Abstract—Utilization of Enhanced Oil Recovery (EOR) methods increase the economic value of existing fields through increased oil recovery and field life extension. When EOR chemicals are transported, reserved, and injected into deep wells for oil recovery, they may pose environmental problems. So, in order to avoid environmental disasters, environmental impacts of EOR methods must be considered in planning and executing of such methods. Major environmental impacts associated with EOR are contamination of surface water and groundwater, and excessive air emissions especially from thermal operations. The objective of this review paper is to quantify some of the environmental effects of EOR methods in petroleum industry.

Keywords—Enhanced Oil Recovery, Air quality, Surface water, Groundwater.

I. INTRODUCTION

ENHANCED Oil Recovery (EOR) is recognized in the petroleum industry as tertiary recovery and it used to recover more oil from a hydrocarbon reservoir than would be achievable using primary or secondary recovery methods. The target of EOR varies considerably for the different types of hydrocarbons. Figure 1 shows the fluid saturations and the target of EOR for typical light and heavy oil reservoirs. For light oil reservoirs, EOR is usually applicable after secondary recovery operations, and the EOR target is ~45% original oil in place. Heavy oils respond poorly to primary and secondary recovery methods, and the bulk of the production (~90%) from such reservoirs come from EOR methods [1]. Environmental assessment in upstream and downstream petroleum industry clearly shows the necessity of the impact of such activities on soil, water and groundwater [2-8].

In order to fulfill the energy future needs, environmental rules and regulations regarding utilization of EOR must be undertaken. U.S. federal legislation that affect the EOR operation requirements include: (a) National Environmental Policy Act of 1969 (NEPA), (b) Resource Conservation and Recovery Act of 1976 (RCRA), (c) Clean Water Act of 1977, (d) Clean Air Act of 1977, (e) Occupational Safety and Health Act of 1970 (OSHA), and (f) the Transportation Safety Act of 1974. These legislations are the basic guidelines for all the EOR rules, regulations and standards. The environmental aspects of EOR require the acquisition of a considerable data base to: (1) assure compliance with lows, regulations, and environmental standards; (2) ensure that a minimum of environmental disturbances occurs as a result of the EOR program; (3) alleviate any accidental environmental damage that might occur. The constraints to EOR development from lows and regulations, water availability, socioeconomic impacts, environmental monitoring programs, etc., must be assessed.

Some areas of research for development of specific data have been suggested by Donaldson [9]. Researches related to environmental concerns of EOR have been suggested by Wilson and Franklin [10] and Kaplan et al. [11]. Important considerations are secure sources of water and other injectants, storage and transportation facilities (like pipelines), surface processing, separation, recycling and upgrading facilities, and environmental and safety requirements [12]. Heavy crude oil also contains significant concentrations of heteroatom (mainly sulfur and metals with very limited aqueous solubility) that would increase the TSS content [13]. The control of greenhouse gases is arguably the most challenging environmental policy issue facing nearly all countries. An approach that is gaining widespread interest is to control CO2 emissions by capturing and sequestering it from fossil-fuel combustion sources [14].

EOR methods fall into three main categories: thermal, chemical and miscible displacement methods. All of these methods involve the injection of fluids into the formation in order to generate properties or interfacial conditions that are

Fig. 1 EOR target for different hydrocarbons

http://dx.doi.org/10.15242/IICBE.C914075
more favorable for oil displacement. The ratio of discovery rate to consuming rate is one to four barrel of conventional oil, thus, the gap between discovery and consumption is big and may grow [15-16]. Therefore, EOR methods and other advanced methods become more important to extract oil from known resources rather than from exploration effort to find new oil accumulation. Thus, the remained oil after primary and secondary methods, which is about 60% of the total oil in a reservoir, is hard to recover by the conventional methods due to physical phenomena such as wettability, capillary pressure and oil viscosity or geological reason such as heterogeneity. In order to recover some of the oil left in the reservoir, EOR methods have to be applied to overcome the physical and geological effects. This paper is pointing out the environmental impacts of EOR methods.

II. AIR QUALITY IMPACTS

The components of concern in EOR methods on air quality impacts are dust, engine exhaust, off-well gases, gas-flaring combustion products, particulates, SO$_2$, CO$_2$, NOx, H$_2$S and hydrocarbons.

