

T-2918

CEMENT HEIGHT AND PICK UP CALCULATIONS
FOR ZERO BUCKLING TENDENCY

by

Mamdouh M. El agawani

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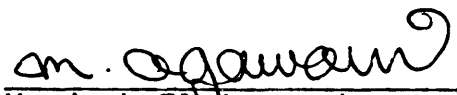
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A thesis submitted to the Faculty and the Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Master of Science (Petroleum Engineering).

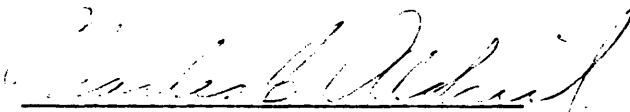
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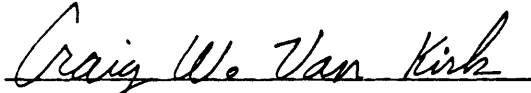

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ABSTRACT

This work is comprised of two parts. The first part is concerned with determining the height of cement required to prevent a positive buckling tendency at the casing freeze point when, after the cement sets, the average casing temperature or the internal fluid pressure is increased. The second part is concerned with determining the pick up weight required, when landing the casing, to prevent a positive buckling tendency at the freeze point if a shortage in the required cement height exists.

Graphs are presented that allow the problems to be solved in the field using standard field data.

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This work is dedicated to my wife Afaf

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INTRODUCTION

When drilling into high pressure formations, often the procedure followed is to drill to a depth near the top of the high pressure formation, set a string of protective casing and then drill into the high pressure formation after increasing the weight of the drilling fluid.

When the mud weight inside the protective casing is increased, positive buckling-criterion occurs as described by Cox⁽³⁾. If the casing is allowed to buckle, drilling problems can be anticipated while drilling the remainder of the hole. Normal problems encountered are high torque and drag, excessive wear of casing and drill string, possible failure of the casing and problems running equipment through the casing.

The phenomena of casing buckling from fluid pressure was investigated in 1951 by Lubinski⁽¹⁾, and Bouman⁽²⁾. They showed that casing fixed at both the upper and the lower ends could be caused to buckle by increasing the fluid pressure on the inside of the casing. Increasing the density of the drilling fluid inside the casing is an example of how the fluid pressure can be increased during normal drilling operations.

In 1955 the API studied the problem and Cox summarized

the work of Lubinski and Bouman by publishing the buckling-criterion equation. Cox's buckling-criterion equation determines the required pick-up weight to eliminate buckling tendencies in casing after the cement sets.

The buckling tendencies, or buckling-criterion, at the casing freeze point are affected by the well head load, the change in casing string temperature, the hole angle, and the internal and external fluid pressures that act on the walls of the casing.

This study considers only vertical holes, and only the internal fluid pressure is allowed to change. This pressure change occurs primarily from changing the density of the drilling fluid as the hole is deepened after cementing the protective casing. However, increasing the internal surface pressure during some pressure control operations is also considered. Other means of changing the fluid pressures are recognized. However, they normally will not occur during the drilling process. Changing the average temperature of the casing string after the casing is cemented and landed is also considered.

Specifically the purpose of this study is to manipulate a portion of the equation presented in Cox's paper "Key Factors Affecting Landing Of Casing"⁽³⁾ into a nondimensional form, when possible, which can be plotted using

standard field data. The resulting plots give a graphical tool that will easily solve engineering problems such as:

- 1) The cement height required to avoid positive buckling-criterion for a specific change in mud weight.
- 2) The additional cement height required to avoid positive buckling-criterion when the average temperature of the casing string is increased after the casing is cemented and landed, i.e. fixed at both ends.
- 3) The additional cement height required to avoid positive buckling-criterion when the surface pressure inside the casing is increased after the casing is cemented and landed, i.e. fixed at both ends.
- 4) The amount of pick up required to avoid positive buckling-criterion when less than the cement required in 1) through 3) above is used for a specific change in mud weight.

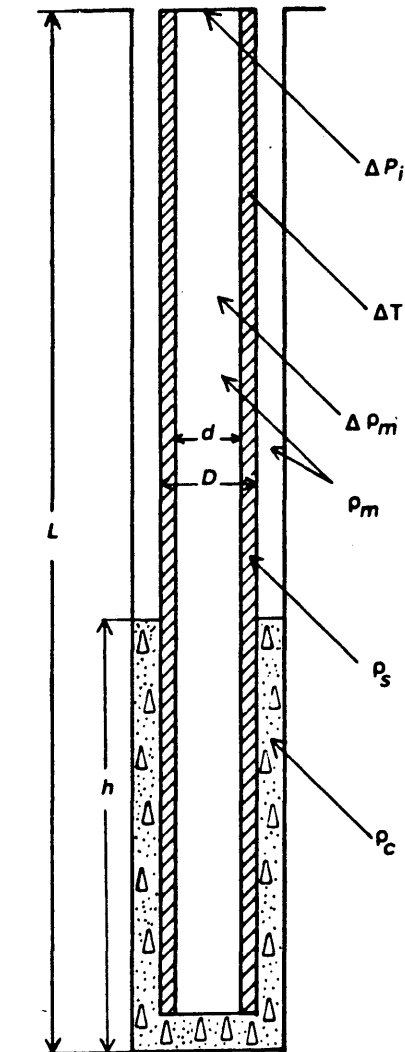
EFFECT OF MUD WEIGHT CHANGE
ON CEMENT HEIGHT CALCULATIONS

The phenomenon of buckling in oil well casing is quite different from the buckling of a normal structure column. In both cases the buckling is caused from a bending moment, however in a normal structure column the bending moment usually results from placing the column in compression. When the column is placed in tension, buckling does not normally occur. Studies of buckling^(1,2,3) in oil-well casing have shown that fluid pressures acting on the casing walls also cause positive buckling tendencies and consequently under certain conditions buckling can occur even though the casing is in axial tension. Increasing the fluid density inside the casing, after the casing is cemented and landed, i.e. fixed at both ends (Figure 1), is a condition that can cause the casing to buckle. In order to avoid positive buckling tendencies above the casing freeze point, later changes of fluid density inside the casing must be considered when selecting the height of cement returns in the annulus and when determining the procedures to be used for landing the casing at the well head.

In Appendix A starting with Cox's buckling-criterion equation, a dimensionless equation has been derived that

FIGURE 1
PARAMETERS FOR CEMENT HEIGHT EQUATIONS

- L = Total casing length.
- h = Length of cemented part of casing.
- ρ_{mi} = Weight per unit volume of mud weight before cement sets.
- ρ_{mf} = Weight per unit volume of mud weight after cement sets.
- $\Delta\rho_m$ = Change in mud weight inside the casing.
- D = Outside diameter of pipe.
- d = Inside diameter of pipe.
- ρ_s = Weight per unit volume of pipe steel.
- ρ_c = Weight per unit volume of cement slurry.
- w_s = Buoyed weight of one foot of the steel.
- W = Buoyed weight of the casing.
- S = Pick up weight of the casing (-S = slack off).
- ΔT = Change in average casing temperature in degrees.
- ΔP_i = Change in surface pressure inside the casing.



relates the percentage of the casing length required to be cemented in the annulus to prevent positive buckling tendencies at the freeze point when the mud weight is changed from the initial weight ρ_{mi} to some increased weight ρ_{mf} (Table 1 and Equation (15) in Appendix A). This equation gives the percentage of the total casing length (L) to be cemented as a function of the mud density ratio (Rm). The equation also contains three dimensionless constants that are functions of the casing geometry (Rs), the initial mud density (Bm), and the density of the cement slurry in the annulus (Bc). For any given well these constants have fixed values and are easily determined. Between two different wells, the constants can have different values depending on the size and the weight of the casing run, the initial mud weight and the specific weight of the cement slurry used to fill the annulus.

Figures 2 through 5 show a graphical solution of Equation (B). A separate graph is required for each different casing size and each different cement slurry weight, for example Figure 2 is for 7 inch casing cemented with 15.8 ppg cement slurry. A family of curves depict various initial mud weights from 9 ppg to 12 ppg. A separate family of initial mud weight curves are required for each casing weight.

TABLE 1
 CEMENT HEIGHT EQUATIONS
 FOR A SPECIFIC MUD WEIGHT CHANGE

A. For any set of consistent units:

$$h/L(\%) = \frac{70 \rho_{mi} (Rm-1)}{.7 \rho_{mi} (Rm-1) + \rho_s (Rs^2 Bc-Bm)} \quad (A)$$

B. For fluid weights expressed in pounds per gallon:

$$h/L(\%) = \frac{100 \rho_{mi} (Rm-1)}{93.5(Rs^2 Bc-Bm) + \rho_{mi} (Rm-1)} \quad (B)$$

