Thermal model of a new concept for hydrate control during drilling

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Hydrate gas influx during Arctic drilling can be controlled by increasing the decomposition temperature through the use of higher mud weights. Hydrate equilibrium conditions are changed so that further decomposition is prevented. The WELLTEMP computer code has been used to simulate the drilling of an Arctic off-shore Panarctic well in which the temperature and decomposition radii in the hydrate interval are predicted. The problem formulation is described and the predicted results are interpreted and discussed.

L'afflux d'hydrates de gaz, lors du forage dans l'Arctique, peut-être limité en augmentant leur température de décomposition au moyen de boues de masse plus élevée. Les conditions d'équilibre des hydrates sont ainsi modifiées et on évite leur décomposition. On a utilisé le code informatique WELLTEMP pour simuler le forage d'un puits de Panarctic dans la mer Arctique et prévoir les rayons de décomposition et les températures dans l'intervalle contenant les hydrates. On décrit la formulation du problème et on commente et interprète les résultats prévus.

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[Ed. note: In the figures, data have not been converted to SI units.]

Introduction

Drilling of formations containing gas hydrates requires knowledge of downhole temperatures in order to properly control hydrate decomposition (Bily and Dick 1974; Goodman 1980; Pui and Kljucec 1975). Panarctic has demonstrated that hydrate gas influx after hydrate intervals are penetrated during Arctic drilling can be controlled by increasing the decomposition temperature through use of higher mud weights (Franklin 1980). The intent is not to increase mud weight to overbalance the decomposed hydrate gas pressure, but simply to change the hydrate equilibrium conditions at the hydrate face so that further decomposition is prevented. This concept is particularly useful for control of hydrate gas influx during tripping and setting of casing.

To test this concept, Enertech's WELLTEMP computer code has been used to simulate the drilling process of a Panarctic well in the Arctic off-shore and to predict temperatures and decomposition radii in the hydrate interval. The major features of the WELLTEMP thermal simulator are:

1. The flowing stream energy balance is fully transient with vertical heat convection and radial heat conduction.
2. A composite of annular materials makes up the wellbore description, including the steel, cement, and fluids present in the well. Fully transient radial heat conduction accounts for the wellbore region. Material heat capacities and natural convection in annular fluids are both included.
3. Radial and vertical heat conduction account for the transient energy transfer in the soil. A key feature in the thermal simulator is the direct coupling of soil and well temperature calculations.

Model Formulation

The WELLTEMP computer program requires user input data for the well geometry, flow history, fluid properties, and geothermal gradient. Other data required by WELLTEMP, such as soil thermal properties, are provided internal to the program. The actual casing configuration for the Panarctic well is shown in Figure 1. Water depth is 902 ft (275 m) with 20-inch diameter casing cemented from 1148 ft (350 m) to the sea-floor. Drill pipe is 5 inches in diameter and the riser 16 inches in diameter. Of interest is the hydrate interval at 2116 ft (645 m) which is exposed during drilling of the hole down to 5282 ft (1610 m).

Drilling Schedule

Drilling involves both circulation and shut-in time periods. Fluid circulation occurs during depth penetration, hole cleaning, and cementing. During tripping of drill pipe, running of casing, pump shutdowns, and logging, the fluid is essentially static in the hole.

For the Panarctic well, the circulation and shut-in data during drilling are plotted (Figure 2) to give time-depth profiles for circulation plus shut-in

