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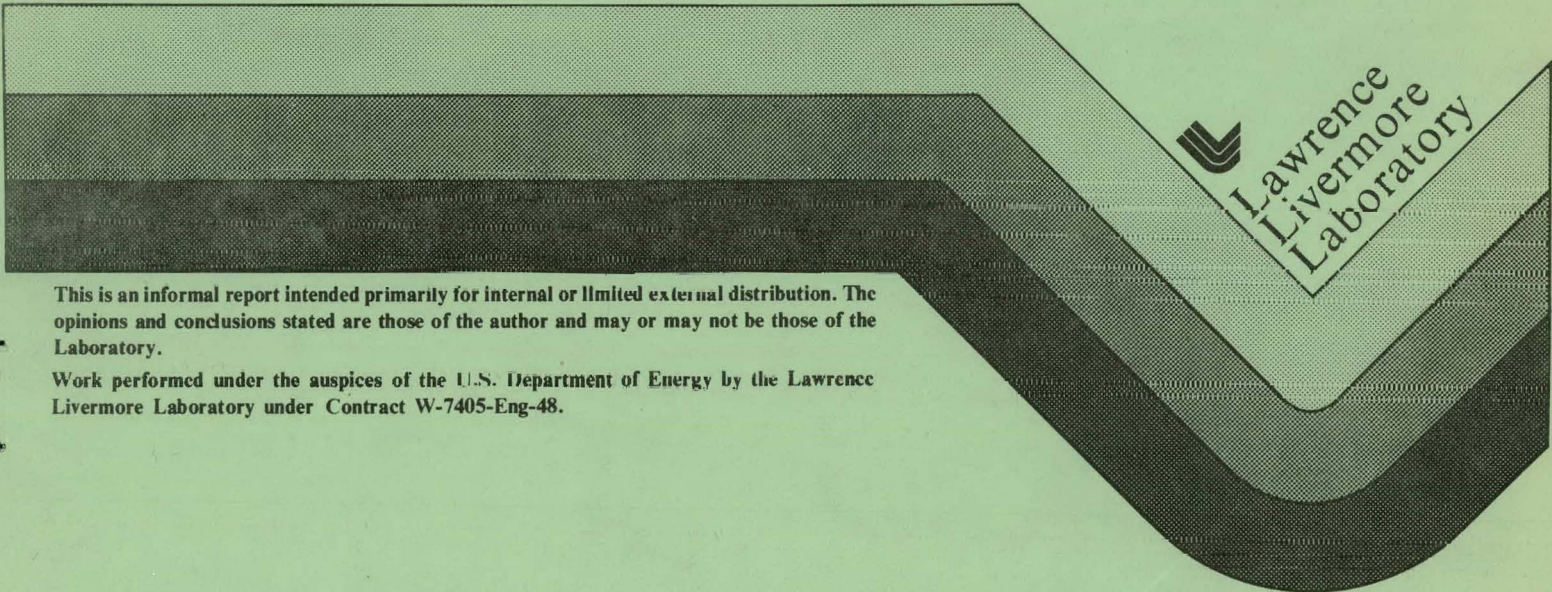
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ENVIRONMENTAL, HEALTH, SAFETY, AND
SOCIOECONOMIC CONCERNS ASSOCIATED WITH
OIL RECOVERY FROM U.S. TAR-SAND DEPOSITS:
STATE-OF-KNOWLEDGE

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Lynn R. Anspaugh
Yvonne E. Ricker

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January 8, 1982



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Under Contract W-7405-ENG-48

DOE Project Manager: G.J. Rotariu

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FOREWORD

This document was prepared for the U.S. Department of Energy, Office of Environmental Programs, Office of Environmental Protection, Safety and Emergency Preparedness to review and assess the environmental status of tar-sand oil-extraction technologies considered feasible for commercial application in the United States. The information contained in this report is based on the present state-of-knowledge about tar-sand oil-recovery systems now being field tested in the U.S. as well as on information contained in a recent Technology Assessment* document. This report is intended to provide an evaluation that will assist decision makers to ascertain the potential environmental, health, and safety risks associated with commercialization of these tar-sand oil-extraction technologies. Furthermore, an effort was made to emphasize the need for additional environmental, health, and safety research that should be coordinated with technology development in order to resolve current uncertainties and ensure deployment of environmentally acceptable commercial systems.

*J.I. Daniels, L.R. Anspaugh, and Y.E. Ricker, Technology Assessment: Environmental, Health, and Safety Impacts Associated with Oil Recovery from U.S. Tar-Sand Deposits, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-53210 (1981).

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LIST OF ACRONYMS

ACRONYM

af	Acre-feet
API	American Petroleum Institute
bb1	Barrel: 1 barrel of oil is equivalent to 42 U.S. gallons or 159 litres.
BOD	Biochemical Oxygen Demand
Btu	British thermal unit
CaO	Calcium oxide (lime)
CaSO ₃	Calcium sulfite
CO ₂	Carbon dioxide
CO	carbon monoxide
COD	Chemical Oxygen Demand
cP	Centipoise
CWA	Clean Water Act
dBA	Sound pressure level expressed in decibels with frequencies weighted according to the "A" scale. The A-weighted scale is a frequency response curve that simulates the response of the human ear.
DOE	Department of Energy
EPA	Environmental Protection Agency
HC	Hydrocarbons
H ₂ S	Hydrogen sulfide
L _{dn}	Average day/night sound level. It is the A-weighted equivalent sound level for a 24-hour period, with an additional 10-decibel weighting imposed on the equivalent sound levels occurring during nighttime hours of 10 p.m. to 7 a.m.
LETC	Laramie Energy Technology Center
L-R	Lurgi-Ruhrigas Company
M	Million
MEG	Multimedia Environmental Goals

LIST OF ACRONYMS (continued)

ACRONYM

mm	Millimetre
Na ₂ CO ₃	Sodium carbonate
NAAQS	National Ambient Air Quality Standards
NH ₃	Ammonia
NO ₂	Nitrogen dioxide
NO _x	Nitrogen oxides
NPDES	National Pollutant Discharge Elimination System
PM	Particulate matter: considered to consist of any airborne solid particles and low vapor-pressure liquid droplets with diameters less than a few hundred micrometres. Particulate-matter measurements in the United States are made most frequently with a high-volume sampler that collects total suspended particulates (TSP) on a glass-fiber filter by drawing air through the filter at about 1.5 m ³ /min.
ppmv	Parts per million by volume
PSD	Prevention of Significant Deterioration standards
SO ₂	Sulfur dioxide
SOHIO	Standard Oil of Ohio
THC	Total hydrocarbons
TSP	Total suspended particulates: considered to be a measurement of the particulate matter (PM) suspended in ambient air when the high-volume sampling method is used.
UIC	Underground Injection Control program
USGS	United States Geological Survey

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ABSTRACT

Tar-sand deposits consist of consolidated or unconsolidated clastic sediments (e.g., sandstone, limestone, diatomite) that have pore spaces partially or completely saturated with a heavy, viscous petroleum known as bitumen. Recent estimates indicate that the U.S. tar-sand resource may contain the equivalent of 36 billion barrels of recoverable oil. Approximately 80% of the domestic resource is predicted to be located in Utah. The remainder is considered to be present in several other states, particularly Alabama, California, Kansas, Kentucky, Missouri, New Mexico, and Texas.

Tar-sand petroleum-extraction procedures undergoing field testing for possible commercial application in the U.S. include both surface (above-ground) and in situ (underground) procedures. The surface tar-sand systems currently being field tested in the U.S. are thermal decomposition processes (retorting), and suspension methods (solvent extraction). Underground bitumen extraction procedures that are also being field tested domestically are in situ combustion and steam-injection.

Environmental control technologies will need to be incorporated into commercial tar-sand facilities in order for them to meet the standards set forth in current Federal regulations. These environmental control technologies are likely to be the same as those proposed for application with commercial oil-shale systems. The costs of protecting land, air, and water quality from degradation could range from \$1.20 to \$2.45 per barrel of oil produced (1980 dollars). However, these costs may be elevated substantially for specific projects depending on whether economies of scale can be achieved for application of environmental control technologies; the stringency of environmental protection regulatory standards; and the environmental control efficiencies necessary for projects to be in compliance with regulatory standards.

No project or facility can be made completely free from hazard, and assessment of the potential environmental, health, and safety risks associated with representative surface and in situ tar-sand oil-extraction systems indicates that certain effects are more likely to occur than others. Nevertheless the combination of additional research to resolve uncertainties related to the present emerging status of tar-sand technologies in the U.S., and cautious advancement toward commercial application, should lead to the development of commercial tar-sand technologies that are environmentally acceptable and facilities that represent reasonably safe places to work.

INTRODUCTION

Recent estimates of the potential barrels (bbl) of oil that may be contained in major world-wide tar-sand deposits appear in Table 1. Although Table 1 indicates that the U.S. tar-sand resource is eclipsed significantly by others, particularly those in Canada and Venezuela, commercial extraction of petroleum from tar sands in the United States can still make an important contribution to domestic oil production. This will be true especially if tar-sand petroleum really is a relatively inexpensive synfuel to produce, as one recent synfuels cost survey has suggested.⁸

Currently Canada is the only country where commercial oil extraction from tar sands is taking place. However, an economic and political climate now exists that is emphasizing the need for the U.S. to reduce its dependence on foreign oil. For this reason both government and industry have started to examine seriously methods for recovering oil from domestic tar-sand deposits. The tar-sand deposits in Utah, California, New Mexico, and Texas are particularly noteworthy because they are considered to be sufficient in size to support commercial tar-sand activities for 20 to 30 years or more.

