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PETROLEUM ENGINEERING

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FUNDAMENTALS OF ENHANCED OIL RECOVERY

STEAM ASSISTED GRAVITY DRAINAGE (SAGD)

Steam-assisted gravity drainage (SAGD; "Sag-D") is an enhanced oil recovery technology for producing heavy crude oil and bitumen. It is an advanced form of steam stimulation in which a pair of horizontal wells is drilled into the oil reservoir, one a few metres above the other. High pressure steam is continuously injected into the upper wellbore to heat the oil and reduce its viscosity, causing the heated oil to drain into the lower wellbore, where it is pumped out. Dr. Roger Butler, engineer at Imperial Oil from 1955 to 1982, invented the steam assisted gravity drainage (SAGD) process in the 1970s. Butler "developed the concept of using horizontal pairs of wells and injected steam to develop certain deposits of bitumen considered too deep for mining". In 1983 Butler became director of technical programs for the Alberta Oil Sands Technology and Research Authority (AOSTRA), a crown corporation created by Alberta Premier Lougheed to promote new technologies for oil sands and heavy crude oil production. AOSTRA quickly supported SAGD as a promising innovation in oil sands extraction technology.

Steam assisted gravity drainage is also defined as a thermal production method for heavy oil that pairs a high-angle injection well with a nearby production well drilled along a parallel trajectory. The pair of high-angle wells is drilled with a vertical separation of about 5m [16ft]. Steam is injected into the reservoir through the upper well. As the steam rises and expands, it heats up the heavy oil, reducing its viscosity. Gravity forces the oil to drain into the lower well where it is produced.

Steam assisted gravity drainage (SAGD) is an outstanding example of a steam injection process devised for a specific type of heavy oil reservoir utilizing horizontal wells. It is widely used in Alberta, Canada for recovery of heavy oil and tar sand resources.

Steam Assisted Gravity Drainage (SAGD) and Cyclic Steam Stimulation (CSS) Steam injection_(oil industry) are two commercially applied primal thermal recovery processes used in the oil sands in Geological formation sub-units, such as Grand Rapids Formation, Clearwater Formation, McMurray Formation, General Petroleum Sand, Lloydminster Sand, of the Manville Group, a Stratigraphic range in the Western Canadian Sedimentary Basin.

Canada is now the single largest supplier of imported oil to the United States, supplying over 35% of US imports, much more than Saudi Arabia or Venezuela, and more than all the OPEC countries combined. Most of the new production comes from Alberta's vast oil sands deposits. There are two primary methods of oil sands recovery. The strip-mining technique is more familiar to the general public, but can only be used for shallow bitumen deposits. However, the more recent steam-assisted gravity drainage technique (SAGD) is better suited to the much larger deep deposits that surround the shallow ones. Much of the expected future growth of production in the Canadian oil sands is predicted to be from SAGD.

"Petroleum from the Canadian oil sands extracted via surface mining techniques can consume 20 times more water than conventional oil drilling. As a specific example of an underlying data weakness, this figure excludes the increasingly important steam-assisted gravity drainage technique (SAGD) method."

— **The Water-Energy Nexus 2011**

Steam Assisted Gravity Drainage emissions are equivalent to what is emitted by the steam flood projects which have long been used to produce heavy oil in California's Kern River Oil Field and elsewhere around the world.

STEAM ASSISTED GRAVITY DRAINAGE HAS SEVERAL ADVANTAGES OVER OIL SANDS MINING:

- Access to resources: More than 80% of Canada's oil sands can only be accessed by drilling technologies, like SAGD.
- Reduced environmental footprint: With horizontal wells stretching more than a kilometer beneath the surface, a large area can be developed with minimal impact to the land. SAGD operations typically disturb only 10% to 15% of the surface of the development area.
- Manageable growth: SAGD allows development in stages, helping to manage costs and workforce peaks. MEG's current operations and future plans are based on multi-stage expansions of between approximately 25,000 and 50,000 barrels per day.
- Technology upside: While SAGD is a proven technology, it is still relatively young and holds the potential for improved recovery rates, greater energy efficiency and lower costs as we continue to research and test potential enhancements.

DISADVANTAGES OF STEAM ASSISTED GRAVITY DRAINAGE

- **Oil and water nexus**

SAGD, a thermal recovery process, consumes large quantities of water and natural gas.

