Effect of Non-Hydrostatic Pore Pressure on the Depth to the Base of the Hydrate Stability Zone

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Summary

Regional estimates of the base of gas hydrate stability in settings like the North Slope of Alaska, the Mackenzie Delta in the Northwest Territories, and even the Gulf of Mexico generally assume a hydrostatic pore fluid pressure model. While this may be suitable for some purposes, the actual pressure in a hydrate reservoir may be significantly above hydrostatic. The result is that the local base of hydrate stability in the reservoir may be deeper than the regional estimate. This has implications for estimating hydrate volume and safely drilling in the zone of 100 m or more below the estimated regional base of hydrate stability.

Introduction

Safely drilling through the hydrate stability zone is an on-going concern in development of conventional Arctic hydrocarbons, and estimating the base of hydrate stability in both a regional sense and in isolated, shallow reservoirs is intimately tied to properly estimating subsurface pore fluid pressure regimes. With gas hydrate migrating from the realm of hazard to resource and with production tests in progress or in the planning stages at places like the North Slope of Alaska and the Mackenzie Delta of the Northwest Territories of Canada, the same considerations as for drilling safety can be employed to improve on hydrate volume estimates in hydrate-bearing reservoirs.

Theory

The pressure term in the hydrate stability equation can be converted to depth to facilitate estimating the vertical extent of the hydrate stability zone (HSZ). The conversion from pressure to depth is generally made assuming that hydrostatic conditions exist downward from the surface, and a gradient of 0.0100 MPa/m is a convenient conversion factor that is often applied. While being a convenient factor, it is suitable for fresh water and is about 5% less than the widely accepted value for hydrostatic pressure caused by brine, i.e., 0.0105 MPa/m. The brine gradient can be expressed as 8.94 lb/gallon equivalent mud weight or 0.465 psi/ft. In the case of the North Slope of Alaska, the reservoir water tends to be fresh, and the hydrostatic gradient is actually slightly less than the 0.0100 MPa/m rule of thumb value, i.e., about 0.0098 MPa/m.

Assuming a hydrostatic gradient is suitable for making regional estimates of the base of hydrate stability. However, the source of the pressure on the hydrate or its water and methane constituents is irrelevant. The key is to have a proper estimate of the pore fluid pressure and to estimate the base of the hydrate stability zone accordingly. If, for some reason, the fluid pressure in a reservoir is higher than the hydrostatic

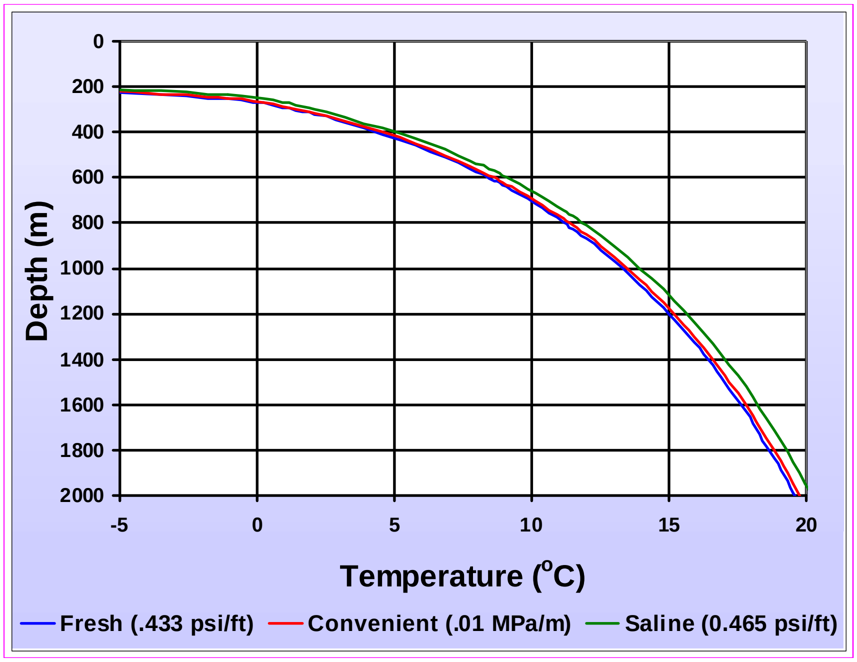

Figure 1. Hydrate stability curves for various hydrostatic gradients. Hydrate forms below or to the left of the curves. The stability temperature limit increases with the pressure gradient for any given depth. These curves are based on typical hydrostatic values. An overpressured case would move the stability temperature limit farther to the right.

pressure on surrounding sediments, hydrate would be stable at higher temperatures, i.e., the base of hydrate stability in the reservoir would be deeper in the isolated reservoir than in the surrounding sediments.

If one is estimating the volume of the hydrate resource in the isolated reservoir, using a hydrostatic model would lead to an underestimate of the resource if the reservoir is actually overpressured. From a drilling safety perspective, if the overpressure case is not recognized, an underbalanced situation could be encountered in which rapid hydrate dissociation could occur and lead to well control problems.