Any chemicals that added to the reservoirs to enhance sweep efficiency or fluid mobility might cause gaseous emission problems if they are vaporized and/or entrained in the steam. While all EOR methods can cause air pollution, thermal methods are most likely to generate air pollution impacts. In-situ combustion processes potentially can produce H$_2$S, fugitive emissions from high volume air compressors. In thermal processes air pollution results mainly from boiler combustion products. Steam and hot water flooding rely on steam generators that usually use the fuel supply available on location and emit SO$_2$, NOx, hydrocarbons, CO, CO$_2$, and other combustion products. In situ combustion can release these same compounds as fugitive emissions and as exhaust from high volume air compressors [17].

In CO$_2$ flooding, venting of H$_2$S and local, short-time, blanketing concentrations of CO$_2$ are the major concerns. Accidental spills and equipment leaks are the other possible ways of air pollution. NOx released together with hydrocarbons escaping from the oil production process constitute a mixture with the potential to generate oxidant far downwind from the point of release. Because miscible flooding does not involve high rates of either fuel combustion or in situ combustion, it is probable that CO$_2$ injection will have a much smaller air-quality impact than will the thermal methods discussed earlier. However, if H$_2$S is injected into a reservoir and subsequently escapes, poisoning of humans and wildlife could result. CO$_2$ is nontoxic, but capable of causing suffocation if concentrations are high enough. It will most likely be obtained from industrial activities, or natural reservoirs.

The main air pollution impact resulting from CO$_2$ recovery methods will be the release of hydrocarbons and H$_2$S from formations into which CO$_2$ is injected. H$_2$S is toxic, flammable, explosive, corrosive, and may be naturally present in reservoirs. The concentration of H$_2$S which constitutes a harmful quantity depends upon the subject being considered, whether humans, the environment, or equipment. Therefore, regulations have been adopted by various governmental agencies to require all stages of H2S operations to conform to safety and environmental standards [18].

Chemical recovery methods do not produce emissions during application. Any air quality emissions from chemical EOR methods would be indirect, in that they would occur from the production of various chemicals and the power generation required in the pumping process. In the case of the chemicals, air pollution impacts from production plants are already covered by existing air quality control regulations. Some light hydrocarbons, ethers, or alcohols are expected to be used in chemical recovery methods. These would presumably be derived from petroleum refineries whose air pollution emissions are of concern, but these may not be new emissions arising solely from EOR. Atmospheric emissions will probably not be important in either process, but monitoring of emissions is necessary to determine their exact levels, and duration; and thus be able to provide proof of insignificant or no environmental deterioration.

III. SURFACE WATER

EOR methods will require significant quantities of water over and above primary recovery methods. It is anticipated that the EOR fresh water requirements would be higher than the demand in present techniques of water flooding. In order to quantify the water requirement, it is assumed that one to six barrels of fresh water is needed for each barrel of oil recovered, this quantity of water consumption would have a greater effect on the environment in most regions than any other EOR impact. Although large quantities of water are required for EOR, the environmental impact on surface waters from EOR activities is anticipated to be only slightly greater than that from secondary recovery methods. The main environmental impact on the surface waters will be the actual consumptive use of the water. Of the three EOR methods considered, chemical methods have the greatest potential for adverse impacts on surface water resources because water consumed would be equal to or greater than for miscible or thermal EOR methods used, and spills of concentrated chemicals would be environmentally more detrimental to water supplies than spills or emissions from other EOR processes.

Miscible EOR methods will have the smallest environmental effect on surface water. As with the previous two methods, the quantities of water consumed in this EOR process would constitute the greatest environmental impact. Chemical spills, well failure, and reservoir leakage are thought to be the only mechanisms by which environmental effects would occur other than those which are a part of routine operations.
The environmental effects on surface water of thermal EOR methods will be greater than those of miscible methods but less than those from chemical processes. As with chemical EOR methods, fresh water consumption in routine operations will have the greatest impact on the environment. Past experience had shown that spills, well fractures, and reservoir leakage are infrequent and basically non-detrimental during thermal EOR operations.