"Petroleum from the Canadian oil sands extracted via surface mining techniques can consume 20 times more water than conventional oil drilling. As a specific example of an underlying data weakness, this figure excludes the increasingly important steam-assisted gravity drainage technique (SAGD) method. We encourage future researchers to fill this hole.

— The Water-Energy Nexus 2011

"Petroleum from the Canadian oil sands extracted via surface mining techniques can consume 20 times more water than conventional oil drilling." However, by 2011 there was inadequate data on the amount of water used in the increasingly important steam-assisted gravity drainage technique (SAGD) method.

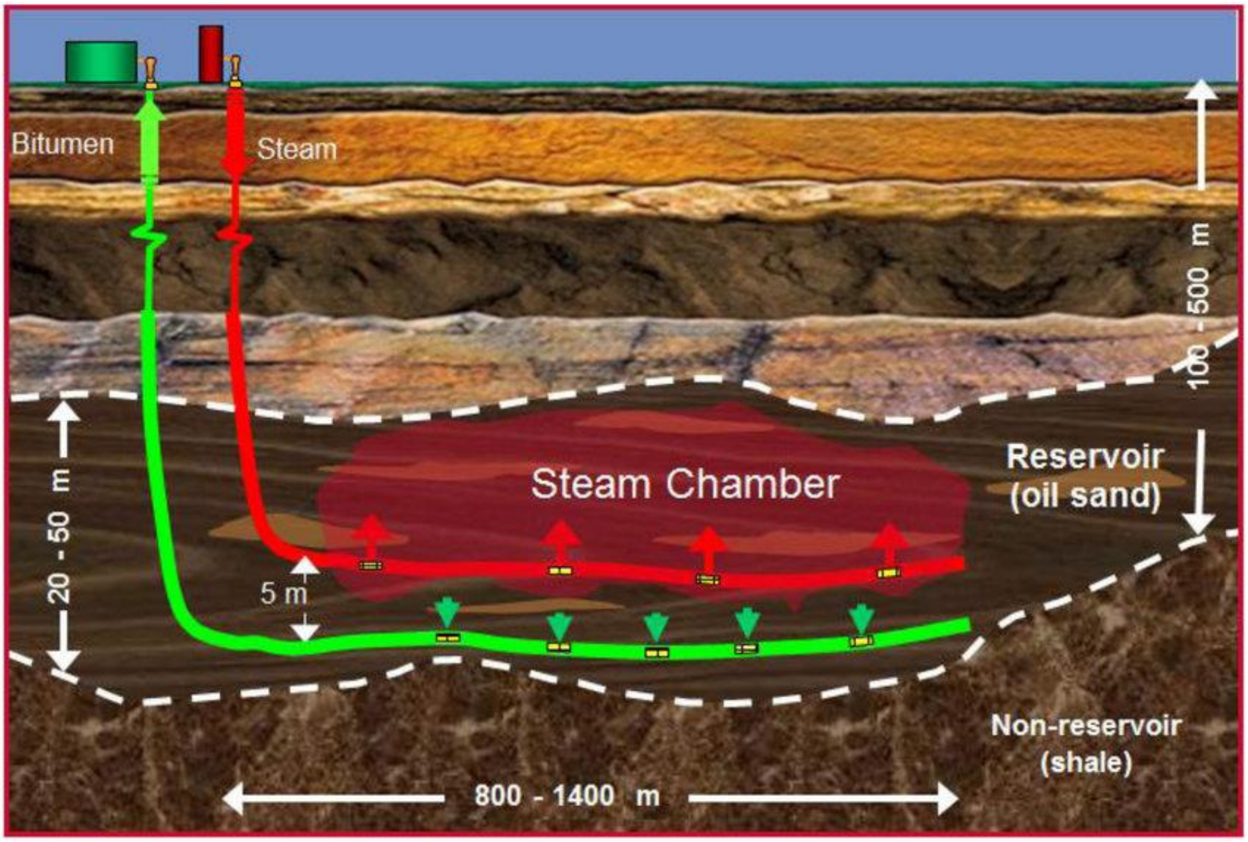
Evaporators can treat the SAGD produced water to produce high quality freshwater for reuse in SAGD operations. However, evaporators produce a high volume blowdown waste which requires further management.