Current activities in the U.S. to recover petroleum from domestic tar-sand deposits involve experiments and small-scale field-projects sponsored by either industry or the U.S. Department of Energy (DOE). These research efforts have concentrated on developing two strategies for commercially extracting bitumen (i.e., petroleum) from tar-sand deposits. One strategy entails mining the tar sands and then separating the oil from the sand grains

TABLE 1. Major world-wide tar-sand deposits.

Country	Estimated barrels of oil equivalent	Reference
Canada	1.3×10^{12}	[1,2]
Venezuela ^a	7.0×10^{11}	[1,3,4]
USSR	1.4×10^{11}	[5]
USA ^b	3.0×10^{10}	[6]
Malagasy	2.0×10^9	[5]

^aHeavy-oil reservoirs may be included in this estimate.

^b1981 revised estimate according to U.S. Department of Energy Office of Fossil Energy is 3.6×10^{10} bbls of oil equivalent.⁷

in surface (above-ground) facilities. The surface-separation methods presently being field tested for their potential commercial applicability and effectiveness are thermal decomposition processes (retorting), and suspension methods (solvent extraction). The other strategy for obtaining oil from tar sands involves inducing in situ (underground) flow of bitumen through the tar-sand formation and transporting the resulting hydrocarbon fluids to the surface. The in situ procedures being field tested in the U.S. are combustion methods and steam-injection techniques. All of the aforementioned procedures may be needed to establish a commercial tar-sand industry in the U.S. This is because the geochemical and physical properties among tar-sand deposits can differ considerably and therefore no single extraction procedure is expected to be suitable for extracting bitumen from all tar-sand deposits.^{9,10}

Present indications are that the first tar-sand oil extraction methods to achieve commercial status in the U.S. will be designed to produce about 20,000 bbl/d.^{7,10-13}

Environmental, health, safety, and socioeconomic concerns associated with construction and operation of 20,000-bbl/d commercial tar-sand surface and in situ facilities have been estimated¹⁰ and are summarized in this report.

The principal regulations that commercial tar-sand facilities will need to address are also discussed, and environmental control technologies are summarized and wherever possible, projected costs of emission controls for 20,000-bbl/d facilities are stated. Finally, the likelihood-of-occurrence of potential environmental, health, and safety problems that have been determined¹⁰ are reviewed, and from this information inference is made as to the environmental acceptability of technologically feasible 20,000-bbl/d commercial tar-sand oil-extraction procedures.

TAR SAND: PROPERTIES, DEFINITION, AND RESOURCE IN THE U.S.

Tar-sand reservoirs have been called by several names including oil sands, bituminous sands, oil-impregnated rocks, bitumen bearing rocks, asphaltic rocks, and heavy-oil producing rocks. The deposits consist of consolidated or unconsolidated clastic sediments (e.g., sandstone, limestone, diatomite) that have pore spaces partially or completely saturated with a heavy viscous petroleum known as bitumen.

Tar-sand bitumen is commonly identified by the following properties^{1,3,14,15}:

- An API Gravity* $\leq 12^\circ$, and
- A viscosity of 10^5 to 10^6 centipoise (cP) or greater

and will exhibit the following behavior²:

- Decreasing viscosity with increasing temperature, and
- General solubility in strong solvent members of the petroleum family (e.g., benzene and toluene).

The latter characteristics of bitumen are used in devising strategies for separating it from its confining mineral matrix.

Another, more formal, definition of tar-sand has been proposed by the U.S. DOE to satisfy legal issues associated with leasing, taxation, and financial

* API Gravity is a scale developed by the American Petroleum Institute to measure the density of petroleum.

assistance for an emerging tar-sand industry. The proposed definition states tar sand to be "... any consolidated or unconsolidated rock (other than coal, oil shale, or gilsonite) that (1) contains a hydrocarbonaceous material with a gas-free viscosity, at original reservoir temperature, greater than 10,000 centipoise, or (2) contains a hydrocarbonaceous material that is extracted from the mined or quarried rock."¹⁶

In comparison to tar-sand petroleum, most crude oils have gravities above 12° API, and crude oils with gravities greater than 18° API and viscosities less than 10⁵ cP are common. Almost all current U.S. production involves crude oils with viscosities lower than 10⁴ cP.¹⁷ Additionally, tar-sand deposits are distinguished from the heavier crude-oil reservoirs by the fact that bitumen cannot be pumped through its confining mineral matrix and collected at a well bore under natural reservoir conditions and heavy oil can (albeit extremely slowly). However, heavy oil and tar-sand bitumen are similar because both are members of the petroleum family of organic substances and neither is economically recoverable by means of the relatively simple techniques used for obtaining typical light-crude oils.

Based on the most recent estimates, over 80% of the U.S. tar-sand resource (approximately 2.9 x 10¹⁰ bbls) is present in deposits located in the state of Utah⁷; the remaining 20% of the resource is divided among deposits located in several other states. California, Kentucky, New Mexico, and Texas have individual tar-sand deposits predicted to contain the equivalent of more than 1 million barrels of oil,⁷ and less well-defined deposits are located in Alabama, Kansas, Missouri, and Ohio.³

Over 96% of the tar-sand resource present in Utah is contained in sandstone host rocks of six giant deposits (Figure 1). The six giant deposits are divided among two groups: a northeast group, called the Uinta Basin group, and a central southeast group.^{2,19} The Asphalt Ridge, Northwest Asphalt Ridge, P.R. Spring, Hill Creek, and Sunnyside deposits are members of the Uinta Basin group, and the Tar Sand Triangle and Circle Cliffs deposits are in the central southeast group.

In addition to the Utah deposits there are others that are now being considered for commercial development. These other deposits are located in California, New Mexico, and Texas.^{7,11,12} The commercial attractiveness of the deposits in Utah, California, New Mexico, and Texas is related to the fact

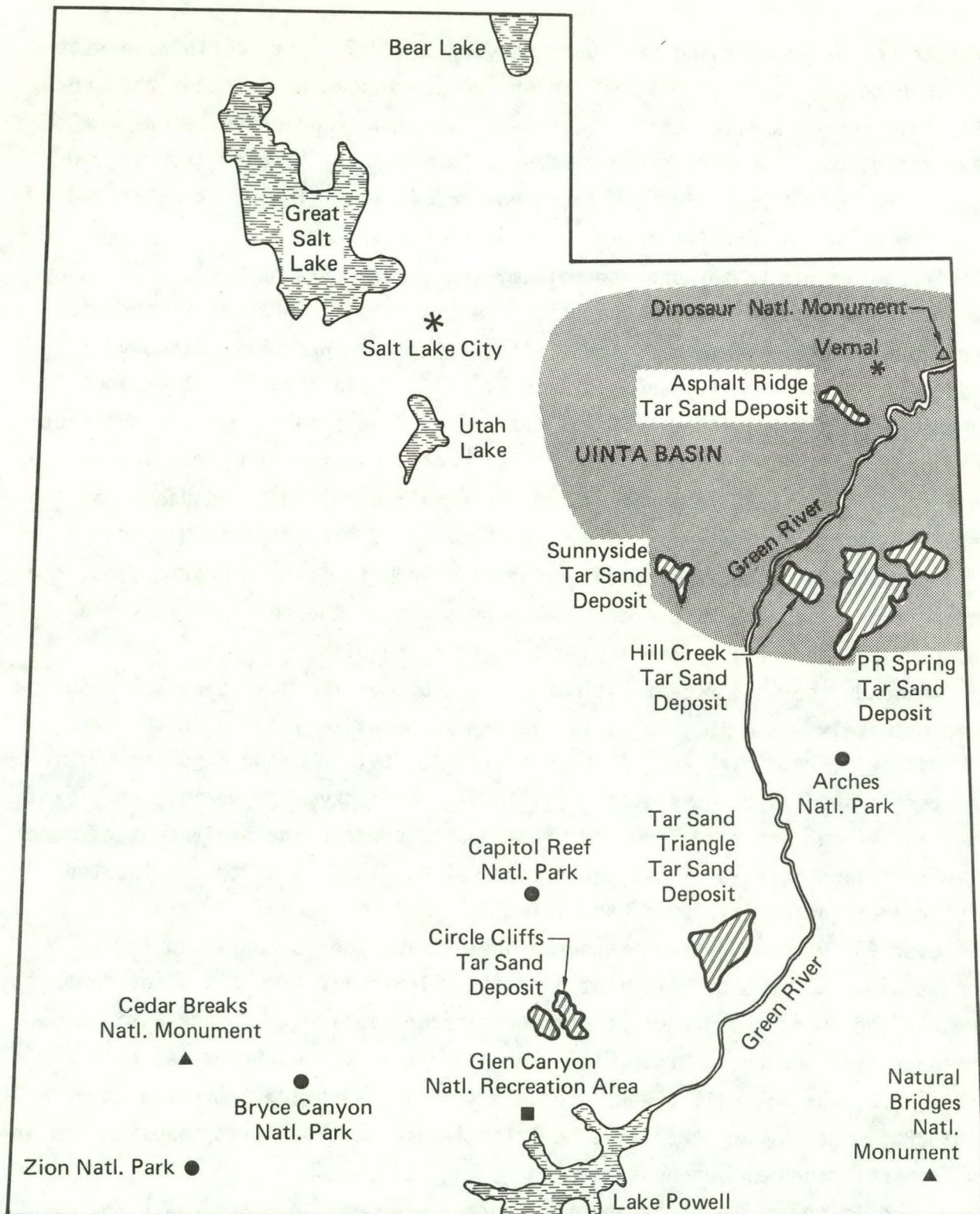


FIGURE 1. Location of the six largest tar-sand deposits in Utah (redrawn from Ref. 18, p. 1312).

that they are all considered to be sufficient in size to be able to support commercial tar-sand activities for 20 to 30 years or more. This extended use of the resource permits industry to take advantage of amortizing its capital investment over the long term.

