7 | 7,005 | Common | 700 | [a] | 5.33 | 6.92 | [b] | 8.0[c] | | | |
| Sour Lake, Tex. | 10¾ | 647 | Common | 500 | 14.77 | 14.0 | 14.77 | 24.27 | 22.15 | 0.5 | 6 | 100 |
| Riverside, Tex. | 5½ | 6,415 | Slow-set | 750 | 10.12 | 8.8 | 11.0 | [b] | 15.16 | | | |
| High Island, Tex. | 7 | 5,704 | Slow-set | 750 | 15.67 | 11.10 | 15.67 | [b] | 23.5 | | | |
| Elk Basin, Wyo. | 7 | 5,300 | Common | 300 | 8.00 | 7.40 | 8.0 | 24.3 | 12.0 | 2.5 | 6 | 90 |

[a] Head leaked.
[b] Not drilled early.
[c] *T* to 100 "poises" × 3.

Table 4 presents a summary of eight field tests in which attempts were made to drill out cement at the minimum WOC time indicated by laboratory tests.

## Discussion of Results

The field tests summarized in Table 4 show by the drilling rates that the cement in each well had passed the final set, and therefore had attained a tensile strength of at least 8 lb. per sq. in. as predicted by laboratory tests. It is also interesting to note the reasonably close agreement between the time to maximum pressure on the casing and laboratory stirring time to 100 poises × 2. These data show that cement tests can be made in the laboratory that will predict the approximate stiffening time of cement in wells. In three field tests, unforeseen events delayed drilling of the plug to a time that approached the usual drilling out time and thus rendered those tests practically useless as far as the subject experiment was concerned. The only information of significance obtained from those tests was that no slurry flowed back into the casing when the pressure was released. Many believe the test of drilling the shoe. They reason that if the cement is soft it will back up into the casing when pressure is released, especially if the common type of float equipment is not used, as in two of the wells tested.

The writer is of the opinion that the tests conducted on the surface pipe cement work at Sour Lake were more severe than those at any other location. The cement was likely to have been much more "green" when it was drilled than at any other test location, owing to the low curing (formation) temperature and pressure. Immediately after the pressure was released, which, as stated before, may be a critical test of whether or not the cement has set, the master valve and blowout preventer for 10¾-in. casing were set down on the casing. The cement not only supported the full weight of the casing at that point but held the very large weight of that equipment. Next, after drilling the wooden plug and baffle collar and 4 or 5 ft. of cement, the driller stopped rotation and set all the weight of the drill pipe, kelley, and swivel (8 points) down on the cement, then increased the pump speed to a relatively high rate to see whether the cement could be washed out. The weight indicator had picked up no weight after circulating 6 min. The driller termed the cement as drilling "firm to hard."

The cement in all the tests where the plug was drilled reasonably soon after the specified time drilled firm to hard inside the pipe and showed no evidence of flow of cement into the casing after the shoe was drilled. Also, in no case was the cement sufficiently soft to be circulated out.

These data indicate that basing WOC time on the time to maximum casing pressure times a factor is fundamentally sound and applicable to field practice. It would appear that such a system as this would be particularly attractive as a basis for State or Field rules, since the time to maximum shut-in casing pressure reflects individual conditions of the well as they affect the particular type of cement used in that well. The multiplier 1.5 merely sets the time back to allow a minimum strength to be developed. Unless further field experience proves that the multiplier 1.5 is too low, there is little reason for suggesting that a waiting period longer than that prescribed by the formula should be used. These tests indicate that seldom will rig operations permit cement to be drilled out at the minimum time. This suggests that the phrase "waiting-on-cement time" should be deleted from our vocabulary, since it has been found that the cement usually waits on the drilling crew.