FIGURE 2
 PERCENT OF CASING TO BE CEMENTED
 FOR ZERO BUCKLING TENDENCY

Casing Diameter 7" OD
 Cement Slurry Weight 15.8 ppg

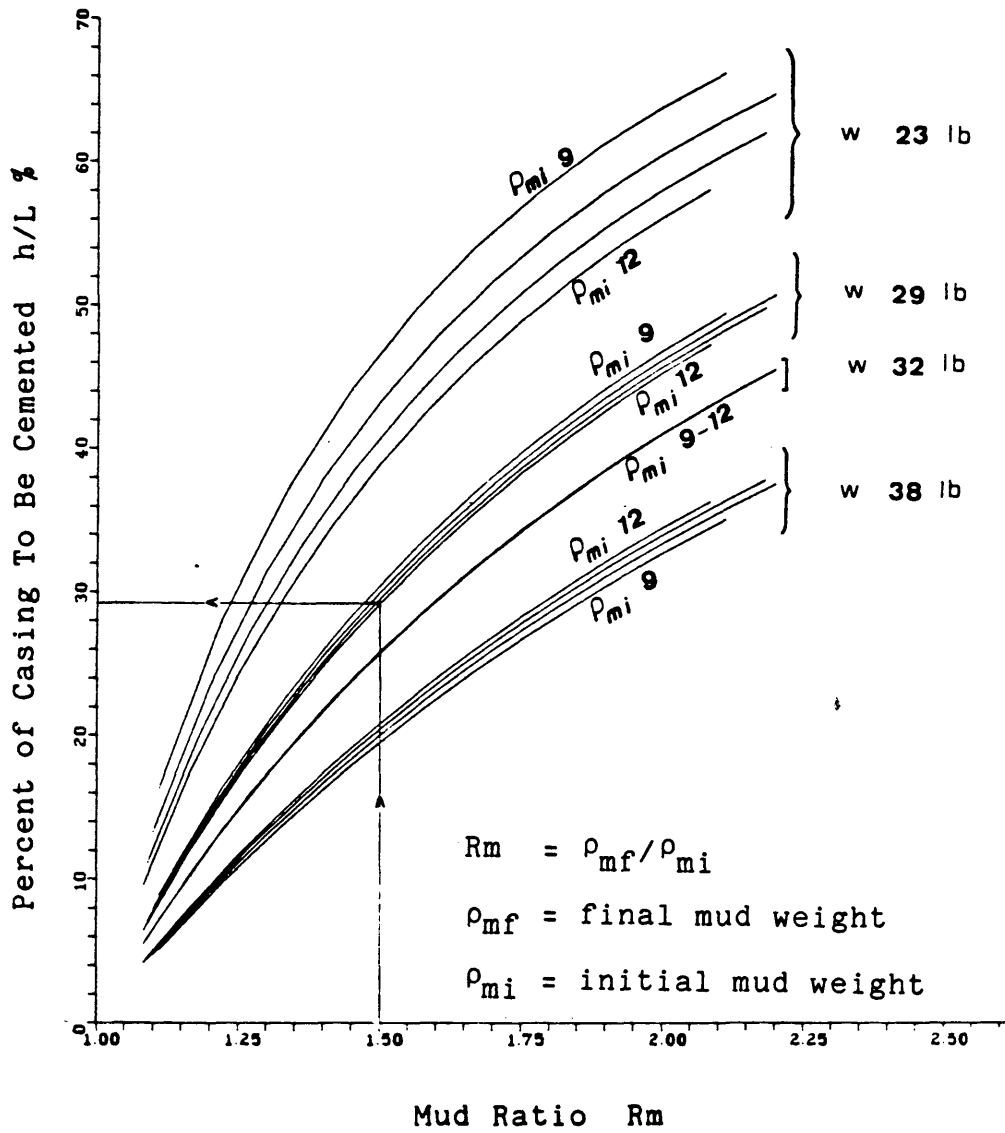


FIGURE 3
 PERCENT OF CASING TO BE CEMENTED
 FOR ZERO BUCKLING TENDENCY

Casing Diameter 7" OD,
 Cement Slurry Weight 13.2 ppg

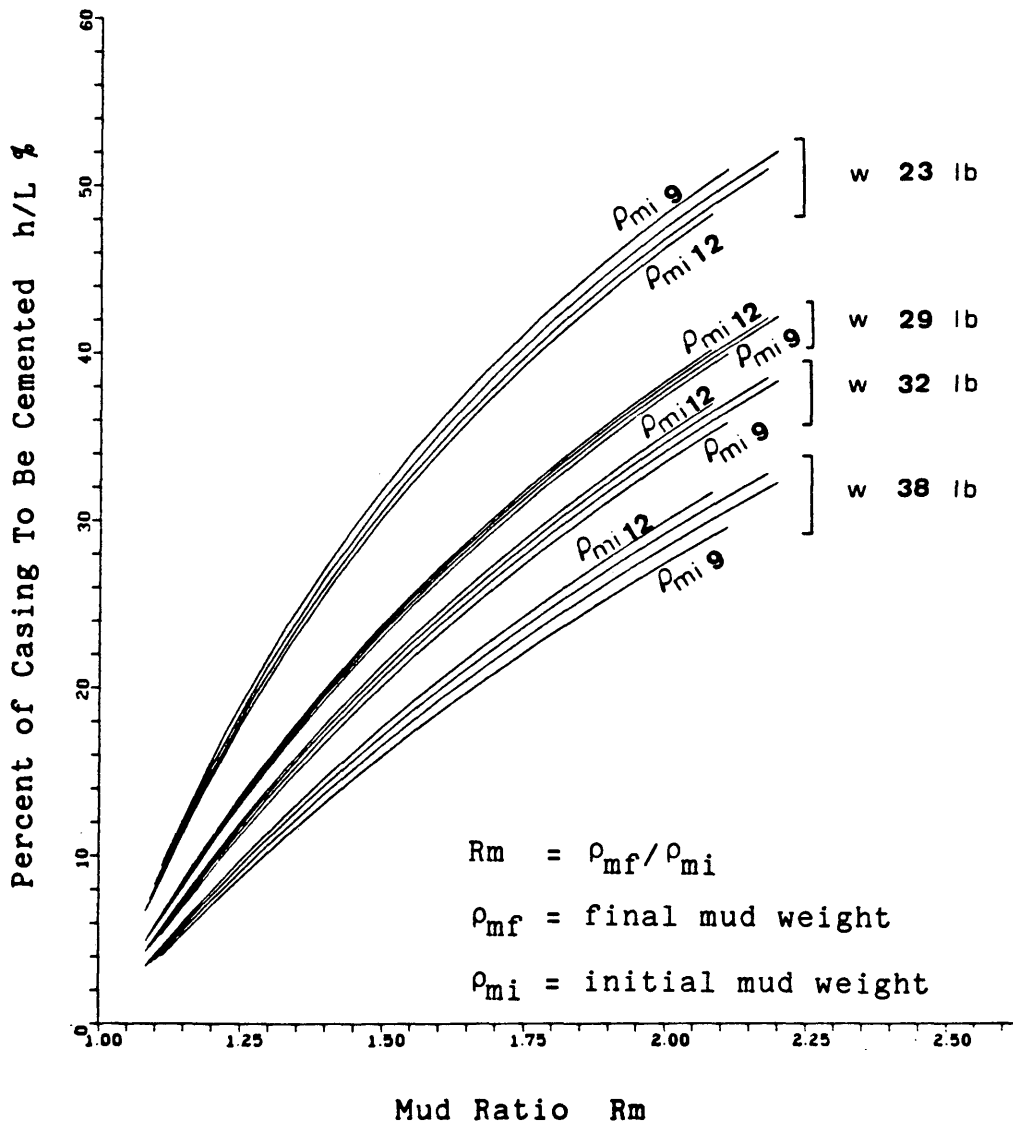


FIGURE 4
 PERCENT OF CASING TO BE CEMENTED
 FOR ZERO BUCKLING TENDENCY

Casing Diameter 9 5/8" OD,
 Cement Slurry Weight 15.8 ppg

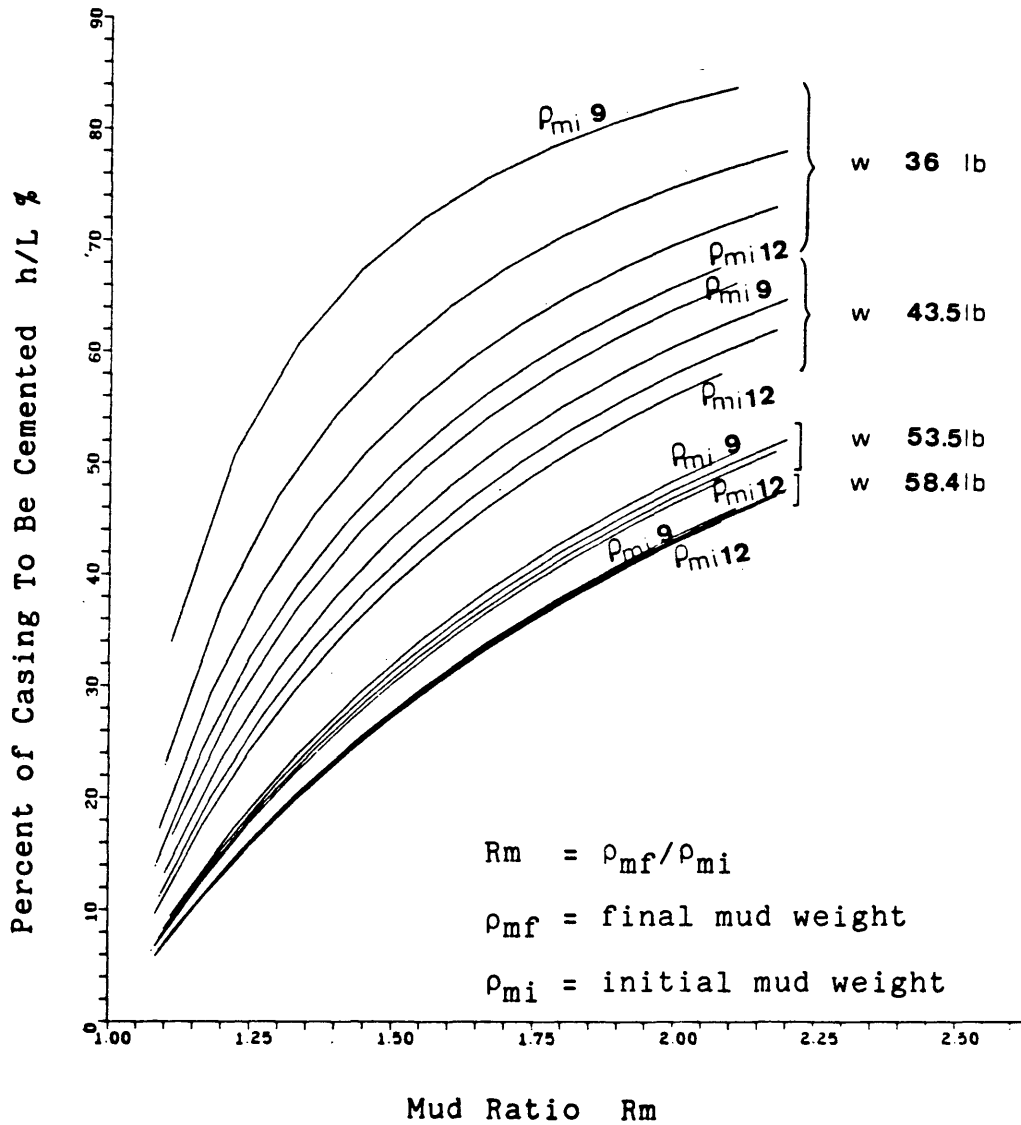
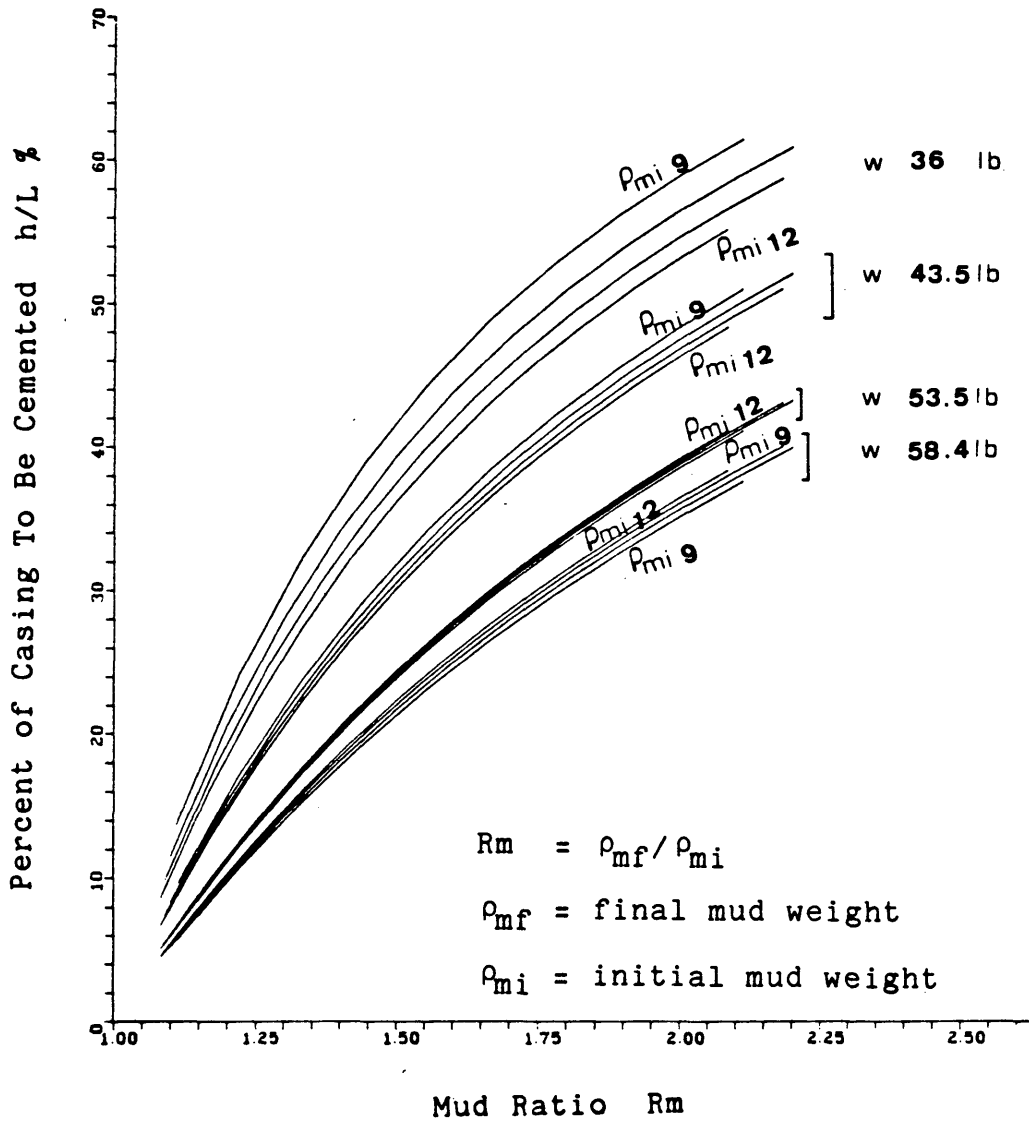


