Nuclear power in heavy oil extraction and upgrading

A technical overview of the use of nuclear plants as a heat source in the oil industry

by Hernán Carvajal-Osorio

The use of heat for stimulating oil production has become a widely accepted method for heavy oil recovery. Although mainly used in secondary and tertiary recovery processes, oil production stimulated by heat has also been employed in primary recovery in oil fields that do not respond to conventional methods. The use of nuclear reactors as the heat source has been often studied but never applied despite conclusions that indicated the economic attractiveness, at the time of the study, of the nuclear option.

The problem has been beyond that of pure economics. Firstly, the temperature and pressure conditions required for heavy oil recovery are usually higher than the maximum values attainable by the current most highly developed and commercialized type of nuclear reactor, the water-cooled reactors (both light water and heavy water). If this is not initially true in any exploitable oil field, it will occur as potentially deeper formations of heavy oil and longer heat transport paths are considered within the same field for which the nuclear plant is to be the heat source. Secondly, the oil market continues to be very unstable and hence the risks associated with a long-term, capital-intensive nuclear project would be untenable. Moreover, at this time, the exploitation of recent large conventional oil deposits, such as in Alaska and the North Sea, together with the abundant and continued supply, at reasonable prices, from the Organization of Petroleum Exporting Countries (OPEC) and other countries does not demand that heavy oil reserves be widely tapped. Thirdly, the institutional issues associated with nuclear power, i.e. safety, waste handling, fuel supply, and public acceptance, continue for the electrical generation industry, resulting in an unfavourable atmosphere for nuclear ventures in new areas.

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Nevertheless, it is in general believed that most of these negative factors concerning the use of nuclear power will progressively fade away as the limited reserves of conventional oil are depleted. Recognizing the energy intensive nature of heavy oil recovery and the subsequent upgrading processes, nuclear power stands out due to its characteristics as an ideal candidate to play an important role.

Thermal-assisted heavy oil recovery and upgrading

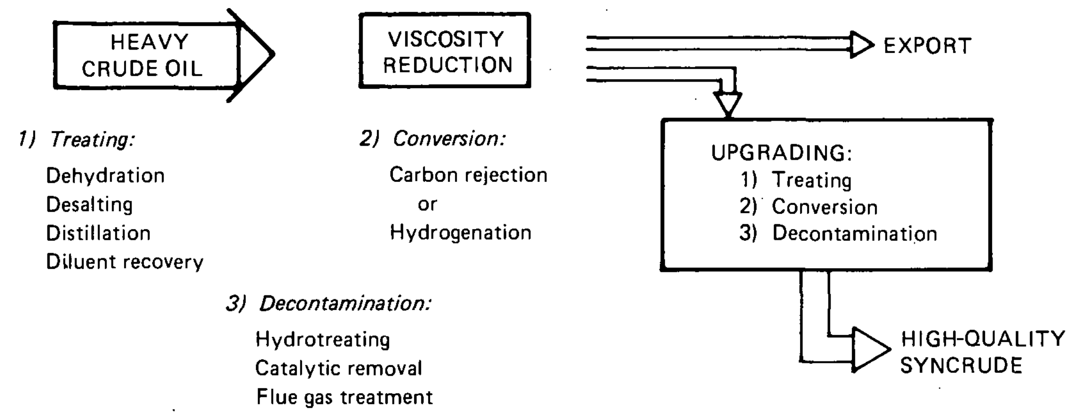
The main methods employed in thermal-assisted oil recovery are: hot fluid injection, mainly hot water; steam injection, in soak and drive conditions, and *in-situ* combustion. Other methods, such as hot gas injection and down-the-hole steam generators, have had only limited application.

Besides thermal stimulation, other methods such as water flooding, gas injection (mainly air and CO_2), chemical additives and others (microbial, electromagnetic heating, foam addition, etc.), have been applied to some extent in secondary and tertiary oil recovery, with different results depending on particular field conditions. The addition of diluents, with or without heat stimulation, is becoming widespread due to its ability to considerably reduce the energy required for the crude oil displacement.

