



## Comparative Study of Thermal and Mechanical Heating Methods for Heavy Oil Recovery

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#### Abstract

Heavy oil recovery is challenging owing to the high viscosity and low mobility of the oil, necessitating the application of modern recovery technologies. This paper presents a detailed comparative study of the four most widely used recovery processes: Cyclic Steam Stimulation (CSS)/Steam Flooding, Steam-Assisted Gravity Drainage (SAGD), In-Situ Combustion (ISC), and THOR Cavitas (mechanical heating system). The qualitative and quantitative comparisons show the relative merits and demerits of the four processes. SAGD has the maximum recovery efficiency (60-70%) for heavy oil in thick, homogeneous reservoirs, while CSS has a moderate recovery (25-30%), with high energy requirements (500-1000 MJ/bbl) and water requirements (2-5 bbl of water per barrel of oil). ISC has the highest energy efficiency (50-60%) and low water requirements (0.5-1.5 barrels of water per barrel of oil), but it has issues with combustion control. THOR Cavitas has high recovery efficiency (50-60%) by mechanically generating heat directly inside the wellbore with water requirements and reduced greenhouse gas emissions, and has significantly lower capital costs when compared with steam-based facilities. CSS and steam flooding are mature and flexible technologies, but are environmentally taxing. While SAGD is good at continuous operation but is limited to certain reservoirs, and ISC utilizes in-situ energy but needs precise operational control. THOR Cavitas is unique in that it is a selective direct contact heating method with environmental advantages, but it is a less mature technology. From the results, we can gather data that can help us in selecting certain techniques, including hybrids and new technology such as THOR Cavitas, which can assist us in recovering heavy oil in an environmentally friendly manner.

## 1. Introduction

Heavy oil and bitumen constitute a substantial portion of the world's remaining hydrocarbon resources. The unconventional oil reservoirs with more than 70% are classified as having heavy or extra-heavy oils. They are mainly located in Venezuela's Orinoco Belt, Canada's Athabasca oil sands, and parts of Russia, the Middle East, and China, according to the International Energy Agency [1]. The unconventional heavy oil reserves represent a significant frontier for energy security but also present essential technical and environmental challenges for economically viable production.

Heavy oil is usually characterized by its high viscosity (generally  $>10,000$  cP under reservoir conditions), low API gravity ( $<22^\circ$ ), and low mobility. Therefore, heavy oil properties make it more difficult to produce than light oil [2]. In the heavy oil reservoirs, the recovery factor is less than 10% of the original oil in place (OOIP), as the primary recovery procedures do not work properly [3], [4]. As a result, enhanced oil recovery (EOR) techniques are essential for economically sustainable development.

Heavy oil reservoirs are often shallow, unconsolidated formations containing highly viscous oil. In deeper formations, recovery becomes even more challenging due to pressure and temperature constraints, as well as the impracticality of conventional steam-based methods [5]. The primary issue is the oil's immobility at reservoir conditions; standard production methods are insufficient because pressure gradients are inadequate to move the oil through the porous rock. Since the 1960s, thermal-enhanced oil recovery (TEOR) technologies have been the primary method for extracting heavy oil. The primary concept behind thermal recovery is to reduce the viscosity of the oil by increasing its temperature. This makes it easier to flow and speeds up the recovery process [6]. Early thermal technologies, traced back to the 1980s, such as cyclic steam stimulation (CSS) and steam flooding, were initially used in locations like Kern River, California [7].

One of the first commercial-scale thermal methods applied was Cyclic Steam Stimulation (CSS), also known as the "huff-and-puff" method. The principle is simple: inject steam into a well, shut it in to soak, and produce oil from it [8]. This technique has been widely employed in nations such as Venezuela, the United States, and China [9]. CSS can significantly speed up recovery in the near term, but its long-term effectiveness decreases with each cycle due to heat loss and steam override.

Steam flooding, developed as an alternative to CSS, is a more continuous method that injects steam into dedicated injector wells while producing oil from offset producer wells. injecting steam into dedicated injector wells, and simultaneously producing oil from offset producer wells. Steam flooding can provide improved areal sweep efficiency, but CSS is strongly dependent on reservoir homogeneity. The Duri field in Indonesia is often mentioned as one of the best steam flooding projects in the world, with recovery rates of 50% or more under the best conditions [10].

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However, all steam-based methods are energy-intensive, often requiring the combustion of natural gas to generate steam. Modern environmental and regulatory systems are increasingly scrutinizing these methods due to their increased greenhouse gas (GHG) emissions and water usage [13], [14].

The system is intended to provide RF antennas to wells that already have them. Depending on the nature of the reservoir, heat is generated by converting energy through a dielectric or resistive method. The system is designed to install RF antennas into wellbores that are already there. The energy may be dissipated in the form of heat either by a dielectric or resistive method. The ISC method can be done either dry (without adding water) or wet (with water added behind the fire front). Successful ISC applications have been reported in the Fosterton field in Canada, as well as in pilot projects in China and Russia [7]. Petrobank's THAI™ (Toe-to-Heel Air Injection) technology is one well-known example. It combines ISC with horizontal well construction to enhance recovery and reduce surface emissions [15].

The THOR (Thermal Heavy Oil Recovery) process by Cavitax Energy represents a modern mechanical heating approach that utilizes high-frequency EM energy to heat the reservoir directly, eliminating the need for water or combustion. The system is designed to add RF antennas to wellbores that are already there. Depending on the properties of the reservoir, energy is converted into heat in a dielectric or resistive manner [16], [17].

Additionally, ISC has not been widely applied, although it has the potential for effectiveness, because of the difficulties associated with the control of ignition, propagation of the combustion front, and the prevention of coke formation and blockage of the reservoir. Moreover, the monitoring and simulation of the combustion front in real time require sophisticated reservoir characterization and control systems, which make the application of ISC a more complicated process than the application of steam injection.

The THOR (Thermal Heavy Oil Recovery) process by Cavitax Energy represents a modern mechanical heating approach. THOR heats through the mechanical motion of a rotor that, in turn, heats a fluid within the sealed body that conducts and radiates out into the formation. Depending on the properties of the reservoir, energy is converted into heat in a dielectric or resistive manner [18].

Despite the wealth of research on individual recovery methods, few studies have conducted a side-by-side comparison that includes both traditional thermal and emerging mechanical heating approaches. The significant disparities in mechanisms, applicability, and infrastructural prerequisites necessitate a comprehensive comparison framework to guide future technology rollout strategies.

Butler [19], modelled SAGD performance in homogeneous reservoirs in great detail, but he did not examine heterogeneous or deep deposits. Sarathi [20] entails ISC pilot programs and points out that they require greater management and control. Mechanical heating has potential; however, Perez et al. [18] and Cavitax [16] note that the novelty of these technologies limits the availability of field data.

The sector is also under increasing pressure to reduce the amount of carbon that oil production puts into the air. Thermal enhanced oil recovery (EOR) operations in Canada generate five times more greenhouse gases (GHGs) than light oil fields, according to Chai et al. [21]. Finding low-emission, high-efficiency recovery methods is crucial.

The framework in this study is different from other ESG assessment models that look at sustainability metrics in isolation or AI-based methods that focus on optimizing one technology. It combines technical, economic, operational, and environmental dimensions across five different recovery methods, including both traditional thermal processes and the new mechanical heating technology (THOR Cavitax). This multidimensional, technology-inclusive comparative structure offers a comprehensive decision-support tool that has not been previously documented in the literature, facilitating informed technology selection based on reservoir conditions, economic limitations, and environmental considerations.

This study aims to provide a comparative analysis of the most prominent thermal recovery techniques (CSS, steam flooding, SAGD, ISC) and the emerging mechanical heating THOR process. The study includes an evaluation of the physical mechanisms, energy efficiency, environmental impact, cost structures, field readiness, and scalability.