FIGURE 5
 PERCENT OF CASING TO BE CEMENTED
 FOR ZERO BUCKLING TENDENCY

Casing Diameter 9 5/8" OD,
 Cement Slurry Weight 13.2 ppg



In Table 1, Equation (A) requires consistent units, i.e. L and h must have consistent units with each other, ρ_{mi} , ρ_c , and ρ_s must have consistent units with each other, and A_i , and A_e must have consistent units with each other. R_s , B_m , B_c , and R_m are dimensionless numbers. In Equation (B), ρ_{mi} , and ρ_c have been converted to field units and must be in lbs per gal.

The equations in Table 1 have been derived for single weight casing strings. A study of the equations for combination-weight strings (3), indicates that no significant error is introduced when the single-weight equations are used for a combination-weight string.

Assumptions: The equations in Table 1 are based on the following assumptions:

- 1) No change in the average casing temperature after the cement sets. (The effect of a temperature change is considered in a later portion of this thesis.)
- 2) No change in surface pressure inside or outside the casing after the cement sets. (The effect of a pressure change inside the casing is considered in a later portion of this thesis).
- 3) No change in mud weight outside the casing after

the cement sets.

- 4) No drop in mud levels inside or outside the casing after the cement sets.
- 5) The casing is landed as cemented.

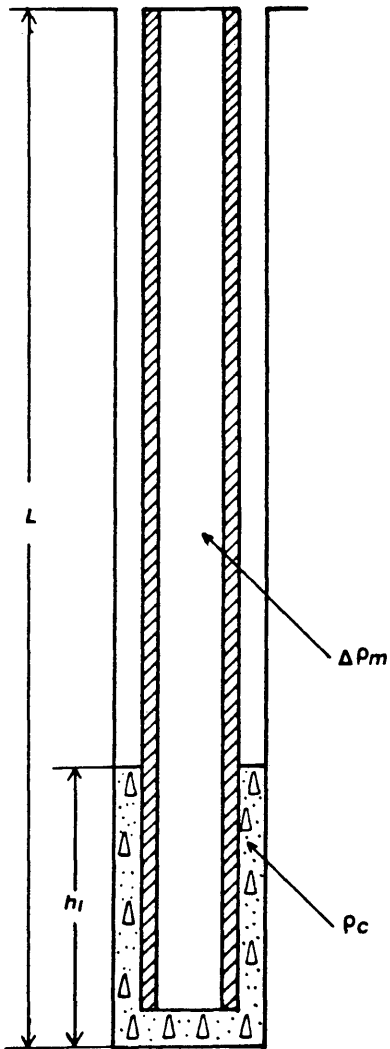
The following example illustrates the use of Figures 2 through 5 to calculate the cement height required for zero positive buckling tendencies at the freeze point when the mud weight changes from ρ_{mi} to ρ_{mf} after the cement sets.

Example 1: Consider a 10,000 ft single weight casing string with the following parameters as represented in Figure 1 and Figure 6.

L = 10,000 ft	ρ_c = 15.8 ppg
w = 29 ppf	ρ_{mi} = 12 ppg
D = 7 in.	ρ_{mf} = 18 ppg
d = 6.184 in	ΔP_i = zero
S = zero, i.e. landed as cemented	ΔT = zero h = unknown

To calculate the required cement height (h_1), Figure 2 is used which represents 7 in. casing cemented with a slurry weight of $\rho_c = 15.8$ ppg. Starting with the mud ratio factor $R_m = \rho_{mf}/\rho_{mi} = 18/12 = 1.5$, draw a vertical line to

FIGURE 6
CASING PARAMETERS FOR EXAMPLES 1 AND 2



intersect the ρ_{mi} 12 ppg curve representing the 29 ppf casing. From the point of intersection, draw a horizontal line and read the percentage (29.3%) of the casing to be cemented to prevent a positive buckling tendency at the freeze point. This shows that 2930 ft. of casing should be cemented, or cement up to a depth of 7070 ft. if the casing is landed as cemented.

In the event a curve such as Figure 2 is not available the required cement height can still be calculated graphically. Figures 7 through 9 have been developed to calculate the cement height required to avoid a positive bending moment at the freeze point when the mud weight is changed from ρ_{mi} to ρ_{mf} for any casing size and weight, and for any cement slurry specific weight.

Figure 7 is a graphical solution to Equation (9) in Appendix B. It shows the relationship between the pipe diameter ratio R_s and the factor k_1 for different cement slurry weights. Figure 8 is a graphical solution to Equation (10) in Appendix B. It shows the relationship between the final mud weight and the factor k_2 for different initial mud weights. Figure 9 is a graphical solution to Equation (15) in Appendix B. It shows the percent of the casing (L) required to be cemented to prevent a positive buckling tendency at the freeze point as a function of the