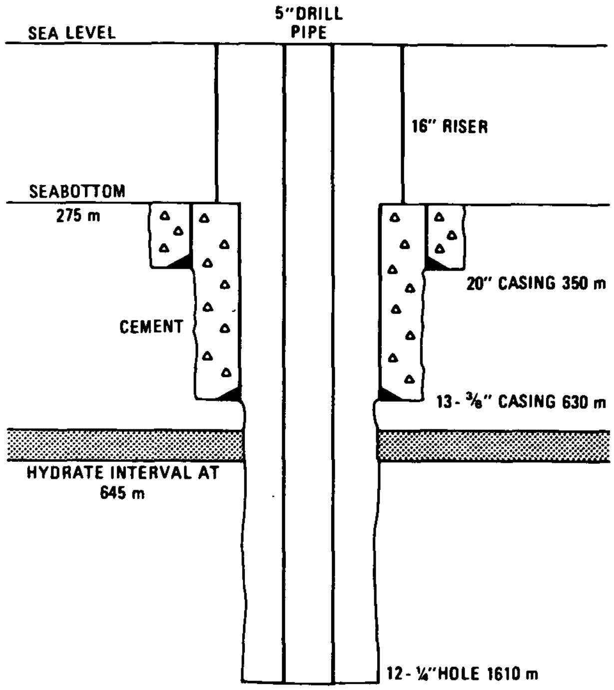

FIGURE 1. Casing program for Panarctic well.

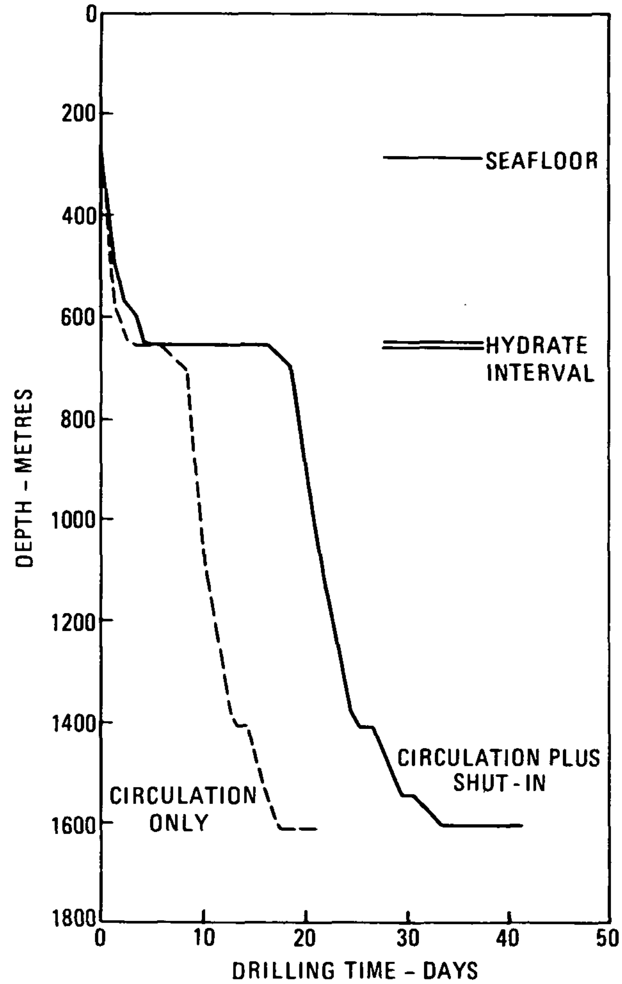

FIGURE 2. Drilling schedule for Panarctic well.

periods. Circulation in Figure 2 represents total time of circulation, whether penetrating or not.

For the heat transfer calculations, WELLTEMP divides each day of drilling into a circulating part and shut-in part, hence, WELLTEMP input requires the time of circulation for each 24-hour period. From a plot of circulating time *versus* total time (Figure 3), the circulating part of each day can be estimated. For example, during the first four days of drilling down to 2066 ft (630 m) the cumulative circulating time is 2.5 days (60 hours), indicating an average of 15 hours per day of circulation for the four-day period.

The plot of drilling depth *versus* time (Figure 4) was compiled and simplified for application of WELLTEMP. The plot is divided into five distinct sections of constant drilling penetration rate. For each section the average circulation time per day, as determined from Figure 3, is specified along with the circulation rate. These distinct time periods are handled explicitly in WELLTEMP since the code allows flowing fluid parameters to be changed as often as needed. Specific time increments and well conditions used for WELLTEMP input data in the Panarctic well simulation are tabulated (Table 1). Time increment numbers 1, 2, 4, and 5 correspond to the first four sections in Figure 4. Increment number 3 is inserted because of a change in mud inlet temperature. The last six time increments constitute the final section in Figure 4 and represent the hole-cleaning, weighting-up, and tripping conditions while at bottomhole.