Thermal stimulation methods prevail in all areas of enhanced oil recovery (EOR).* For example, of the total EOR projects in the United States in 1988, 73% of the production was obtained by thermal methods. Venezuela, the second largest user of EOR in the Western

* The term EOR is usually reserved to cases where energy must be added to the oil reservoir to produce significant amounts of additional oil. It does not include reservoirs that have never produced oil or from which the oil does not flow by natural pressure or that must be heated to be pumped. EOR includes, besides thermal stimulation, any other way to add energy to the oil reservoir.

Main processing steps in heavy oil recovery and upgrading



Hemisphere, employs thermal stimulation almost exclusively, as well as Indonesia, another important EOR user. Steam injection is the preferred thermal stimulation method for its simplicity, relative low cost, and its success in present projects.

Steam temperature and pressure conditions for injection into oil formations depend on oil deposit characteristics, such as depth and permeability, and on crude properties, like viscosity and gravity. Temperatures around 350°C with pressures between 12 and 17 MPa might be common for deposits ranging from 500 to 1000 metres in depth. For deeper deposits, steam injection has reduced efficiency, although improved well insulation and higher steam temperature and pressures would permit exploitation of deeper reservoirs.

In the extraction of extra-heavy oil and bitumen, and in oil recovery from mined oil sands and oil shales, thermal methods are the only choice.* Heavy oil and bitumen, after being extracted, must go through an upgrading process to remove impurities and to increase the hydrogen to carbon ratio in order to obtain higher quality products in subsequent conventional refining. Relatively large concentrations of sulfur and metals, such as vanadium and nickel, are usually found in heavy crude oils.

A number of processing steps are involved in heavy oil exploitation. *(See accompanying figure.)* Although either carbon rejection or hydrogenation methods could be applied for increasing the hydrogen to carbon ratio of heavy oils, hydrogenation is preferred for its higher oil conversion rate and for its improved yield of lighter crude fractions. Hydrogenation, however, implies a relatively large consumption of hydrogen whose production also requires a large amount of energy.

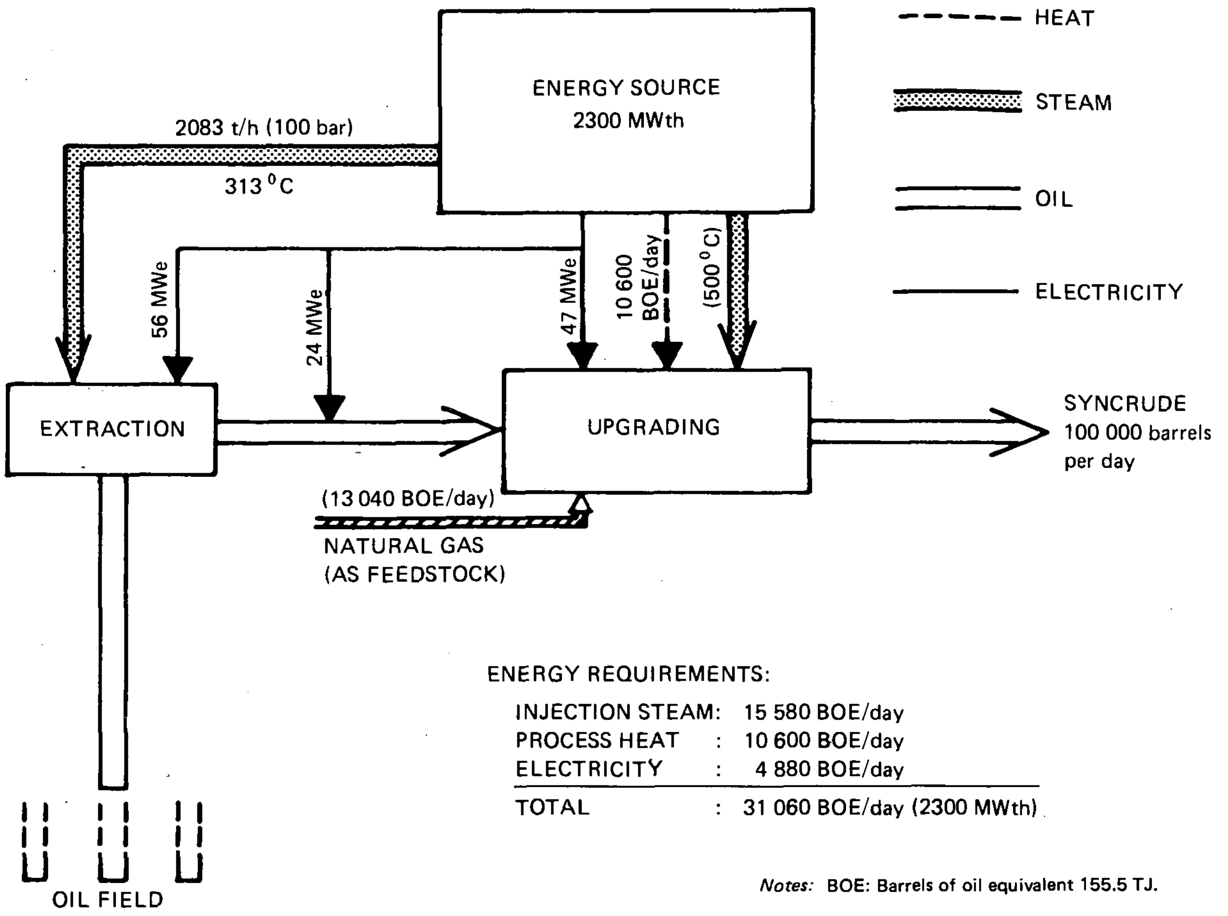
With respect to the costs involved in heavy oil exploitation, costs between US $9 and 15 per barrel have been reported for heavy oil extraction and oil sands processing, except in Venezuela, where heavy oil lifting costs of around US $5 per barrel are claimed.* The upgrading process could add an extra cost of US $10 per barrel or more, depending on the particular project and the degree of crude treatment needed.