FIGURE 7
K1 FACTOR

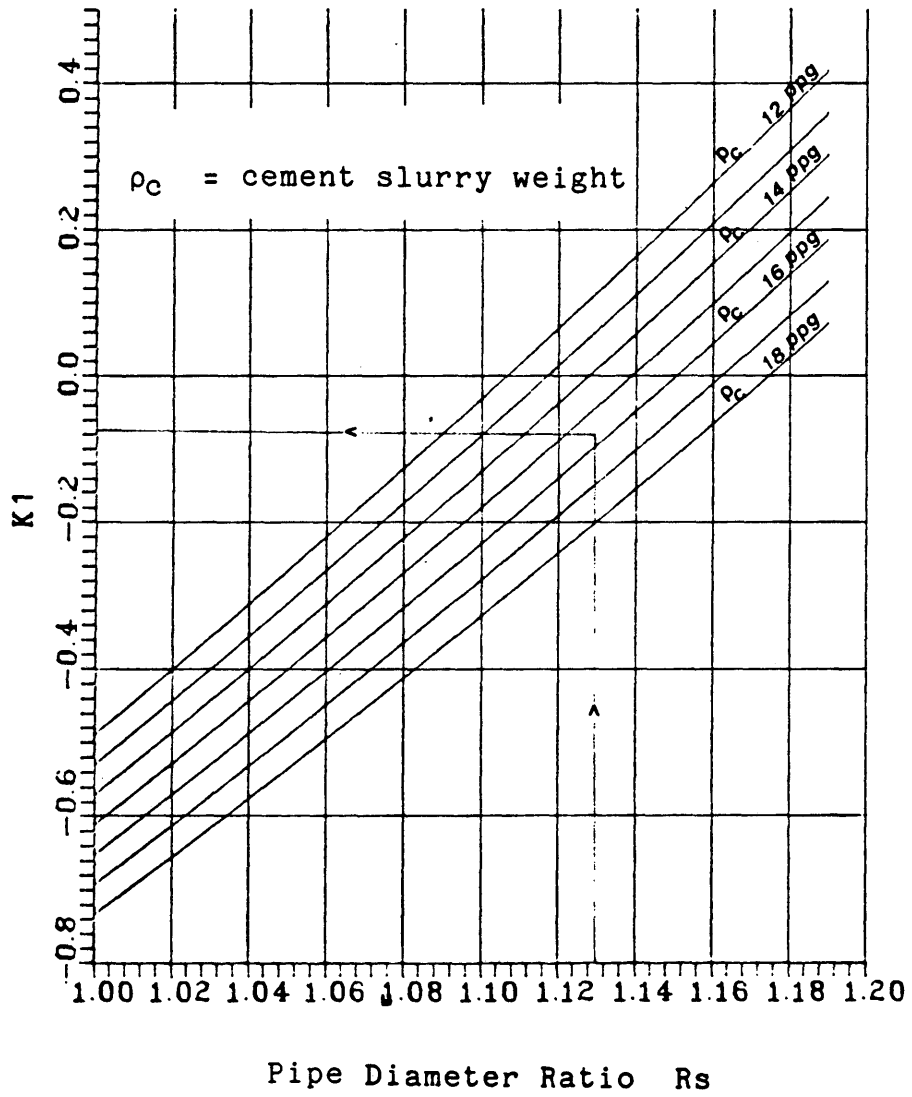


FIGURE 8
K2 FACTOR

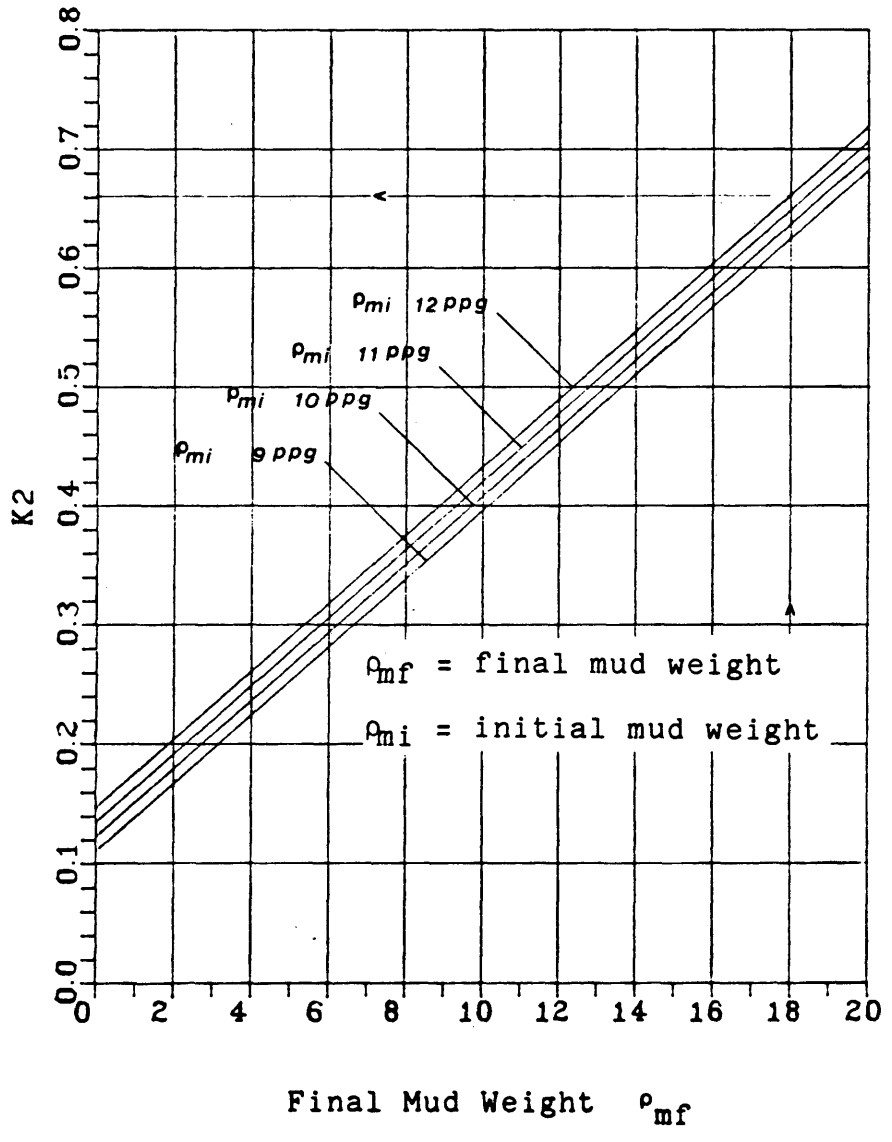
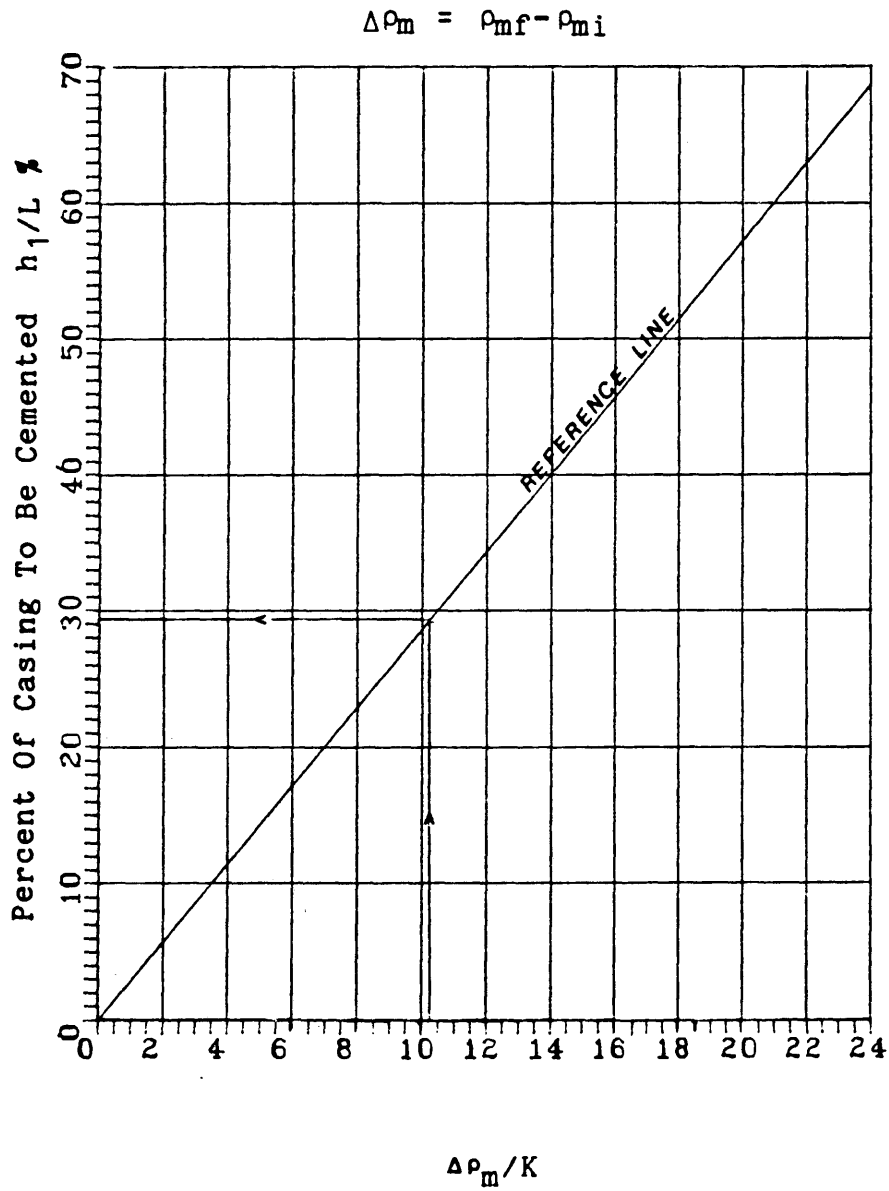


FIGURE 9
 CEMENT HEIGHT FOR ZERO BUCKLING TENDENCY
 DUE TO CHANGE IN MUD WEIGHT



change in mud weight and the two factors k_1 , and k_2 .

The following example illustrates how to use Figures 7 through 9 to calculate the cement height required for zero buckling when the mud weight changes from ρ_{mi} to ρ_{mf} after the cement sets.

Example 2: Consider the same casing used in Example 1 and Figure 6. To determine the required cement height (h), start by calculating the diameter ratio of the casing.

$$R_s = D/d = 7/(6.184) = 1.132$$

Using Figure 7, draw a vertical line from the point where R_s equals 1.132 to intersect with the cement density line of ρ_c equals 15.8 ppg. At the point of intersection draw a horizontal line to determine the value of k_1 equal to minus 0.075. Next using Figure 8, draw a vertical line from the final mud weight of ρ_{mf} equals 18 ppg to intersect with the initial mud weight line of ρ_{mi} equals 12 ppg. At the point of intersection draw a horizontal line to determine the value of k_2 equal to 0.661. Add k_1 to k_2 to determine the value of $K = .586$. Next using Figure 9, start with the value of $\Delta\rho_m/K$ equals $(18-12)/.586 = 10.23$, and draw a vertical line to intersect the reference line. At the point of intersection draw a horizontal line to determine the percent of the casing that requires cement (29.3%), the same

amount calculated in Example 1.

THE EFFECT OF TEMPERATURE CHANGE
ON CEMENT HEIGHT CALCULATIONS

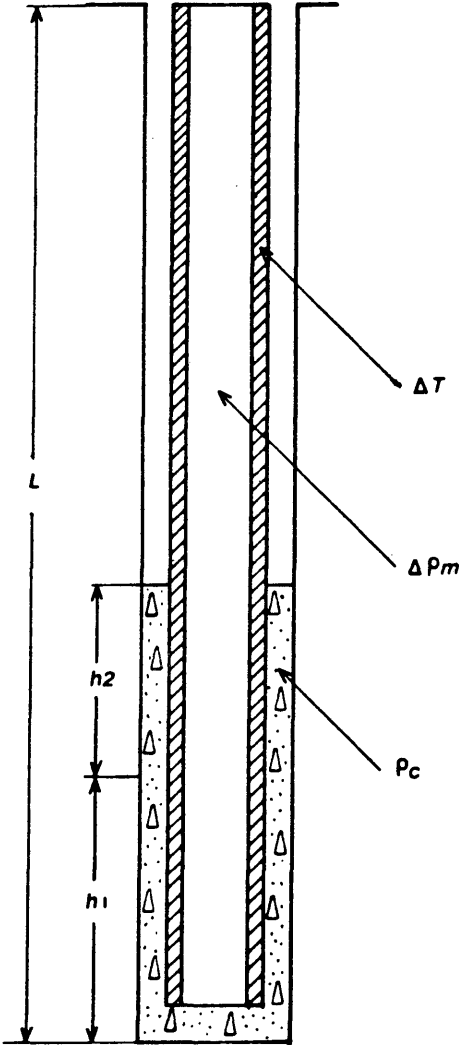
The temperature of the earth generally increases with increasing depth. For this reason after a protective casing string is cemented and landed the average temperature can increase by some ΔT as the hole is drilled deeper. Normally the increase in temperature would cause the casing to elongate because of the thermal coefficient of expansion. The casing cannot elongate however, because it is fixed at both ends. Consequently a thermal expansion causes a compression force in the casing at the freeze point that causes a positive buckling tendency. Therefore additional cement height is required to eliminate the positive buckling tendencies at the freeze point.

In Figure 10, h_2 represents the cement height required to eliminate positive buckling tendencies at the freeze point as a result of increasing the average temperature by some ΔT above the initial temperature (T_i) when the cement sets.

In Figure 10, h_1 represents the cement height required to change the mud weight from ρ_{mi} to ρ_{mf} discussed in the previous section.

In Appendix B, starting with Cox's buckling-criterion

FIGURE 10
CASING PARAMETERS FOR EXAMPLE 3



equation, Equation (16) is derived to show the relationship between the change in the average casing temperature and the cement height required to maintain a zero buckling tendency at the freeze point. The equation is not dimensionless because it is not dependent upon the total casing length (L). The equation is dependent upon the casing geometry, the specific weight of the cement slurry and the initial and final mud weights. Figure 11 shows a graphical solution of Equation (16).

Assumptions: Equation (16) is based on the following assumptions:

- 1) No change in mud weight outside of the casing after the cement sets.
- 2) The height of the fluid column inside and outside of the casing does not change after the cement sets.
- 3) The casing string consists of one size and weight.

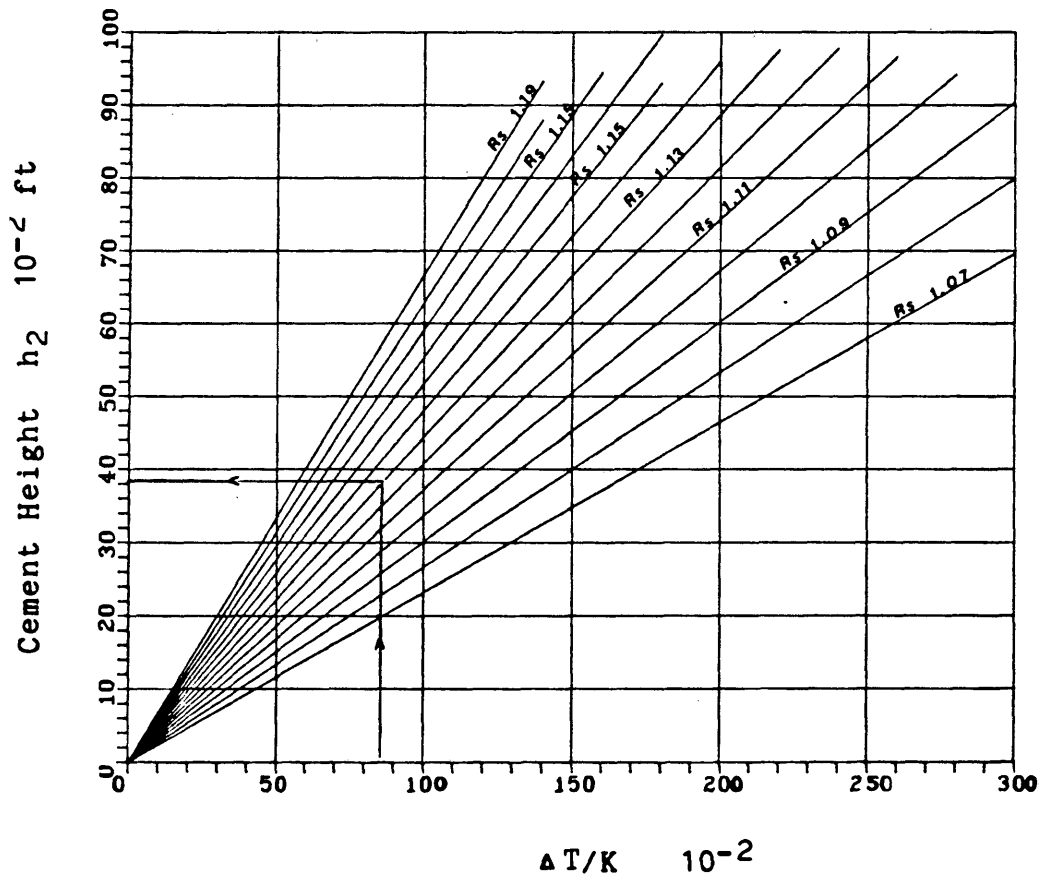
The following example illustrates the use of Figure 11.