Note that the drill depth in time increments 1 and 2 is 1997 ft (609 m) instead of 2055 ft (630 m) (*see* Figure 4). This minor adjustment has been made in order to properly simulate the circulation of time increment number 2 without circulating past the hydrate zone which is modelled at 2200 ft (671 m).

Properties

Density, plastic viscosity, and yield point of the drilling fluid are required as input to WELLTEMP. Thermal properties of the mud are calculated by WELLTEMP from density, viscosity, and yield point. Viscosity is allowed to change with predicted temperatures and is updated within WELLTEMP as

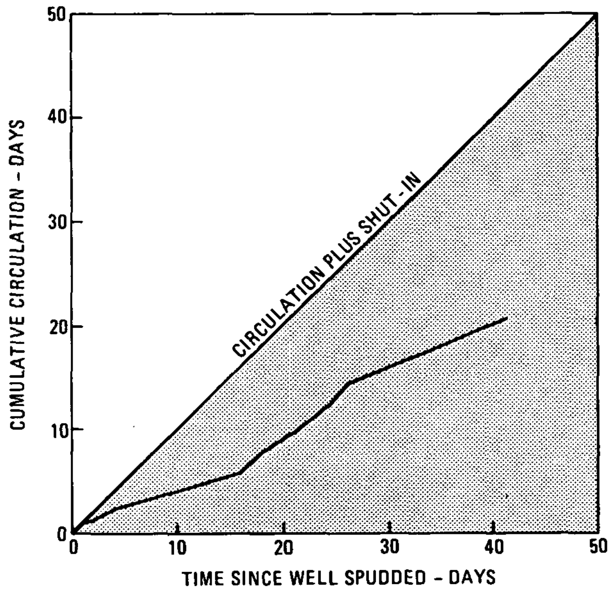

FIGURE 3. Circulation history for Panarctic well.

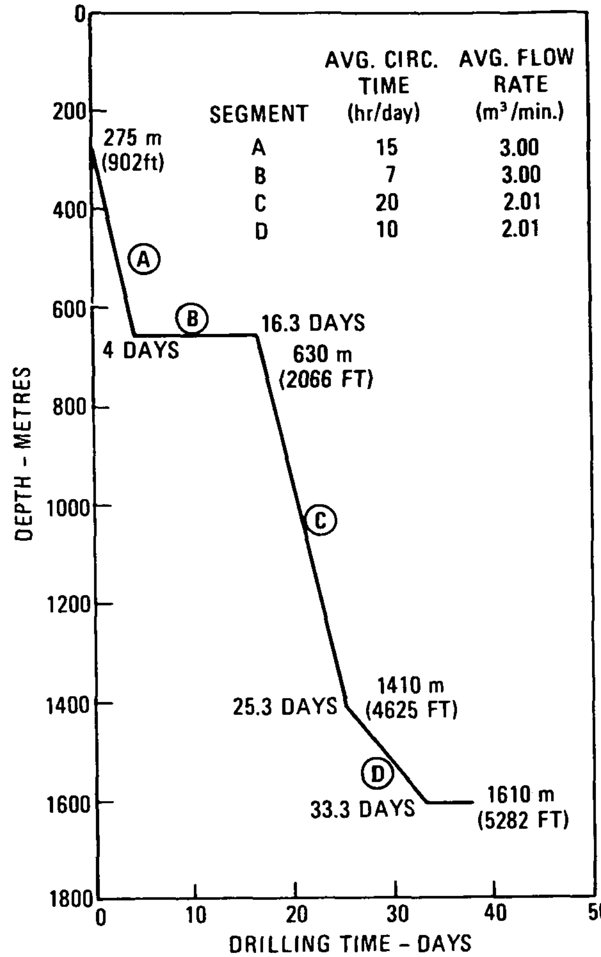

FIGURE 4. WELLTEMP drilling simulation.

temperature changes. Input values for the Panarctic well are as follows:

Density	10 lb_m/gal	(1200 kg/m^3)
Plastic Viscosity	12 centipoise	(12 m Pa·s)
Yield Point	21 $lb_f/100\,ft^2$	(10 Pa).