Much must be done before full advantage can be taken of the indicated savings in time. Aside from the fact that certain regulations will have to be modified, certain of the routine of rigging up and handling of rig operations may have to be shifted. For example, much of the rigging up or repair around a rig that now is deferred until WOC time may be handled by extra roustabout help, or may be done by the rig crew during slack time while drilling. Also, much time is not spent in changing rams on blowout preventers and in the installation of the master valve and the blowout preventer after setting surface pipe. If this equipment were made up in a shop ready to be flanged onto the surface pipe, it appears that it could be installed as a unit with a great deal more efficiency.

As an example of the saving that might be effected by reducing WOC time, the over-all average WOC time on Stanolind Oil and Gas Co. properties is approximately 51 hr. per casing cement job. This figure is lower than might be expected because it includes practices in areas where no regulations exist. The over-all average WOC time indicated by the method proposed in this paper is estimated to be approximately 15 hr. per casing cement job. This suggests a saving of 36 hr. per job. However, practical considerations teach that very seldom would the crew be able to start drilling on the plug so early. It has been estimated that, at least until the present rig routine is appropriately modified, the plug cannot easily be drilled out before an average time of approximately 21 hr. after cementing casing. Therefore, it appears that an average of 30 hr. per cement job might be saved without much difficulty.

Translating rig time into dollars at $20.00 per hour, the saving should be an average of $600 per casing cement job, or at least $1200 per well, assuming two cement jobs per well. Realizing that more than 24,000 wells were drilled in the United States during 1944, one can appreciate how reducing WOC time might benefit the industry.

## Summary

It has been shown that the minimum waiting-on-cement time in wells can be reasonably accurately predicted by laboratory well-simulation tests, but can be more simply determined by observing the shut-in pressure on the casing to a maximum value then multiplying by a factor of 1.5

the time from initial mixing of cement to the time when maximum pressure is reached. Field tests show that the cement has ample strength to support the pipe and withstand the shock of drilling at that time.

A great deal of WOC time may be eliminated if regulations are relaxed and if rigging up and drilling routine is adjusted to fit in with minimum waiting-time requirements.

## Acknowledgment

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Stanolind Oil and Gas Company has made an extensive study of chemical and physical properties of cements over the past several years in an effort to secure a better understanding of the performance of cement in wells. The chemical make-up of cements is a complex subject; however, the physical properties and physical ~~properties~~ behavior of cement are ~~more~~ easy to comprehend.

## ~~DISCUSSION RELATIVE TO REQUESTS FOR REDUCTION IN WOC TIME~~

Exh. L #90

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For example, When water is added to dry cement the slurry thus formed will remain fluid for a period of time, then it will gradually stiffen, set, and gain strength. If the cement slurry is agitated or pumped for just a short time after it is formed, thick gels or false body systems will develop in the slurry, giving it the appearance of a partially set cement. This behavior is sometimes called false set. The cement in this state is a semi-plastic and actually possesses some bonding strength. However, a slight vibration or movement of the cement before the initial set occurs will cause the cement to revert back to a fluid state. After cement takes a final set it assumes the properties of a solid and cannot again be reduced to the fluid state. After it becomes a solid it resists distortion by the amount of its strength in shear. When a force or pressure is applied to it which is greater than the shearing strength of the cement, it simply breaks, cracks or crumbles. Therefore, since the period between the initial set and the final set marks the transition from a fluid state to a solid state, if it can be proved that cement in a well at the time of its final set possesses sufficient strength and rigidity to support the pipe opposite it, to exclude undesirable fluids or gases, and to withstand the shock of drilling, then the time to the development of that physicial state in cement would be the absolute minimum WOC time.