Example 3: Consider the same casing used in Example 1 with the exception that the average temperature increases 50°F. Using the value of $K = .586$, which was determined previously in Example 2, determine the value of $\Delta T/K = 50/.586 = 85.30$. Starting with this value and using Figure 11 draw a

FIGURE 11
CEMENT HEIGHT FOR ZERO BUCKLING TENDENCY
DUE TO CHANGE IN CASING TEMPERATURE

ΔT = change in temperature

R_s = pipe steel diameter ratio D/d



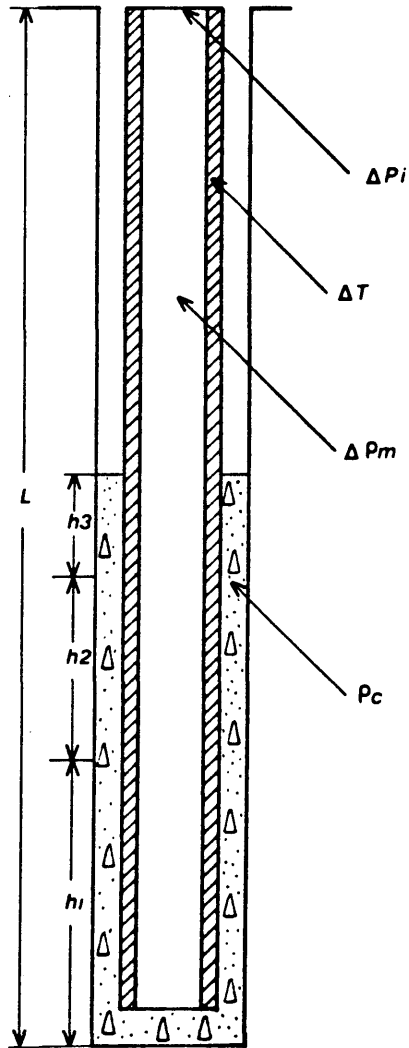
vertical line to intersect with the line that represents $R_s = (7.0/6.184) = 1.132$. At the point of intersection draw a horizontal line and read the value of h_2 (3850 ft). This represents the additional cement height required to maintain a zero positive buckling tendency at the freeze point when the casing temperature is increased by an amount of ΔT .

THE EFFECT OF INTERNAL SURFACE PRESSURE
CHANGE ON CEMENT HEIGHT CALCULATIONS

The internal surface pressure on the casing, when the cement sets, will depend upon the pump pressure that is maintained after the plug bumps. Often this pressure is reduced to zero. During later drilling operations the internal surface casing pressure could be increased. For example when holding back pressure on the annulus with the choke or testing the casing. An increase in the internal surface pressure will cause an increase in the positive buckling tendency in the casing. Therefore additional cement height is required to eliminate positive buckling tendencies at the freeze point.

In Figure 12, h_3 represents the additional cement height required to eliminate positive buckling tendencies at the freeze point as a result of increasing the internal surface pressure from by some ΔP_i above the initial internal surface pressure P_i when the cement set. In Figure 12, h_1 and h_2 represent the required cement height, after increasing the mud weight from ρ_{mi} to ρ_{mf} and after increasing the average casing temperature by some amount ΔT , as discussed in the two previous sections. In Appendix B, starting with Cox's buckling-criterion equation, Equation (17) is derived which

FIGURE 12
CASING PARAMETERS FOR EXAMPLE 4



relates the relationship between the change in the internal surface pressure and the cement height required to maintain a zero buckling tendency at the freeze point. The equation is not dimensionless because it is not dependent upon the total casing length (L) however the equation is dependent upon the casing geometry, the specific weight of the cement slurry, and the initial and final mud weight. Figure 13 shows a graphical solution of Equation (17).

Assumptions: Equation (17) is based on the following assumptions:

- 1) No change in mud weight outside of the casing after the cement sets.
- 2) The height of the fluid column inside and outside of the casing does not change after the cement sets.
- 3) The casing string consists of one size and weight.

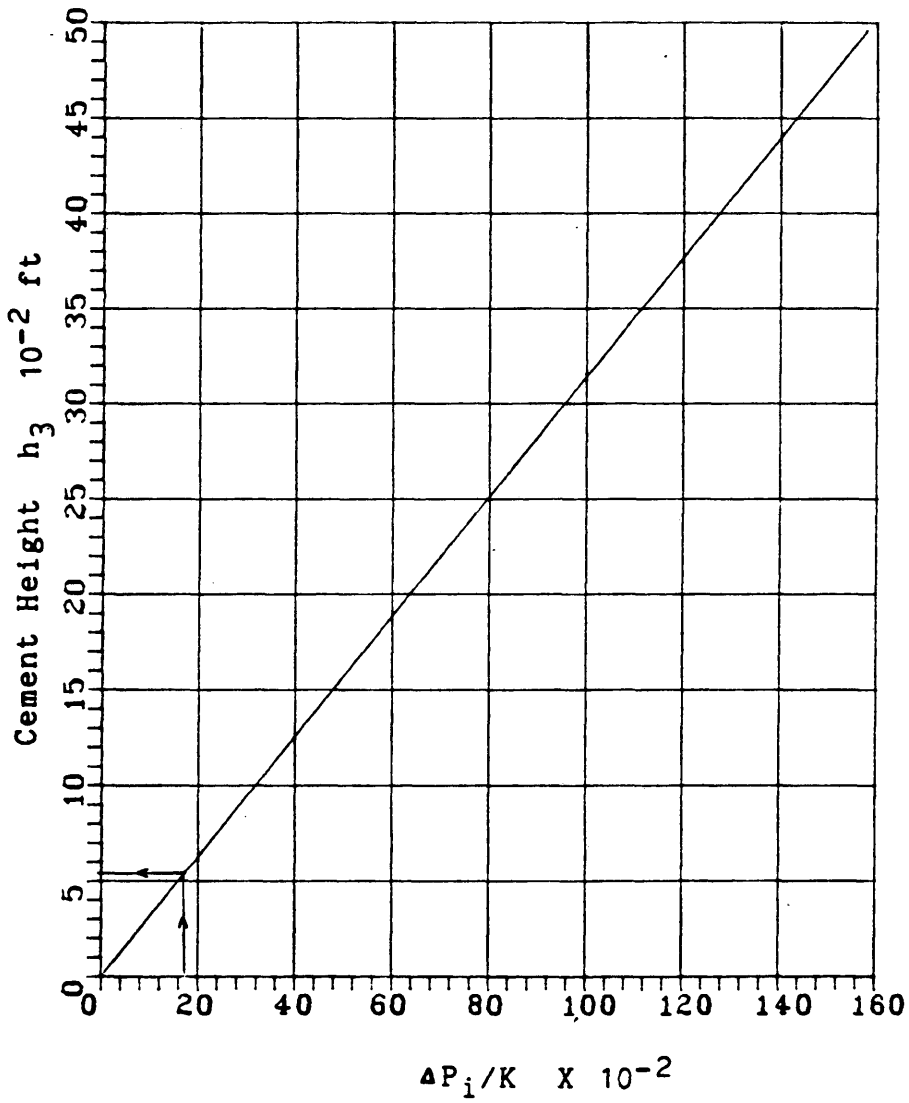
The following example illustrates the use of Figure 13.

Example 4: Consider the same casing used in Example 3 with the following additional considerations: The internal surface pressure equals zero when the cement sets and changes to 1,000 psi sometime after the casing is landed. Using the value of $K = .586$, which was determined previously in

FIGURE 13

CEMENT HEIGHT FOR ZERO BUCKLING TENDENCY
DUE TO INTERNAL SURFACE PRESSURE CHANGE

ΔP_i = internal surface pressure change



Example 2, determine the value of $\Delta P_i/K = 1,000/.586 = 1706$. Starting with this value and using Figure 13, draw a vertical line to intersect with the reference line. At the point of intersection, draw a horizontal line and read the value of h_3 (540) ft. This represents the additional cement height required to maintain a zero positive buckling tendency at the freeze point, when the internal surface pressure is increased by an amount of ΔP_i .

PICK UP WEIGHT IN LIEU OF CEMENT IN THE
ANNULUS TO PREVENT A POSITIVE BUCKLING
TENDENCY AT THE FREEZE POINT

On some occasions the amount of cement calculated in the previous sections, (h_1, h_2, h_3) may not be placed in the annulus. For example a limited amount of cement slurry could be pumped for economical reasons, an equipment failure could prevent placing the desired amount of cement slurry in the annulus or perhaps some type of logging device shows the top of the cement to be at a lower depth than desired. If the cement top in the annulus does not achieve the height calculated in the previous sections the casing must be picked up during landing by some amount (S) to prevent a positive buckling tendency at the freeze point during the later operations. In Figure 14, h_1 , h_2 , and h_3 represent the cement height required in the annulus to prevent positive buckling tendencies at the freeze point when the mud weight, average temperature and the internal pressure are changed by $\Delta\rho_m$, ΔT , and ΔP_i . The actual cement attains the height h and is short of the desired height by Δh . The casing is picked up by the value S after the cement sets.

In Appendix C, starting with Cox's equation, Equation (17) is derived to show the relationship between the

required pick up, shown as a percent of the total buoyed casing weight, and the cement height shortage, shown as a percent of the total casing length. The equation is dependent upon the casing geometry, the specific weight of the cement slurry and the initial and final mud weights. Figures 15 and 16 show a graphical solution of Equation (17). A separate graph is required for each different casing size, each different cement slurry weight, and each different initial mud weight, for example Figure 15 is for 7 inch casing weighting 29 ppf, cemented with a 15.8 ppg cement slurry, with an initial mud weight of 12 ppg. A family of curves account for varying final mud weight after the cement sets.

Assumptions: Equation (17) is based on the following assumptions:

- 1) No change in mud weight outside of the casing after the cement sets.
- 2) The height of the fluid column inside and outside of the casing does not change after the cement sets.
- 3) The casing string consists of one size and weight.