- **Use of natural gas for steam generation**

As in all thermal recovery processes, cost of steam generation is a major part of the cost of oil production. Historically, natural gas has been used as a fuel for Canadian oil sands projects, due to the presence of large stranded gas reserves in the oil sands area. However, with the building of natural gas pipelines to outside markets in Canada and the United States, the price of gas has become an important consideration. The fact that natural gas production in Canada has peaked and is now declining is also a problem. Other sources of generating heat are under consideration, notably gasification of the heavy fractions of the produced bitumen to produce syngas, using the nearby (and massive) deposits of coal, or even building nuclear reactors to produce the heat.

- **Use of water for steam generation**

A source of large amounts of fresh and brackish water and large water re-cycling facilities are required in order to create the steam for the SAGD process. Water is a popular topic for debate in regards to water use and management. As of 2008, American petroleum production (not limited to SAGD) generates over 5 billion gallons of produced water every day. The concern of using large amounts of water has little to do with proportion of water used, rather the quality of the water. Traditionally close to 70 million cubic metres of the water volume that was used in the SAGD process was fresh, surface, water. There has been a significant reduction in fresh water use as of 2010, when approximately 18 million cubic metres were used. Though to offset the drastic reduction in fresh water use, industry has begun to significantly increase the volume of saline groundwater involved. This, as well as other, more general water saving techniques have allowed surface water usage by oil sands operations to decrease by more than threefold since production first began. Relying upon gravity drainage, SAGD also requires comparatively thick and homogeneous reservoirs, and so is not suitable for all heavy-oil production areas.



TYPICAL STEAM ASSISTED GRAVITY DRAINAGE (SAGD) PROCESS

CYCLIC STEAM STIMULATION (CSS)

Cyclic Steam Stimulation is a method of thermal recovery in which a well is injected with steam and then subsequently put back on production. A cyclic steam-injection process includes three stages. The first stage is injection, during which a slug of steam is introduced into the reservoir. The second stage, or soak phase, requires that the well be shut in for several days to allow uniform heat distribution to thin the oil. Finally, during the third stage, the thinned oil is produced through the same well. The cycle is repeated as long as oil production is profitable. Cyclic steam injection is used extensively in heavy-oil reservoirs, tar sands, and in some cases to improve injectivity prior to steamflood or in situ combustion operations. Cyclic steam injection is also called steam soak or the huff `n puff (slang) method.

The mechanism proceeds through cycles of steam injection, soak, and oil production. First, steam is injected into a well at a temperature of 300 to 340° Celsius for a period of weeks to months. Next, the well is allowed to sit for days to weeks to allow heat to soak into the formation. Finally, the hot oil is pumped out of the well for a period of weeks or months. Once the production rate falls off, the well is put through another cycle of injection, soak and production.

This process is repeated until the cost of injecting steam becomes higher than the money made from producing oil. The CSS method has the advantage that recovery factors are around 20 to 25% and the disadvantage that the cost to inject steam is high.

Canadian Natural Resources use "employs cyclic steam or "huff and puff" technology to develop bitumen resources. This technology requires one well bore and the production consists of the injection and production phases. First steam is "injected for several weeks, mobilizing cold bitumen". The well is then shut in for several weeks or months to allow the steam to soak into the formation. Then the flow "on the injection well is reversed producing oil through the same injection well bore. The injection and production phases together comprise one cycle. "Steam is re-injected to begin a new cycle when oil production rates fall below a critical threshold due to the cooling of the reservoir. Artificial lift method of production may be used at this stage. After a few cycles, it may not be economical to produce by the huff and puff method. Steam flooding is then considered for further oil recovery if other conditions are favorable. It has been observed that recovery from huff and puff can be achieved up to 30% and from steam flooding recovery can be up to 50%'' (CNRL 2013).

Cyclic Steam Stimulation (CSS) also has a number of CSS Follow-up or Enhancement Processes, including PressureUp and BlowDown (PUBD), Mixed Well Steam Drive and Drainage (MWSDD), Vapor Extraction (Vapex), Liquid Addition to Steam for Enhanced Recovery of Bitumen (LASER) and HPCSS Assisted SAGD and Hybrid Process.

Cyclic steam injection (or cyclic steam stimulation) is the alternating injection of steam and production of oil with condensed steam from the same well or wells.