Recent studies conducted by the US Department of Energy concluded that if oil prices steadily climb to the US $40–50 per barrel range by the year 2000, a yield of 19.4×10^9 barrels of additional heavy oil would be attained in the USA, nearly twice as much as has been produced through 1985. The same study indicated, however, that if oil prices only increased from a level of US $12 per barrel up to $21 per barrel by the year 2000, thermal EOR production rate would start to decline from its present 500 000 barrels per day. The study also concluded that, if the oil price could sustain a 5% yearly increase up to US $36 per barrel by the year 2000, the thermal-assisted production rate would reach the one million per day figure, with *in-situ* combustion providing the highest increase.

* For the difference between heavy oil and bitumen, the Second UNITAR (United Nations Institute for Training and Research) Conference in 1982 defined that when oil viscosity at reservoir temperature is below 10 000 cp, it is considered crude oil, and that above 10 000 cp, is termed bitumen. Crude oil was then classified as extra heavy oil when the gravity is below 10 API, heavy oil for gravities between 10 and 20 API, and conventional oil for gravities above 20 API, all gravities measured at 15.6°C.

* One barrel is equivalent to 0.159 cubic metres.

Energy requirements of Orinoco Belt extra-heavy oil exploitation



Notes: BOE: Barrels of oil equivalent 155.5 TJ.

Heavy oil resources and exploitation energy cost

The world's important heavy crude reserves have been estimated as 2×10^{12} barrels. Of these, Venezuela holds about 72%, with other countries, mainly the Soviet Union, United States, and Iraq, holding less than 10% each.

Canada is well known for its large deposits of oil sands (mostly classified as bitumen) with 2.95×10^{12} barrels of oil in place, an amount larger than the total world reserves of heavy oil, and representing about 82% of the world's total. Of this total, about 5×10^{11} barrels of heavy crude and 2×10^{11} barrels of bitumen are considered to be recoverable using known technology.

The USSR heavy crude and bitumen deposits are estimated to contain 2×10^{12} barrels, of which 0.5×10^{12} are considered as reserves. The present heavy crude production rate in the USSR is very low, only 25 000 barrels per day.

Oil shale deposits also contain considerable amounts of hydrocarbons. In oil shale the crude is not present as liquid but is contained inside the shale in the form of kerogen. Heat, at temperatures around 370°C, must be added to decompose the kerogen into a relatively light "shale oil", with yields ranging between 40 and 400 litres per ton. At present, oil shale reserves are still unknown but they are believed to be large and distributed around the world, with major concentrations in the USA and the USSR, and other substantial accumulations in China and Brazil. Only in the USA has the recoverable shale oil been estimated to be 1×10^{12} barrels of oil.