The following example illustrates the use of Figures 15 and 16 to calculate the pick up required for zero bending moments at the freeze point when the desired cement height

FIGURE 15

PICK UP WEIGHT FOR ZERO BUCKLING TENDENCY

Casing Diameter 7" OD
 Casing Weight 29 ppf
 Cement Slurry Weight 15.8 ppg
 Initial Mud Weight 12 ppg

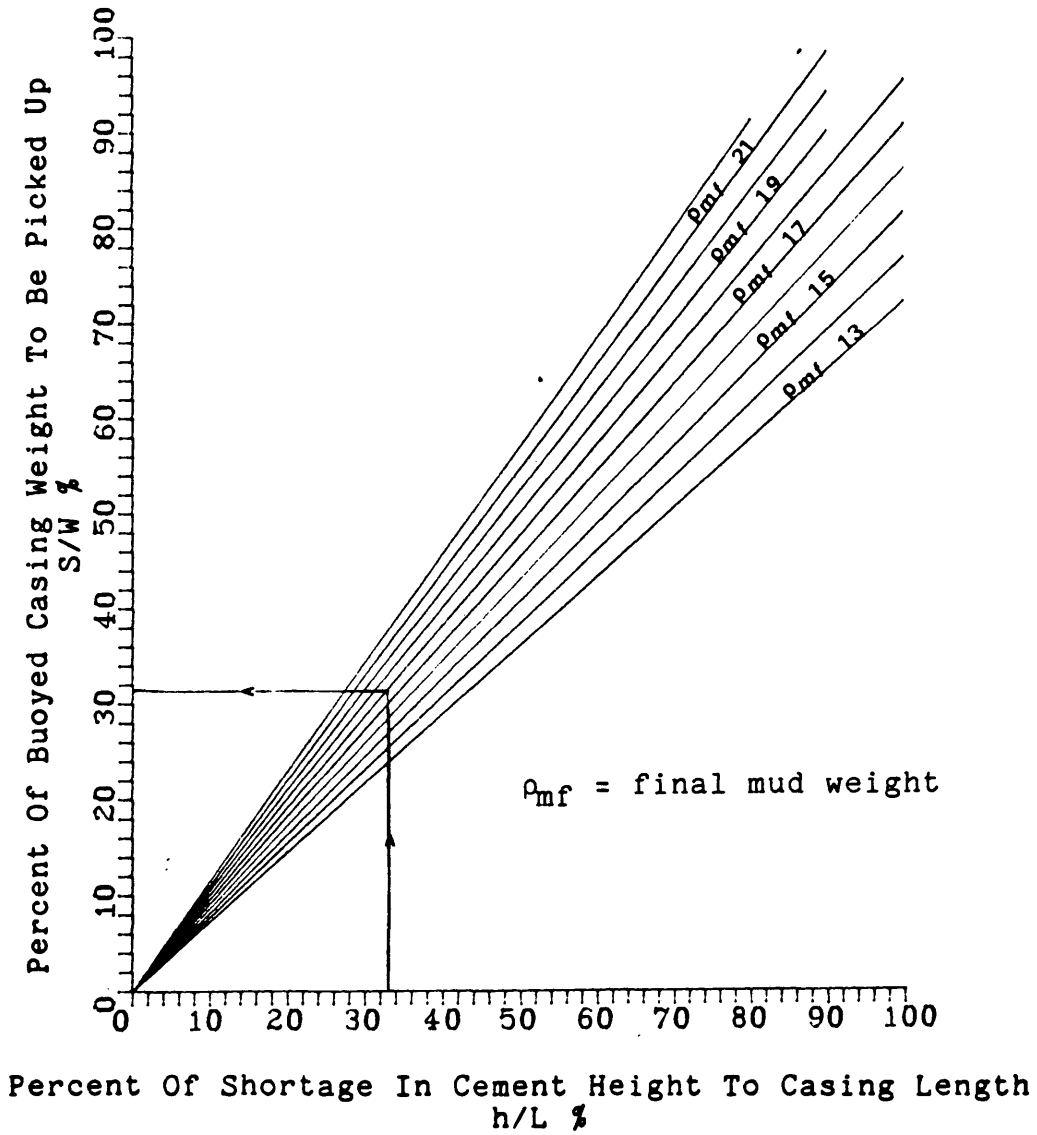
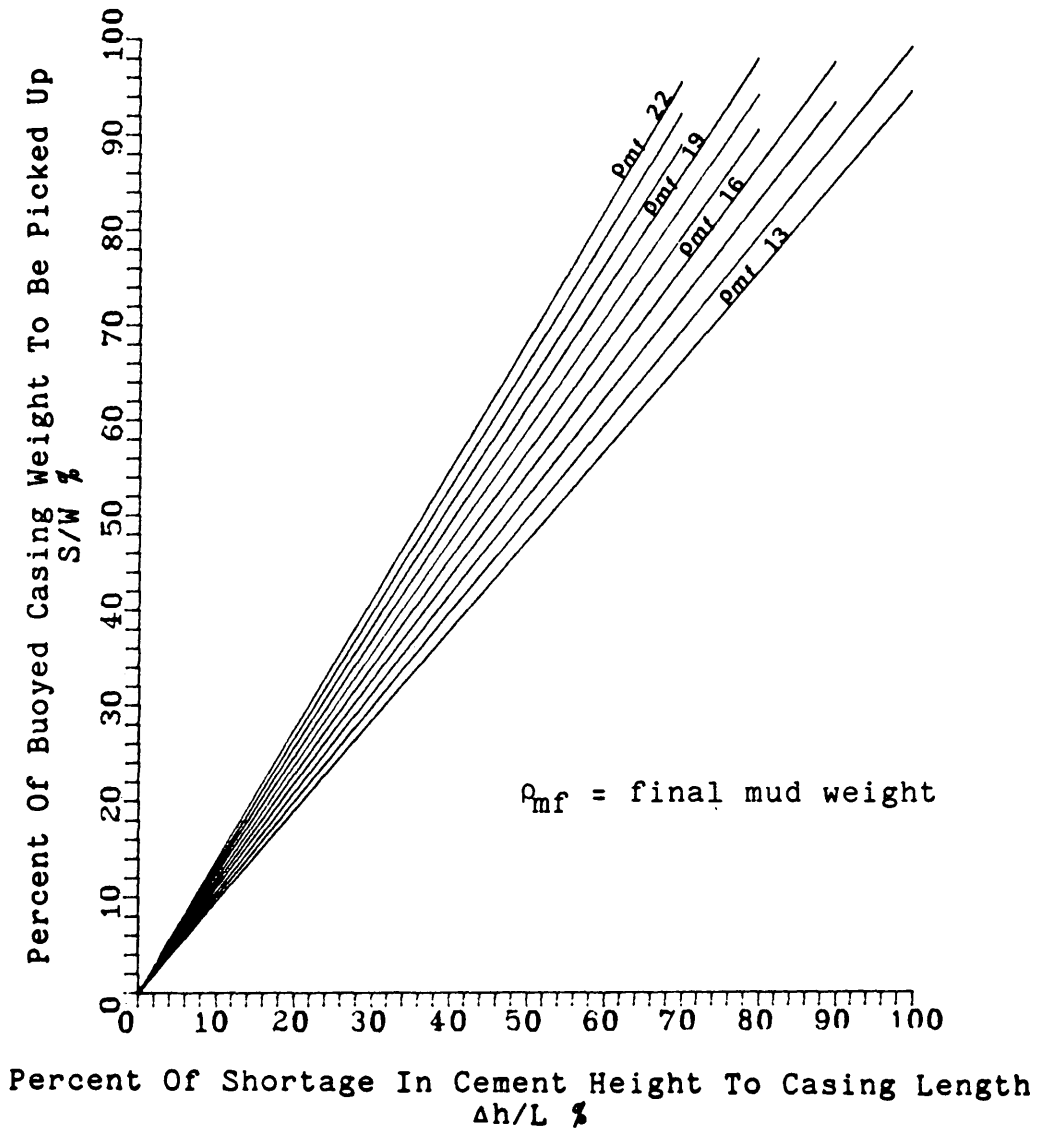


FIGURE 16

PICK UP WEIGHT FOR ZERO BUCKLING TENDENCY

Casing Diameter 7" OD
 Casing Weight 29 ppf
 Cement Slurry Weight 13.2 ppg
 Initial Mud Weight 12 ppg

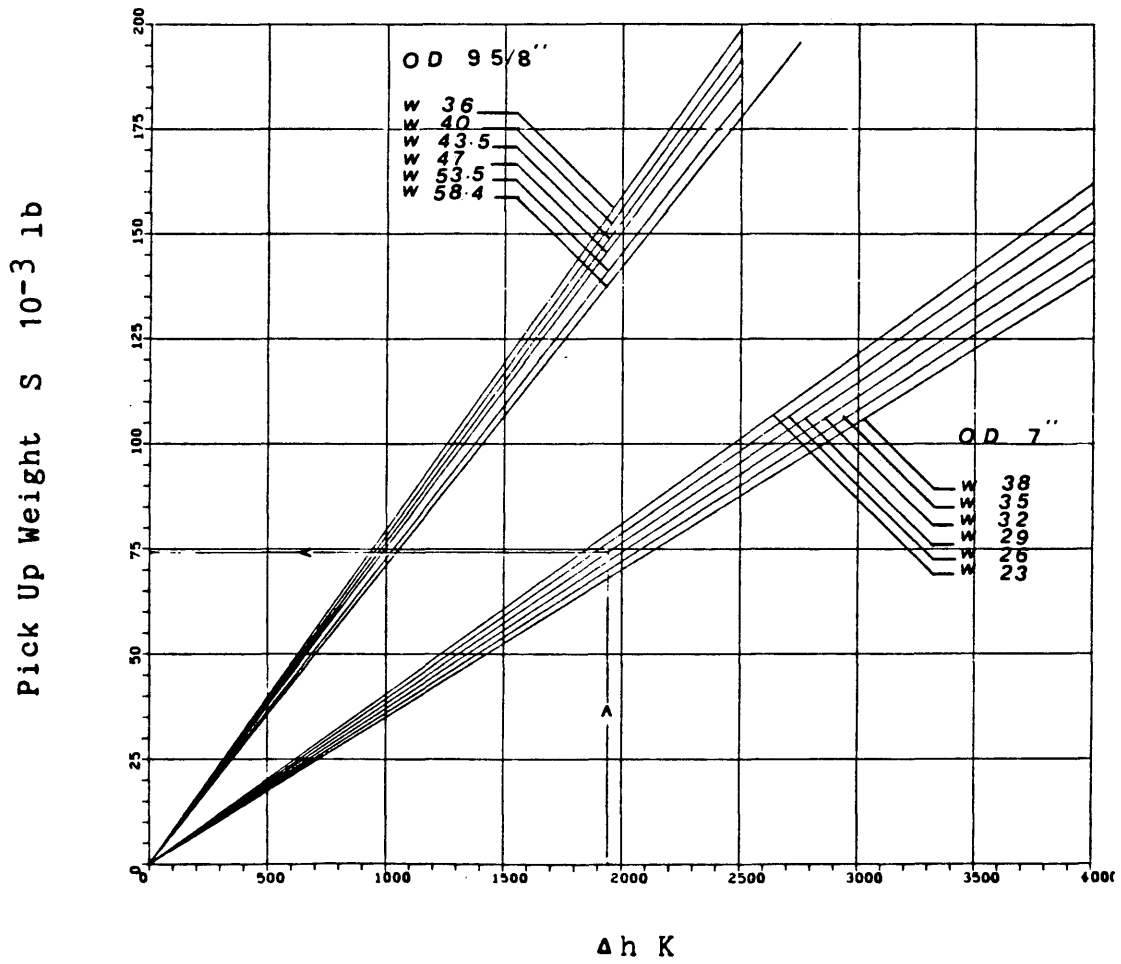


is short by a given Δh .

Example 5: Consider the same casing used in Examples 1 through 4 where $h_1 = 2930$ ft, $h_2 = 3850$ ft, and $h_3 = 540$ ft. The required cement height in the annulus to prevent a positive bending moment at the freeze point during the later operations is 7320 ft if the casing is landed as cemented. Assume for some reason the casing is cemented up to a depth of 6000 ft., i.e., a 4000 ft cement height. This represents a 3320 ft (Δh) shortage. Starting with this value of Δh determine the percentage of h/L that is short ($h/L\% = (3320)(100)/10,000 = 33.2\%$). Starting with this value and using Figure 15 draw a vertical line to intersect the 18 ppg final mud weight line. From the point of intersection draw a horizontal line and read the percent of the buoyed casing weight (31.7%) to be picked up. This amounts to $(.317)(10,000\text{ft})(29 \text{ ppg})(1 - 12/65.44) = 75,075$ lbs.