Thus, this process is predominantly a vertical well process, with each well alternately injecting steam and producing heavy oil and steam condensate. In practice, steam is injected into the formation at greater than fracturing pressure. This is followed by a soak period after which production is commenced. The heat injected warms the heavy oil and lowers its viscosity. A heated zone is created through which the warmed heavy oil can flow back into the well. This is a well-developed process; the major limitation is that less than 30% (usually less than 20%) of the initial oil in place can be recovered.

Cyclic steam stimulation is often the preferred method for production in heavy oil reservoirs that can contain high-pressure steam without fracturing the overburden. The minimum depth for applying cyclic steam stimulation is on the order of 1,000 ft, depending upon the type and structure of the overlying formations.

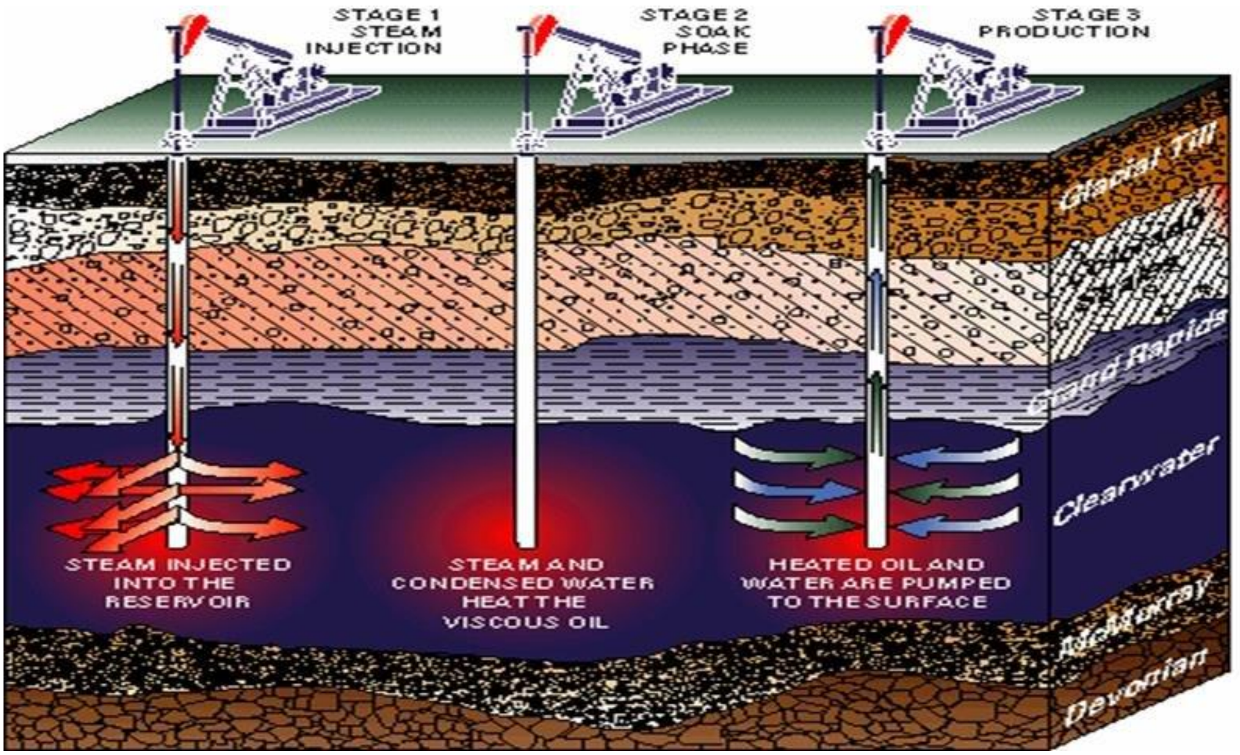
Cyclic steam stimulation works best when there are thick pay zones (>10 m) with high porosity sands (>30%). Shale layers that reduce vertical permeability are not a problem for vertical wells that penetrate thick pay zones. However, good horizontal permeability (>1 d) is important for production. Recently, cyclic steam stimulation has been applied to wells with multilateral horizontal legs.