In the exploitation of heavy oil and other non-conventional oil resources, the economy of the energy cycle, as in any energy intensive activity, becomes of great importance. A tremendous waste of energy resources could arise, with a high environmental impact and with the possibility of having negative net energy balances (all processes taken into consideration) when not enough attention is paid to the energy issue.

The energy costs in current heavy oil projects range from about one-fifth of the energy content of the oil produced, as is the case in Indonesia, up to about one-third in more demanding projects. These figures cover only the extraction process. If upgrading is included, 40 to 50% of the oil being produced may have be consumed in an integrated model for heavy oil exploitation. Such a fraction changes considerably depending on oil field conditions and crude characteristics. Hydrogen production, needed for the crude oil hydrotreating as part of the upgrading process, requires special consideration since it is the most energy-demanding step in the whole process. Several hydrogen production methods are available, water electrolysis and steam-methane reforming being the most common. Steam-methane reforming, which makes use of natural gas or other hydrocarbon as feedstock, is the most economical of the two.

As an example, estimated values were calculated for the energy requirements in the extraction and preprocessing of extra-heavy crude from the Venezuelan Orinoco Oil Belt, a case where rather extensive treatment is required. *(See accompanying figure.)* Including the natural gas used as feedstock for hydrogen production, the energy input totals about 44% of the energy equivalent of the output produced.

Energy consumption in heavy oil extraction by steam injection is measured by the oil-to-steam ratio (OSR) (sometimes the inverse is specified), expressed in barrels of oil per ton of steam. High ratios are desired for an improved energy economy and lower costs. In some cases, the steam is injected first in a cyclic way, just enough to enhance oil production, using part of the same producing wells as injectors. This stage is called soak production. When field production starts to decline considerably, then continuous steam injection is applied until the field exploitation becomes uneconomical. This is called the drive stage. In passing from the soak to the drive stage, injection steam demand jumps to high values, consequently lowering the OSR substantially. Common figures are 25 barrels per ton for the soak phase and 5 or lower for steam drive. In the USA, OSR values above 1.6 barrels per ton in EOR projects with conventional fossil-fuel burning for steam production, are considered profitable.

Nuclear power in heavy oil recovery: Past studies and state-of-the-art

In developing nuclear-assisted heavy oil recovery, new technology challenges will have to be confronted in the adaptation and optimization processes. Massive steam production and its delivery at relatively high temperature and pressures, inexpensive treatment of large quantities of raw water, ground stability problems, together with operational optimization of a multipurpose nuclear plant, are some of the main tasks to be confronted. In addition, oil field characteristics and petroleum properties change from place to place, resulting in varying demand for steam volume as well as varying steam conditions. A probable shorter oil field production time than reactor life also represents a new challenge.

Many of these aspects point in an opposite direction from standardization of nuclear plant design and construction with the intended purpose of reducing costs. The nuclear steam supply system and other plant components may, however, still be capable of some standardization.

A Canadian study on the use of Candu reactors covered the application of nuclear power in heavy oil extraction from oil sands by steam injection in reasonable detail. At the time of the study (1980), cost savings from 25 to 50% with respect to burning coal for the steam production were estimated. An organic-cooled Candu reactor was also proposed for oil sand deposits deeper than 650 metres which required higher steam pressures. However, as already noted and despite the several advantages of LWRs and HWRs, these reactors are still limited in temperature and pressure capability for oil recovery from deep deposits.