IV. GROUNDWATER

Potential for ground water contamination resulting from fluid injections associated with EOR operations appears minimal. This conclusion is supported by the lack of ground water contamination problems associated with conventional water floods. Only 74 ground water injection problems resulted from operating 44,000 injection wells in Texas between 1960 and 1975 and only 3 of these occurred during the last decade. Similar safe operating records exist in the other major oil-producing states with large numbers of water floods. Because EOR injection operations are basically the same as water floods, often using the same injection wells in the same formations, an increase in the rate of ground water contamination is not expected. In fact, it is anticipated that the safety record will improve because EOR injection fluids are more costly than the water now used in water floods and operators could be expected to take additional precautions to prevent loss of these fluids during the EOR process. As with surface waters, use of water from aquifers for EOR operations could put a strain on freshwater supplies in areas where reserves were limited. In areas where the rate of consumption exceeds the rate of recharge, the impacts would be severe. Recent field tests indicate that brine tolerant EOR processes are feasible, and could significantly reduce the impact of EOR operations on freshwater aquifers if used.

V. GEOLOGIC HAZARD

Potential geologic hazards connected with EOR methods are subsidence and possible seismic activity. A great deal of subsidence data associated with primary oil recovery has been collected in the Long Beach, Calif., area (Mayuga and Allen, 1973). When compared with primary recovery methods, it is anticipated that subsidence actually will be reduced during EOR operations. The reason for this reduction is that fluids will be left in the reservoir after the oil is removed, except when in situ thermal methods are used. There has been some research relating seismic activity to the use of secondary recovery methods. Results of this research imply that seismic activity will not be increased by EOR methods. The Rocky Mountain Arsenal near Denver, Colo., conducted deep well injections which resulted in an increase in seismic activity in the Denver Area (Colorado School of Mines, 1968). It should be noted, however, that these injections were generally made into deep crystalline rock which did not ordinarily contain fluids. Injected fluid acted as a lubricant to the existing stress zone which is believed to have caused the increased seismic activity.

VI. NOISE

Although the compressors and other equipment used in EOR generate high levels of noise, it is unlikely that this noise will cause any serious environmental impact. The loudest noises such as those which would accompany preparation for injection of steam in a cyclic steam process are of short duration. In regions where the local biota or human population would be adversely affected by noise, maximum muffling and noise abatement procedures will need to be imposed [19].

VII. BIOTA

Enhanced oil recovery technologies present a variety of potential biological effects; those are summarized according to relative significance in Table 1, and most do not appear very serious. While some do pose potentially significant problems, most can be adequately addressed and avoided. Many areas where EOR activities would take place have already undergone primary and secondary development, and environmental impacts will therefore not result from EOR activities alone. Some of the potential impacts are common to all processes, while others are the result of or dependent upon a particular process. Table 1 identifies the activities that might be expected to create biological impacts.

<table>
<thead>
<tr>
<th>Process</th>
<th>Impacts</th>
</tr>
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<tbody>
<tr>
<td>Thermal</td>
<td>Air emissions</td>
</tr>
<tr>
<td></td>
<td>Cooling and consumptive water use</td>
</tr>
<tr>
<td></td>
<td>Energy source</td>
</tr>
<tr>
<td>Miscible</td>
<td>Air emissions</td>
</tr>
<tr>
<td></td>
<td>Pipeline and source of CO₂</td>
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<td></td>
<td>pH changes</td>
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<tr>
<td>Chemical</td>
<td>Manufacturing, handling, and disposal of chemicals</td>
</tr>
</tbody>
</table>

VIII. DISCUSSION

Nearly 2.0 × 10¹³ barrels of conventional oil and 5.0 × 10¹² barrels of heavy oil will remain in reservoirs worldwide after conventional recovery methods have been exhausted. Much of this oil would be recovered by EOR methods [1]. During EOR, heat (such as steam), gases (such as CO₂), or chemicals are injected into the reservoir to improve fluid flow. Environmental problems result only when the materials are allowed to escape. The following mechanics that may be responsible for such escape are listed in Table 2.
TABLE II
ESCAPE MECHANICS OF EOR METHODS

<table>
<thead>
<tr>
<th>Escape Mechanics</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>Transit Spills</td>
<td>Spills which may occur when material is being prepared at or transported to the field site.</td>
</tr>
<tr>
<td>Onsite Spills</td>
<td>Spills which may occur at the field site from surface lines and/or storage facilities.</td>
</tr>
<tr>
<td>Well System Failure</td>
<td>Escape of materials which may occur from failure of the injection or producing well due to casing leaks or channeling.</td>
</tr>
<tr>
<td>Reservoir Migration</td>
<td>Fluid may migrate outside of the confining limits of a reservoir through fractures or through a well bore which interconnects reservoirs.</td>
</tr>
<tr>
<td>Operations</td>
<td>The effects caused by routine activities and by the support facilities and activities associated with EOR production.</td>
</tr>
</tbody>
</table>