Typical recovery factors for cyclic steam stimulation are 20–35% with SORs of 3–5.22. Steamflood processes may follow cyclic steam stimulation. While cyclic steam stimulation produces the heavy oil around a single wellbore, steamflooding recovers the heavy oil between wells. For example, a five-spot pattern with four producing wells surrounding a central steam injection well is a common configuration. The well spacing can be less than 2 acres for a field in steam flood. The steam heats the oil to lower its viscosity and provides pressure to drive the heavy oil toward the producing wells. In most steamflood operations, all of the wells are steam-stimulated at the beginning of the flood. In a sense, cyclic steam stimulation is always the beginning phase of a steamflood. In some cases, even the steamflood injection wells are put on production for one or two cyclic steam stimulation cycles to help increase initial project production and pay out the high steam flood capital and operating costs.

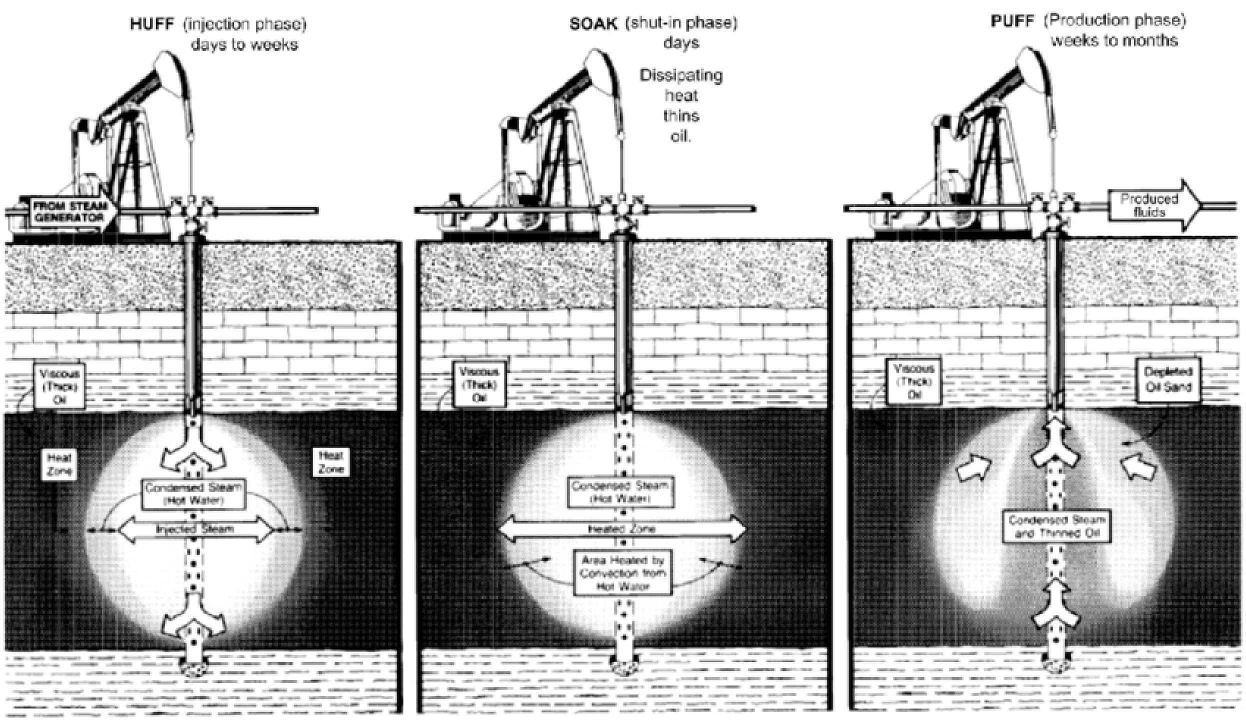
Cyclic steam injection is used extensively in heavy oil reservoirs, tar sand deposits, and in some cases, to improve injectivity prior to steamflooding or in situ combustion operations.

In practice, steam is injected into the formation at greater than fracturing pressure (150–1,600 psi for Athabasca sands); this is followed by a soak period and production (Burger, 1978; Winestock, 1974). The technique has also been applied to the California tar sand deposits (Bott, 1967) and in some heavy oil reservoirs north of the Orinoco deposits (Ballard et al., 1976). The steamflooding technique has been applied, with some degree of success, to the Utah tar sands (Watts et al., 1982) and has been proposed for the San Miguel (Texas) tar sands (Hertzberg et al., 1983).