COMMERCIAL TAR-SAND OIL EXTRACTION FROM U.S. RESOURCES

The only commercial tar-sand oil-extraction activities now taking place are being conducted on the Athabasca tar-sand formation near Edmonton, Alberta, Canada.¹ No commercial-scale facility has been constructed in the U.S. for two main reasons: (1) the simple oil-recovery technique used commercially on the Canadian deposits is not suited for direct application to most domestic tar-sand resources and (2) until recently, economic and political conditions have not favored domestic development of commercially feasible tar-sand oil-extraction processes. Now, however, increasing oil prices and the need for the U.S. to reduce its dependence on foreign oil have combined to stimulate the development of tar-sand oil-extraction procedures that may be suitable for domestic commercial application. Moreover, based on the anticipated successful completion of field tests now underway that deal with surface and in situ processes, commercial tar-sand oil-extraction facilities have been announced for operation by 1990 on tar-sand deposits in California, Utah, and Texas (Table 2). If these announced projects and other possible commercial developments, that remain proprietary at this time, do

TABLE 2. Proposed commercial development of tar-sand resources in the United States by 1990.^a

Company	Proposed extraction procedure	Estimated production capacity (bbl/d)	Location
Getty Oil Company	Surface	20,000	McKittrick, CA
Standard Oil of Ohio	Surface	25,000	Vernal, UT
Conoco Oil Company	<u>In situ</u>	25,000	Uvalde, TX

^a From Reference 10.

materialize, then oil production from the U.S. tar-sand resource by 1990 could be 80,000 to 120,000 bbl/d. Based on current economic conditions and engineering designs, each commercial tar-sand oil-extraction facility that would contribute to the projected 1990 production level will probably produce about 20,000 bbl/d.¹⁰

Among the several surface and in situ tar-sand oil-extraction procedures now being investigated in the U.S., two projects are distinguished by the availability of quantitative information concerning system operation in the field. One of these projects involves the testing of both representative surface-retort and surface-solvent oil-extraction pilot units for potential commercial application on privately-owned diatomaceous-earth tar sands located near the city of McKittrick, California. The other project involves the field testing of typical in situ (underground) combustion and steam-drive procedures for possible commercial application where mining and surface extraction is not economically feasible. While the first research effort is being conducted by private industry, the second one is being performed by the U.S. DOE Laramie Energy Technology Center (LETC) on leased land near the city of Vernal, Utah. Descriptions of these representative surface and in situ tar-sand oil-extraction methods as 20,000-bbl/d facilities follows. Although other procedures are being considered for possible commercial application in the U.S.,¹⁰ they are not discussed here because field-operation data are severely limited for these methods, due mainly to their very early stage of development and/or proprietary status. Extrapolation of such limited data to identify the potential environmental, health, safety and socioeconomic impacts that might result from commercial application of these systems as 20,000-bbl/d facilities would not be meaningful.

REPRESENTATIVE SURFACE MINING AND OIL-EXTRACTION PROCESSES

One method of recovering petroleum from tar sand involves mining the ore and then separating the bitumen from the sand grains in surface (above-ground) facilities.

Mining

Surface mining (as opposed to underground mining or modified in situ mining) is the method most likely to be selected for use with commercial

surface tar-sand facilities in the U.S.¹⁰ Figure 2 is a diagram depicting the geometric configuration and salient features of a conceptual phased multi-bench open-pit surface mine that could be used for excavating tar-sand ore. Its dimensions are based primarily on the phased multi-bench open-pit surface mine planned for the proposed 20,000-bbl/d surface tar-sand project to be located in Kern County, California, near the city of McKittrick. Operating parameters for the surface mining project planned near McKittrick, California, are presented in Table 3. These surface mining activities involve a variety of materials handling operations, such as³

- Surface clearing and removal of overburden,
- Mining of tar sands,
- Removal of barren rock or ore that is too low-grade,
- Construction of haul roads,
- Transportation of ore to processing facility,
- Construction of impoundments and drainage diversion channels,
- Transportation of tailings,
- Surface grading and contouring for reclamation, and
- Rehandling of temporarily stored waste for ultimate disposal.

The reclamation activities that must be performed will probably consist of backfilling the mined-out area with overburden, spent ore, and low-grade ore; followed by replacement of top soil and subsequent recontouring and revegetation.¹²

Once removed from the formation tar-sand ore will be subjected to a surface oil-extraction process that separates the bitumen from the sand grains and in so doing converts it to a liquid petroleum. These surface oil-extraction procedures can be 90% efficient, although mining and handling losses can lower this value considerably.^{1,3} The two above-ground oil-extraction processes approaching commercial application as 20,000-bbl/d facilities and for which quantitative data are available involve 1) thermal decomposition of bitumen by coking in a retort system, and 2) oil-extraction by means of suspending bitumen in a petroleum solvent.

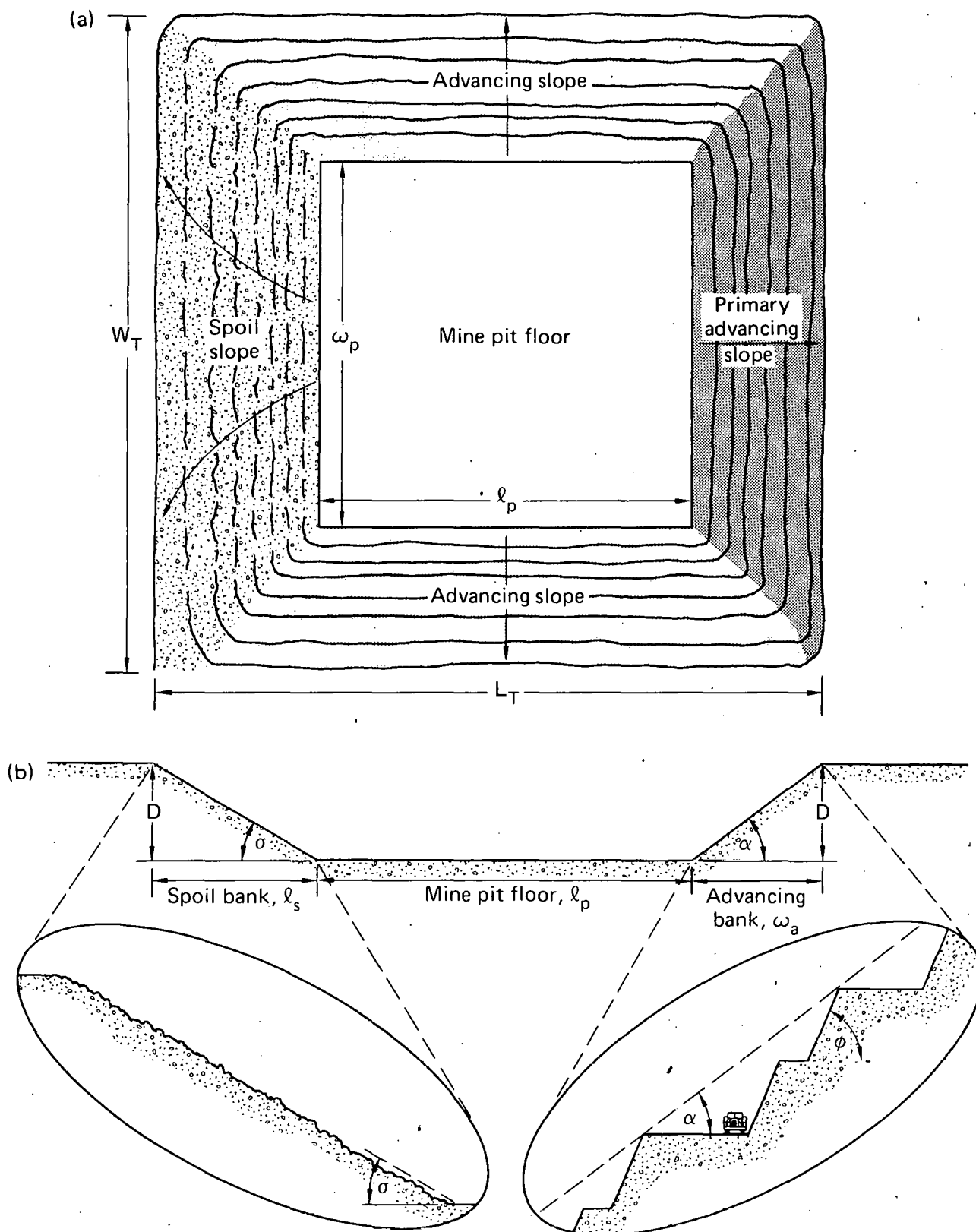


FIGURE 2. Diagram of a conceptual phased multi-bench open-pit surface mine for excavating tar-sand ore: (a) Top view, (b) Cross-section. Based primarily on available technical data for the excavation of diatomaceous-earth tar sands near McKittrick, California.¹²

Dimensions for the conceptual surface mine presented in Figure 2.