Air quality problems; seemingly outweigh all others in steam flooding because of the sheer volume of air pollutants produced from a typically large project. In relatively new fields where all wells have been meticulously logged and where all previously abandoned wells have properly cemented, injection of fluids under pressure should cause little trouble, but in older fields where these conditions may not obtain, aquifer contamination is a realistic concern. There are fugitive or uncontrolled air emissions from in situ combustion projects, and occupational health and safety hazards for workers exposed to irritating, toxic, or caustic chemicals, particularly in micellar polymer, caustic and polymer floods.

Brine disposal is a problem common to all oil recovery operations and is particularly important in tertiary projects for which the ratio of produced water to produced oil can run as high as 10:1 or more. Produced water re-injection is an important option in productivity enhancement through a produced water management strategy. It simultaneously allows converting waste to value and preserving the environment [20].

Land disturbances, secondary impacts and socioeconomic effects certainly bear consideration, but these are lesser issues compared to air and water problems.

Issues associated with general petroleum production such as the use of chemicals for well-cleaning and treatment, and the disposal of drilling muds ought to be discussed principally in the context of their incremental use in tertiary recovery. As mentioned earlier, there are at least seven media in which EOR operations could have environmental impacts: air, surface water, ground water, land use, seismic disturbances and subsidence, noise, and biological and public health. Certain types of impacts will be far more important in some regions than in others. For example, air pollution is a concern primarily in urbanized portions of the Coastal Plains and in Interior Basins where air quality is already in violation of air quality standards. Similarly, land-use conflicts arise in heavily populated areas where land values tend to be high and multiple-potential uses exists for a given parcel of land. Ground water use and pollution is a grave concern in areas where ground water is a principal component of the water supply. Surface water pollution is important in areas with high surface runoff and at sites adjacent to surface water bodies. Noise is a concern in both urban and open areas, although natural ecosystems differ widely in their sensitivity to noise. Results show that the chemical EOR projects may have the greatest potential for environmental impacts and thermal the least, or the biota may be the most impacted and land the least.

Table 3 illustrates the relative environmental impacts of each method and relative comparison between each method. Selecting one method to improve oil production, of course, depends on many factors such as feasibility, economical aspects and so on.

As we see in Table 3, usually some environmental impacts are the same in different EOR methods. It means, for example, it is clear both thermal methods and miscible flooding (CO₂ injection) have environmental impacts on air quality, but we can say almost environmental impacts of thermal recovery are greater than CO₂ injection because impacts of CO₂ on air quality except some cases which it has impurity is negligible. In other case we can compare impacts of chemical injection and thermal methods. In both of them there is some environmental impact on water quality but in chemical methods it is much than thermal methods. So we cannot say exactly which method is better or which method has no environmental impact. Finally, if we want to select one method to enhance oil recovery among applicable methods by regarding large quantity of CO₂ reserves and global warming effect we can think about CO₂ injection as a preferred method. Of course in the future novel methods such as using microwave, electric, acoustic energy, seismic vibrations and ultrasonic waves can be good choices for enhancement of oil recovery.

IX. CONCLUSION

The following conclusions are made from the study:
1. CO₂ injection satisfies environmental concerns with a disposal of its capturing emissions from industrial sources and the most method expected to continue to increase in the future. Thus, CO₂ captured from flue gas or gas-processing plants can be used in EOR fields.
2. Thermal EOR processes produce atmospheric pollutants from the combustion of large quantities of oil, either in steam generators (the steam injection process) or in the reservoir itself (the in situ combustion process).

3. Chemical EOR projects may have the greatest potential for environmental impacts and thermal the least, or the biota may be the most impacted and land the least.

ACKNOWLEDGMENT

The author gratefully acknowledges the financial and administration support to Ministry of Higher Education (MOHE), Universiti Teknologi Malaysia (UTM), and VOTE No. 00K86. Also, the author wishes to express his thanks and appreciation to his group members in the faculty of Petroleum Engineering & Renewable Energy Engineering.

REFERENCES

http://dx.doi.org/10.1260/0958-305X.23.8.1339
http://dx.doi.org/10.1080/10916460903530473
http://dx.doi.org/10.1080/10916460903117545
http://dx.doi.org/10.1007/BF02072655

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