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Design of Caprock Integrity in Thermal Stimulation of Shallow Oil-Sands Reservoirs

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Summary

Stakeholders in in-situ oil-sands development take caprock-integrity issues seriously. The industry is faced with the challenge of determining an optimal operating pressure in the reservoir where, in general, the pressure should stay significantly low to ensure the caprock integrity while being significantly high for enhanced oil production and economics. This paper presents a comprehensive work program on the subject for a shallow oil-sands play.

Caprock integrity considers the induced stress and deformation in a caprock during the thermal stimulation of an oil-sands reservoir. A minifrac-test program is undertaken to define the original in-situ stress state. Laboratory tests are carried out to measure the deformation and strength properties. Simulations are run to calculate the induced stresses and evaluate them against the mechanical strength. This paper describes some important quality-control issues for these activities. For the minifrac tests, multiple cycles and use of flowback are promoted for enhanced efficiency and accuracy. Laboratory tests are recommended on whole cores in a drained condition at a slow strain rate. Numerical simulations should use site-specific and laboratory-measured material properties. On the basis of the limited sensitivity analyses, the thermal-expansion coefficient of the reservoir and Young's modulus of the caprock are found to significantly affect the caprock deformation and/or induced stresses.

Introduction

Collectively, caprock refers to a certain interval in the overburden rock formations above a petroleum reservoir containing the reservoir fluids within the reservoir. It is normally shaly, with high clay content and low permeability. Sometimes, it immediately overlies the pay zone. In other cases, there is a buffer zone between the caprock and pay zone. During petroleum exploitation, the caprock plays an important role in safeguarding against the hydrocarbon fluid, stimulating materials, and/or their mixture invading zones above the caprock. Often, these zones contain groundwater aquifers.

Ultimately, caprock integrity considers hydraulic integrity—no reservoir fluids should escape through the caprock into the groundwater aquifers or to the surface. In general, the hydraulic integrity is already maintained naturally, as in the geological history of the caprock preventing further upward hydrocarbon migration. It is the process-induced mechanical deformation and potential failure of the caprock during thermal operations that may introduce new hydraulic conduits and thus compromise the hydraulic integrity. Therefore, hydraulic integrity becomes a mechanical integrity issue.

Caprock integrity also considers caprock mechanical integrity (i.e., deformation and failure in the caprock strata). For example, surface heave, which is rock deformation reflected on the ground, can alter the environment by changing the landscape or the surface or shallow subsurface hydrogeological conditions. Such surface heave could damage surface installations and infrastructures, and have other unintended impacts. Furthermore, rock deformation and failure (e.g., reactivation of pre-existing weak planes) can damage the well casing, breaking its hydraulic-sealing capacity.

Whether hydraulic or mechanical, caprock integrity becomes a geomechanical issue related to caprock deformation and potential failure. Caprock-integrity analysis compares the prevailing stress conditions against the material strength. The ongoing stress condition is the induced stresses superimposed on the virgin in-situ stresses. Therefore, there are three major components to any geomechanical work program: determination of the original in-situ stresses, evaluation of the induced stresses, and measurement of the mechanical properties. Minifrac tests are the most reliable method to measure the in-situ minimum stress; the induced stresses are normally inferred from geomechanical simulations; and the mechanical properties should be measured ideally from cores obtained from the project sites. This general geomechanical work program is followed in the oil-sands industry now. However, special considerations are warranted for oil-sands development where the formations are relatively shallow. This paper will present some relevant examples of how to ensure quality control in these special cases.

Both the industry and government regulatory agencies take the caprock-integrity issue seriously. For the in-situ development of the Alberta oil-sands reservoirs, systematic efforts in this regard were first initiated for cyclic-steam-stimulation (CSS) operations (Smith et al. 2004). More recently, steam-assisted gravity drainage (SAGD) has become another mainstream commercial in-situ oil-sands recovery process. SAGD is normally thought to be gentler on the caprock because it operates at a lower pressure than CSS. However, as the operational experience with SAGD grows, evidence indicates that proactive precautions are still necessary to safeguard the caprock integrity. Yuan (2008) presented theoretical arguments about why attention also should be paid to integrity issues in SAGD. The current paper will apply these theoretical principles in the context of shallow oil-sands reservoirs.