- ω_p = width of pit floor, 500 ft (150 m) } minimum allowable dimensions to
 ℓ_p = length of pit floor, 500 ft (150 m) } accommodate vehicle turn-around
 and ensure equipment and
 personal safety
- A_p = surface area of the mine pit floor: $A_p = \omega_p \times \ell_p$
- D = maximum depth of surface mine, 1200 ft (360 m)
- σ = angle of spoil bank, 31°
- α = angle of entire advancing-bank slope, 37°
- ℓ_s = size of the base of the spoil bank: $\ell_s = D/\tan \sigma$
- ω_a = size of the base of the three advancing banks: $\omega_a = D/\tan \alpha$
- W_T = total width of the surface mine from the top of one advancing bank to the top of the one directly opposite it on the other side of the mine: $W_T = \omega_a + \omega_p + \omega_a$
- L_T = total length of the surface mine from the top of the spoil bank to the top of the advancing bank directly opposite it on the other side of the mine: $L_T = \ell_s + \ell_p + \omega_a$
- A_T = total area of surface mine at any one time, 350 acres (1.5×10^7 ft²):
 $A_T = L_T \times W_T$
- ϕ = angle of individual bench slopes, 62° . This slope is greater than the slope of the advancing banks, and is governed by the capability of intact tar-sand ore to resist localized failures on a slope. Individual benches can be maintained at slopes greater than those for the advancing banks because a few small slopes can fail and not adversely impact operation of the mine. Bench widths alternate between 40 ft (12 m) and 120 ft (36 m) at 50 ft (15 m) high intervals to accommodate drilling and blasting or other excavation practices.

TABLE 3. Operating parameters for a phased multi-bench open-pit surface mine planned for the proposed 20,000-bbl/d commercial surface tar-sand oil-extraction project located near McKittrick, California.^a

Parameter	Amount
Total mined area over 48-year active lifetime for mine	1026 acres (410 ha)
Total amount of material excavated, consisting of	1.1 x 10 ⁹ tons
Process-grade diatomite ore,	5.9 x 10 ⁸ tons
Overburden,	3.4 x 10 ⁸ tons
Underburden (waste material mined with the ore)	6.4 x 10 ⁶ tons
Low-grade ore (18 gallons of oil/ton)	1.2 x 10 ⁸ tons
Total work force (necessary to provide 90 workers/shift for 3 shifts per day each day of the year)	307 workers
Water requirement for mining and related activities	4000 m ³ /d (3.2 af/d)
Total fuel consumption rate for all mining equipment (including shovels, trucks, drills, auxiliary and miscellaneous machinery and vehicles)	300 bbl/d

^aBased primarily on information taken from Reference 12.

Coking Bitumen in a Retort System

Coking is a proven technology and uses temperatures between 480 and 650°C (900 to 1200°F) to produce gases and a solid coke from the bitumen present in tar-sand ore. Condensation of the volatilized organic compounds yields a

hydrocarbon liquid with a lower average-molecular-weight, sulfur content, and carbon-to-hydrogen ratio (C:H) than the bitumen. The coke residual is composed mostly of carbon but also contains the sulfur removed from the liquid product. The combination of higher temperatures (760°C; 1400°F) and additional oxygen can be used to burn off the residual coke from the sand grains and produce a hot clean sand that can be used to provide heat for recirculation in the retort apparatus.

The Lurgi-Ruhr gas (L-R) retort procedure developed by Mineraltechnik of West Germany is a representative coking method that is scheduled for pilot testing in the fall of 1981 on a privately owned tar-sand deposit of oil-impregnated diatomaceous-earth (i.e., tar-sand ore composed of the fossilized remains of marine diatoms saturated with bitumen) near McKittrick, California.^{11,12} This testing will be used to determine the acceptability of the system as a 20,000-bbl/d commercial facility. A schematic diagram of this representative retort system is presented in Figure 3. A complete 20,000-bbl/d retort system involves the integrated operation of several essential components¹²:

- The L-R retort apparatus for producing 20,000 bbl/d of oil and naphtha from approximately 32,000 tons per day of diatomite tar-sand ore.
- The sulfur-recovery system necessary for removing quantities of gaseous sulfur-compounds (e.g., 98% emission control) contained in (1) the raw product gas, (2) the L-R retort flue gases, (3) sour-fuel gas produced by the hydrogenation unit, and (4) off-gas from the sour-water stripper used to remove the ammonia and hydrogen sulfide from the sour-gas liquor.
- The hydrogenation unit used to treat the product oil to make it acceptable for transport and refining.
- The hydrogen production plant to manufacture hydrogen for the hydrogenation unit.

The total water complement for the retort system depicted in Figure 3 is projected to be 1800 m³/d (1.5 af/d) and will probably need to be fresh water exclusively.¹² The exclusive use of fresh water is necessary for

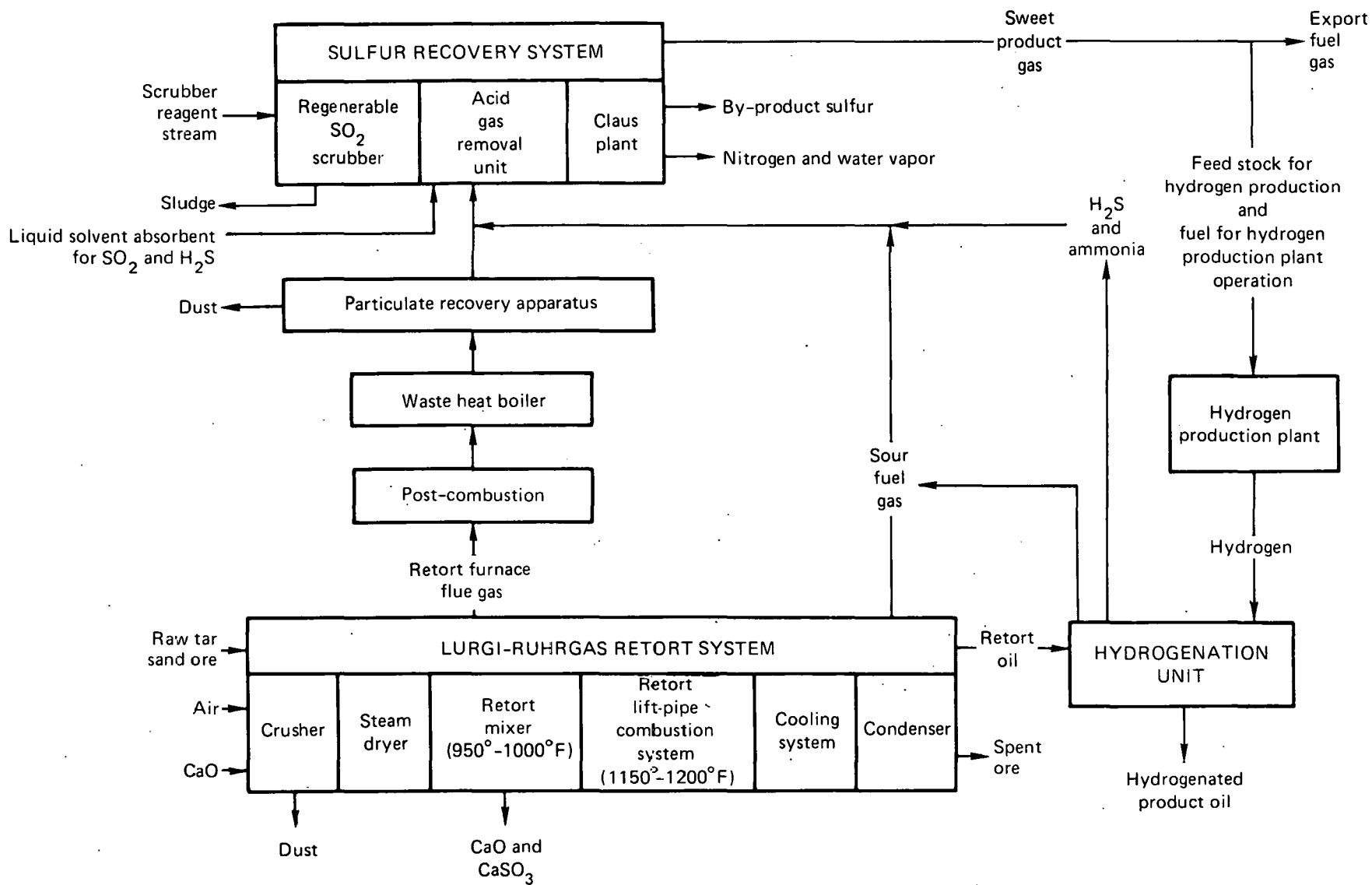


Figure 2. Schematic diagram of a representative 20,000-bbl/d commercial surface-retort system for extracting petroleum from surface-mineable domestic tar-sand ore.

efficient and dependable operation of the retort process because high-pressure steam is produced as part of the process. The maximum permissible levels of contaminants and treatment chemicals in feed water used to produce steam decreases with increasing pressure so that scale formation and corrosion can be prevented.

Manpower requirements for constructing and operating the representative 20,000-bbl/d retort system have also been predicted¹²:

- Construction work force: 1000 employees during peak periods; and an average daily work force of 500 for the anticipated two-year installation period.
- Operating work force: 146 employees per 24-hour operating day.

Suspension of Bitumen in a Petroleum Solvent

The extraction of bitumen from tar-sand ore with a petroleum solvent basically involves washing the ore with the solvent. This allows the bitumen to come into contact with the solvent and be dissolved. The solvent with the dissolved bitumen can then be separated from the sand grains, and treated (e.g., by distillation) to remove the bitumen and recover the solvent for recycling through the process. The solvent can be a light hydrocarbon such as benzene or toluene, or a combination of light hydrocarbons such as a heptane, cyclohexane, and ethanol mixture.

