Development of the Maximum Operating Pressure Formula for Steam-Assisted Gravity Drainage Schemes in the Shallow Thermal Area

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1 Introduction

On May 18, 2006, a catastrophic surface release of steam occurred at the Total E&P Canada Ltd. (Total) Joslyn Creek steam-assisted gravity drainage (SAGD) scheme, located about 60 kilometres north of Fort McMurray. The scheme was approved to operate below the tensile failure pressure of the McMurray Formation at well depth. However, during the circulation and semi-SAGD[1] warm-up period of well pair 204-I1P1, at times the steam injection pressure reached the estimated reservoir tensile failure pressure at well depth. A few days after the well was converted to SAGD, and while the well was operating at a steam injection pressure below the tensile failure pressure at well depth, a steam release occurred.

At a cursory level, the cause of the Joslyn Creek steam release seems obvious; steam was being circulated and injected at the estimated tensile failure pressure at well depth. However, the technical reviews by Total[2] and the Alberta Energy Regulator (AER)[3] indicated that the exact pathway the steam followed in the reservoir, the timing, and the mechanisms responsible for the pathway are unclear due to conflicting data and interpretations.

2 Risk Implications of the Joslyn Creek Steam Release

Since shallow SAGD schemes need to operate at pressures closer to the caprock tensile and shear failure thresholds than deeper schemes to achieve economic bitumen production rates, the risk of a caprock breach is increased. Risk is the product of probability × consequence, and these two components are discussed below as they relate to the Joslyn Creek surface steam release and to shallow SAGD schemes in general.

2.1 Probability

The Joslyn Creek steam release illustrates how difficult it can be to analyze the mechanism of a caprock failure. It is probable that steam found a pathway to the base of the caprock during circulation, and while excessive pressures were likely responsible, it is not clear how the significant steam migration occurred or what pathway it followed.

The uncertainty in the pathway that the steam took at Joslyn Creek indicates how challenging it is to predict such events using analytical and numerical models. There are unknown variations in reservoir porosity, permeability, and fluid distribution, as well as in reservoir and caprock geomechanical properties and stress fields.

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1 Semi-SAGD is the term used by Total to represent the final stage of warm-up, when the upper well is converted to steam injection, while the lower well continues to circulate.

2 *Summary of Investigations into the Joslyn May 18th 2006 Steam Release, Total E&P Canada Ltd.*, December 2007.

3 *Total E&P Canada Ltd., Surface Steam Release of May 18, 2006, Joslyn Creek SAGD Thermal Operation—ERCB Staff Review and Analysis*, February 11, 2010.

The AER believes that there are too many unknowns to accurately assess the probability of a caprock breach for shallow SAGD schemes that operate, at any time, at or near the tensile and shear failure thresholds of the caprock. Complex, localized steam pathways may develop and cannot be reliably predicted by even the most sophisticated coupled geomechanical and reservoir simulators.

2.2 Consequence

The Joslyn Creek incident has shown that a caprock breach at shallow SAGD schemes can result in a catastrophic surface release that has the potential to damage surface facilities and to pose a safety risk to anyone close to the release. While this cannot be ruled out as a consequence for a deeper thermal scheme, the presence of secondary barriers, thick aquifers, and the longer pathway to surface make it far less likely for steam to reach the surface. Therefore, a caprock breach at a deeper thermal scheme, while not desirable from an environmental or conservation perspective, is less likely to be a safety concern.

After only four months of circulation and one month of semi-SAGD, there was sufficient energy in the reservoir from one well pair to cause a catastrophic release. In SAGD, energy is continually added to the reservoir as the steam chamber expands. Had the Joslyn Creek steam release occurred after a longer period of SAGD injection rather than just after warm-up, the magnitude of the release might have been even greater.

3 Maximum Operating Pressure Formula

The formula for calculating the maximum operating pressure (MOP) was developed to ensure that the bottomhole injection pressure would be below the caprock tensile failure pressure throughout the life of the project. As a result, no matter what pathway the steam follows or how quickly it rises, tensile failure of the caprock should not occur.