Example

Gas is commonly trapped in reservoirs above the hydrostatic pressure in surrounding sediments. Higher pressure in the reservoir causes the base of hydrate stability in that reservoir to become deeper. This effect may help to explain why the base of the HSZ reported for the Hot Ice 1 well on the North Slope was approximately 120 m shallower than the gas hydrate that dissociated contributing to the 1992 blowout of the Cirque 1 well, which was just a few miles to the west.

Reported mud weights from the Cirque 1 well were between 9.1 and 9.4 lb/gallon. Mud weights in this range should have been sufficient to contain hydrostatic pressures based on gradients mentioned above, i.e., 8.9 ppg. However, the Cirque 1 well blew out indicating that the reservoir pressure was higher than anticipated.

The Cirque 2 well was drilled about a year after the Cirque 1 well was controlled, and the mud weight that was used to drill through the problem zone, the K-10 sand, was reported to be 10.4 ppg. If this pressure gradient is applied to the depth range of the K-10 sand, the stability diagram in Figure 2 indicates that the K-10 sand could have been hydrate bearing through those depths even though the top of the sand was penetrated 30 m below the estimated regional based of hydrate stability.

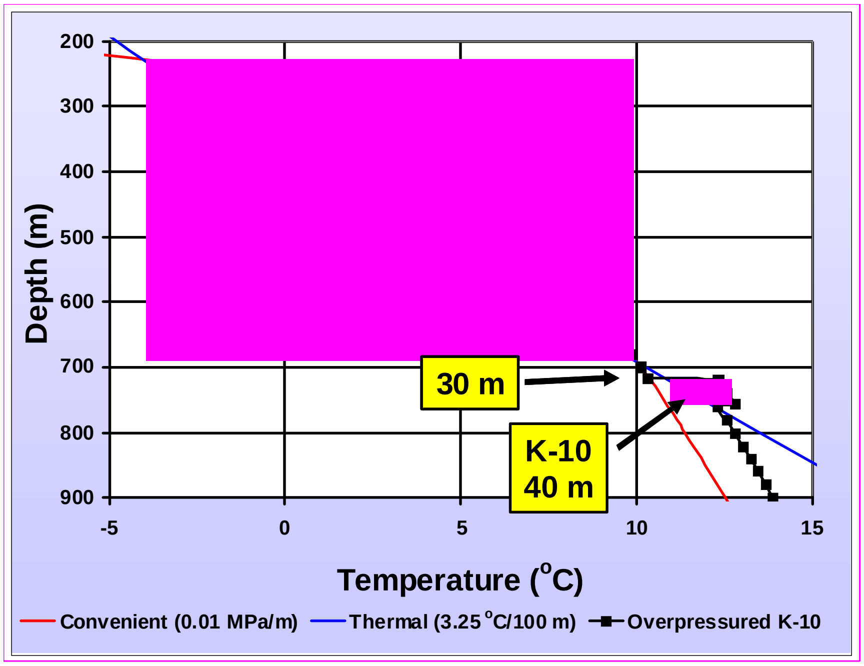

Figure 2. Hydrate stability in the K-10 sand at Cirque 1. The regional hydrate stability field extends approximately to 700 m based on the hydrostatic assumption and an accepted value for the geothermal gradient. The top of the K-10 sand is about 30 m below the estimated regional base of hydrate stability. With overpressure in K-10 of about 0.0122 MPa/m (10.4 lb/gallon), the stability temperature is pushed to the right of the geothermal gradient thereby providing the conditions for hydrate formation. This graph depicts the stability curve for a vertical well through K-10. K-10 is about 40 m thick at this location. If one followed the K-10 sand downdip , the base of hydrate stability would be encountered about 100 m below the estimated regional base of hydrate stability.

The low mud weight and warm and saline drilling fluid could have allowed the hydrate in the K-10 sand to rapidly dissociate giving rise to the blowout. Other explanations of the source of the gas are also possible, e.g., any gas from dissociation might have originated in shallower horizons within the regional hydrate stability field.

Conclusions

Defining the depth extent of gas hydrate in reservoirs requires realistic estimates of the pore fluid pressure in the reservoirs. Depth extents based on hydrostatic pressure assumptions may be significantly too shallow. In the example of the Cirque 1 location, the base of hydrate stability within the penetrated reservoir could be as much as 100 m below the estimated regional base of hydrate stability.

This effect may be even more problematic in the case of the Gulf of Mexico where sands can be structurally hyperpressured. Because individual, steeply dipping sands on the flanks of salt features may have different pressure centroids, the pressures in the updip segments of the respective sands could vary. The various pressures would give rise to stability zone bases of varying depths. This could account for bright reflections caused by free gas trapped under the hydrate that do trace out a smooth surface like the classic bottom simulating reflection.

Acknowledgements

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References

Cirque 1 background, http://aogweb.state.ak.us/weblink7/DocView.aspx?id=14130 (live 1-8-2009)

Cirque 2 background, http://aogweb.state.ak.us/weblink7/DocView.aspx?id=14111 (live 1-8-2009)

Cirque 3 background, http://aogweb.state.ak.us/weblink7/DocView.aspx?id=27307 (live 1-8-2009)

Hot Ice 1 background, http://www.netl.doe.gov/technologies/oil-gas/FutureSupply/MethaneHydrates/projects/DOEProjects/AlaskaPerm-41331.html (live 1-8-2009)