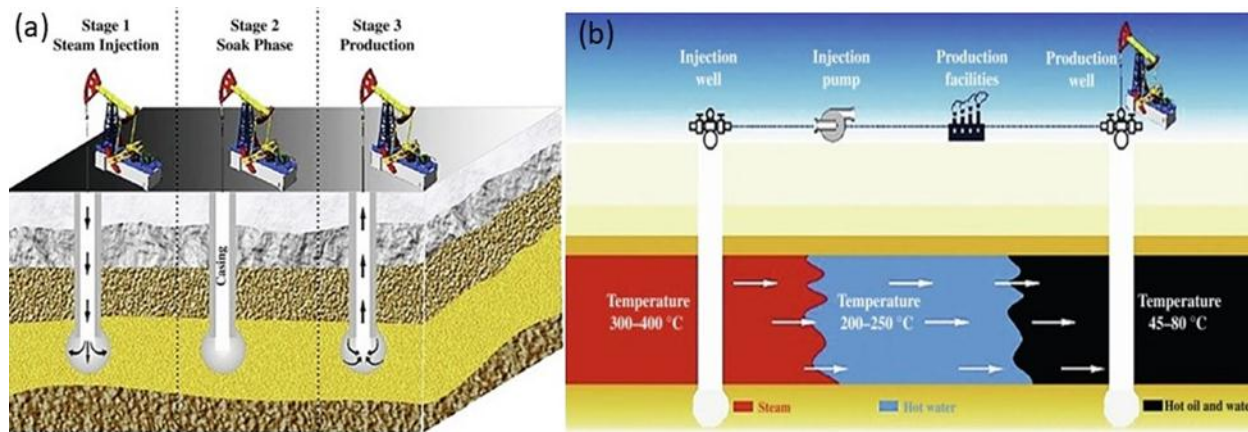
## 2. Cyclic Steam Stimulation (CSS) and Steam Flooding

## 2.1. Principles and Mechanisms

Cyclic Steam Stimulation (CSS) and Steam Flooding are two proven thermal EOR techniques that are mostly applied in heavy oil and bituminous reservoirs. The application of these two EOR techniques is based on the injection of steam into the reservoir with the main aim of reducing the viscosity of the heavy oil (high viscosity) so that it can flow. Even though these two EOR techniques have the same main objective of enhancing oil recovery through a thermal method, they are very different.

The "huff and puff" technique, also referred to as CSS, involves a process that includes stages in manufacturing, soaking, and injection. A single well is used to inject steam into the reservoir in the first stage, typically at temperatures ranging from 300°C to 400°C. Steam injection takes anywhere from days to weeks, depending on the reservoir depth, permeability, and oil saturation [19]. The one- to two-day immersion seals the well. After injection, the well is heat-sealed. Heat from the steam conducts through the formation, reducing the viscosity of the oil and increasing its movement. Finally, the same well is put into production to return the heated, more mobile crude to the surface with steam condensate and water. Recovery efficiency decreases with each repetition of this cycle.

Steam flooding utilizes dedicated injection wells for continuous steam injection, whereas production utilizes separate production wells. This method creates a reservoir thermal displacement front that moves oil toward producing wells. Steam flooding uses convection to move oil toward producing wells, unlike CSS, which uses heat conduction around a single wellbore. This displacement is facilitated by a decrease in viscosity, thermal expansion of oil, steam expansion, and steam condensation-driven condensate [22]. In CSS, all three phases occur in the same well, while steam flooding utilizes a multi-well pattern involving both injectors and producers. Steam flooding is generally more suitable for thick, homogeneous reservoirs where a more uniform sweep can be achieved, as shown in Figure 1.



**Figure 1:** Illustrates the operational difference between (a) CSS and (b) Steam Flooding (adapted from [9]).

## 2.2. Advantages

Oil recovery from heavy oil reservoirs is significantly improved by both CSS and steam flooding, which have both proven considerable advantages. The ability to achieve high recovery factors is undoubtedly the most important of these abilities. To be more specific, CSS can recover between 20% and 40% of the oil that was originally in situ (OOIP). Steam flooding, on the other hand, has been demonstrated to produce recovery rates ranging from 40% to 60% in specific field applications [23]. The significant fall in oil viscosity, which in heavy oil deposits can be reduced by more than 90 percent when temperatures are raised [2], is the primary factor responsible for these high recovery efficiencies.

The Kern River and Midway-Sunset fields in California have provided clues to the validity of thermal recovery systems on multiple occasions. Thermal EOR has been applied in these sectors since the 1960s, and studies have

shown that it can achieve cumulative recovery factors of up to 60 percent in certain zones [24], [25]. Some success stories are described to provide empirical support for the robustness of thermal methods in geological contexts that are well-suited for their application.

One more advantage is that these technologies have already been demonstrated to be effective. As a result of decades of operational data, engineering models, and simulation tools that are accessible for field planning and optimization, CSS and steam flooding are among the most mature EOR methods available [26]. They have a solid understanding of their operating concepts, which helps reduce the uncertainty involved in estimating production and constructing thermal projects.

CSS offers a significant amount of operational flexibility, in particular. Therefore, it is ideal for pilot experiments or in marginal areas where full-scale steam flooding may not be economically viable. It can be deployed in isolated wells or in small clusters, making it ideal for both scenarios. CSS also reduces the need for infrastructure by utilizing the same well for both production and injection activities. Butler [19] states that it works better for heterogeneous or compartmentalized reservoirs, which are reservoirs that constantly flood and may cause steam override or channeling.

Table 1 presents a side-by-side comparison of key factors, including cycle length, steam-to-oil ratio, infrastructure needs, and recovery potential. This table shows the differences in performance and operational aspects between steam flooding and CSS.

**Table 1:** Comparison of CSS and Steam Flooding [8], [23], [26].

Parameter	Cyclic Steam Stimulation (CSS)	Steam Flooding
Injection Method	Cyclic (same well)	Continuous (injection wells)
Production Method	Same well after soaking	Separate production wells
Steam-to-Oil Ratio (SOR)	2 – 5	3 – 6
Recovery Factor (%)	20 – 40	40 – 60
Suitable Reservoir Depth	< 900 m	< 1000 m
Reservoir Type	Heterogeneous or Marginal	Homogeneous, Thick
Operational Flexibility	High	Moderate
Water Requirement	Moderate to High	High
Energy Consumption	High	Very High

### 2.3. Limitations

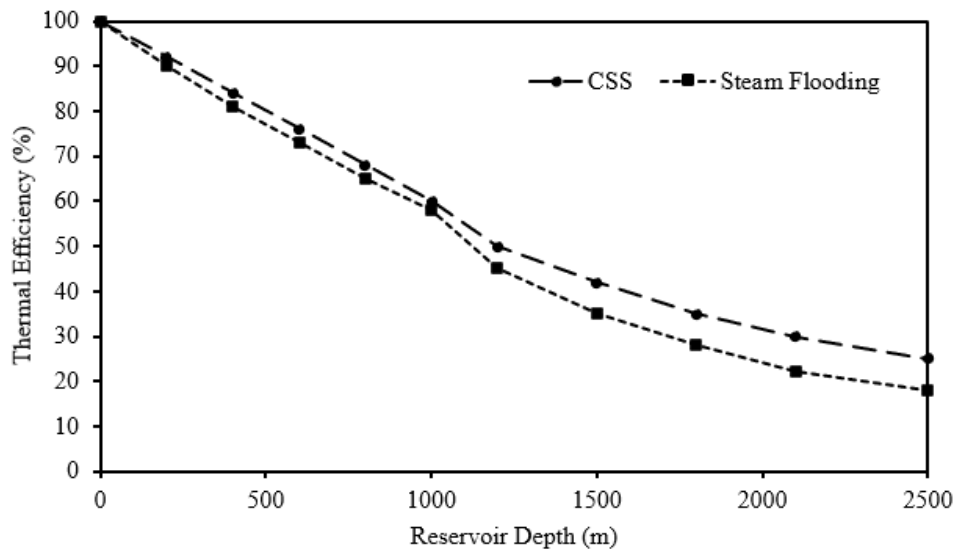
The disadvantages of CSS and steam flooding include high costs, harm to the environment, and the inability to store large amounts of water. One of the major disadvantages of the production of steam is that it consumes a lot of energy. A large quantity of natural gas is required to produce good-quality steam. All these consume more energy and emit more carbon. The steam-to-oil ratio (SOR) of steam-based EOR may vary from 2 to 6 barrels of steam per barrel of oil produced [10]. As the SOR increases, the thermal efficiency reduces, and the cost also rises. The surface facilities, such as boilers, separators, and water treatment plants, contribute largely to the capital costs of thermal projects.

In addition to energy, water use is also important. The generation of steam requires a significant amount of water. Water use and disposal laws may impact the feasibility of a project, especially in arid or environmentally sensitive areas. Improper water management can lead to scaling, corrosion, and reservoir clogging [5].

The deep effectiveness of steam injection presents another disadvantage. The heat transfer to the adjacent rock and overburden increases with the depth of the reservoir. At 3,000 feet (900 meters), the steam quality deteriorates before it reaches the desired area, thereby decreasing the thermal efficiency. Insulated tubing and downhole steam injection are costly and technically complex [27].

The injection of steam into unconsolidated or weakly cemented formations can cause caprock fracturing, well collapse, and ground motion.

Figure 2 illustrates the effects of deeper reservoirs on heat loss and oil recovery efficiency per unit of energy input. Figure 2 illustrates the effects of reservoir depths and thermal efficiency on two types of thermal EOR methods, namely, Cyclic Steam Stimulation (CSS) and Steam Flooding. With the increase of reservoir depths, the heat loss to the adjacent formations reduces the thermal efficiency of these two EOR methods, as demonstrated by the curves in Figure 2. Steam flooding has lower thermal efficiency than CSS at any reservoir depth. CSS is cyclic; thus, heat is localized around the wellbore during soaking, resulting in decreased heat loss compared to steam flooding. The graph also demonstrates that both systems lose efficiency faster at 1000 meters. This tipping point showed that pressure and thermal losses at deeper reservoirs restrict thermal EOR efficiency. Steam flooding worsens with depth. This figure supports the engineering consensus that thermal EOR is most effective in shallow to moderately deep reservoirs and that CSS may be a viable alternative where steam flooding is less cost-effective.