Latent heat of solid hydrate is approximately the same as ice, namely 9000 BTU/ft^3 (32 cal/cm^3). For the Panarctic hydrate layer, the soil has 10 per cent porosity and a density of 130 lb_m/ft^3 (2.1 g/cm^3), and hence, the latent heat specified in WELLTEMP for the soil-hydrate composite is 7 BTU/lb_m (15.2 cal/g).

Two geothermal gradients are used for the Panarctic simulation, one through the sea-water interval and one through the soil below. For the sea-water, the surface temperature is 28°F (−2°C) and the sea-floor temperature is 32°F (0°C). Starting at the sea-floor, the soil gradient is then constant to 5282 ft (1610 m) where the temperature is 102.2°F (39°C).

TABLE 1. WELLTEMP input data in the well simulation

Time increment	Drill time Days	Drill depth Ft (m)	Inlet temp. °F (°C)	Flow rate GPM (m^3/min)	Circ. time Hr/day
1	4.0	1997 (609)	50 (10)	792 (3)	15
2	16.3	1997 (609)	50 (10).	792 (3)	7
3	24.0	4264 (1300)	48 (9)	531 (2)	20
4	25.3	4625 (1410)	55 (13)	531 (2)	20
5	33.3	5282 (1610)	59 (15)	531 (2)	10
6	33.6	5282 (1610)	54 (12)	531 (2)	8
7	34.6	5282 (1610)	54 (12)	531 (2)	0
8	35.1	5282 (1610)	54 (12)	531 (2)	12
9	36.1	5282 (1610)	54 (12)	531 (2)	0
10	36.2	5282 (1610)	54 (12)	531 (2)	2
11	37.2	5282 (1610)	54 (12)	531 (2)	0

Hydrate Decomposition Temperature

The hydrate zone at 2200 ft (671 m) has an undisturbed geothermal temperature of 52.8°F (11.56°C). The hydrate decomposition temperature for modelling purposes is assumed to be the same or slightly greater than the geothermal temperature. Therefore, the hydrate decomposition temperature is set in WELLTEMP at 52.9°F (11.61°C) while drilling to 5282 ft (1610 m).

The thermal effect of increased mud weight on hydrate decomposition during circulation at bottom hole (after 34.6 days) is modelled by increasing the hydrate decomposition temperature in accordance with the pressure–temperature equilibrium conditions for methane hydrate (Katz 1971). In the Panarctic well, the mud weight increase is 3.6 ppg (432 kg/m^3) which generates a mud pressure increase of 400 psi (2.76 MPa) at the hydrate depth. From the methane-hydrate equilibrium curve, this pressure change corresponds to a 5°F (2.8°C) temperature increase.

By increasing the decomposition temperature, the subsequent effect at the hydrate face during circulation and shut-in can be evaluated from the "thaw" and temperature response. If the thaw radius does not increase during the time interval of interest, then gas release due to decomposition does not occur. Moreover, by plotting the temperature distribution in the hydrate layer and comparing values to the new decomposition temperature, one can assess the relative influence of the mud weight increase.

Model Predictions

Decomposition of the hydrate layer is governed by the circulating mud temperature downhole opposite the hydrate zone and by the heat transfer characteristics of the hydrate–soil system. The thermal behaviour both within and outside the well are discussed.

Mud Temperatures

The annulus mud temperature at the hydrate depth 2200 ft (671 m) is predicted as a function of drilling time (Figure 5). The open circles represent temperatures while circulating and the shaded circles represent shut-in temperatures. The distribution indicates a general trend of increasing temperature which is expected because the mud is exposed continually to higher *in situ* temperatures during drilling, and also because the mud inlet temperature increases with time. The large jump at 24 days is due to the increase in mud inlet temperature from 48°F (8.9°C) to 55°F (12.8°C). At 33.3 days the inlet temperature decreases from 59°F (15.0°C) to 54°F (12.2°C).

