A PROTOCOL TO EVALUATE CAPROCK INTEGRITY FOR THERMAL HEAVY OIL AND BITUMEN RECOVERY OPERATIONS

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ABSTRACT
Thermal production of heavy oil and bitumen worldwide is on the rise as world demand for energy is constantly growing. The majority of heavy oil and bitumen deposits such as oil sands in Western Canada are fairly shallow. Steam injection processes are a commonly used technology in thermal heavy oil and bitumen production. To assure a successful steam-based project, competent caprock is needed because of environmental and safety issues and potential excessive heat loss if the caprock is breached. These factors severely impact the economics of thermal recovery.

The paper describes a detailed laboratory protocol to evaluate the low and high temperature sealing capacity of caprock formations under steam injection conditions. The protocol has been used extensively for thermal heavy oil and bitumen recovery projects in Western Canada.

INTRODUCTION
World demand for oil continuously increases while production of conventional oil decreases and conventional crude deposits become more difficult to find. Steam injection is a common enhanced oil recovery (EOR) method of extracting heavy crude oil. Steam Drive, Cyclic Steam Stimulation (CSS) and Steam Assisted Gravity Drainage (SAGD) are the main types of this EOR technology (Speight, 2013). Canada ranks third, after Saudi Arabia and Venezuela, in terms of proven crude oil reserves. Alberta's total proven oil reserves are over 170 billion barrels ninety nine percent of which are in oil sands containing heavy oil and bitumen (Alberta Government, 2014).

Presence of a thick continuous confining shale caprock over top of the bitumen producing formation is a general requirement for successful thermal enhanced oil recovery applications. Caprock needs to act as a containment seal for high pressure steam that would be used in steam injection projects. Caprock integrity is a topic that has received considerable attention from the industry and technical understanding continues to evolve (Uwiera-Gartner et al, 2011; Carlson, 2012; Yuan et al, 2013). Primary motivations for thermal project sealing caprock are: (1) environmental and ground water contamination issues; (2) safety (gas/H_2S/CO_2/caustic steam condensate migration) and (3) excessive pressure and heat loss that can severely impact economics of a project.

The paper describes a detailed laboratory protocol to evaluate the low and high temperature sealing capacity of caprock formations under steam injection conditions. The protocol has been used extensively for thermal heavy oil and bitumen recovery projects in Western Canada (Bennion, 2009). The protocol is designed to evaluate (1) natural or induced fractures, (2) lithology of the caprock and (3) thermal degradation of the caprock at the elevated temperatures. The testing method provides a rapid and accurate evaluation of the matrix thermal sealing capacity (low and high temperature permeability and threshold intrusion pressure to steam).

EXPERIMENTAL

The Effect of Caprock Parameters on Reservoir Performance

In Western Canada, CSS and SAGD are two primary thermal methods to produce heavy oil and bitumen. Thermal sealing capacity of caprock is an issue in SAGD as this technology is used for more shallow reservoirs.

Fluid loss and heat loss rates as a function of caprock permeability for a typical SAGD project have been evaluated. Based on the calculations, caprock permeability needs to be below 0.0001 mD to assure a successful SAGD project. If caprock permeability is below 0.001 mD, such caprock can be considered “acceptable” and, as a matter of fact, this is typical permeability of caprock from SAGD projects in Western Canada based on laboratory data. If caprock permeability is below 0.01 mD, such caprock can be considered “passable” and location specific. In case if laboratory testing shows caprock permeability above 0.05 mD, this is generally unacceptable and such caprock can not be considered a good seal for thermal projects.

When sealing capacity of caprock is considered, the caprock permeability can be compromised by (1) natural or induced fractures, (2) caprock lithology and/or (3) changes in the caprock characteristics at elevated temperatures associated with steam injection. A test protocol has been developed to evaluate these three factors. The protocol includes:

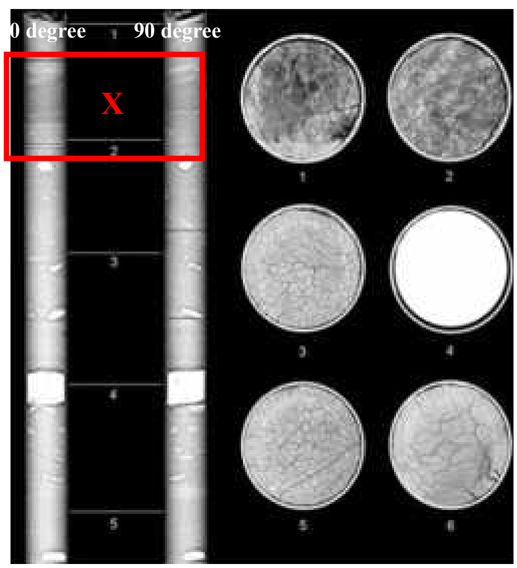
1. Obtaining competent preserved state caprock samples in the field,
2. Computer tomography (CT scan) for appropriate sample selection,
3. 450 MPa mercury intrusion testing and petrographic characterization,
4. Reservoir temperature and maximum thermal operation temperature effective permeability to steam condensate,
5. Threshold intrusion pressures at maximum steam temperature to gas/steam.