**Figure 2:** Thermal Efficiency vs Reservoir Depth.

### 3. Steam-Assisted Gravity Drainage (SAGD)

#### 3.1. Principles and Mechanisms

Steam-Assisted Gravity Drainage (SAGD) is a technique in the recovery of oil or bitumen from the formation using gravity and heat to assist in the flow of the oil or bitumen. In this technique, there are usually two horizontal wells drilled parallel to one another in the formation. The upper well is for injecting the steam, and the lower one is the production well. Initially, both wells may be steam-circulated to heat the formation and establish thermal communication between them. Once a thermal link is created, continuous steam injection begins in the top well while the lower well produces the mobilized fluids (oil plus condensed steam).

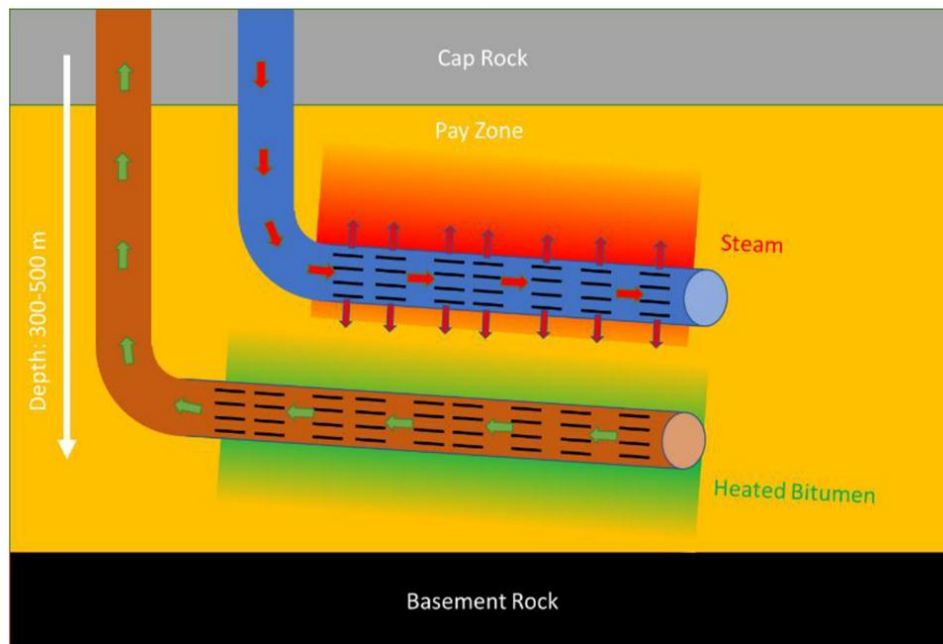
When steam is injected into the upper well, it migrates radially and vertically through the reservoir, forming a “steam chamber.” As it advances, the steam condenses upon contacting cooler oil, delivering latent heat into the formation [28]. This heat raises the temperature of the neighboring oil zones, causing the viscosity of the heavy oil to drop dramatically. The now less viscous oil, along with water from steam condensation, drains downward under the influence of gravity into the lower production well. In an idealized sense, one can think of the steam chamber expanding upward and laterally, heating the oil in advance of the chamber front by conduction, and then allowing the heated oil to flow downward (gravity drainage) toward the producer [2].

The process is controlled by a mix of heat transfer (both conduction and convection, including latent heat release) and multiphase flow, which is affected by gravity. As steam moves into colder areas, the chamber expands, and

the heated oil flows downward toward the producing well [29]. In the steady state or later stages, the chamber can be maintained so that new, unheated oil is always in contact with it and can circulate. To work effectively, a balance must be struck between the steam injection rate, chamber expansion, pressure drop in the producer, and maintaining a "steam trap" (a pool of liquid that prevents steam from short-circuiting to the producer) [30].

A key practical design parameter is the vertical separation between the injection and production laterals (often in the range of 3–10 m), which must allow a stable steam chamber without excessive thermal losses or steam breakthrough. Proper control of pressure, temperature, and "subcool" (difference between steam saturation temperature and fluid temperature in the producer) is required to ensure that steam does not prematurely reach the producer. If steam bypasses prematurely, thermal efficiency is lost [31].

Further complexity arises because real reservoirs are heterogeneous, and steam does not advance uniformly as a single front. The shape and efficiency of the steam chamber can be distorted by phenomena such as steam fingering (the creation of preferential high-permeability channels), heterogeneity, layering, and the presence of non-condensable gases. It is also possible for multiphase (emulsion) flows, capillary effects, and heat losses to the overburden or underburden to occur within the zone of interaction. Accurate modeling and design must account for these effects to avoid over-prediction of performance [32]. The schematic working mechanism of SAGD is illustrated in Figure 3.



**Figure 3:** Schematic of a pair of horizontal wells in SAGD operations.

### 3.2. Advantages

One of the principal advantages of the SAGD method is its ability to achieve relatively high recovery factors, especially in favorable reservoir conditions. Under ideal or well-characterized reservoirs, bitumen or heavy oil recoveries on the order of 60 to 70% of the original oil in place (OOIP) have been reported (or targeted) in many projects. This is significantly higher than what conventional cold production of heavy oils can achieve. The efficient heat delivery and continuous contact of steam with unheated zones help mobilize oil over a large volume [33].

Because the process is continuous rather than cyclic, SAGD tends to minimize production interruptions. Once the steam chamber is well-established, steam injection and fluid production can proceed in tandem, thereby reducing downtime associated with cyclic processes, such as cyclic steam stimulation (CSS). This operational continuity gives better predictability in production rates and smoother scheduling of field operations [34], [35].

Another significant benefit is the relatively lower water usage compared to some other steam-based thermal methods (like cyclic steam or steam flooding) when the produced water is recycled, and when system design aggressively limits losses. Because SAGD recycles condensate and utilizes steam efficiently in a gravity-drainage scheme (rather than brute-force flooding), the net freshwater demand can be moderated. Additionally, the steam-oil ratio (the amount of steam required per unit of oil produced) tends to be favorable when the process is well optimized [36].

Moreover, as surface mining or excavation is not necessary, this method can be applied to deep or uneconomic oil sands or heavy oil deposits. It provides an opportunity to exploit heavy oil resources using an in-situ recovery method and surface disturbance that is less severe than full mining operations.

### 3.3. Limitations

Although SAGD is successful commercially, it has a number of limitations regarding the reservoir features, such as capital cost and environmental performance. This approach is more suitable when the reservoirs are thick, with a thickness of 15 meters, have higher permeability, and are homogeneous. The thin formations or heterogeneous reservoirs that contain shale barriers or interbedded mudstones hinder steam chamber development. This causes poor oil recovery and non-uniform heating distribution [33]. Therefore, steam fingering and bypassed oil recovery result in a loss of energy and a decrease in efficiency.

In addition, the capital expenses contribute significantly as a result of the required multiple horizontal wells, massive steam production facilities, and water treatment. It is possible for the infrastructure for steam generation, which is typically gas-fired, once-through steam generators (OTSGs), to account for more than fifty percent of the total costs of the project [37]. Therefore, it is difficult to achieve long-term production due to some operational issues such as steam breakthrough, scaling, corrosion, and maintaining steam–oil conformance.

Concerns continue to be raised regarding the environmental impact of SAGD. Every barrel of bitumen typically results in the production of 0.07–0.12 t CO<sub>2</sub>e, making steam generation an energy-intensive process. Thus, SAGD is considered to be one of the most carbon-intensive methods of oil recovery [38]. In addition, a lot of water is also required to be supplied, treated, and recycled, which is a problem in terms of its sustainability and regulatory compliance. These are currently being addressed in terms of their environmental and energy impacts through developments in new technologies like solvent co-injection (SA-SAGD), mechanical heating, and geothermal-assisted SAGD. Innovations are also in development.

## 4. In-Situ Combustion (ISC)

In-situ combustion (ISC) is a thermal method of enhanced oil recovery (EOR) that is employed to recover heavy oil and bitumen from subsurface reservoirs. ISC is a unique method among other thermal methods because it does not involve the use of heat from external sources, such as steam. In this method, heat is generated within the reservoir through the controlled combustion of some of the oil in place. This method has enormous potential for achieving a high recovery factor, particularly in heavy oil reservoirs that would be difficult to produce economically through other methods.

### 4.1. Principles and Mechanisms

The main idea of ISC is to send an oxidizing agent, such as air, whereas pure oxygen and enhanced air are also sent into the oil formations. The fire starts by oxidation and reacts with some existing hydrocarbons. As a result of the presence of oxygen, the hydrocarbons start burning because of high temperature oxidation reaction. Therefore, these reactions from heat, carbon dioxide (CO<sub>2</sub>), and water vapour (H<sub>2</sub>O). The nitrogen oxides (NO<sub>x</sub>) appear if the air is used [39].