A representative solvent system that employs a heptane, cyclohexane, and ethanol mixture is the Dravo solvent-extraction process and this system is currently being field tested for possible commercialization on privately-owned diatomite tar sands near McKittrick, California.^{11,12} This process is schematically drawn in Figure 4 as a representative 20,000-bbl/d surface-solvent system. Such a system would require an estimated 37,000 tons per day of diatomite ore to produce at least 20,000 bbl/d (and perhaps more than 24,000 bbl/d) of oil.¹² The essential parts of the Dravo solvent-extraction process are

- A multi-stage solvent-extraction system where the heptane, cyclohexane, and ethanol solvent is mixed with crushed diatomite ore to create a "miscella" (oil-solvent-water mixture),

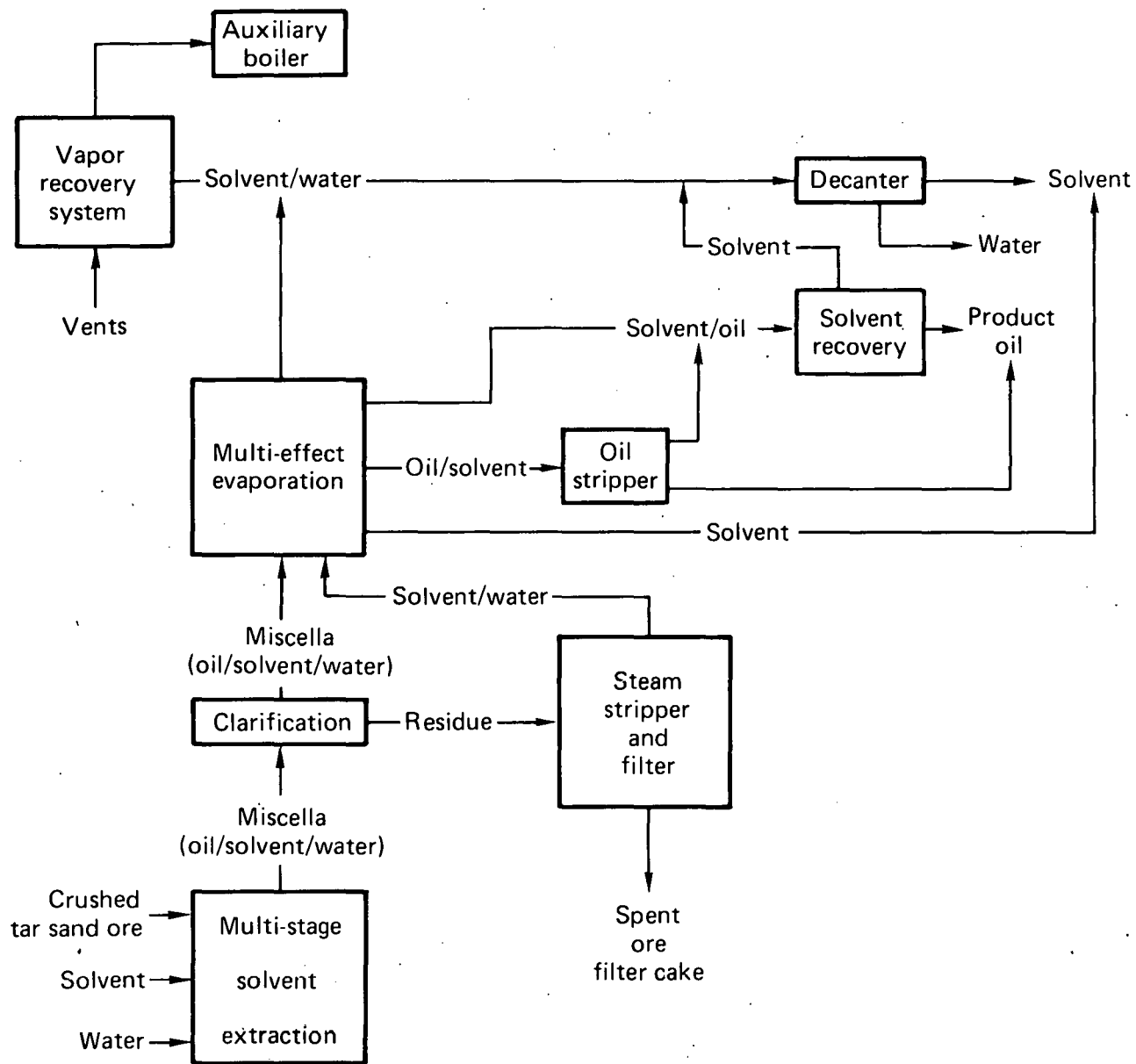


FIGURE 4. Schematic diagram of a representative 20,000-bbl/d commercial surface-solvent system for extracting petroleum from surface-mineable domestic tar-sand ore.

- A multi-effect evaporation process for separating the miscella into (1) a solvent/water mixture that can be separated in a decanter, (2) a solvent/oil mixture that can be separated in a solvent-recovery system, (3) an oil/solvent mixture that can be separated by oil stripping, and (4) a clean solvent (oil and water free),
- A steam-stripping apparatus for extracting residual solvent from spent ore for reuse; thereby producing a final spent-ore filter-cake,
- A vapor-recovery system to prevent the escape of the volatile solvent mixture and to recover solvent and water for reuse, and
- A decanter for separating solvent and water.

A surface-solvent system like the one just described will probably not require additional sulfur recovery devices because a combustion process is not an integral part of the system.

The water requirement for the surface-solvent system in Figure 4 is predicted to be more than 16,000 m³/d (approximately 13 af/d); however, unlike the direct-coking L-R retort system, the total water complement for the solvent process does not have to be fresh water exclusively. Instead over 99% of the water can be treated waste water.¹² The treated waste water is acceptable because low-pressure steam is produced during operation of the solvent process. More specifically, the production and use of low-pressure steam means that the maximum permissible concentrations of contaminants and treatment chemicals that can be in the feed water without contributing to scaling and corrosion can be greater than if high-pressure steam was involved.

Employment requirements for construction and operation of the commercial solvent facility have also been estimated¹²:

- Construction work force: 450 employees during peak periods, and an average daily work force of 200 for the anticipated two-year installation period, and
- Operating work force: 128 employees per 24-hour operating day.

REPRESENTATIVE IN SITU PROCESSES

Only 20% of the tar-sand deposits located in the U.S. are estimated to possess a ratio of overburden-to-payzone thickness (i.e., typically ≤ 1)

economically favoring surface-mining practices.^{1,2} Therefore, to recover the oil from the deeper deposits, in situ (underground) oil-extraction procedures are likely to be selected. In situ procedures are estimated to achieve a total recovery efficiency of 50 to 60%.^{1,3} The in situ processes that are currently considered commercially feasible for extraction of oil from tar sands are similar to those already used for enhanced oil recovery. These processes are in situ combustion and in situ steam injection. In both these thermal recovery procedures the objective is to remove a "trapped" petroleum by reducing its viscosity with heat and then causing the resulting fluid to be readily driven through the formation for collection and transport to the surface. Other in situ techniques such as those involving introduction of solvents or electrical heating are economically questionable at this time or unproven, respectively.¹⁰

In-Situ Combustion Methods

In situ combustion methods basically involve lighting a fire in the tar-sand formation to produce temperatures between 320 and 480°C (600 and 900°F). These temperatures volatilize the light hydrocarbons and vaporize the water contained in the bitumen. Combustion is sustained in the formation by injecting air and burning the residual bitumen and coke. The injected air also serves as the driving force for moving the fluids through the formation.

Figures 5 and 6 are schematic diagrams of the two in situ combustion methods currently being investigated for possible commercial application on deep tar-sand deposits in the U.S.^{3,20} These methods are

- Forward combustion where ignition of a fire in the tar-sand formation and injection of air to drive the produced fluids and maintain combustion are both introduced at the same injection well (Figure 5), and
- Reverse combustion where the fire is ignited at the production well but compressed air is injected at an injection well so that it can conduct the volatilized hydrocarbons through the burn front and burned-out zone behind the backwards moving flame front (Figure 6).

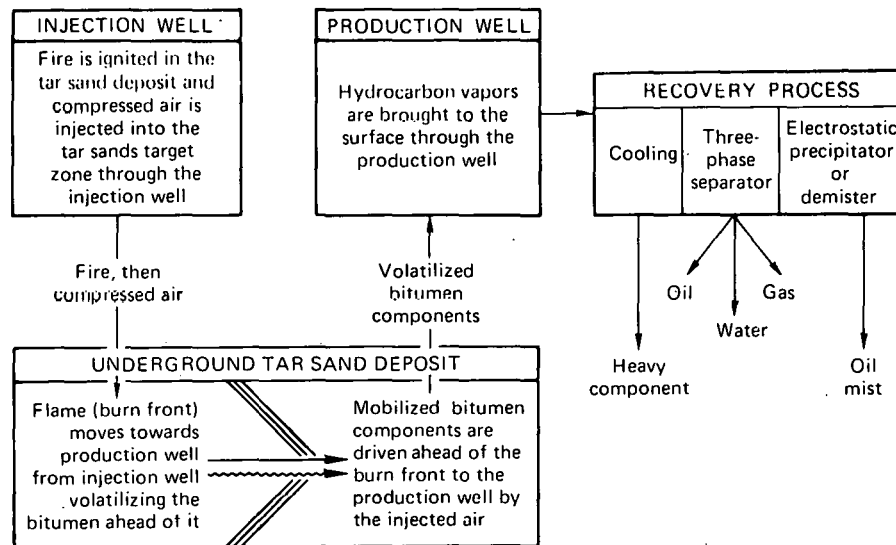


FIGURE 5. Schematic diagram of a representative 20,000-bbl/d commercial in situ forward-combustion procedure for extracting petroleum directly from underground tar-sand deposits in the U.S.