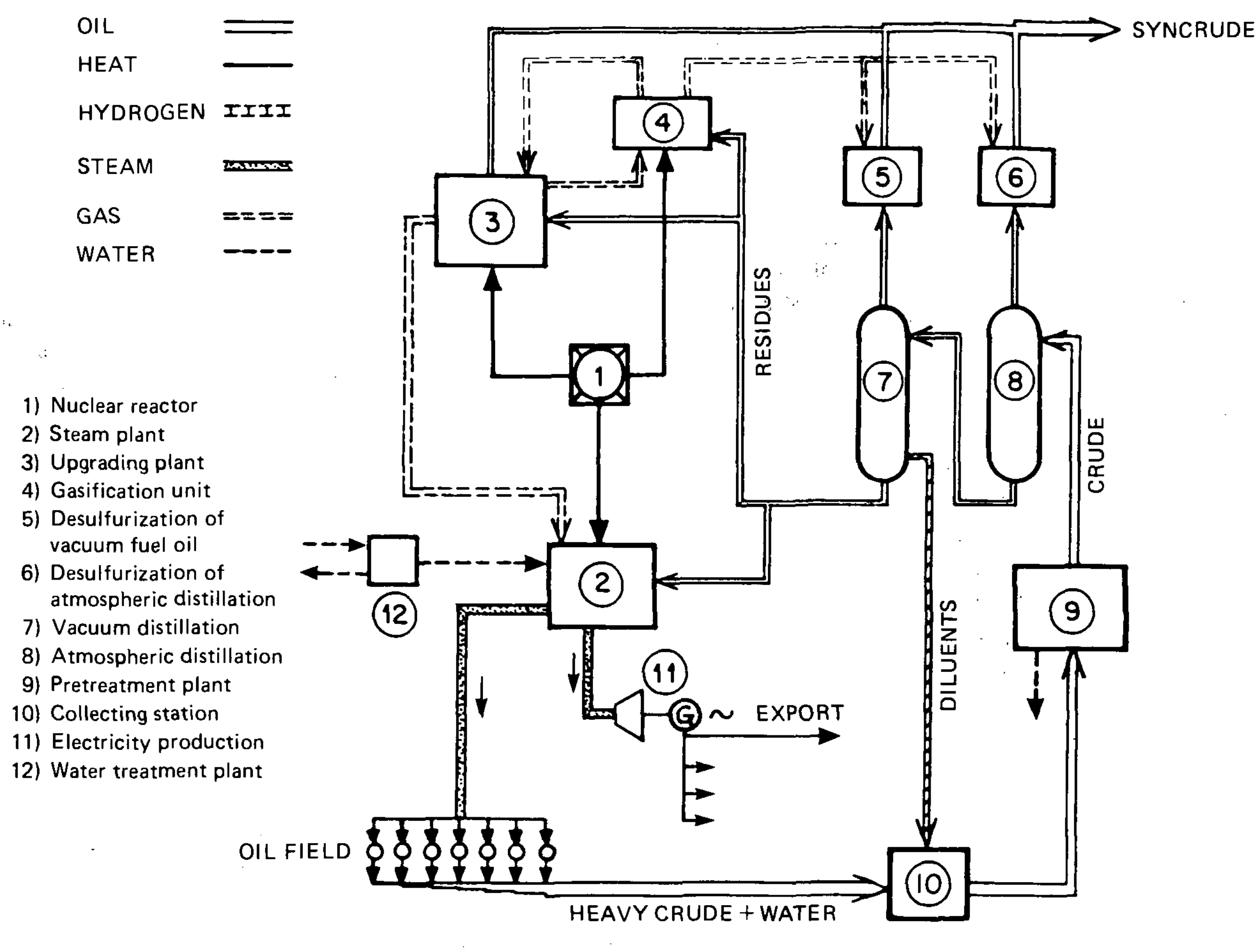
In 1981, the General Electric Company in the United Kingdom proposed the use of Magnox reactors for heavy oil recovery. The employment of natural uranium as fuel and the use of unsophisticated materials in the reactor fabrication, were very attractive features of this reactor concept, especially for developing countries. However, the reactor's low uranium resource utilization and its relatively large plutonium production were the main drawbacks.

Companies such as General Atomics in the USA, the European ASEA-Brown-Boveri Company and, more recently, Siemens in the Federal Republic of Germany, have performed extensive studies on the design and application of high-temperature gas-cooled reactors (HTGR) for EOR, including heavy oil recovery. Other countries, such as the USSR, the People's Republic of China, and Japan, have also carried out design studies for HTGR reactors to be employed in process-heat generation, the first two countries with specific interests in heavy oil recovery.