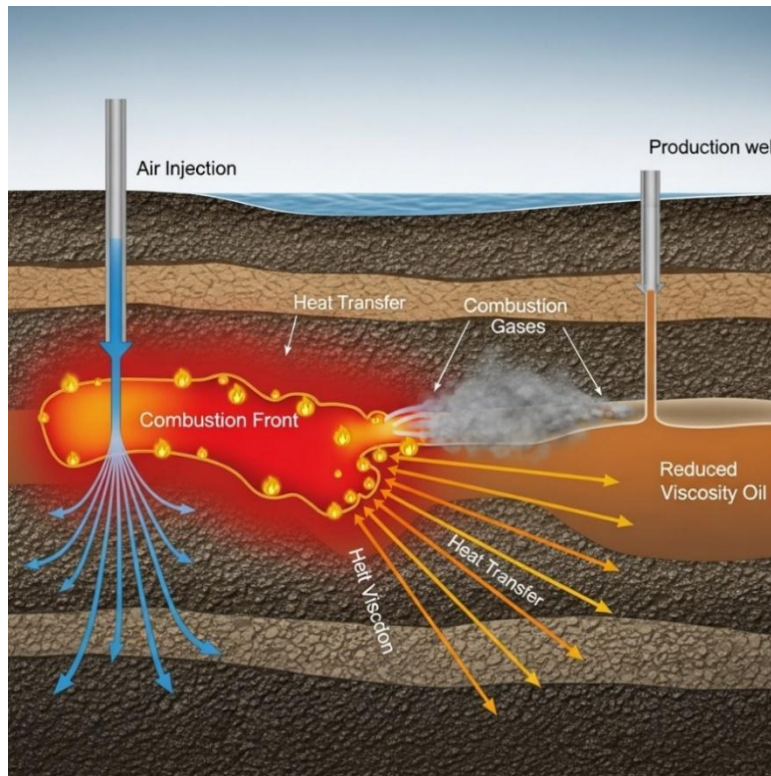
There are three temperature regimes categorized for Combustion in ISC, such as low, medium, and high-temperature oxidation. The desired temperature for effective ISC operations is above 300°C [15].

The heat makes the oil less thick, which makes it easier for it to move and flow through the reservoir's porous media. Combustion gases like CO<sub>2</sub> and nitrogen also help transport oil and raise the pressure in the reservoir. A

combustion front forms and flows through the reservoir, forcing oil into the production wells in front of it. The combustion front steady and stable are required for successful ISC operations, which helps high sweep efficiency and stopping fire front breakthrough [40].

Dry combustion and wet combustion are the two basic types of ISC. Only air is introduced when the fire is dry. In wet combustion, air and water (typically in the form of steam or hot water) are put into the same space at the same time. Water helps keep the temperature in the combustion zone steady and makes it simpler for heat to go deeper into the reservoir. This could make the process work better [41].

To start the process, you need an ignition system. These could be electric heaters that work down the hole, chemical igniters, or gas burners. Once the fire starts and a self-sustaining fire front is formed, air is added to keep the oxidation reactions going. In order for the ISC project to work, it is highly important to be able to adjust the speed and pressure of air injection and keep an eye on where the combustion front is [42]. Figure 4 shows the simplified working mechanics of ISC.



**Figure 4:** Simplified Schematic of ISC Process.

#### 4.2. Advantages

In-situ combustion offers a range of advantages over other EOR methods, particularly for reservoirs containing heavy oils. Superior recovery performance and energy efficiency form due to the internal generation of heat and gases under the right conditions.

The high energy efficiency is one of the most advantageous aspects of ISC. As a result of the minimum requirement for external energy to burn, which relies more on the oil in place to generate the necessary heat, compared to the steam injection approaches that requires huge amount of sur-face-generated steam. Therefore, ISC has lower operational costs and makes the process more suit-able in the long term. Also, the heat from combustion is employed within the reservoir, which cuts down on heat loss during surface heat transfer [43].

As a result of losing heat from the surface to the formation, steam injection does not work sufficiently in the deep reservoirs, while ISC works best in deeper heavy oil reservoirs. Therefore, ISC is more suitable for deeper reservoirs since it gets beyond the problems that arise with steam-based technologies, such as temperature drops, condensation losses, and mechanical inefficiencies in wellbore insulation [44].

ISC may get high recovery factors, particularly in reservoirs that have the right properties, such as moderate to high permeability, constant oil saturation, and the right shape. Successful ISC operations have been able to recover up to 70% of the original oil in situ (OOIP). This great efficiency is due to the use of many recovery methods, such as gas drive, viscosity reduction, and thermal expansion [45].

ISC utilizes less water than steam flooding, which is great for the environment and the economy, particularly in situations where water is hard to come by or where it is dry. Wet combustion still consumes water, although not as much as other thermal methods do [39].

When the conditions are correct, ISC might become a process that operates on its own once it begins. As long as there is adequate air and fuel, the combustion front can keep moving ahead without producing additional heat. This is because the combustion front oxidizes hydrocarbons. This self-sustaining feature makes ISC an excellent option for plans to develop the sector over the long run [46].

In certain cases, the high temperatures that happen during ISC cause the crude oil to partly improve. Thermal cracking may break down larger hydrocarbon molecules into smaller, more usable ones. This in-situ upgrading might make the oil produced more marketable, particularly in reservoirs containing a lot of heavy oil.

#### *4.3. Limitations*

In-Situ Combustion (ISC) is a very advantageous process, but there are some technical issues that have to be overcome before it can be applied successfully.

One of the major issues is the control of the combustion front. Its behavior depends on the differences in the reservoir, the rate of air injection, the oil it contains, and its permeability. To maintain a smooth process, you have to monitor the situation and adjust the parameters in real time to prevent irregular phenomena such as channeling, early gas breakthrough, and front disappearance [47].

If you do not control the situation well, you may end up damaging the reservoir and the wellbore. If you do not monitor the high temperatures, they may alter the rock properties, cause the formation to break down, or make the well unstable. High pressure or gas production can damage the completions and surface facilities, and the approach of the combustion front to the production wells is very hazardous from both safety and operational considerations [48].

Even if ISC is energy efficient, environmental concerns remain. The process generates CO<sub>2</sub> and other greenhouse gases, which may need to be captured and stored to lessen their effect on the climate. We also need to deal with the carbon footprint of air injection compressors and monitoring systems, as well as the possibility of aquifer pollution from by-products that move [49].

Ignition and sustainability are especially difficult in areas with limited permeability or excessive water saturation. It may be essential to preheat or dry the formation, which will make things more expensive and complicated. If the ignition fails or the front isn't strong enough, it might cause costly delays and restarts [50], [51].

It is still not clear whether it is economically feasible. Investors may be put off by the high initial expenses of specialist equipment, control systems, and safety precautions, as well as the fact that they rely on oil prices and reservoir features. Not all reservoirs are good for ISC. If the formations are very fractured, if the vertical continuity is poor, or if the oil saturation is low, ISC does not work.

## **5. THOR Cavitas**

The THOR Cavitas system is a mechanical downhole heating technology. Unlike electromagnetic heating concepts that rely on antennas, dielectric mechanisms, or wave propagation, THOR operates through a mechanically driven rotor contained inside a sealed downhole tool.

In heavy oil and bitumen reservoirs, where viscosity is the main thing that stops flow, any method that can raise the temperature significantly around the producing interval can greatly improve mobility, lower pressure drawdown needs, and speed up production rates. THOR Cavitas does this downhole with electrically generated, mechanical energy. This method is especially appealing in places where it's hard to get water, where making steam is expensive or bad for the environment, or where steam channelling and poor sweep are caused by differences in the environment [52].