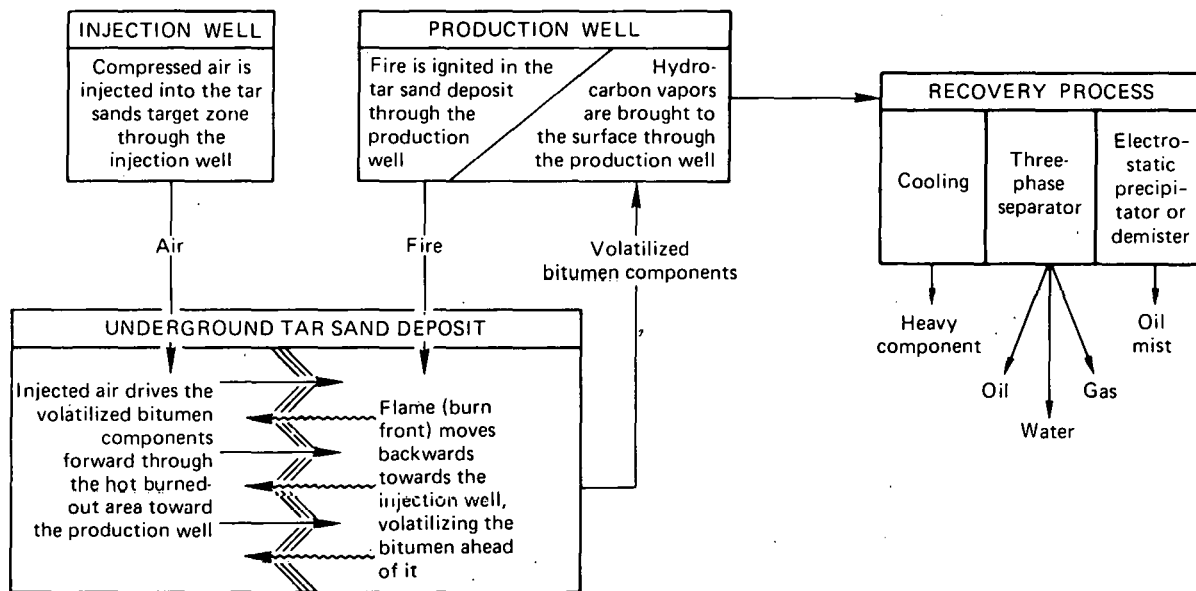


FIGURE 6. Schematic diagram of a representative 20,000-bbl/d commercial in situ reverse-combustion procedure for extracting petroleum directly from underground tar-sand deposits in the U.S.

The latter method can eliminate plugging problems that may occur in forward combustion systems because fluids can congeal in the relatively cooler area ahead of the burn front.

During the 1970s a major effort was initiated by the U.S. Department of Energy Laramie Energy Technology Center (LETC) in Laramie, Wyoming, to study the application of in situ combustion procedures on a 10-acre site in Utah leased from Standard Oil of Ohio (SOHIO) under the terms of a cooperative agreement. This site is located in NE Utah on the Northwest Asphalt Ridge tar-sand deposit (see Figure 1).

In-Situ Steam-Injection Methods

Steam-drive procedures have been used successfully for recovery of high-viscosity heavy oil. During the early 1960s the method was field-tested on Canadian tar sands where four barrels of steam were required to produce each barrel of oil.³ The technique consists of the continuous introduction of high-temperature steam into the tar-sand formation through an injection well. The steam heats the bitumen and thereby reduces its viscosity, and drives the resulting fluids to the production wells surrounding the injection well. Successful extraction of petroleum from the tar-sand formation with steam-injection depends on good communication between injection and production wells and the use of steam with sufficient temperature and pressure to mobilize the bitumen and drive it to collection wells for transport to the surface.^{3,11,14}

Recently, researchers from LETC began field testing steam-drive procedures on the tar-sand formation below the LETC 10-acre lease site near Vernal, Utah. Figure 7 is a schematic representation of a 20,000-bbl/d commercial steam-drive process that may evolve from present research activities.

UPGRADING PROCESSES

Surface or in situ oil-extraction procedures may need to be followed by an appropriate upgrading technique in order to make the liquid petroleum acceptable as a refinery feedstock. Upgrading entails (1) the removal of residual mineral matter from the extracted oil, (2) further reduction of density, viscosity, molecular weight and C:H ratio, and (3) lowering the

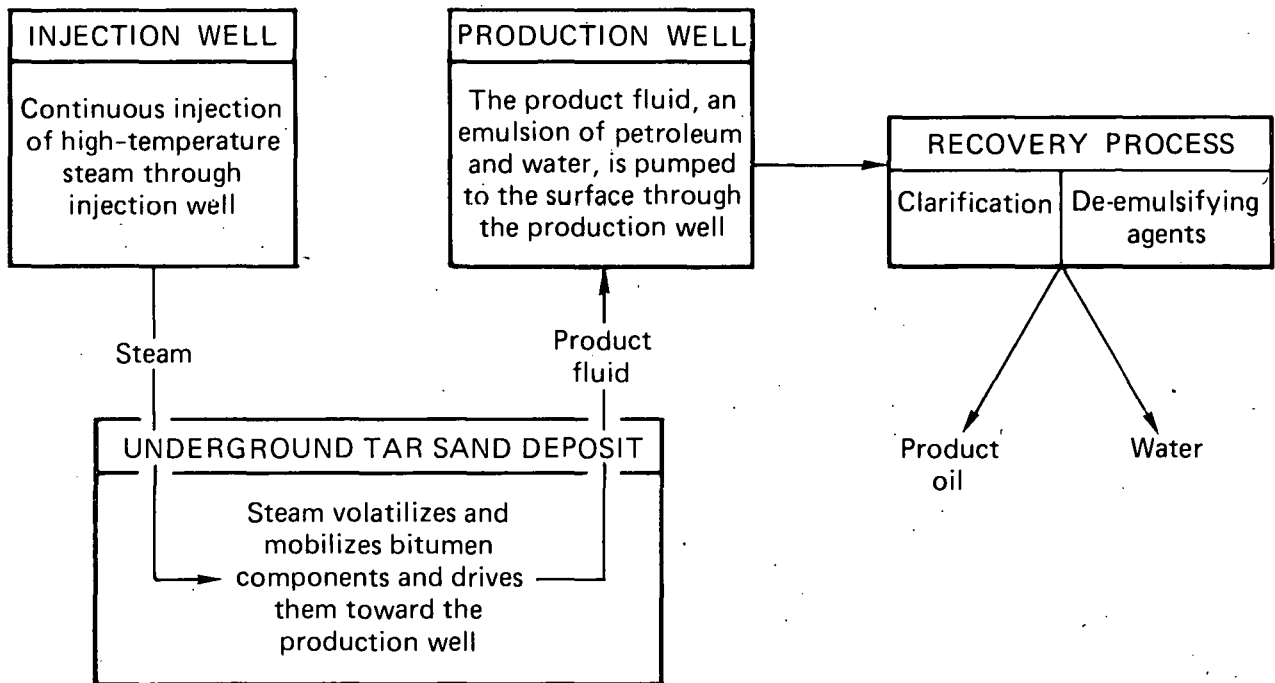


FIGURE 7. Schematic diagram of a representative 20,000-bbl/d commercial in situ steam-injection procedure for extracting bitumen directly from underground tar-sand deposits in the U.S.

sulfur content of the extracted petroleum to a level acceptable for refining. Several upgrading procedures are currently being considered for possible compatibility with commercial tar-sand oil-extraction procedures.¹⁰ These prospective upgrading techniques need to be investigated further, however, because they might be useful as supplements to one another or as primary surface-extraction systems that can yield directly high-quality synthetic crude oil and other valuable petroleum by-products.

REGULATORY AND CONTROL CONSIDERATIONS

REGULATORY FRAMEWORK

Commercial tar-sand projects will have to comply with a regulatory framework that includes standards for air, water, solid waste, worker health and safety, and toxic substances. These standards and other applicable regulations including those concerning protection of objects of historical significance are set forth in the following Federal Acts:

- Clean Air Act
- Clean Water Act
- Safe Drinking Water Act
- Resource Conservation and Recovery Act
- Toxic Substances Control Act
- Occupational Safety and Health Act
- National Historic Preservation Act

Furthermore, U.S. Geological Survey (USGS) Regulations contained in chapters 221²¹ and 231²² of Title 30 of the Code of Federal Regulations may also be applicable to commercial tar-sand projects.

The most important aspects of current regulatory strategies are outlined in Table 4. Legal compliance with these regulations by developers of commercial tar-sand facilities is considered to be feasible, but implementation of environmental assessment programs during early development is essential to ensure sufficient data are available to certify that compliance can be achieved. Moreover, the market value of the product oil and the costs for the best available control devices and strategies will influence

TABLE 4. Principal regulatory framework confronting the emerging tar-sand industry in the U.S.