It was reasoning along such lines that prompted the Stanolind Oil and Gas Company to conduct tests in both the laboratory and in the field for a more scientific answer to WOC time problems. The paper entitled "Method for Determining Minimum Waiting-on-Cement Time" presented before the A.I.M.E. in October, 1945, reported the results of some of that work. One of the first efforts in that connection was a study of the bonding strength of cement in the annulus between 5-1/2-inch and 9-5/8-inch casing at early ages or short WOC times. ~~This work showed that the gels and false body systems developed in the fluid slurry would more than support the weight of the inner string of pipe opposite it long before the cement takes the initial set. In other words, were it not for the fact that the gels and false body systems are easily broken down before the slurry takes the initial set, the minimum WOC period might be based upon the development of a given gel strength development in cement slurries.~~ This work showed that When the cement reached the final set, i.e. when the irreversible transition from a fluid to a solid was completed, the cement had a bonding strength of 4,550 pounds per linear foot of cement in the annulus. From these data it can be calculated that each linear foot of cement in an annulus at the time of the final set should support 267 feet of 5-1/2-inch 17-pound casing. Since most engineers regard a safety factor of 2 as being ample for most engineering problems, and since this work suggested a safety factor of 267 to 1 insofar as support of pipe in the hole is concerned, it appeared obvious that any WOC time spent beyond the time required for the cement to take its final set (approximately 8 p.s.i. tensile strength) would be time wasted. ~~effort.~~

Following this development, attention was turned to the thought of conducting field tests to verify the laboratory's suggestion that the minimum safe WOC time is the time of the final set (8 p.s.i. tensile strength). Before field tests could be conducted, however, means had to be devised for accurately determining <u>when</u> the final set of cement will occur in a well. This problem was easily and conveniently solved by utilizing the well established fact that cement slurries liberate heat more rapidly during the setting processes, i.e. during the fluid-state-to-solid-state transition period, than at any time before or afterward. Laboratory tests established the fact that all the cements tested would attain the final set (8 p.s.i. tensile strength) by or before a period corresponding to 1.5 times the time to the point of maximum heat development in cement. Field tests were then conducted to prove that the heat of hydration of cement slurries in any well will heat drilling fluid on the inside of the casing to the extent that, when the casing is shut in, the pressure at the surface will increase and reach a maximum almost simultaneously with maximum heat development of the cement in the well. The field tests not only proved this thought but also proved that cement may be drilled any time after it reaches the final set or 8 p.s.i. tensile strength.* This method for determining minimum WOC time has been used in a number of fields in a routine manner for approximately a year. To my knowledge there has been no case of failure attributable to drilling of the plug too early.

While there are several advantages in using a formula for determining minimum WOC time, i.e., 1-1/2 times the time to the maximum shut-in casing pressure, it has the disadvantage that leaky casinghead connections or other leaks may prevent the normal pressure build-up on the casing. When this occurs on a Stanolind well, ~~the~~ an alternate method for determining minimum WOC time is applied which is based on the limit of pumpability of cement slurries at high pressures and temperatures in simulation of those which exist in the average well at any depth. However, since information of the latter type is not now available to all operators, it is believed that the minimum WOC time should be based on a flat-time, at least for the present time.

Therefore, studies were made of the setting times of many of the types of cements used in cementing surface pipe, intermediate strings, and oil strings to determine what fixed minimum time might be applied to each type of casing

* Relating the strength development of cements to the heat of hydration during the setting process was one of the most important developments of this work, since it provided for the first time a means of determining the rate at which cements actually set in wells. The heat generated by cement during the setting process has been known for years and has been used in connection with [illegible]

cement job. The following times were recommended:

| | Under Pressure, Hrs. | Drilling Plug, Hrs. |
|---|---|---|
| Surface pipe | 16 | 24 |
| Intermediate | 24 | 30 |
| Oil string* | 24 | 30 |

~~These times have been used in several fields in Texas during the past year without difficulty.~~

Under pressure in this case has reference to the ~~means that~~ ~~below cement outside of the casing. In other words if~~ pressure on the cement - not necessarily the pressure on the casing at the surface.

These times are generally somewhat greater than those which would be obtained by the pressure build-up method.

~~This method for determining minimum WOC time~~

The Texas RR commission has adopted these WOC time practices for several field and it has operated almost a year without difficulty.