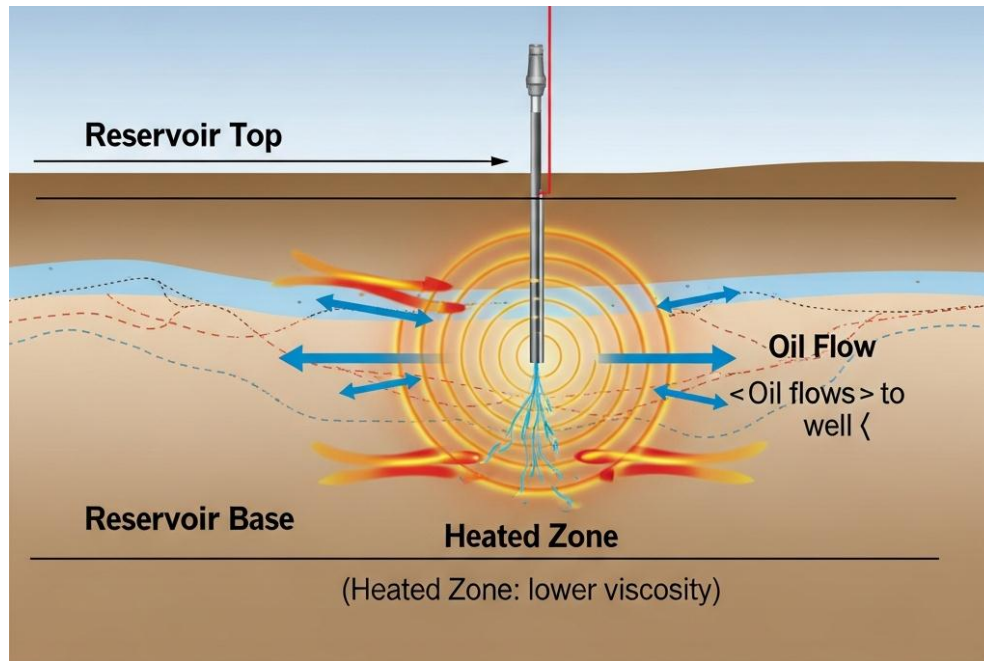
### *5.1. Principles and Mechanisms*

The THOR (Thermal Oil Recovery) Cavitas system is a mechanically powered downhole heating technique that aims to solve the problems of heavy oil extraction by aiming heat directly at the source of the problem. THOR works inside the wellbore instead of using steam injection or heat from the surface like other thermal systems. It uses a special mechanical process to create heat.

The system is based on a mechanically driven rotor that is housed inside a sealed downhole tool. A downhole motor powers this rotor. It can be used with typical artificial lift systems like Rod Pumps, Electrical Submersible Pumps (ESPs), or Progressing Cavity Pumps (PCPs), making it easy to use in a variety of ways. The THOR tool is built in a modular way, like a pump, so you can add more heat modules to the assembly to make it work better with thicker oil or higher flow rates. Engineers may change the tool to fit the needs of a specific well and production goals because it is modular. Sensors built into the completion give real-time data that lets you manage the downhole temperature exactly right, which improves output while making sure all the equipment stays within its limits.

The mechanical principle has a lot of benefits when it comes to energy density and efficiency. THOR makes heat directly downhole, which the company says is the "highest downhole heat energy density." This means that it delivers 50 to 100 times more heat per foot than regular electrical cable heaters. It is strategically placed on the well's perforations or just below the production pump. The heat makes the oil less thick near the wellbore when it is placed over the perforations. This means that the oil doesn't need as much pressure to enter the wellbore. When you apply it below the pump, it keeps wax and asphaltene from building up, which makes the pump work much better. This targeted strategy makes sure that practically all of the heat that is made is used to transfer oil. This cuts down on the heat that is wasted to the surrounding formation [53].

Below is a conceptual schematic (not to scale) illustrating the basic idea of RF heating around a well and subsequent mobilization toward production (Figure 5). This schematic emphasizes the near-wellbore heating concept. More advanced designs may create heating between wells, in layered segments, or along laterals to manage sweep and reduce bypassed oil.



**Figure 5:** Illustrating the basic idea of mechanical heating around a well.

The effectiveness of THOR Cavitas depends heavily on reservoir properties. Table 2 summarizes critical parameters and their influence.

**Table 2:** Key Physical Parameters Relevant to RF Heating [16], [54].

Parameter	Typical Range in Heavy Oil Reservoirs	Effect on THOR Cavitas Performance
Water saturation (Sw)	0.15–0.50 (variable)	Higher Sw generally increases conductivity.
Brine salinity	Low to very high	Higher salinity increases conductivity.
Formation permeability	10 mD to several Darcy	Higher permeability improves production.
Clay content	Low to moderate	Clays can raise dielectric loss and conductivity.
Reservoir depth	Shallow to deep	Greater depth increases cost.
Temperature	10–80°C typical	Higher initial temperature reduces the viscosity baseline; heating requirements decrease.
Oil viscosity	1,000–100,000 cP	Higher viscosity increases the value of heating.

### 5.2. Advantages

The THOR system has a lot of benefits that make it a great next-generation option for enhanced oil recovery. These benefits include better operational performance, higher economic returns, and less harm to the environment.

THOR greatly lowers the viscosity of oil, which makes it easier to produce. Field deployments have shown that production can go up by three to six and a half times the initial amount. For example, one well in California went from zero barrels per day to more than 60 barrels per day. The technology not only boosts flow, but it also greatly improves the efficiency of artificial lift. Reports show that pump efficiency can go up by as much as 77%, and the operational run life of downhole pumps can go up by more than 50%. Its small size makes it easy to install on production tubing without the need for heavy tools like coiled tubing. Operators can also keep an eye on and regulate downhole temperatures in real time from a distance using a cellular link or an app. This means that engineers don't have to be on site all the time [55].

THOR has a quick and strong return on investment (ROI) in terms of money. The technology has shown payback durations of fewer than 30 to 50 days in different projects by using an OPEX-based rental model and keeping the initial capital costs of surface infrastructure low. Costs for incremental lifts can be less than \$9 per barrel, which can change assets that aren't making money into lucrative ones. For example, a well in the US made more than \$1.7 million a year. Also, THOR is marketed as a low-carbon option. It only releases 1.51 gCO<sub>2</sub>/MJ while it is running, which is over 20 times less than standard thermal methods. Compared to classic steamflood procedures, it can cut overall carbon emissions by up to 95%. This makes it an important tool for operators who want to achieve strict environmental and ESG (Environmental, Social, and Governance) goals while getting the most out of their recovery [56].

Controllability may aid in improved reservoir management. Table 3 compares the THOR Cavitas conceptually with steam injection approaches such as CSS (cyclic steam stimulation) and SAGD (steam-assisted gravity drainage).

**Table 3:** Conceptual comparison of THOR Cavitas and CSS/SAGD [8], [16], [23], [26], [54].

Criterion	THOR Cavitas (Mechanical Heating)	Steam-Based (CSS/SAGD)	Thermal
Primary heat delivery	Mechanical heating energy deposition in the reservoir.	Steam injected; heat delivered via condensation and conduction.	
Water requirement	Minimal to none for heating.	Very high.	
Conformance control	Potentially controllable via mechanical placement and power shaping.	Often challenged by heterogeneity and steam channeling.	
Surface infrastructure	Electrical generation, power electronics, and downhole tools.	Boilers, water treatment, steam pipelines, injectors.	
Typical temperature levels	Moderate to high, depending on design.	High steam saturation temperatures	
Emissions dependency	Depends heavily on the electricity source.	Typically, high steam is generated by natural gas.	
Suitability in thin pay	Potentially favorable.	Often difficult due to heat loss.	
Technology maturity	Emerging/less proven.	Mature with extensive field history.	

### 5.3. Limitations

A primary limitation of THOR Cavitas is maturity. Steam injection has decades of operational history, extensive best practices, and large-scale field demonstrations across many reservoir types. While conceptually well understood and successfully used in other industries (such as industrial drying and heating), it has fewer large-scale petroleum field deployments. The issue matters because reservoirs are complex systems where small uncertainties in property distributions can lead to large performance differences. A technology can work well in controlled laboratory tests or pilot trials, but face unexpected complications when scaled [57], [58].

Maturity issues often include uncertainty in the achievable radius of influence, risks of uneven heating, reliability of downhole components under high temperature, and the long-term behaviour of the formation as it undergoes repeated heating cycles.

While the THOR Cavitas system has several advantages, it's important to consider its limitations and the specific situations where it works best. These are determined by its technological features and its current position in the market.

The main problem with THOR is that it only works for a certain set of problems. It is not a universal alternative for primary recovery methods, it is a focused intervention for Enhanced Oil Recovery (EOR), flow assurance, and reducing viscosity. The method works well in wells that have thick oil, wax buildup, or asphaltene buildup. It

works great in these situations, but it might not be as useful in regular light oil reservoirs where temperature control isn't a big problem. The system is also designed to work with artificial lift systems; therefore it can only be used if the well already has rod pumps, ESPs, or PCPs. THOR has built-in mechanical reliability limits because it is a mechanically powered system with moving parts that work in a hot downhole environment. The manufacturer says that the tool should last 3 to 5 years if it uses parts that have been tested in the oilfield. However, the rotor assembly is more complicated than simpler static technologies like chemical injection or cable heaters, which means there are more places where it could fail. Even while the technology has received honors and worked well in places like the US and the Middle East, it is still a new technology made by a tiny, specialized company with fewer than 10 workers. This scale may make it hard to quickly grow globally, keep the supply chain strong, and have a lengthy history of reliability that bigger companies frequently need before widespread use [56].