In the event a curve such as Figure 15 is not available the required cement height can still be calculated graphically. Figure 17 has been developed to calculate the pick up required to avoid a positive bending moment at the freeze point when the cement height is short by some Δh for any casing size and weight, for any cement slurry specific

FIGURE 17
 PICK UP WEIGHT FOR ZERO BUCKLING TENDENCY



weight and for any initial and final mud weight.

Figure 17 is a graphical solution to Equation (17) in Appendix B. It shows the relationship between the required pick up in pounds and the factor ΔhK , where Δh is the cement shortage in feet and K is a factor defined by Equation (11) in Appendix B.

Example 6: Consider the same casing used in Example 5. Starting with a cement shortage of 3320 ft and $K = .586$, calculated previously in Example 2, determine the value of $\Delta hK = (3320)(.586) = 1946$. Starting with this value and using Figure 17 draw a vertical line to intersect the 7 in. casing 29 ppf reference line. From the point of intersection draw a horizontal line and read the actual pick up 74,500 lbs. The same amount calculated in Example 5.

GRAPH EVALUTATION

Figures 2 through 5 show the functional relationship between the mud ratio (R_m) and the percentage of casing to be cemented for zero buckling tendency at the freeze point when the mud density is increased after the cement sets. For a given casing size and mud ratio the graphs show that as the casing weight increases, the initial mud weight has less effect on the required percentage of h/L to be cemented. A critical value occurs when $R_s^2 B_c$ is equal to one. In Figure 2 the critical casing weight is approximately 32 ppf. At that time the graph shows the function between the percent of h/L to be cemented and the mud ratio (R_m) is not effected by the initial mud weight (ρ_{mi}). However the mud ratio increases when the initial mud weight is lowered so the percent of h/L to be cemented always increases when the initial mud weight is decreased, but at a decreasing rate as the weight of the casing increases. Figure 3 shows the critical value occurs between 23 ppf and 29 ppf. This indicates that when lighter cement slurry is used the initial mud weight has less effect on the percent of h/L to be cemented.

The physical significance of Figure 7 is that a lighter cement slurry density will reduce the percent of h/L

required to be cemented in any of the cases considered. This is easily seen because decreasing ρ_c will always increase the value of K used in Equations 14 through 16 in Appendix B. The reverse is true when picking up the pipe to allow for a cement shortage. A greater pick up is always required for any given cement shortage (Δh) when the density of the cement slurry is reduced.

CONCLUSIONS

1. A functional relation has been developed between the percent of the casing to be cemented to prevent positive bending moments at the freeze point after the cement sets and the changes to the internal mud density, the average casing temperature and the internal surface pressure expected to occur after the cement sets. This functional relation allows the engineer to design the primary cement job based on known future operations and anticipated contingencies.

2. A functional relation has been developed between a known cement slurry shortage and the required pick up to be applied before landing the casing. This functional relation allows the supervisor at the well location to adjust the pick up, for the actual cement slurry height observed, when landing the casing.

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APPENDIX A
 CEMENT HEIGHT REQUIRED FOR ZERO BUCKLING
 TENDENCY AT THE FREEZE POINT WHEN THE MUD
 WEIGHT IS INCREASED AFTER THE CEMENT SETS

Starting with Cox's (3) Equation (13), Appendix A which is

$$\begin{aligned}
 \Delta S > 59.8 w' \Delta t - hw + .785 D_e^2 [hd_c - .7L \Delta d_e \\
 - 0.4 \Delta P_e + (d_e + \Delta d_e)(.4m + .3m^2/L)] \\
 - .785 D_i^2 [hd_i - .7L \Delta d_i - 0.4 \Delta P_i \\
 + (d_i + \Delta d_i)(.4n + .3n^2/L)] \quad (1)
 \end{aligned}$$

Applying the assumptions stated earlier i.e.

$$\Delta t = 0$$

$$\Delta P_e = 0$$

$$\Delta P_i = 0$$

$$\Delta d_e = 0$$

$$\Delta d_i \neq 0$$

$$n = 0$$

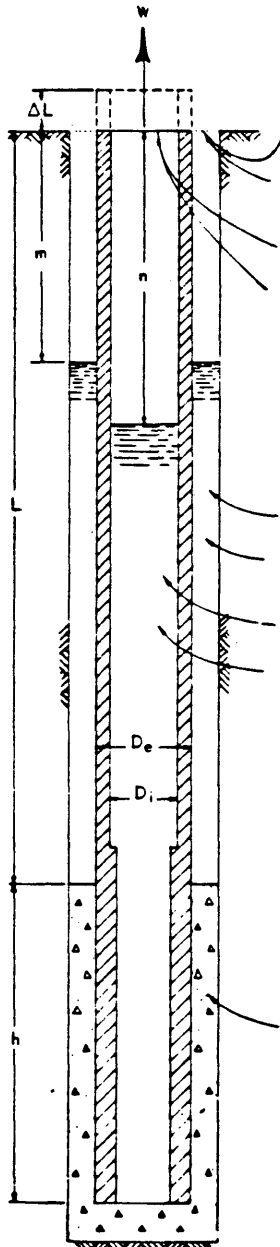
$$m = 0$$

$$\Delta S = 0$$

and changing to the notation of this paper Cox's equation

FIGURE 18

PARAMETERS OF THE BUCKLING-CRITERIA EQUATION ($C_{ox}^{(3)}$)



- W = wellhead load, lb.
- ΔS = pickup when hanging casing, lb ($-\Delta S$ = slack-off).
- ΔL = pickup when hanging casing, in. ($-\Delta L$ = slack-off).
- P_o = surface pressure outside casing when cement sets, psi.
- ΔP_o = change in surface pressure outside casing after cement sets, psi.
- P_i = surface pressure inside casing when cement sets, psi.
- ΔP_i = change in surface pressure inside casing after cement sets, psi.
- m = fluid-level drop outside casing after cement sets, ft.
- n = fluid-level drop inside casing after cement sets, ft.
- Δt = average change in casing temperature above cement top after cement sets, deg F.
- d_o = fluid weight outside casing when cement sets, lb per gal.
- Δd_o = change in fluid weight outside casing after cement sets, lb per gal.
- d_i = fluid weight inside casing when cement sets, lb per gal.
- Δd_i = change in fluid weight inside casing after cement sets, lb per gal.
- D_o = outside diameter of casing, in. ($A_o = 0.785 D_o^2$ sq in.).
- D_i = inside diameter of casing above cement top, in.
For term B_i use inside diameter below cement top.
For term W_c use average inside diameter in string ($A_i = 0.785 D_i^2$ sq in.).
- w = weight of casing in cemented zone, lb per ft.
- w' = weight of casing above cement top, lb per ft.
- w'' = average weight of casing in string, lb per ft.
- d_c = cement slurry weight, lb per gal.
- L = distance from cement top to casing hanger, ft.
- h = distance from casing shoe to cement top, ft.

Note: All Δ or change quantities plus when increase and minus when decrease.

becomes

$$0 > -hw + .785 D^2 h\rho_c - .785 d^2 h\rho_{mi} + .785 d^2 .7 (L-h) \Delta\rho_m \quad (2)$$

Substituting $.785d^2 = A_i$ and $.785D^2 = A_e$ and rearranging equation (2) becomes

$$h(w + \rho_{mi} A_i - \rho_c A_e) - .7(L-h) A_i \Delta\rho_m > 0 \quad (3)$$

This equation states that zero buckling tendency occurs at the freeze point when the argument is equal to or greater than zero. Using the least value, i.e. equal to zero, the equation can be rearranged to

$$h(w + \rho_{mi} A_i - \rho_c A_e) = .7 (L-h) A_i \Delta\rho_m \quad (4)$$

Substituting $w = \rho_s (A_e - A_i)$

$$h[\rho_s (A_e - A_i) + \rho_{mi} A_i - \rho_c A_e] = .7(L-h) A_i \Delta\rho_m \quad (5)$$

Dividing both sides by L and rearranging

$$\frac{h}{L} (\rho_s A_e - \rho_s A_i + \rho_{mi} A_i - \rho_c A_e) = (1-h/L)(.7A_i \Delta\rho_m) \quad (6)$$

Solving equation (6) for h/L

$$h/L = \frac{.7 A_i \Delta \rho_m}{A_e(\rho_s - \rho_c) - A_i(\rho_s - \rho_{mi}) + .7 A_i \Delta \rho_m} \quad (7)$$

Dividing both the numerator and the denominator of the right hand member of equation (7) by A_i and rearranging

$$h/L = \frac{.7 \Delta \rho_m}{(A_e/A_i) \rho_s (1 - \rho_c/\rho_s) - \rho_s (1 - \rho_{mi}/\rho_s) + .7 \Delta \rho_m} \quad (8)$$

Defining the following dimensionless parameters that are related to the casing geometry, the initial mud weight and the specific weight of the cement slurry

$$Rs^2 = A_e/A_i = D^2/d^2 \quad (9)$$

$$Bc = (1 - \rho_c/\rho_s) \quad (10)$$

$$Bm = (1 - \rho_{mi}/\rho_s) \quad (11)$$

$$Rm = \rho_{mf}/\rho_{mi} \quad (12)$$

Substituting the dimensionless parameters into equation (8) and noting that $\Delta \rho_m = \rho_{mi} [(\rho_{mf}/\rho_{mi}) - 1]$

$$h/L = \frac{.7 \rho_{mi} (Rm - 1)}{\rho_s (Rs^2 Bc - Bm) + .7 \rho_{mi} (Rm - 1)} \quad (13)$$

multiplying both sides of the equation by 100 changes h/L to percent L

$$\%L = \frac{70 \rho_{mi} (Rm-1)}{\rho_s (Rs^2 Bc - Bm) + .7 \rho_{mi} (Rm-1)} \quad (14)$$

Equation (14) requires consistent units, i.e. ρ_s must be in the same unit as ρ_m and ρ_c . The equation can be changed to any convenient field units by substituting the actual specific weight for steel, i.e. using pounds per gallon then ρ_s equals 65.45 ppg.

$$\%L = \frac{100 (Rm-1)}{(93.5/\rho_{mi}) (Rs^2 Bc - Bm) + (Rm-1)} \quad (15)$$

When using Equation (15), the fluid weights are in pounds per gallon and the following equations apply

$$Bc = \frac{65.45 - \rho_c}{65.45} \quad (10a)$$

$$Bm = \frac{65.45 - \rho_{mi}}{65.45} \quad (11a)$$

APPENDIX B

CEMENT HEIGHT REQUIRED FOR ZERO BUCKLING TENDENCY
AT THE FREEZE POINT WHEN THE MUD WEIGHT, AVERAGE
TEMPERATURE, AND INTERNAL SURFACE PRESSURE ARE
ALL CHANGED AFTER THE CEMENT SETS.