Legislation	Regulatory strategy/standards
<u>Clean Air Act</u>	Involves protection of ambient-air-quality from significant degradation and where necessary improvement and restoration of air quality to acceptable levels. Commercial tar-sand facilities will therefore need to comply with (1) National Ambient Air Quality Standards (NAAQS) that include maximum allowable atmospheric concentrations for nitrogen dioxide (NO ₂), sulfur dioxide (SO ₂), carbon monoxide (CO), hydrocarbons (HC), and particulate matter (PM); (2) Prevention of Significant Deterioration (PSD) regulations that establish maximum allowable increments of increase-over-baseline concentrations for particulates and sulfur dioxide in areas where these NAAQS are not exceeded (e.g., the most restrictive being those for areas which include the National Parks); and (3) Nonattainment rules that prevent development in areas where any NAAQS are already exceeded unless the new industry can "offset" (i.e., reduce) those emissions that contribute to exceeding the NAAQS.
<u>Clean Water Act</u>	Establishes a permitting process to protect surface waters from contamination. This process prohibits the discharge of pollutants to U.S. waters without a permit. Permitting is administered under the National Pollutant Discharge Elimination System (NPDES). NPDES regulations function to establish

Table 4. (continued)

Legislation	Regulatory strategy/standards
<u>Safe Drinking Water Act</u>	specific levels of performance that must be maintained by a discharger, and require the discharger to report failures to achieve the specified levels.
<u>Resource Conservation and Recovery Act</u>	Establishes applicable Safe Drinking Water Standards and programs to prevent degradation of surface and underground potable waters. The Underground Injection Control (UIC) program is designed specifically to prevent pollution of underground drinking water supplies from the generation or disposal of hazardous or toxic waste, and Public Drinking Water Standards are intended to ensure that the quality of all potable waters is protected from degradation and therefore remains safe for public consumption. Sets forth regulations designed to minimize the potential impacts resulting from the generation and disposal of hazardous waste. These regulations are stated specifically in Subtitle C., "Hazardous Waste Management," of Title II - Solid Waste Disposal of the Resource Conservation and Recovery Act of 1976.

Table 4. (concluded)

Legislation	Regulatory strategy/standards
<u>Toxic Substances Control Act</u>	Concerns the unreasonable risk of health damage or environmental deterioration from the manufacture, processing, distribution in commerce, use, or disposal of a chemical substance or mixture. Testing and, when necessary, use-restrictions may be applicable to synfuels and the re-use of process waters and waste materials.
<u>Occupational Safety and Health Act</u>	Establishes the maximum permissible concentrations of exposure to hazardous chemical and physical agents that can be tolerated by workers in the occupational setting without jeopardizing their health and safety.
<u>National Historic Preservation Act</u>	Mandates protection for sites, buildings, structures, and objects of significance in American history, architecture, archaeology, or culture.
<u>Geological Survey Regulations</u>	Designed to promote operating practices on Federal land (and private land developed simultaneously with Federal land by the same company) which will avoid, minimize, or correct impacts to the environment and public and worker health and safety. Compliance with the stated objective is subject to the judgment and discretion of the USGS area supervisor due to variability in the conditions in different locations.

the rate of development of commercial systems. Enactment of proposed changes in present regulatory standards and their administration (particularly in standards set forth in the Clean Air Act) will also influence the development of commercial tar-sand projects.

ENVIRONMENTAL CONTROL TECHNOLOGIES

The suitability of a particular environmental control technology for a tar-sand petroleum-extraction process will depend on several factors:

- Emission levels allowed by environmental regulatory standards,
- Products desired from the tar-sand facility and emission-control process,
- Availability and cost of water and electrical power to operate a pollution-control system,
- Land availability for solid-waste disposal of the by-products from pollution-control systems,
- Reliability of a pollution-control system, and
- Labor, material, and maintenance requirements for operating the system.

Therefore, the compatibility of a particular pollution-control system with a specific tar-sand technology is ultimately process-dependent and for the most part site specific.

The total cost associated with environmental control technologies needed by commercial tar-sand facilities to comply with regulatory standards for protecting air, land, and water quality could range from \$1.20 to \$2.45 or more per barrel of oil produced. This range in cost of environmental control systems is based on estimates for other industries (notably oil shale), and costs could be even higher because they are influenced by many factors, especially: (1) project lifetime, (2) facility design, (3) scale of operation, and (4) amount of emission-removal efficiency desired or required to achieve compliance with standards set forth in Federal and State environmental regulations. Nevertheless, for tar-sand technologies to be in compliance with Federal standards, this range of cost is assumed to be accurate to within a

factor of two, and these costs appear to be of minor economic importance now that the average cost of oil is more than \$36 per barrel. Additionally, it appears that oil prices will continue to increase at a rate no less than that of inflation, depending of course on world economic conditions, supply interruptions, major discoveries and synfuels development.¹⁰

Appendix A reviews the principal environmental control technologies that may be suitable for implementation with tar-sand processes without extensive research, development, and modification. Wherever possible the effectiveness of these technologies is indicated and an estimate of cost is provided.

REVIEW OF ENVIRONMENTAL, HEALTH, SAFETY, AND SOCIOECONOMIC CONCERNS

Data from current U.S. field activities involving surface tar-sand oil-extraction processes (specifically retort and solvent procedures) and in situ methods (specifically combustion and steam-drive techniques) have been extrapolated to determine the potential environmental, health, safety, and socioeconomic impacts that could be associated with 20,000-bbl/d commercial versions of each of these technologies.¹⁰ These potential impacts are listed below and are summarized in Table 5 along with some of the possible costs or cost-related factors associated with mitigating measures:

- Land surface disturbance and alteration,
- Atmospheric emissions,
- Noise and light problems,
- Worker exposure to hazardous substances and situations,
- Ground or surface water availability, consumption, contamination and interruptions,
- Waste generation and disposal, and
- Impacts on community infrastructure.

In addition to the potential impacts mentioned in Table 5, commercial tar-sand projects might also affect the pristine environment within Federal lands. The fact that potential sites of commercial tar-sand activities in Utah are near Federal lands (see Figure 1) emphasizes this concern.

Table 5. Summary of environmental, health, safety, and socioeconomic concerns and mitigating costs or cost factors associated with 20,000-bbl/d surface and in situ tar-sand petroleum-extraction technologies.^a

Technology	Land surface disturbance and alteration	Atmospheric emissions	Noise and/or light problems	Worker exposure to hazardous substances and situations	Water-related impacts	Waste generation and disposal	Impact on community infrastructure
<u>Surface methods</u>							
Surface mining	May (1) destroy critical habitats, (2) threaten existence of endangered species, (3) cause erosion and dispersal of solids, heavy metals, and organic compounds, (4) destroy historical, paleontological, and archaeological artifacts, and (5) disrupt the intrinsic beauty of the natural environment.	Can contribute to atmospheric emissions of criteria air pollutants (e.g., SO ₂ , NO _x , CO, THC, and TSP from mining equipment, and fugitive TSP and THC from the mine pit and ore-storage areas).	The predicted noise level of 61 dBA at 500 ft from the mining activities is not expected to be sufficient to cause the EPA short-term sound-level goal for communities to be exceeded. Illumination for nighttime mining can disrupt local ecology (e.g., interrupting circadian rhythms) as well as create a nuisance for nearby communities by interfering with the visual character of the natural setting.	Occupational exposure to noise is not expected to exceed ranges recommended in the Noise Control Act of 1972. Equipment-related occupational injury corresponding to the manual operation of mining machinery, vehicles, and conveyors needs to be prevented. Worker exposure to suspended particulate matter and substances absorbed/adsorbed to their surfaces (e.g., sulfates) as well as worker exposure to natural environmental problems (e.g., severe climate, and indigenous disease) may be significant and require implementation of mitigating measures.	Interruption or disruption of surface and underground aquifer systems by physical diversion or chemical contamination can lead to ecological impacts and degradation of potable water sources. Competition for limited water supplies is also conceivable.	Spent tar-sand ore used as backfill for mine reclamation may contain residual hydrocarbons and heavy metals. These can be leached by run-off and percolation, thereby contaminating surface- and ground-water.	The required work force necessary to operate a surface mine supporting a 20,000-bbl/d surface tar-sand facility is not sufficient to impact a community with an established labor pool (e.g., Kern County, California, with a population of 300,000 people) but can significantly strain services in rural communities that are sparsely populated, have undergone slow historical rates of change, (e.g., Unita Basin in Utah with a population of only 33,000 people) and already have cities with limited public services and rental housing that require expansion (e.g., Vernal, Utah).

^aSummarized from information presented in Reference 10.

Table 5. (continued)

Technology	Land surface disturbance and alteration	Atmospheric emissions	Noise and/or light problems	Worker exposure to hazardous substances and situations	Water-related impacts	Waste generation and disposal	Impact on community infrastructure
Surface retort and solvent systems	May cause destruction of critical habitats; endangered species; valuable historical, paleontological and archaeological artifacts; aesthetics associated with rural and natural settings; and cause additional run-off as a result of land clearing, and installation of buildings and roadways.	Preliminary estimates of the maximum ambient-air-quality impacts at ground level indicate that controlled criteria pollutant emissions from the retort flue gas and solvent system auxiliary boiler-flue-gas will not cause National Ambient Air Quality Standards (NAAQS) to be exceeded. Whether Prevention of Significant Deterioration (PSD) increments for SO ₂ and TSP will be exceeded remains to be determined.	A noise level between 73 and 88 dBA at 50 ft for retort and solvent systems is not considered sufficient to cause the EPA short-term sound-level goal for communities to be exceeded. No problems from nighttime illumination are expected.	Adverse health effects can arise from worker contact with hot pipes, fluids, and vapors. For example, worker exposure to (1) caustic compounds for sulfur control in retort systems; (2) the heptane, cyclohexane, and ethanol solvent vapors in a solvent system; and (3) the petroleum product itself may produce carcinogenic or chronic effects (e.g., dermatosis). Enclosure of noise-producing equipment, limiting employee exposure to elevated sound levels, and installing noise-suppression devices will minimize noise impacts to the proximal work force.	Consumptive water use necessary for retort or solvent commercial processes can deplete potable water supplies. Use of treated waste water can result in spills during transport and use that could lead to contamination of ground and surface water supplies or aquatic habitats.	Disposal of waste material (including water, solids, environmental control technology by-products, and spent catalysts not reprocessed for metals recovery) as part of the mine reclamation activities is considered feasible. However, potential effects on water quality from leaching of toxic substances contained in such waste need to be determined so that any possible transport of toxic substances can be avoided.	The work force needed for construction and operation of surface facilities probably will not impact communities with established labor pools (such as Kern County in California where the population is 300,000) but could significantly impact regions with small indigenous populations (such as in the Uinta Basin region of Utah where only 33,000 people reside). For instance, public services and rental housing are already extended to their maximum limits in the city of Vernal, Utah, which is located in the Uinta Basin. The services involved include sewage treatment, schools, and drinking water supplies.