Sample Preservation

Core needs to be preserved in the field and delivered to the lab chilled (4^{o}C) in tubes or sealed bags purged with nitrogen. Another option is to protect full diameter core samples in plastic wrap and wax. Freezing must be avoided as water expands when freezing occurs. If that happens, the caprock core would be fractured and will not be suitable for testing. Samples need to be sealed and kept in a refrigerated condition prior to testing. Generally, leaving the samples in the core tubes with bleed holes covered and ends tightly capped is a good short term (1-4 months) solution. For longer preservation, laminate wraps or heat strippable plastic preserving materials are recommended.

Caprock Characterization and Sample Selection

While the core is in tubes and kept chilled, it needs to be subjected to the CT scan to select samples for testing (after that the quantitative permeability testing needs to be done to confirm that samples are suitable caprock). Longitudinal CT scans at 0 degrees and 90 degrees and three axial scans per a 75 cm – 1 m interval are recommended. CT scan images of caprock core with an interval selected for testing ("X") are shown in Figure 1a. Figure 1b shows CT scan images of the core with fractures which is not suitable for testing. A 25–30 cm full diameter core sample is recommended for coreflood testing.



a)

b)

Figure 1. Longitudinal and axial CT scan images of caprock core showing an interval X suitable for testing (a) and caprock core not suitable for testing (b)

Caprock Permeability and Threshold Intrusion Pressure Test Procedure

To evaluate low and high permeability and threshold intrusion pressure on preserved caprock core the following procedure has been developed:

1. Mount sample for testing in a high temperature sleeve (full diameter core is preferred, slabbed vertical core or vertical plugs can also be used in some situations);
2. Set overburden stress, pore pressure and temperature to initial reservoir conditions;

3. Measure brine permeability at approximately 500-1,000 kPa pressure differential over 200-300 hour flow period;
4. Slowly heat to test temperature over approximately 48 hours (200-265^{o}C) to avoid thermal expansion and fluid expansion induced fracturing of caprock;
5. Measure long term (300-400 hours) high temperature permeability to brine at steam temperature with sufficient pore pressure to maintain liquid phase water at 500-700 kPa pressure differential;
6. Measure threshold incremental permeability with water saturated nitrogen gas to simulate steam intrusion at increasing differential pressures, typically 50, 100, 200, 500 and 700 kPa;
7. Measure effective gas/steam permeability of the caprock if gas breakthrough occurs.

A schematic of the caprock test apparatus is presented in Figure 2.