HTGR type reactors are capable of producing heat and steam at temperatures and pressures even higher than required for heavy oil recovery. They are thus capable of simultaneously producing high-quality steam for both processing and electricity generation, together with the injection steam. Such a cogeneration scheme adds versatility to the operation of a plant, since oil field steam demand variations could be accommodated by diverting steam to electricity production, with part of the electricity satisfying the plant demand and the excess for export.

In a heavy oil project requiring large amounts of injection steam, steam diversion directly from the secondary cycle would not be feasible since conditions in the secondary cycle require water of a much higher purity and quality, and hence, a more expensive water treatment, than demanded for injection steam. However, the use of reboilers solves this problem with, of course, an

Orinoco Belt extra-heavy oil extraction and processing (HDH Process) with a nuclear reactor as main energy source



added capital cost and a minor penalty in injection steam conditions.

There is an expanded scheme for using nuclear power in both the recovery and upgrading operations, corresponding to the HDH process for Venezuelan extra-heavy crudes. *(See accompanying figure.)* In this scheme, an HTG reactor could provide most of the process heat needs with temperatures in the range of 500–700°C, besides high-pressure injection steam. The higher temperature attained with more advanced versions of the HTGR under development (as proceeding in Japan and other countries), with temperatures around 900°C or more, would permit the capability of using process heat from the reactor to also power a steam-methane plant for hydrogen production in addition to providing steam and electricity production. The recent emphasis on the smaller output, modular versions of the HTGR also provides additional flexibility in terms of oil field demand requirements, the ability to dedicate different modules to different types of service, if necessary, and more benign behaviour in terms of operation and safety.

Other reactor designs have also been considered for process-heat applications. Liquid-metal cooled reactors, able to produce 500°C heat, and particularly the small modular versions under development in the USA, could certainly have possibilities for application in future heavy oil exploitation.

Reactor cores which could sustain the most adverse circumstances with extremely low risks of even reaching fuel-melting temperatures (so there is no significant fission product release in case of an accident) are now the design goal of the advanced reactor concepts under development for commercial application.

From the economic point of view, studies have indicated, at the time of the study, economic advantages against fossil-fuel burning, including coal and oil residues. For example, a study performed by General Atomics in the USA in 1983, on the application of an 1170 MWth HTGR to extract oil from shale by the direct steam retorting process, indicated a price of US $41 (1983 dollars, 30-year levelized) per barrel of upgraded shale oil for a plant starting operations in year 2005. Cost analysis in other than shale oil projects may indicate more favourable exploitation costs.

Nevertheless, to compete against the burning of upgraded oil residues with very low commercial value may be difficult. These oil residues do have, however, large impurity concentrations, such as sulfur and nitrogen, which certainly would have a detrimental impact on the environment when burned. Under tight environmental regulations, it might become forbidden to burn such residues or to force the addition of costly equipment to remove the impurities. The absence of such type of emissions in the nuclear option favours its application.

Oil market forecasts generally show that, by the beginning of next century, oil prices will rise to the neighbourhood of the above-mentioned price levels. Thus, nuclear-assisted heavy oil exploitation has real possibilities for commercialization in a not so distant future.

Perspective for nuclear power applications

Several studies on the use of nuclear power as a heat source for heavy oil exploitation have demonstrated that under more favourable oil market conditions, the nuclear option presents economical and environmental benefits as compared to conventional methods.

However, due to the large investment required and the high economic risks involved, a strong commitment, based on realistic national energy policies and improved oil market conditions, is needed for any country to go ahead with a nuclear-assisted oil project. Large foreign debts in many countries preclude the application of capital intensive solutions, such as nuclear, unless special terms and conditions can be arranged.

The development of the next generation of nuclear power plants, some of them almost technologically ready now and able to produce high enough temperatures and pressures for heat and steam supply in both heavy oil extraction and upgrading processes, open entirely new perspectives for the application of nuclear power in the oil industry. Due to their advanced stage of development and outstanding safety characteristics, HTGRs constitute a promising reactor design for such an application.

The nuclear alternative could considerably increase the production yield of important oil resources, with a reduced environmental impact and high safety standards, contributing to the development of many nations by extending a sufficient oil supply for unsubstitutable uses. The present tendency to continue increasing safety properties of the most recent nuclear reactor designs certainly will produce a positive impact on the development of nuclear-assisted processes, including heavy oil exploitation.