### 6. Comparative Analysis of Thermal and Mechanical Heating Methods

Heavy oil recovery is a difficult process because there are many factors that need to be taken into consideration, including the geological constraints, economic feasibility, and stricter environmental regulations. This section compares the four major recovery processes that have been discussed in the study. These processes include Cyclic Steam Stimulation (CSS), Steam Flooding, Steam-Assisted Gravity Drainage (SAGD), In-Situ Combustion (ISC), and THOR Cavitas, which is a type of mechanical heating technology. The study extends beyond mere performance comparisons. It also considers factors such as the physics of the reservoir, the difficulty of implementation, the cost of implementation over time, and environmental impacts. The aim is to identify which technologies are suited to which applications, what trade-offs are most desirable, and how they can be combined.

A primary difficulty in any comparison analysis is the formulation of a unified evaluation framework. The efficacy of any Enhanced Oil Recovery (EOR) technique is not inherent but is fundamentally associated with particular reservoir attributes, such as depth, thickness, porosity, permeability (both absolute and relative, especially vertical permeability), oil saturation, and oil composition (viscosity, API gravity, and reactivity). As a result, a strategy that is considered "better" in one geological setting may not work at all or cost too much in another. The four main sections that this analysis will cover are the technical performance, economic feasibility, operational robustness, and environmental/social impacts. Quantitative information gathered from previous field projects, pilot projects, and engineering models will be used to divide these sections [15], [59]. This will then be compared to qualitative assessments of operational hazards and technical maturity.

The development of these technologies is a historical process that tries to get around the problems with older systems. As first-generation thermal approaches, CSS and steam flooding showed that heat is the best way to lower viscosity. However, their efficiency is greatly reduced by gravity override (when steam climbs to the top of the formation), steam channelling (when steam flows preferentially via high-permeability streaks), and large heat losses to cap and base rock, especially in thinner reservoirs. To solve these problems, SAGD was designed to use gravity as the main force and closely spaced horizontal wells to make a controlled, expanding steam chamber. This was a change from "flooding" to "drainage" as the way to get back to normal. ISC adopts a completely new technique by putting the energy source inside the reservoir itself. This should make it more energy-efficient and useful in deeper formations where steam heat losses would be too high. THOR Cavitas and other EM technologies are a big change from conductive/convective heat transfer to volumetric dielectric heating [14], [16], [37]. This new method promises unmatched control and selectivity. This historical context is essential for comprehending the distinct strengths and weaknesses inherent in each method.

The core technical performance metrics are Recovery Factor (RF), the percentage of original oil in place (OOIP) that can be economically recovered, and the energy efficiency of the process, often expressed as the Steam-Oil Ratio (SOR) for thermal methods or its equivalent, the Energy-Input-to-Oil Ratio (EIOR), for EM methods.

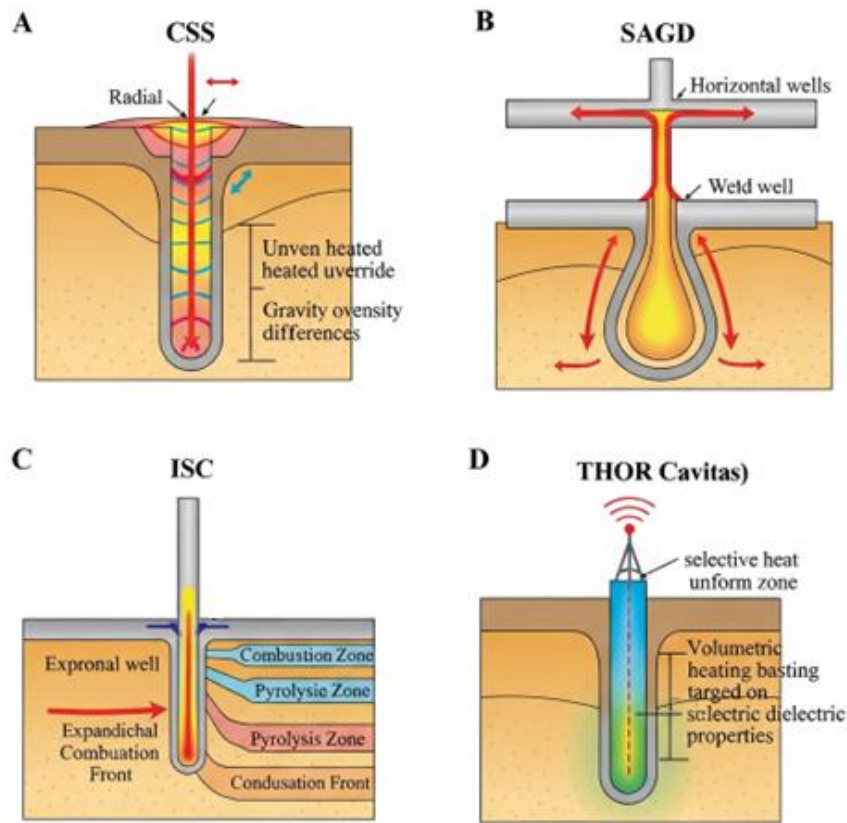
**Table 4:** Comparative Technical Performance Metrics Under Ideal Reservoir Conditions [16], [31], [36], [40].

Method	Typical Recovery Factor (RF)	Key Efficiency Metric (Ideal Range)	Critical Reservoir Parameters for Success	Dominant Recovery Mechanism
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CSS / Steam Floodin g SAGD	25% - 50%	SOR: 2.5 - 4.5 (bbl steam/bbl oil)	Depth (< 3000 ft), Net Pay (> 20 ft), Good Permeability (k > 500 mD)	Viscosity Reduction & Pressure Drive
	50% - 70%	SOR: 2.0 - 3.5	Thick Pay (> 50 ft), High Vertical Permeability, Homogeneous Sand	Gravity Drainage & Viscosity Reduction
ISC	40% - 60%	Air-Oil Ratio (AOR): 3000 - 6000 scf/bbl	High Oil Saturation (So > 40%), Reactive Oil, Moderate Permeability	Thermal & Gas Drive from Combustion
THOR Cavitas (EM)	40% - 65% (Pilot Scale)	EIOR: 150 - 350 kWh/bbl oil	High Oil Saturation, Favorable Dielectric Contrast (Oil vs. Rock/Water)	Volumetric Dielectric Heating & Drainage

Table 4 shows that SAGD has the best chance of recovering oil since its efficient, gravity-stable drainage mechanism cuts down on oil that is not used. But this high RF only works if the reservoir conditions are "ideal," which means the sands are thick, clear, and easy to get through. CSS and steam flooding have reduced, but still considerable RF. They work better on thinner or somewhat heterogeneous formations, but they cost more in SOR. ISC's RF is similar to steam approaches, but it is more unstable. Successful projects may receive a lot of recovery, while those that fail because of poor combustion stability may receive a lot less. Based on limited field data, THOR Cavitas suggests that RF could be effective when used with high-end steam technology. Pilot projects in Canada and Venezuela have demonstrated good results. EIOR, the efficiency measure for RF, varies significantly based on the frequency used, the source of the power supply, and the mechanical heating properties of the individual reservoir.

The results are based on the physics of the reservoir. Steam-based technologies, such as CSS, SAGD, and flooding, rely on latent heat transfer, which means that the heat transfer is provided by a change of state. The diffusivity of the reservoir and the shape of the heated volume control the effectiveness of the process [60]. Compared to the radial or linear fronts in CSS/flooding, SAGD's paired horizontal wells generate a superior shape (a rising cylindrical chamber). This aspect means that heat is better contained, and the SOR is reduced. There are many zones in an ISC reaction front, including a burnt zone, a cracking/vaporization zone, a condensation/viscosity-reduction zone, and a virgin oil bank. The stability and progress of this front depend on how reactive the oil is, how fast air is injected, and how different the reservoir is [22]. Mechanical heating makes it possible to heat the oil in a specific way because water and most minerals in the reservoir have different dielectric characteristics [61]. This choice is a major difference since it cuts down on energy waste by not heating the whole rock matrix and the water around it.



**Figure 6:** Schematic of heat distribution mechanisms. Panel 1 (CSS): A vertical well with a radial, uneven heated zone showing gravity override. Panel 2 (SAGD): Two horizontal wells with a uniform, expanding elliptical steam chamber. Panel 3 (ISC): An injection well with a narrow, advancing combustion front and multiple reaction zones. Panel 4 (THOR Cavitas): A well with volumetric, somewhat uniform heating throughout a targeted zone, highlighting the concept of selective heating based on properties.

The economic landscape of heavy oil recovery is characterized by high upfront capital expenditure (CapEx) and ongoing operational expenditure (OpEx). The balance between these two cost centers varies significantly between technologies [62].

**Table 5:** Comparative Economic Analysis.

Method	Capital Intensity (CapEx)	Primary OpEx Drivers	Breakeven Oil Price (WTI Equivalent, Approx.)	Economic Risks
CSS/ Steam Flooding	Moderate-High. Requires steam generation plants and water treatment.	Fuel for steam (50-70% of OpEx), water sourcing, and well workovers.	\$40 - \$55 / bbl	Volatile natural gas prices, water disposal costs.
SAGD	Very High.	Fuel for steam, electricity for pumping.	\$50 - \$65 / bbl	A high fixed-cost base requires large, sustained production

ISC	Moderate. Requires air compression plants.	Electricity for air compression and extensive downhole monitoring.	\$35 - \$50 / bbl	Project economics highly sensitive to combustion stability.
THOR Cavitas (EM)	High.	Electricity cost (80-90% of OpEx).	\$45 - \$60 / bbl  (highly dependent on electricity cost)	Immature supply chain for downhole equipment.