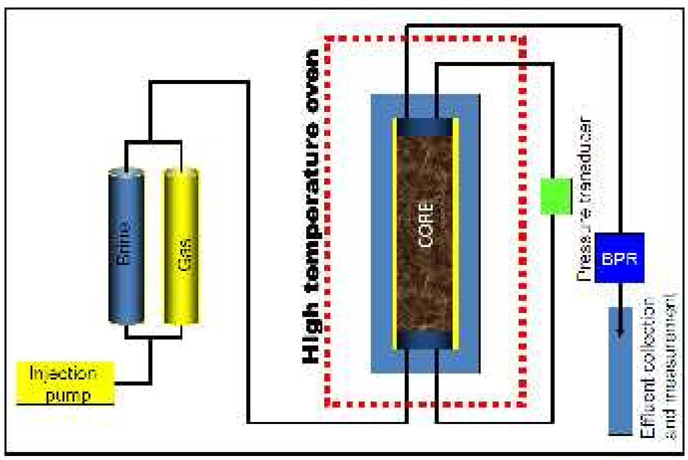


Figure 2. A schematic of caprock test apparatus

TYPICAL TEST RESULTS

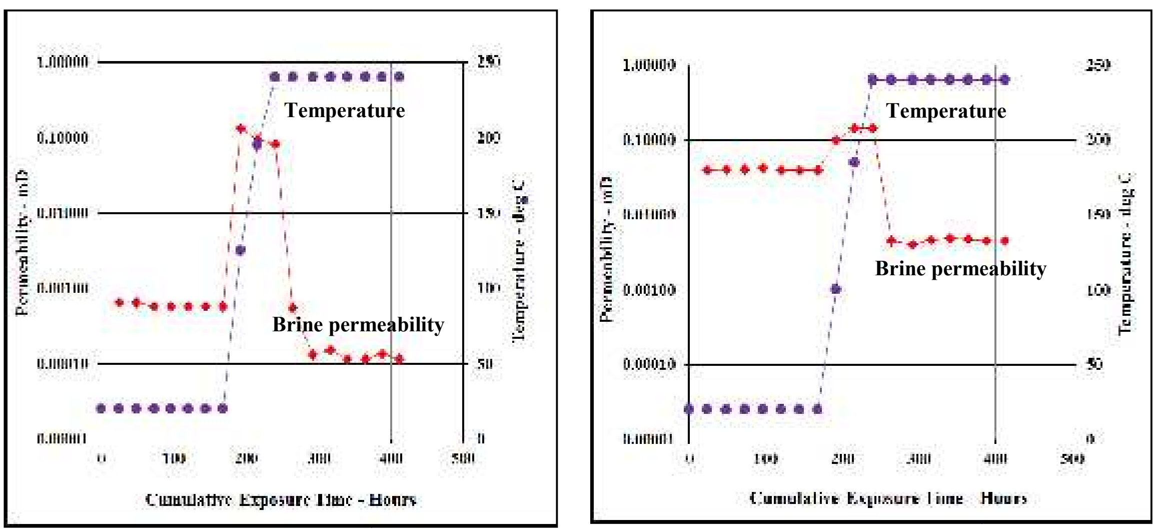
Typical test results for two preserved full diameter samples of caprock from shale formations overlaying heavy oil and bitumen deposits in Western Canada are shown in Table 1 and Figure 3. Table 1 provides data about threshold gas/steam intrusion pressure and permeability at high temperature (240^{o}C). Figure 3 shows low (20^{o}C) and high (240^{o}C) temperature brine permeability versus time.

For caprock sample 1, low temperature permeability is approximately 0.0006 mD and high temperature permeability is approximately 0.0001 mD. No permeability to gas was detected till the differential pressure of 700 kP was applied. Based on the test results, this caprock can be considered "acceptable", good seal under the simulated conditions.

For caprock sample 2, low temperature permeability is approximately 0.03 mD and high temperature permeability is approximately 0.005 mD. Low temperature permeability is above 0.01 mD what is considered to be the criteria of "passable" caprock but the high temperature permeability is below this value. Measurements of gas/steam threshold intrusion pressure show gas/steam breakthrough at the lowest applied pressure (35 kPa). Based on the test results, a conclusion should be made that the caprock might not be a good seal under the simulated conditions and additional testing is needed. Sealing capacity of this caprock in the field would depend on the total thickness, lateral expansion, fractures and other factors which would affect steam containment.

Table 1. Threshold gas/steam intrusion pressure and permeability at 240°C for two caprock samples

Cumulative Time (hrs)	Applied Gas Pressure (kPa)	Sample 1		Sample 2	
		Gas Rate at P and T (cc/hr)	Gas/Steam Permeability (mD)	Gas Rate at P and T (cc/hr)	Gas/Steam Permeability (mD)
48	35	0.000	0.000000	0.020	0.000096
96	70	0.000	0.000000	0.502	0.001202
144	140	0.000	0.000000	1.33	0.001592
192	206	0.000	0.000000	4.25	0.003457
240	350	0.000	0.000000	5.57	0.002667
336	700	0.010	0.000002	20.7	0.004955



a) b)

Figure 3. Low and high temperature brine permeability versus time for caprock sample 1 (a) and for caprock sample 2 (b)

The sharp increase in permeability during the temperature increase is an artifact which can be attributed to the expansion of the system and should not be taken into account. A decrease in brine permeability at high temperature compared to brine permeability at low temperature can be attributed to the effect of steam (fresh) water on clay. Petrographic post test analysis is useful to evaluate swelling of clay minerals and potential changes in mineralogical composition of clay due to the effect of steam.

Based on the test results obtained over the period of over 30 years, approximately 60% of samples fall into the "definitely acceptable" category and approximately 80% of samples fall into the "acceptable" category.

CONCLUSIONS

1. A laboratory protocol has been developed to evaluate the in-situ low and high temperature competency of "matrix" caprock samples for thermal projects.
2. Based on the caprock permeability, the caprock in thermal projects can be classified as:
    - Ideal if permeability is below 0.0001 mD,
    - Acceptable/typical if permeability is below 0.001 mD,
    - Passable (location specific) if permeability is below 0.01 mD,
    - Generally unacceptable if permeability is above 0.05 mD.
3. Based on the test results, approximately 60% of samples fall into the "definitely acceptable" category and approximately 80% of samples fall into the "acceptable" category.
4. The testing method provides a rapid and accurate evaluation of matrix thermal sealing capacity.

ACKNOWLEDGEMENTS

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