In the following sections, case histories are given to illustrate important quality-control issues in various caprock-integrity studies. First, complexities encountered in the oil-sands and the corresponding best practices during minifrac tests are described. Next, geomechanical laboratory tests are explored. The subsequent section is dedicated to a study of the geomechanical simulations which combine both the field-obtained data and laboratory-measured material properties to derive the safe SAGD operating pressure. The effect of reservoir depth on caprock integrity is also specifically discussed.

The target reservoir discussed in this paper belongs to the McMurray formation sandstones of the Lower Mannville in the Fort McMurray area. **Fig. 1** offers a schematic about the general stratigraphic column. The reservoir is generally less than 100 m deep, but its thickness is approximately 40 m, making the asset attractive. The Clearwater formation constitutes the regionally continuous caprock, which is mostly shale with interbedded silty-to-sandy mudstone. The caprock thickness ranges from 46 to 61 m. A Wabiskaw member is sandwiched between the Clearwater caprock and McMurray pay zone. It is a marine shore face system conformably overlying the McMurray formation. It may also contain sand facies that can be bitumen-saturated. Therefore, the Wabiskaw member constitutes a transitional buffer zone from the reservoir pay zone upward to the caprock. A solvent-assisted low-pressure SAGD is proposed to develop the reservoirs (Palmgren et al. 2011). Significant efforts have been commissioned by the

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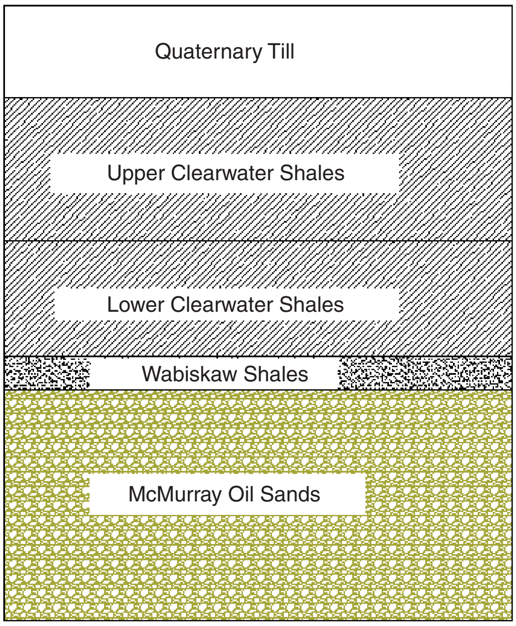

Fig. 1—A schematic about the general well stratigraphic columns encountered in the shallow reservoir.

operator, some of which are still ongoing, to design an operating pressure that maintains the caprock integrity.

Minifrac Tests. Mini [illegible] ts, commonly called minifrac tests, [illegible] he industry to measure the in-situ str [illegible] ly as the most reliable method to de [illegible] s, S_{min}. Using controlled high-pressure water injection, the minifrac tests create a fracture and propagate it for a sufficient distance from the injection well and into the formation. This ensures the fracturing behaviour being dominated by the far-field stress condition. The pressure data are analyzed to estimate the fracture-closure pressure P_c. The latter can then be equated to the in-situ minimum stress acting perpendicular to the fracture. For more background information on minifrac tests in the industry, one may refer to the review paper by Hudson et al. (1993). Bell et al. (1994) summarized the in-situ stress measurements made mostly at deep depths in the western Canadian sedimentary basin. Some tests were performed in the context of oil sands [e.g., those reported in Settari and Raisbeck (1979), Chhina and Agar (1985), Chhina et al. (1987), Kry (1989), Proskin et al. (1990), Kry et al. (1992)]. Our test procedures and analysis methods incorporate the learnings from these earlier works and also implement new developments and/or adjustments dedicated to the shallow depths and the unconsolidated nature of the oil sands and overlying caprock intervals.

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S_v as a Quality-Check Index. At the shallow depths associated with the target oil-sands reservoir, the original in-situ stress condition can be defined by three principal normal stress components: the vertical stress S_v and two horizontal stresses, which are commonly denoted as the maximum and minimum horizontal stresses, SH_{max} and SH_{min}, respectively. S_v can be estimated reliably from the overburden lithological column by integrating the density log, which typically ranges from 20 to 22 kPa/m. As a rule of thumb, S_v=21 kPa/m.