One thing that makes SAGD stand out is how much financing it needs. Before a business can start making money, it may need billions of dollars for just one project. This makes it hard to get started and means that businesses need a huge resource base to reach economies of scale. Because of this, its economy is based on long-term, steady oil prices [37]. CSS and Steam Flooding projects can be a little more modular and phased, which makes it possible to build smaller accumulations. ISC usually has a reduced CapEx profile because it doesn't have to build a huge steam production facility. However, this can be countered by increased technical risk and possibly higher operational costs if controlling combustion is hard [46]. THOR Cavitas has a unique economic profile: its capital expenditures (CapEx) are mostly for surface power and transmission equipment, while its operating expenses (OpEx) are mostly based on the cost of electricity. Because of this, its economics are quite sensitive to the price of power in the area and the carbon intensity of the grid. If there is a lot of cheap renewable electricity in an area (such hydro, geothermal, or solar), mechanical heating could be a very cost-effective and environmentally friendly option [16].

The idea of "energy return on investment" (EROI) is becoming more and more important. SOR assesses how well steam is used, but it doesn't take into account the energy needed to get, treat, and pump water or to make the steam itself. A thorough lifecycle energy analysis typically shows that the energy cost of air compression can make the apparent efficiency advantage of ISC (low SOR) less useful. The EIOR for mechanical heating must also be compared to the main source of energy used to make electricity [61].

Not only does good design matter for operational success, but so does being able to deal with the geological uncertainties and process instabilities that come with it.

Steam-based approaches have a lot of trouble with reservoir heterogeneity. In SAGD, low-permeability obstacles like shale strata can separate the steam chamber or induce severe channelling in Steam Flooding. This makes it hard to sweep and causes early steam breakout at producers. Finding water and treating produced water are big, ongoing logistical and environmental problems. High-temperature brine can cause scaling and corrosion in wells and surface facilities, which are major maintenance issues [63].

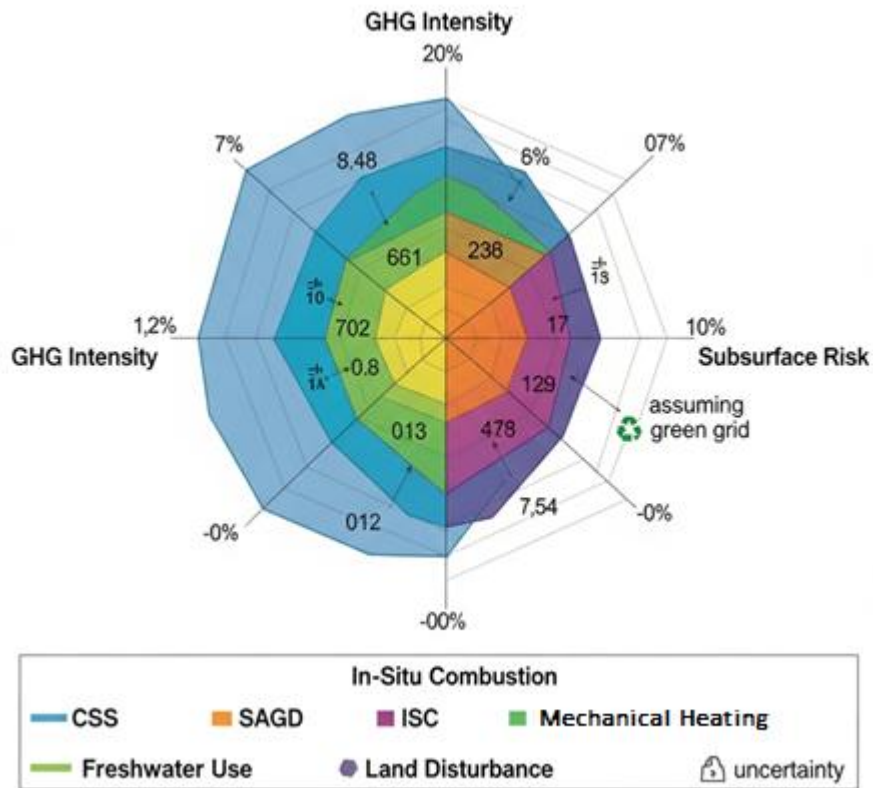
ISC is probably the most complicated way to do things. The combustion front is a dynamic, nonlinear system that is hard to keep an eye on and govern in real time. Risks include early oxygen breakthrough at producers (a major safety risk), high water saturation putting out the front, or low-permeability coke forming and blocking flow. To handle these hazards, you need advanced downhole instruments, real-time modelling, and very experienced workers [41].

THOR Cavitas has a separate set of problems when it comes to running. It is hard for mechanical heating to move through different types of underlying materials, which can cause uneven heating (with "hot spots" and "cold spots"). At full commercial scale, it is not certain how reliable and long-lasting downhole antennas and electrodes will be in settings that are chemically hostile and very hot. Also, the technology may have problems with regulations and public image because of mechanical heating field emissions, even though it works at frequencies and powers that are considered safe [16].

**Table 6:** Operational Risks and Mitigation Strategies [8], [23], [26].

Method	Primary Operational Risks	Key Mitigation Strategies & Monitoring Technologies
CSS / Steam Flooding	Steam channeling, gravity override, scaling/corrosion, water management.	4D seismic for steam front monitoring, injectivity profile control, chemical additives for scale inhibition, and advanced water treatment.
SAGD	Reservoir heterogeneity (shale barriers), steam trap control, top-water or gas cap coning.	Horizontal well geosteering, fiber-optic distributed temperature sensing (DTS), controlled start-up procedures, and solvent co-injection.
ISC	Unstable combustion front, oxygen breakthrough, corrosion, and high-temperature well failure.	Tailored air/oxygen injection schemes, downhole gas composition analyzers, specialized high-alloy well materials, and real-time reservoir simulation.
THOR Cavitas (EM)	Uneven heating due to heterogeneity, antenna failure, power supply reliability, and mechanical heating interference.	Multi-frequency antenna design, advanced mechanical heating tomography for heating monitoring, robust downhole electrical insulation, and redundant power systems.

The environmental footprint of heavy oil recovery is under intense scrutiny, making this a decisive factor in technology selection and regulatory approval. The impact areas include greenhouse gas (GHG) emissions, water usage, land disturbance, and potential subsurface impacts [64].



**Figure 7:** Qualitative Comparison of Environmental Impact Footprints. GHG Intensity, Freshwater Use, Land Disturbance, and Subsurface Risk. Each method (CSS, SAGD, ISC, and Mechanical Heating) would have a polygon shape. Steam methods (CSS/SAGD) would show high GHG and high water use. ISC would show moderate GHG, low Water, but high Subsurface Risk. Mechanical heating would show low GHG (assuming green grid), very low Water, low Land Disturbance, but moderate Subsurface Risk (uncertainty).

Steam generation is overwhelmingly the largest source of GHG emissions in CSS, SAGD, and Steam Flooding, typically from natural gas combustion. Carbon Capture, Utilization, and Storage (CCUS) is being actively piloted for SAGD facilities, but it adds substantial cost and complexity. Water use is huge; SAGD needs about 2 to 3 barrels of water (usually fresh or brackish) for every barrel of oil it makes. Recycling rates are over 90% in current operations, but the need for net water make-up and the disposal of concentrated tailings are still problems [61], [65].

When ISC burns fuel, it releases CO<sub>2</sub> directly into the air. However, if the burning is done well and doesn't consume fuel from outside sources, the overall GHG footprint per barrel can be lower than that of steam techniques. It does not make much water. But it can also give off other gases, including SO<sub>x</sub> and NO<sub>x</sub>, depending on the type of oil and how hot it burns. Extreme temperatures can also move contaminants, like heavy metals, around [14], [66].

THOR Cavitas holds the potential for the lowest direct environmental impact. It uses negligible water, causes minimal surface disturbance compared to sprawling steam plants, and produces no direct combustion emissions. However, its indirect GHG emissions are a direct function of the electricity grid's carbon intensity. In Alberta's coal-heavy grid, the advantage diminishes; in Quebec's hydro-dominated grid, it becomes a near-zero emission extraction technology. This creates a powerful synergy with the global transition to renewable energy [16], [67].

SAGD is the undisputed champion for thick (>25m), homogeneous, permeable sands with minimal top gas or bottom water—the archetype of the Canadian McMurray Formation. Its high recovery and continuous production justify the massive capital outlay in these world-class resources [68].