Starting with Cox's (3) Equation (13), Appendix A which is:

$$\begin{aligned} \Delta S > 59.8 w' \Delta t - hw + .785 D_e^2 [hd_c - .7L \Delta d_e \\ - 0.4 \Delta P_e + (d_e + \Delta d_e)(.4m + .3m^2/L)] \\ - .785 D_i^2 [hd_i - .7L \Delta d_i - 0.4 \Delta P_i \\ + (d_i + \Delta d_i) (.4n + .3n^2/L)] \end{aligned} \quad (1)$$

Applying the assumptions stated earlier i.e.

$$\Delta t \neq 0$$

$$\Delta P_e = 0$$

$$\Delta P_i \neq 0$$

$$\Delta d_e = 0$$

$$\Delta d_i \neq 0$$

$$n = 0$$

$$m = 0$$

$$\Delta S = 0$$

$$w' = w$$

and changing to the notation of this paper, Cox's equation

becomes

$$S > 59.8 w \Delta t - hw + .785 D^2 h \rho_c - .785 d^2 [h \rho_{mi} - .7 (L-h) \Delta \rho_m - .4 \Delta P_i] \quad (2)$$

Substituting $.785 d^2 = A_i$ and $.785 D^2 = A_e$ and rearranging Equation (2) becomes

$$h (-w + A_e \rho_c - A_i \rho_{mi}) + A_i .7(L-h) \Delta \rho_m + A_i .4 \Delta P_i + 59.8 w \Delta T < S \quad (3)$$

This equation states that zero buckling tendency occurs at the freeze point when the argument is equal to or less than the pick up force. Using the minimum pick up force the equation can be rearranged to:

$$A_i .7 (L-h) \Delta \rho_m = S + h (w - A_e \rho_c + A_i \rho_{mi}) - A_i .4 \Delta P_i - 59.8 w \Delta T \quad (4)$$

Substituting $w = \rho_s (A_e - A_i)$

$$A_i .7(L-h) \Delta \rho_m = S + h (A_e \rho_s - A_i \rho_s - A_e \rho_c + A_i \rho_{mi}) - A_i .4 \Delta P_i - 59.8 \Delta T \rho_s (A_e - A_i) \quad (5)$$

Dividing by A_i

$$\begin{aligned} .7 (L-h)\Delta\rho_m &= S/A_i + h[\rho_s(A_e/A_i - 1) - \rho_c(A_e/A_i) + \rho_{mi}] \\ &- .4\Delta P_i - 59.8 \Delta T \rho_s (A_e/A_i - 1) \end{aligned} \quad (6)$$

Substituting $Rs^2 = A_e/A_i$

$$\begin{aligned} .7 (L-h)\Delta\rho_m &= S/A_i + h[\rho_s(Rs^2 - 1) - (\rho_c Rs^2 + \rho_{mi})] \\ &- .4 \Delta P_i - 59.8 \Delta T \rho_s (Rs^2 - 1) \end{aligned} \quad (7)$$

Converting to oil field units, i.e. pounds per gallon, substituting $A_i = .785 d^2$ and rearranging

$$\begin{aligned} h[2.67(Rs^2 - 1) - .0408 Rs^2 \rho_c + .0408 \rho_{mi} + .0286 \Delta\rho_m] \\ = .0286 L \Delta\rho_m + 159.67 (Rs^2 - 1) \Delta T + .314 \Delta P_i - S/d^2 \end{aligned} \quad (8)$$

$$\text{let } k_1 = 2.67 (Rs^2 - 1) - .0408 Rs^2 \rho_c \quad (9)$$

$$k_2 = .0408 \rho_{mi} + .0286 \Delta\rho_m \quad (10)$$

$$\text{and } K = k_1 + k_2 \quad (11)$$

Substituting Equations (9), (10), and (11) into Equation (8)

$$\begin{aligned}
 hK &= .0286 L \Delta \rho_m + 159.67 (R_s^2 - 1) (\Delta T) \\
 &+ 314 \Delta P_i - S/d^2
 \end{aligned}
 \tag{12}$$

Solving for h

$$\begin{aligned}
 h &= .0286 L (\Delta \rho_m / K) + 159.67 (R_s^2 - 1) (\Delta T / K) \\
 &+ .314 (\Delta P_i / K) - S / (d^2 K)
 \end{aligned}
 \tag{13}$$

$$\text{Let } h_1 = .0286 L (\Delta \rho_m / K) \tag{14}$$

$$h_2 = 159.67 (R_s^2 - 1) (\Delta T / K) \tag{15}$$

$$h_3 = .314 (\Delta P_i / K) \tag{16}$$

$$\Delta h = S / (K d^2) \tag{17}$$

Then the actual cement height (h) when the bending moment at the freeze point is zero will be:

$$h = h_1 + h_2 + h_3 - \Delta h \tag{18}$$

APPENDIX C

DERIVATION OF THE EQUATION THAT
RELATES THE CHANGE IN PICK UP TO A
CHANGE IN CEMENT HEIGHT WHEN THE MUD
DENSITY HAS BEEN CHANGED FROM ρ_{mi} to ρ_{mf} .

Starting with Cox's (3) Equation (13), Appendix A which is

$$\begin{aligned} \Delta S > 59.8 w' \Delta t - hw + .785 D_e^2 [hd_c - .7L \Delta d_e \\ - 0.4 \Delta P_e + (d_e + \Delta d_e)(.4m + .3m^2/L)] \\ -.785 D_i^2 [hd_i - .7L \Delta d_i - 0.4 \Delta P_i \\ + (d_i + \Delta d_i) (.4n + .3n^2/L)] \end{aligned} \quad (1)$$

Applying the assumptions stated earlier and used in Appendix A with the exception that S is not equal to zero, i.e.

$$\begin{aligned} \Delta t &= 0 \\ \Delta P_e &= 0 \\ \Delta P_i &\neq 0 \\ \Delta d_e &= 0 \\ \Delta d_i &\neq 0 \\ n &= 0 \\ \Delta \rho_m &= 0 \\ \Delta S &\neq 0 \end{aligned}$$

and changing to the notation of this paper Cox's equation becomes

$$S > -hw - .785d^2 h\rho_{mi} + .785D^2 h\rho_c + .785d^2 (.7 L\Delta\rho_m) \quad (2)$$

Substituting $.785 d^2 = A_i$ and $.785 D^2 = A_e$ and rearranging Equation (2) becomes

$$S + h (w + \rho_{mi} A_i - \rho_c A_e) - .7(L-h) A_i \Delta\rho_m > 0 \quad (3)$$

This equation states that zero buckling tendency occurs at the freeze point when the argument is equal to or greater than zero. Using the least value, i.e. equal to zero the equation can be rearranged to

$$S = .7 (L-h) A_i \Delta\rho_m - h (w + \rho_{mi} A_i - \rho_c A_e) \quad (4)$$

Substituting $w = \rho_s (A_e - A_i)$

$$S = .7 (L-h) A_i \Delta\rho_m - h (\rho_s A_e - \rho_s A_i + \rho_{mi} A_i - \rho_c A_e) \quad (5)$$

Dividing by the buoyed weight of the total casing string (W)

and rearranging

$$S/W = (1/W) [.7(L-h) A_i \Delta \rho_m - h [A_e (\rho_s - \rho_c) - A_i (\rho_s - \rho_{mi})]] \quad (6)$$

The buoyed weight of the casing string is equal to the weight in air times the buoyancy factor

$$W = \rho_s (A_e - A_i) L (1 - \rho_{mi}/\rho_s) \quad (7)$$

Substituting Equation (7) into the right side member of Equation (6)

$$S/W = \frac{.7(L-h)A_i \Delta \rho_m - h[A_e(\rho_s - \rho_c) - A_i(\rho_s - \rho_{mi})]}{\rho_s L (A_e - A_i)(1 - \rho_{mi}/\rho_s)} \quad (8)$$

Rearranging the equation

$$S/W = \frac{.7(L-h)A_i \Delta \rho_m - h \rho_s [A_e(1 - \rho_c/\rho_s) - A_i(1 - \rho_{mi}/\rho_s)]}{\rho_s L (A_e - A_i)(1 - \rho_{mi}/\rho_s)} \quad (9)$$

Dividing the numerator and denominator of the right hand member by A_i and rearranging

$$S/W = \frac{.7(L - h)\Delta\rho_m}{\rho_s L[(A_e/A_i) - 1][1 - \rho_{mi}/\rho_s]} - \frac{h[(A_e/A_i)(1 - \rho_c/\rho_s) - (1 - \rho_{mi}/\rho_s)]}{L[(A_e/A_i) - 1][1 - \rho_{mi}/\rho_s]} \quad (10)$$

Defining the following dimensionless parameters that are related to the casing geometry, the specific weight of the cement slurry, and the mud weight.

$$Rs^2 = A_e/A_i = D^2/d^2 \quad (11)$$

$$Bc = (1 - \rho_c/\rho_s) \quad (12)$$

$$Bm = (1 - \rho_{mi}/\rho_s) \quad (13)$$

$$Rm = \rho_{mf}/\rho_{mi} \quad (14)$$

Substituting the dimensionless parameters into Equation (10)

$$S/W = \frac{.7(1 - h/L)\Delta\rho_m}{\rho_s(Rs^2 - 1)Bm} - \frac{(h/L)(Rs^2 Bc - Bm)}{(Rs^2 - 1)Bm} \quad (15)$$

taking the derivative of S/W with respect to h/L

$$\frac{\partial(S/W)}{\partial(h/L)} = - \frac{.7\Delta\rho_m}{\rho_s(Rs^2 - 1)Bm} - \frac{Rs^2 Bc - Bm}{(Rs^2 - 1)Bm} \quad (16)$$

Converting to oil field units, changing h to percent of L and S to percent of W and solving equation (16) in terms of delta values

$$\left(\frac{\Delta S\%}{W}\right) = - \left(\frac{\Delta h\%}{L}\right) \frac{.0107 \rho_m + R_s^2 B_c - B_m}{(R_s^2 - 1) B_m} \quad (17)$$

Since Δh represents the shortage in the cement column, it has a negative sign which makes the change in the pick up ΔS a positive number. When using Equation (17) the fluid weights are in pounds per gallon and the following equations apply

$$B_c = \frac{65.45 - \rho_c}{65.45} \quad (12a)$$

$$B_m = \frac{65.45 - \rho_{mi}}{65.45} \quad (13a)$$

APPENDIX D
NOMENCLATURE

English Symbols

- A_i = Internal cross sectional area of the casing.
- A_e = External cross sectional area of the casing.
- B_m = $1 - \rho_{mi}/\rho_s$
- B_c = $1 - \rho_c/\rho_s$
- D = Outside diameter of pipe.
- d = Inside diameter of pipe.
- h_1 = Cement height required due to change in mud weight inside the casing after the cement sets.
- h_2 = Cement height required due to change in average casing temperature after the cement sets.
- h_3 = Cement height required due to change in surface pressure inside the casing after the cement sets.
- h = Length of cemented part of casing.
- k_1 = A function of casing geometry and specific weight of cement slurry.
- k_2 = A function of the initial and final mud weight.
- K = $k_1 + k_2$.
- L = Total casing length.
- R_m = ρ_{mf}/ρ_{mi} = Ratio between mud weight after and before cement sets.
- R_s = D/d = Diameter ratio of the steel pipe.
- S = Pick up weight of the casing (-S = slack off).

W = Buoyed weight of the casing.

w = Weight of the casing in air.

w_s = Buoyed weight of one foot of the steel.

Greek Symbols

Δt = Change in average casing temperature in degrees F.

ΔP_i = Change in surface pressure inside the casing.

ρ_s = Weight per unit volume of steel.

ρ_c = Weight per unit volume of cement slurry.

ρ_{mi} = Weight per unit volume of mud weight before cement sets.

ρ_{mf} = Weight per unit volume of mud weight after cement sets.

$\Delta \rho_m$ = Change in internal liquid weight per unit volume after cement sets.

Δh = Shortage in cement height.

SUBSCRIPTION

e = external

i = internal or initial

m = mud

mf = final mud

mi = initial mud

s = steel