The MOP formula is:

$$MOP_{(bottomhole)} = \text{Safety factor of 0.8} \times \text{Caprock fracture closure gradient} \times \text{Depth at shallowest base of caprock}$$

3.1 Safety Factor

The MOP formula uses a safety factor of 0.8 to account for potential errors and uncertainties in estimating the caprock fracture closure gradient. There is some evidence that the fracture closure gradient of the caprock may vary across a project area. Three diagnostic fracture injection tests submitted to the AER on caprocks at relatively shallow depths showed fracture gradients significantly below the vertical stress gradient. These results do not conform to the theory that the minimum principal stress at these depths should be vertical and fractures should be horizontal. The test results are summarized in the table on the next page.

Measured caprock fracture gradients below the vertical stress gradient

Well ID	Test date	Caprock fracture gradient (kPaa/m)*	Test depth (m)
15-34-094-06W4M	February 2009	15.5	268
05-22-088-08W4M	March 2010	13.8	45
13-26-090-09W4M	February 2010	14.7	75

* kPaa/m = kilopascals absolute per metre.

One explanation for such low horizontal stress gradients at these shallow depths is that faults, incising channels, or localized subsidence features could have reduced the horizontal stresses below the vertical stress. Another possible explanation is the way the tests were conducted and analyzed.

While a safety factor of 0.9 has been used historically in setting MOPs for conventional waterfloods and water disposal schemes, the greater number of unknowns and the potentially more severe consequences of caprock failure under high-temperature, high-pressure, high-compressibility steam injection require a more conservative safety factor.

3.2 Caprock Fracture Closure Gradient

The MOP formula uses the fracture closure gradient rather than the fracture propagation gradient. Although a steam injection pressure above the fracture closure pressure would not always lead to the propagation of fractures, the fracture closure gradient is used because it would preclude any pre-existing natural fractures from propagating. As indicated in section 3.1, there is some evidence that the fracture closure gradient may vary across a project area. The AER will use what it considers to be the lowest valid caprock fracture closure gradient obtained from representative diagnostic fracture injection tests.

3.3 Calculation Depth

Calculating the MOP at the shallowest base of the caprock instead of at the estimated top of the steam chamber should ensure that the steam chamber pressure will always be below the caprock tensile failure pressure. This would eliminate the uncertainty of trying to determine where the steam chamber is in all parts of the reservoir at all times and the need to reduce the pressure as the steam chamber rises. If steam finds a pathway upwards ahead of the main steam chamber, the MOP should ensure that the pressure is still below the caprock tensile failure pressure.

3.4 Horizontal Stress Reduction

Heave due to expansion of the rock within the heated zone may affect the horizontal stresses in the overlying unheated zone, reducing the horizontal compressive stresses that existed at initial conditions. Therefore, there is a need to consider whether the pressure calculated by the MOP formula should be decreased to account for horizontal stress reduction.

Horizontal stress reduction in the caprock occurs prior to caprock heating because of lateral expansion of the rock in the steam chamber. Once caprock heating begins, the thermal expansion rapidly increases the compressive horizontal stresses above initial conditions and stress reduction is no longer a concern. For a given operating pressure and temperature, modelling estimates of maximum stress reduction and the time period over which stress reduction occurs can vary significantly, depending on the model used and the fluid and rock properties, geology, and fluid distribution entered into the model. The maximum stress reduction at the base of the caprock is expected to occur just before caprock heating begins.

Horizontal stress reduction at the base of caprock becomes a concern if all of the following occur:

a) steam reaches a caprock that is still at or near the initial temperature;
b) caprock stress reduction is high enough to reduce the horizontal stress below the vertical stress, thereby reducing the tensile failure pressure; and
c) steam injection pressure is equal to or greater than the stress-reduced tensile failure pressure.

The MOP formula results in a steam injection pressure that is significantly below the tensile failure pressure at well depth, reducing opportunities for steam to find a localized pathway and rise rapidly to the base of caprock. The probability of steam migrating to the caprock under circumstances where all three of the above conditions are met is small. The pressure calculated by the MOP formula is sufficiently conservative. Hence the pressure does not need to be decreased because of possible stress reduction.