In theory, a properly executed and interpreted minifrac test should never measure an S_{min} larger than the density-derived S_v. Hydraulically driven fracture propagation is always perpendicular to the direction of S_{min}. This direction represents the least resistance (i.e., requiring the smallest pressure to extend the fracture). Away from the mechanical influence domain of the borehole, the fracture should be perpendicular to the least of the three stress components: S_v, SH_{max}, and SH_{min}. Therefore, if S_v is the minimum stress, it should be detected by the minifrac tests and the fracture being measured is horizontal. If the minifrac tests detect an S_{min} smaller than the density-derived S_v, it means the fracture being measured is vertical. The measured stress represents SH_{min}. Thus, the fracture-closure pressure measured in a minifrac test is, at most, equal to S_v and in any case should never be larger than S_v.

Three test programs were conducted for the target shallow reservoir in the particular study. They were performed by three different service providers on four different wells. The first test program was completed in 2009 by a wireline unit. It measured fracture-closure-pressure gradients at 24 to 36 kPa/m [Appendix 2 and Appendix 3 of Clearwater Pilot Application submitted to Energy and Resources Conservation Board (ERCB) of Alberta, January 2010]. Doubts should be raised about these values because they are larger than the density-derived S_v at approximately 21 kPa/m. Indeed, subsequent analysis led to a conclusion that most measurements provided data of low confidence and should be deemed inconclusive, although one successful measurement did provide a closure-pressure gradient of 20.57 kPa/m.

A borehole is a stress concentrator. Stresses around a borehole are higher than the far-field in-situ stress condition. Therefore, a proper minifrac test should inject a sufficient volume of liquid for the fractures to propagate outside of the stress-concentration area and for the majority of test length analyses to focus on far-field stresses. In the previously described tests completed in 2009, the total injected volume was only up to 10 L per test. This small injection volume may be one of the reasons for the unusually high fracture-closure pressure as described previously. The fracture may have stayed within the influence domain of the borehole. Therefore, the interpreted fracture-closure pressure reflects the stress concentration near the borehole, not the far-field stress condition.

Multiple Test Cycles for Consistency Check. The in-situ stress magnitudes are small at shallow depths. Thus, accurate interpretations of the fracture closure become an important issue. For example, a 50-kPa inaccuracy in the interpreted closure pressure, P_c, is equivalent to 0.5 kPa/m at a 100-m depth, but only 0.05 kPa/m if the test depth is 1000 m. Two measures can help to enhance the interpretation's certainty. One is to use multiple injection and shut-in cycles, and the other is to use flowback, as described later. When using multiple injection and shut-in cycles, the interpreted closure pressure from each cycle should remain similar as compared with their average from the multiple cycles, thus better representing the in-situ minimum stress. **Fig. 2a** shows one example minifrac test performed in the McMurray sands with nine cycles. The pressure declined quickly during the shut-in, making it difficult to derive a reliable P_c. As a result of on-site real-time analysis, the difficulty was spotted immediately and the corresponding corrective measures were taken. More cycles were used, which yielded consistent closure behaviour eventually in the last four cycles (Fig. 2b). Therefore, real-time analysis and multiple shorter cycles certainly assisted in enhancing the data quality in this difficult situation.

High formation-breakdown pressures and fracture-propagation pressures were observed during the test previously described (Fig. 2a). This was caused by the significant near-wellbore friction during the injection. It can be observed during the step-rate test in Cycle 6. Every time the injection rate increased or decreased abruptly, the injection pressure rose or dropped correspondingly by a relatively large amount **(Fig. 3),** which is evidence of flow-induced friction in the injection system. Near-wellbore complexities are responsible for the high friction. One example is perforation damage, where the explosive action of the perforating operation and the associated high temperatures likely cause significant compaction to the rock.

Flowback. A further enhancement to the minifrac test is a flowback procedure. For the flowback, a certain volume of water is withdrawn manually from the injection system (wellbore plus the fracture) during the shut-in period. In [illegible] fracturing pressure to decline in respons [illegible] from the fracture, the fracture now closes [illegible] induced pressure drop. As a result, t [illegible]

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