Technical challenges for cyclic steam stimulation and steamflooding are primarily related to reducing the cost of steam, which is generated in most locations using natural gas. The economics may be improved by also generating and selling electricity and by using waste heat for cogeneration. Alternative fuels (coal, heavy ends, and coke) are discussed separately below; they could also reduce the cost of steam generation. Monitoring and controlling the steam front could also reduce costs by redirecting steam to zones where the heavy oil has not been produced. Steam could be shut off from zones that have been successfully swept and directed toward unswept regions.



CYCLIC STEAM STIMULATION SHOWING THE THREE DIFFERENT STAGES



TWO CYCLIC STEAM STIMULATION PROCESS

HOT WATER FLOOD

Hot Water Flooding, also known as hot water injection is a technique of increasing crude oil production from a producing well by injecting hot water into the reservoir. The hot water is injected through an injection well which is drilled parallel to the primary producing well. The heat from the hot water acts as a way of reducing the viscosity of crude oil, making it to flow toward the producing well with ease. Hot water flooding is generally used to extract crude oil which has an API degree of less than 20.

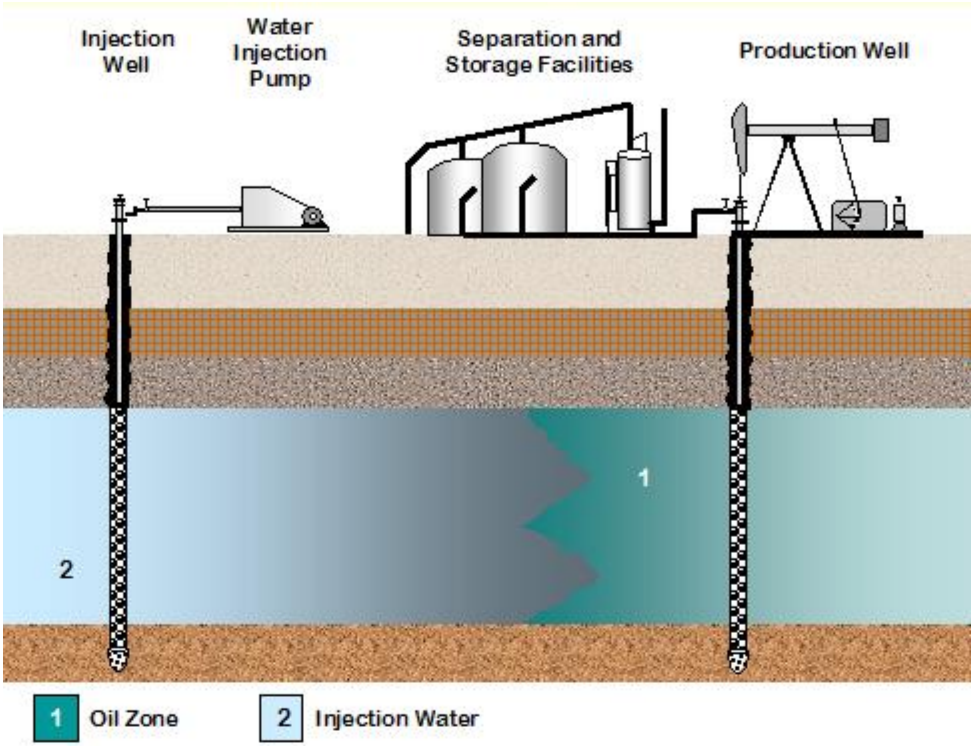
Hot water flooding is considered as one of the techniques of increasing crude oil production under Enhanced Oil Recovery Technique (EOR) and thermal recovery. It is less effective than steam injection process, due to the fact that hot water has a lower heat content as compared to steam.

Over time the pressure in an oil reservoir slowly and steadily decreases and as a result the production rate decreases. This is one of the techniques used by E&P organizations to enhance the production of heavy to medium category crude oil from a reservoir. To use this technique, an injection well is drilled parallel to the primary producing well through which hot water is injected forcefully into the reservoir in the direction of the producing well.

The benefits of injecting water into the reservoir are:

- It supports the reservoir pressure, also known as voidage replacement.
- As oil is lighter than water hence it floats on top of the water. Also, the heat content of the water reduces the viscosity of heavy crude oil, making it not to stick on the edges of the reservoir and move quickly toward the producing well. Thus, water helps in displacing oil from its location in the reservoir and pushes it toward the producing well.