The distribution in Figure 5 indicates that the downhole mud temperature at the hydrate depth does not increase above the decomposition temperature until after the 24th day of drilling, even though the drilling depth is 4300 ft (1311 m) and the *in situ* temperature is 85°F (29.4°C). This suggests that the mud inlet temperature and circulation rate govern the rate of heat transfer i.e. the mud circulates fast enough so that heat transfer from the surrounding formation to the fluid is relatively small and mud temperatures change little during a circulation loop. This does not mean that significant amounts of heat are not transferred from the fluid to the soil, because indeed the hydrate layer does absorb significant heat as demonstrated by the extent of thaw.

Profiles are illustrated (Figure 6) for the uniform circulating mud temperature *versus* depth. Due to the relatively high flow rate and shallow depth, the bottomhole temperature is nearly the same as the inlet

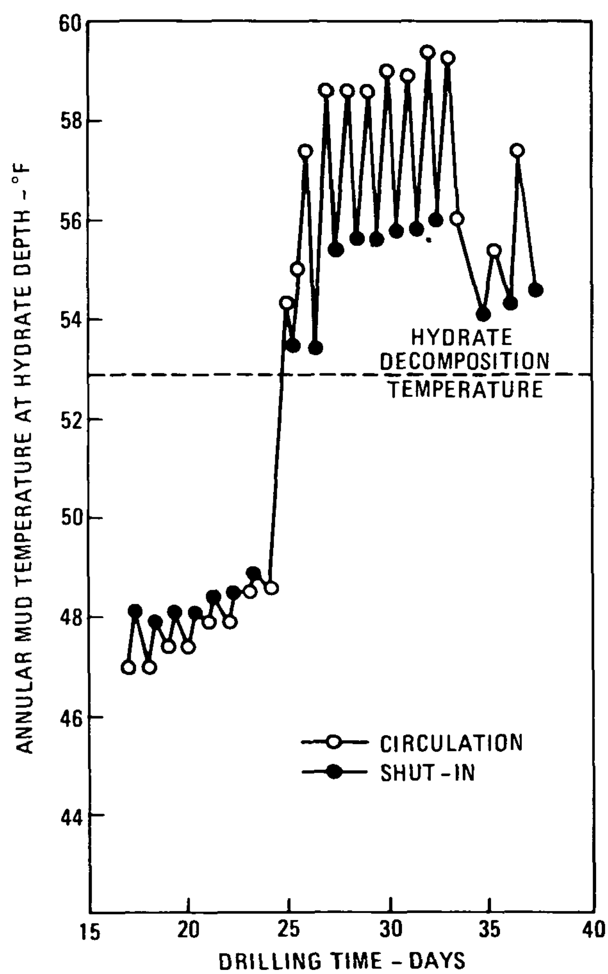

FIGURE 5. Mud temperature opposite hydrate zone.

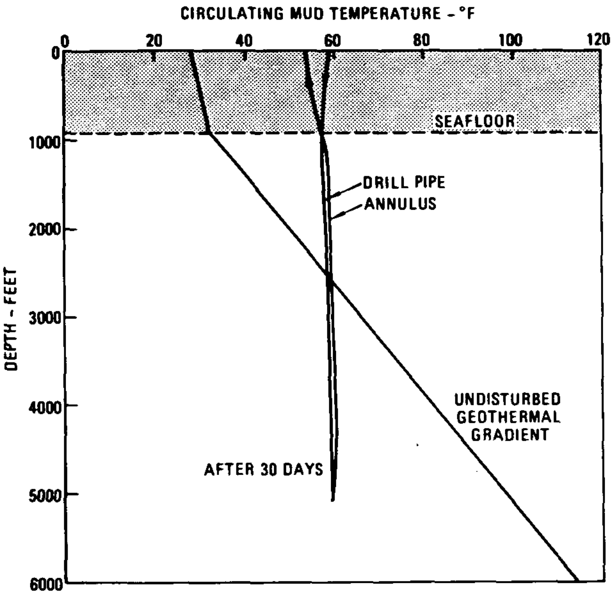

FIGURE 6. Mud temperature profile in drill pipe and annulus.