CSS and Steam Flooding remain workhorses for shallower, thinner, or somewhat heterogeneous reservoirs where SAGD is not geometrically feasible, or capital is constrained. They offer flexibility and a vast repository of operational experience [69].

ISC finds its niche in deeper (>1000m), higher-pressure reservoirs with reactive oil, where steam heat losses would be prohibitive and where operational expertise exists to manage its complexity. It can also be effective in post-steam recovery to scavenge heat and residual oil [70].

THOR Cavitas and mechanical heating methods present compelling opportunities in heterogeneous or thin reservoirs, shale-hosted heavy oil, reservoirs with sensitive caprock (low fracture pressure), or in jurisdictions with cheap, low-carbon electricity. They also have the potential to help revive "cold" heavy oil wells that have been left alone.

Furthermore, the integration of real-time data from fiber optics, mechanical heating tomography, and downhole sensors with machine learning and dynamic reservoir simulation will enable "closed-loop" reservoir management.

## 7. Conclusion and Future Directions

Heavy oil recovery remains a major factor in the world's energy balance due to the sheer number of heavy oil and bitumen reserves on the planet. These are difficult to transport and have high viscosity levels, which makes manufacturing with them extremely difficult. To recover these reserves, we need new and efficient methods that are environmentally friendly. From the research, it is clear that each method has its advantages and disadvantages, and to make a good choice, one needs to have a good understanding of the reservoir's characteristics, economic constraints, and environmental considerations.

### 7.1. Summary of Key Findings

CSS and steam flooding are among the most recognized and commonly applied recovery strategies. Their key benefit is their proven effectiveness in the field, particularly in shallow reservoirs, as well as their operational flexibility. However, these technologies often demand major energy input and huge amounts of water. Furthermore, CCS and steam flooding are more suitable for shallow- to medium-depth heavy oil reservoirs with excellent permeability.

In comparison to the cyclic steam process, SAGD has the reputation of achieving a high rate of recovery and the ability to sustain the process of production, which results in a steady rate of output. It is also known for the efficient use of water compared to the CSS process. SAGD has the reputation of having high construction costs and weights, despite the characteristics of the process. Uniform and thick formations of the reservoir are required for the development of chambers in the SAGD process.

By generating heat inside the reservoir through controlled burning, a completely new approach is offered by ISC. This approach is most interesting when applied to deeper reservoirs because steam injection is not feasible or is too expensive due to the potential for large thermal efficiencies. In addition, this approach is seen to have the potential for large recoveries under suitable geology. However, this approach is operationally complex and requires control of the burning front to prevent instability and potential reservoir damage. In addition, this approach is seen to include problems with respect to the environment due to emissions. This approach is seen to be most suitable when applied to deeper reservoirs with suitable oil composition and permeability.

THOR Cavitas, as an alternative to conventional heating technologies, by its ability to provide selective heating, lower dependency on water usage, and the prospect of lower greenhouse gas emissions, could be considered a viable alternative to conventional heating technologies. The ability of the technology to perform well in a wider range of reservoir conditions could also be considered an advantage of the technology. The relatively old age of the technology, the high initial costs of the technology, and the lack of field experience are still challenging that the THOR Cavitas technology has to overcome.

### 7.2. Comparative Insights

The comparative analysis proves that none of the recovery techniques is universally better than the others. On the contrary, the choice of method depends on the properties of the reservoir, the economy of the project, the availability of infrastructure, as well as environmental concerns. CSS and steam flooding are the cornerstones of heavy oil exploitation, although there are now concerns about their limitations in terms of water use and energy requirements. SAGD is known to offer high recovery rates with stable production rates, although it is still constrained by capital costs and the need for a thick homogeneous reservoir. ISC provides a potentially "energy-friendly" answer to the question of deeper reservoirs, although it brings its own problems concerning control and emissions. THOR Cavitas is a relatively new technology, which brings many advantages concerning the environmental and operational characteristics, particularly in reservoirs where steam injection is not effective. To provide a concise overview of the key differentiating factors among the five methods discussed in this study, the following summary comparison table 7 is presented.

**Table 7:** Comparative Summary.

<b>Method</b>	CSS/Steam Flooding	SAGD	ISC	THOR Cavitas
<b>Recovery Factor</b>	20–50%	50–70%	40–60%	40–65% (pilot)
<b>Energy Efficiency</b>	Moderate–High (SOR 2.5–5)	High (SOR 2–3.5)	High (AOR 3000–6000 scf/bbl)	Moderate (EIOR 150–350 kWh/bbl)
<b>Water Requirement</b>	High	Moderate–High	Low	Minimal
<b>GHG Emissions</b>	High	High	Moderate	Low-Moderate

Technology Maturity	Mature	Mature	Intermediate	Emerging
Best Application	Shallow, permeable reservoirs	Thick, homogeneous, continuous pay	Deep reservoirs, reactive oil	Heterogeneous, thin pay, water-sensitive areas

### 7.3. Actionable Recommendations Based on Comparative Findings

Based on the comparison measures in this study, the following recommendations are made for practitioners and policymakers:

- For shallow reservoirs (depth < 900 m) that are easy to access and have adequate permeability, CSS or Steam Flooding are recommended as cost-effective, technically sound choices with established operational guidelines.
- For thick, uniform reservoirs (pay thickness > 20 m, vertical permeability > 5 D), SAGD is the best technology since it has the highest recovery rate, even if it costs a lot of money to get started.
- For deep reservoirs (depth > 1000 m) where steam injection is not possible, ISC should be explored as long as thorough reservoir characterization shows that oil reactivity and combustion stability can be kept up with real-time monitoring.
- For reservoirs that do not have enough water, are sensitive to the environment, or can get low-carbon energy, THOR Cavitas or other mechanical heating technologies are a great low-water, low-emission option. This is especially true for pilot-scale use to gather field validation data.
- For pay zones that are thin or not uniform, steam-based solutions don't work well since they do not fit well: To make the sweep more efficient and use less energy, we should look into hybrid methods that combine electromagnetic pre-heating with solvent or steam injection.

### 7.4. Future Directions in Heavy Oil Recovery

Technology and innovation will improve heavy oil recovery efficiency and sustainability. Hybrid processes like electromagnetic heating with steam or solvent injection can reduce steam, increase compliance, and lower emissions. Dynamic closed-loop reservoir management will be possible with real-time monitoring technologies like fiber-optic distributed temperature sensing and mechanical heating tomography.

Ecological sustainability will increasingly influence technological choice. Carbon capture, utilization, and storage (CCUS) will reduce steam-based emissions, while solar thermal, geothermal, or renewable electricity can reduce steam and mechanical heating carbon footprints. Water recycling and treatment will remain crucial for freshwater conservation.

### 7.5. The Role of THOR Cavitas in the Future of Heavy Oil Recovery

THOR Cavitas is a major step forward in the recovery of heavy oil because it provides a means of mobilizing heavy oil through selective heating with reduced water consumption and the potential for lower greenhouse gas emissions. These factors make it a very attractive option compared to conventional steam-based thermal recovery methods, especially in reservoirs where steam injection is inefficient, environmentally problematic, or difficult to implement. However, to move from being a promising technology to a widely accepted field solution, THOR Cavitas will have to address challenges that are currently associated with high capital costs, technology maturity, and a lack of experience with large-scale applications. Future research and development will be key to creating a confident environment in the industries and determining the best use of the technology. As the technology for mechanical heating becomes even more advanced and less costly, THOR Cavitas could be a major player in the future of heavy oil recovery.

### 7.6. Final Thoughts

Heavy oil recovery is a technically demanding process, and it requires careful evaluation of the conditions, the process of operation, and the economic and environmental aspects of the process. From the comparative analysis presented in the article, it is clear that CSS/steam flooding, SAGD, ISC, and THOR Cavitas are alternative methods for the recovery of heavy oil, but each of these methods has its shortcomings, which need to be addressed appropriately.

The changing global energy scenario will require the industry to increasingly focus on enhancing existing recovery technologies, developing environmentally friendly new technologies, and consuming fewer resources. By integrating existing technologies with new ones, such as THOR Cavitas, the heavy oil industry can tap into enormous resources while becoming more sustainable and economically viable.

It is important to note that the findings presented in this study are derived from a synthesis of published field data, pilot projects, and structured estimates from the literature. While every effort was made to ensure accuracy and reliability, the reliance on partially estimated data for certain methods, particularly ISC and THOR Cavitas, means that the policy conclusions should be interpreted as preliminary insights rather than definitive recommendations. Real-world validation through expanded field trials and commercial-scale demonstrations remains essential before these findings can inform policy decisions or large-scale technology deployment strategies.

As the world moves toward lower-carbon energy sources, the heavy oil business needs to keep improving current technology, coming up with new ideas, and using hybrid methods that combine the best parts of several ways. The industry can access huge amounts of heavy oil this way, while also making the economy more stable and having less of an effect on the environment.

**Conflict of Interest:** The authors declare that they have no conflict of interest.

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