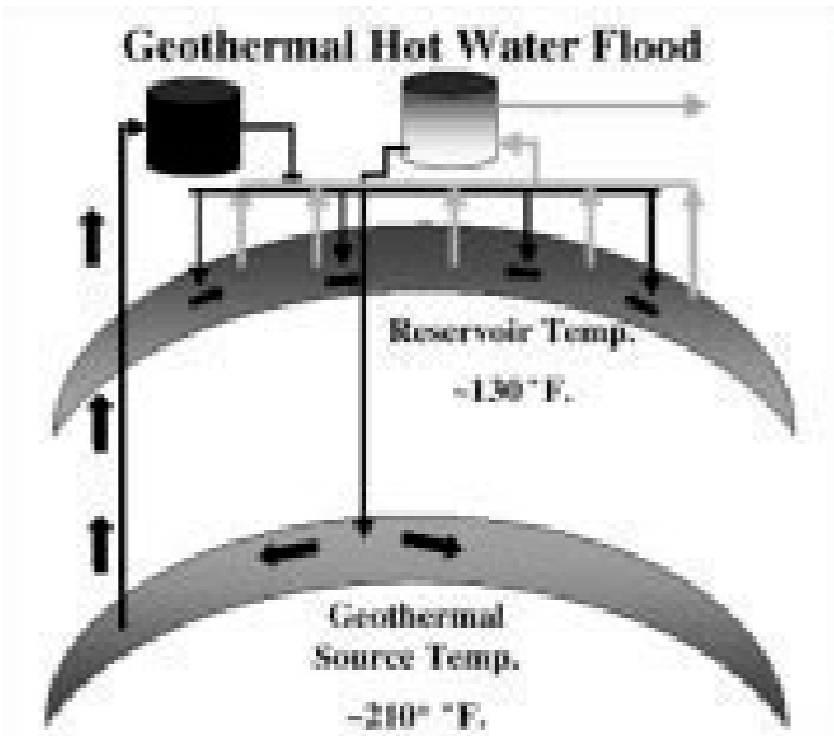
With this technique, oil recovery factor can be increased and well production rate can be maintained for a longer period.



In Canada, heavy oil is typically referred to as oil with an API gravity of less than 20. It is found in all types of underlying formations, mostly in unconsolidated sands reservoirs with permeabilities of a few Darcies and porosities of more than 30%. Having very low mobility, the primary and secondary recovery of heavy oils is low. Typical primary recoveries may vary from 3 to 8 % of oil originally in place (OOIP) and may increase up to 15% after secondary recovery, mostly through waterflooding (Meyer et al., 1981; Farouq Ali, 1974). Waterflooding is the most widely utilized enhanced oil recovery (EOR) methods (Willhite 1986; Forrest and Craig 2004). However, it is typically very inefficient in heavy oil reservoirs due to the unfavorable mobility ratio pertaining to the high viscosity of heavy oil, which causes severe fingering of the injected water, resulting in low sweep efficiency, early water breakthrough, high water cut and low recovery factor (Martin et al., 1968; Farouq Ali, 1974; Adams, 1982; Karakas, 1986).

Among the several thermal methods, hot water injection is the least expensive process. It is similar to conventional waterflooding utilizing hot water instead of cold water (Martin et al., 1968; Farouq Ali, 1974). Although steam has three times the heat capacity of water, it is expensive to generate and implementation is intensive. Hot water has certain advantages particularly for conditions pertaining to clay swelling problems. It also provides injection with higher pressure than steam and is more efficient in maintaining reservoir pressure.

Hot waterflooding is rarely used in the oil industry due to high heat loss in the surface facilities, wellbore, and formation which causes a significant temperature drop, and as a result, impedes the performance of the thermal process. However, it can be considered as an alternate method for deep heavy oil reservoirs where steam is not applicable. (Sutton, 1968; Farouq Ali, 1974; Diaz-Munoz and Farouq Ali, 1975; Poetmann et al., 1983; Donaldson et al., 1989; Dornan, 1990; Somerton, 1992; Forrest and Craig, 2004; Kumar et al., 2008).



SCHEMATIC DIAGRAM OF HOT WATER FLOODING FROM A GEOTHERMAL SOURCE

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