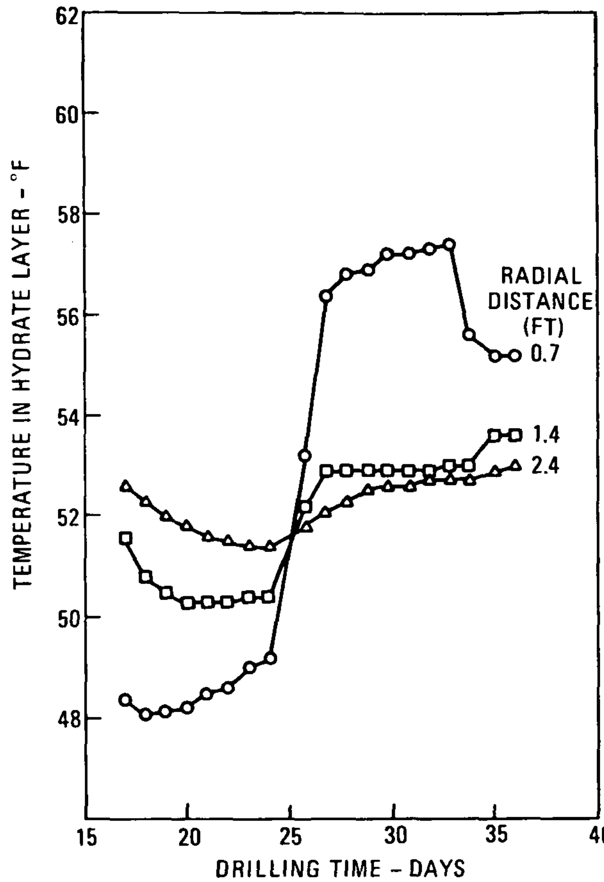

FIGURE 7. Temperature build-up in hydrate layer at various radial locations.

temperature, but differs from the bottomhole undisturbed temperature by almost 40°F (22°C).

Temperatures in the drill pipe and annulus differ by about 10°F (5.5°C) for depths below the sea-floor, with higher temperatures in the annulus. At the seafloor, the drill pipe and annulus temperatures cross. Opposite the sea-water, the annulus exhibits significantly greater cooling than the drill pipe because of the proximity of the annulus to the sea-water and also because of the greater annular area exposed to heat transfer.

Soil Temperatures

Temperature build-up curves at selected radii around the wellbore in the hydrate zone are presented in Figure 7, but only temperatures during circulation, not shut-in, are plotted. Near the wellbore at $r = 0.7$ ft (0.2 m), the temperature closely follows the thermal behaviour in the flowing stream (*see* Figure 5). But, at further distances from the wellbore, the behaviour is different. Instead of cooling down quickly and then heating as at $r = 0.7$ ft (0.2 m), the soil away from the wellbore cools down slowly and only begins heating after 24 days when the mud inlet temperature increases. The temperature increase after 24 days at the further radii is not as dramatic as near the wellbore, and temperatures remain at or near the hydrate decomposition temperature of 52.9°F (11.61°C).

The rise in temperature after 33.3 days at radii 1.4 ft (0.4 m) and 2.4 ft (0.7 m) is due to the change in decomposition temperature from 52.9°F (11.61°C) to 57.9°F (14.39°C). With the change in decomposition temperature, latent heat no longer accumulates in the hydrate layer, and hydrate temperatures can increase until the new decomposition temperature is reached.

In decomposition or "thaw" build-up with time (Figure 8), thaw does not occur until near the 25th day and then increases rapidly. The kink in the curve at 26 days is due to the increase in mud inlet temperature from 55°F (12.8°C) to 59°F (15.0°C). After 34.6 days, the thaw remains constant due to the increase in decomposition temperature associated with increase in mud weight. Maximum thaw is 1.82 ft (0.55 m).

The inhibition of further thaw after 34.6 days demonstrates that mud weight increase can prevent hydrate decomposition in the Panarctic well for at least 2.6 days while either circulating or shut-in at the bottomhole depth of 5282 ft (1610 m). Thaw inhibition is achieved because the hydrate face at 1.82 ft (0.55 m) is far enough away from the heat source in

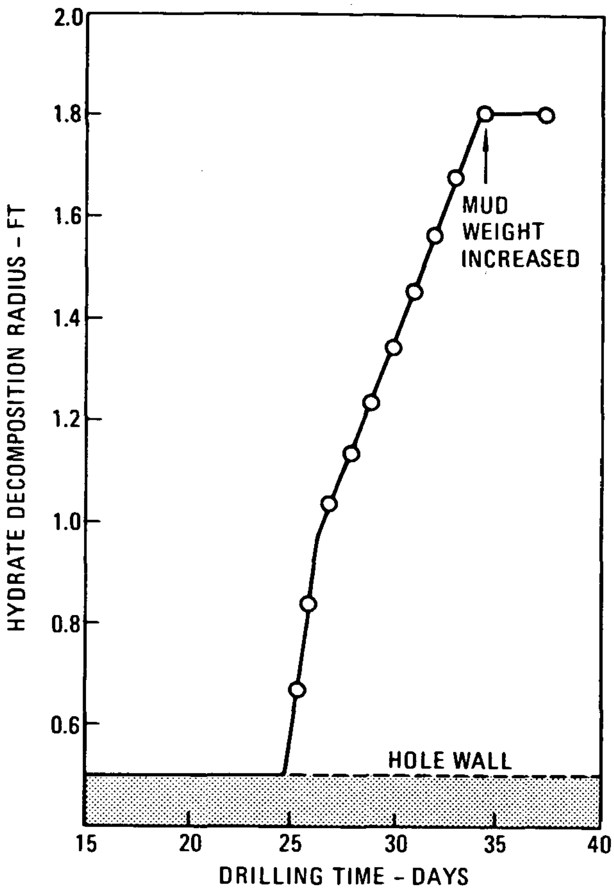

FIGURE 8. Hydrate decomposition with time.

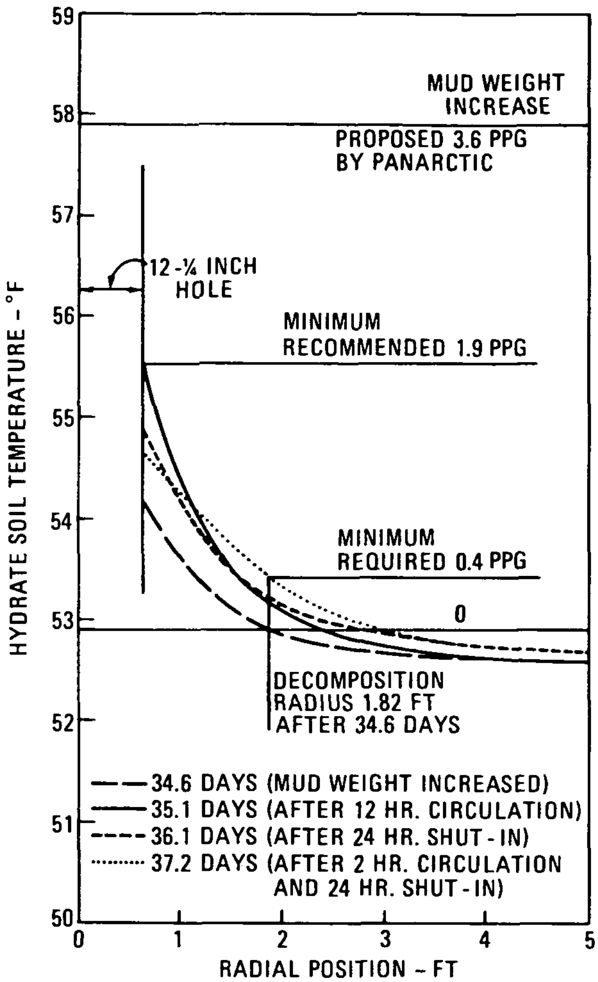

FIGURE 9. Mud weight increase for hydrate stabilization.

the well to limit the heat transfer over the period of interest, 2.6 days. At an earlier time, say 26 days, when the hydrate face is only at 0.95 ft (0.3 m), this method may not be successful in preventing decomposition because the soil temperature at this radius is more sensitive to the wellbore temperature (*see* curve for r = 0.7 ft (0.2 m) in Figure 7).

Effect of Mud Weight Increase

The thermal behaviour during the entire drilling schedule down to 5292 ft (1610 m) has been examined. In this section, the results concentrate on the circulating and shut-in periods after total depth is reached and the mud weight is increased. Temperature profiles with radius are given (Figure 9) at four selected times, starting at 34.6 days when the mud is weighted up, followed by 12-hr circulation, then 24-hr shut-in, and 26-hr combined circulation plus shut-in. Superimposed on the plot of Figure 9 are mud weight increases associated with distinct hydrate decomposition temperatures.

The highest soil temperature occurs at the wellbore face after the initial circulation period. At the hydrate face, however, the highest temperature occurs at the end of the last shut-in period. The curves cross because the outer region beyond 2.5 ft (0.76 m) is cooled beyond the *in situ* undisturbed temperature (due to earlier circulation) and the region inside 2.5 ft (0.76 m) is heated. Hence, during shut-in, temperatures near the wellbore decrease whereas temperatures away from the wellbore increase.

Temperatures at the hydrate face located at r = 1.82 ft (0.55 m) increase after 34.6 days, and, therefore, continued hydrate decomposition would be expected if the mud weight were not increased. Based on the temperature predictions in Figure 9, the minimum mud weight increase to inhibit decomposition at the hydrate face for the 2.6 days time period is 0.4 ppg (48 kg/m^3). The minimum recommended mud weight increase based on the maximum predicted temperature outside the wellbore is 1.9 ppg (228 kg/m^3). These values are significantly less than the mud weight increase of 3.6 ppg (432 kg/m^3) used by Panarctic.

Discussion and Conclusions

The present analysis of hydrate decomposition considers thermal effects as governed by the pressure–temperature equilibrium curves of hydrates. Chemical effects in porous media are not taken into account, and these may influence the decomposition when the mud weight is increased. It is assumed that the downhole pressure increase in the wellbore is instantly transmitted to the hydrate face and that the hydrate immediately responds with an increase in decomposition temperature.

Based on the WELLTEMP predictions of downhole temperatures and decomposition radii, the following conclusions are presented:

1. The mud weight increase of 3.6 ppg (432 kg/m^3) used by Panarctic is more than enough to inhibit hydrate decomposition for the 2.6 days of circulation and shut-in at bottomhole. Minimum required mud weight increase is 0.4 ppg (48 kg/m^3). Minimum recommended increase based on maximum temperatures is 1.9 ppg (228 kg/m^3).
2. The hydrate zone at 2200 ft (671 m) cools down during the first 24 days of drilling to 4300 ft (1311 m) because of relatively low mud inlet temperatures and low formation and sea temperatures above the hydrate zone.
3. Hydrate decomposition does not begin until after 24 days, but then increases rapidly, reaching a radius of 1.82 ft (0.55 m) after 33.6 days.
4. During the circulation and shut-in periods after reaching bottomhole, maximum temperature at the wall of the 12¼-inch (30 cm) hole is 55.5°F (13.1°C) and maximum temperature at the hydrate face ($r = 1.82$ ft) is 53.5°F (12.0°C), indicating a 2°F (1.1°C) differential across the decomposed layer. These temperatures compare to the hydrate decomposition temperature of 57.9°F (14.39°C) after a 3.6 ppg (432 kg/m^3) increase in mud weight.
5. The results for the Panarctic well should not be extrapolated to other well sites or drilling conditions. Decomposition of the hydrate zone is dependent on a large number of variables, including mud inlet temperature, flow rate, drilling schedule, well configuration, geothermal gradient, and soil properties. A change in any of these variables can generate a significant change in predicted temperatures and hydrate decomposition.

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