^aSummarized from information presented in Reference 10.

Table 5. (continued)

Technology	Land surface disturbance and alteration	Atmospheric emissions	Noise and/or light problems	Worker exposure to hazardous substances and situations	Water-related impacts	Waste generation and disposal	Impact on community infrastructure
<u>In-situ procedures</u>							
Combustion and steam-injection procedures	In addition to ecosystem impacts and potential loss of historical artifacts, three possible effects directly related to <u>in situ</u> processes are (1) soil loss from erosion associated with land clearing, (2) seismic activity induced by fluid injection and increased pressures acting to lubricate fault planes in a tar-sand formation, and (3) subsidence as a result of fluid withdrawal from the reservoir such that pore pressures in the formation are reduced to a level that permits sediments to compact.	Preliminary estimates of uncontrolled atmospheric emission rates and resulting ambient-air-quality impacts from potential 20,000-bbl/d <u>in situ</u> combustion and steam-injection systems indicate a need for application of environmental control technologies, and more monitoring and pollutant modeling during field testing. Combustion methods appear to produce significant quantities of ethylene, CO, HC, COS, H ₂ S, NO _x , NH ₃ , and TSP. Major emissions from steam-injection processes appear to be SO ₂ and NO _x from steam boilers	Noise levels have not been estimated for commercial scale <u>in situ</u> combustion or steam-injection procedures; however, it is unlikely that detrimental effects will result from sound levels associated with these procedures. This is because similar methodologies are already being employed by the oil and gas industry without causing standards to be exceeded. No problems from nighttime illumination are expected.	Adverse health effects can result from worker contact with high-temperature fluids, piping, and operating equipment; or exposure to hazardous or toxic agents in recovered process oil and water, water-treatment chemicals, and stack or process-line gases. Safety precautions to avoid worker contact with the aforementioned equipment and substances have already been implemented at the LETC test facility near Vernal, Utah, and at commercial heavy-oil operations in California where similar <u>in situ</u> procedures are used.	Consumptive water use by <u>in situ</u> technologies may require creative water development plans, especially where competing interests for limited water supplies are involved. Mechanisms of water contamination from commercial <u>in situ</u> development activities include contamination of ground water from contact with drilling muds; communication between aquifers; and migration of produced gases or process waters away from a tar-sand formation and into aquifers. Contaminants include metals, nutrients, and organic compounds.	Recovered process water and the sludges that precipitate from it represent the most serious waste generation and disposal problem. Approved landfills represent one site for disposal of these substances. Environmental ramifications from surface disposal, however, include evaporation of light hydrocarbons contributing to air pollution, leaching of toxic agents, and potential fire hazards. Underground injection of waste substances and treatment and reuse of water are alternative methods to surface disposal. For these methods, care must be taken to prevent ground water contamination.	The work force associated with commercial <u>in situ</u> projects cannot be easily estimated at this time; however, impacts on community infrastructure are expected to be significant if a substantial proportion of the work force must come from outside the resource area. For instance services such as sewage treatment, rental housing, schools, and community water supply could be adversely impacted from a large influx of people to a rural area with slow historical rates of change (e.g., Vernal, Utah and the surrounding Uinta Basin where public services and rental housing are already extended to their maximum limit).

^aSummarized from information presented in Reference 10.

Table 5. (concluded)

Technology	Land surface disturbance and alteration	Atmospheric emissions	Noise and/or light problems	Worker exposure to hazardous substances and situations	Water-related impacts	Waste generation and disposal	Impact on community infrastructure
<u>Cost or Cost factors associated with mitigation of impacts from commercial surface and in situ tar-sand technologies</u>	Cost of land reclamation could range from \$4,000/acre to \$10,000/acre or amount to 1 to 4 cents per bbl of oil produced. (see Appendix A)	The overall cost to control only criteria pollutant atmospheric emissions may range from \$0.92 to \$1.20 per bbl of oil produced or considerably more depending on the control efficiency desired and the stringency of regulatory standards. A 10-MBtu/h non-vented downhole steam-delivery system for in situ steam-injection projects, exclusively, could eliminate surface steam boilers and their atmospheric emissions entirely but based on very preliminary cost estimates might have a capital cost of more than \$1,100,000 with an annual operating cost in excess of \$1,200,000 (see Appendix A)	The operating hours of the facility, its proximity to neighboring communities, its overall visibility to the public, and the local ecology, are all factors that will influence the costs associated with mitigating measures needed to limit impacts from noise and lighting.	Safety precautions for preventing worker exposure to toxic substances may involve equipping workers with respirators and protecting them from head-to-toe with fabric (e.g., neoprene) that is an effective barrier to the toxic substances.	The cost of complete water treatment for commercial tar-sand systems may range from \$0.25/bbl to \$1.25/bbl. The disposition of treated waste water could be recycling, evaporation, irrigation, or injection depending on the control system selected and the stringency of applicable regulatory standards. (see Appendix A)	In addition to the costs for actual waste disposal (e.g., user fees or the costs of monitoring sites for transport of hazardous substances), the cost of hauling the waste must also be considered.	The costs of mitigating socioeconomic problems will depend on (1) the scope and pace of new development, (2) its location, (3) the method of response (before or after the fact), (4) the amount of lead time for instituting programs to manage change, (5) the selection and organization of committees, and (6) decisions on who bears the cost of all mitigating programs, strategies, and related activities.

^aSummarized from information presented in Reference 10.

ASSESSMENT OF ENVIRONMENTAL, HEALTH, AND SAFETY IMPACTS

Subjectively determined values indicating the likelihood-of-occurrence of potential environmental, health, and safety impacts have been derived for representative conceptual 20,000 bbl/d tar-sand surface retort and solvent systems and in situ combustion and steam-injection procedures.¹⁰ This information, presented in Table 6, represents an assessment based on extrapolation of data from current U.S. field experiments involving tar-sand oil-extraction techniques and experience from other energy industries concerning health and ecosystem effects from air pollutants, measurements of ground-water transport of organic pollutants, and the effectiveness of environmental control technologies. Uncertainties associated with the figures contained in Table 6 are related to (1) the early stage of development of tar-sand technologies in the U.S.; (2) the efficacy of changes in process design vs "retrofits" for achieving environmental, public and occupational safety; (3) the preparedness of commercial tar-sand facilities to mitigate effectively hazards unique to the technology; and (4) the influence of regulatory and economic factors.

Atmospheric Effects

A 20,000-bbl/d surface retort or solvent system with atmospheric emission control systems operating is not expected to release concentrations of nitrogen dioxide (NO₂), sulfur dioxide (SO₂), carbon monoxide (CO), hydrocarbons (HC), and total suspended particulates (TSP) that would cause National Ambient Air Quality Standards (NAAQS) designed to protect public health to be exceeded. However, in those regions already meeting NAAQS, SO₂ and TSP emissions from surface retort and solvent technologies may be sufficient to cause U.S. Prevention of Significant Deterioration (PSD) increments to be exceeded.

A 20,000-bbl/d commercial in situ combustion or steam-injection procedure is certain to require air-pollution control devices and strategies because estimated ambient-air-quality impacts revealed that uncontrolled emissions from such processes may cause several legislated or recommended air-pollutant standards to be exceeded. Moreover, emissions of hydrogen sulfide (H₂S)

Table 6. Likelihood-of-occurrence of effects from the operation of commercial tar-sand oil-recovery procedures.

Possible effects	Effect according to process	
	Surface extraction	<u>In situ</u> recovery
Airborne effluents:		
Public health	2	2
Ecosystems	2	2
Surface-water contamination:		
Public health	1	1
Ecosystems	1	1
Ground-water contamination:		
Public health	2	2
Land subsidence	NA	2
Induced seismicity	NA	1
Land-surface contamination:		
Public health	2	1
Ecosystems	2	1
Worker health	3	2

Key: 3 - Effect likely to occur based upon experience in other industries.

2 - Effect may occur but will be localized and/or controllable.

1 - Effect possible but unlikely to occur.

NA - Not applicable.

from in situ combustion procedures may not be sufficiently reduced by current air-pollution control technologies to levels that will ensure the protection of public health in the immediate vicinity.¹⁰

The magnitude of the public-health impacts that might result from air pollution produced by commercial surface and in situ tar-sand projects has been estimated.¹⁰ These estimates were calculated using a health-damage

relationship for SO₂ emissions from coal-fired power plants of 0 to 0.8 premature deaths per 1000 tons of SO₂ emitted (or 0 to 120 deaths per year of operation within the 80% confidence interval).²³ This health-damage function was derived from a model that assumes Gaussian plume dispersion, first-order kinetics of chemical reactions, a linear dose-response function, and a population of approximately 3 x 10⁶ people within 80 km of the source (i.e., a coal-fired power plant located in a city in the Eastern U.S.).²⁴ Thus, an eastern coal-fired power plant with an annual SO₂ emission rate of more than 100,000 tons per year could be responsible for as many as 80 deaths per plant year. This figure is based on the application of the model just mentioned with the parameters previously discussed, and the derived maximum health-damage function of 0.8 premature deaths per 1000 tons of SO₂ emitted.²⁴ In comparison, the number of premature deaths resulting from SO₂ released by representative 20,000-bbl/d surface and in situ tar-sand facilities will be substantially lower. This is because the annual emission rate of SO₂ from such facilities and the exposed populations nearby (within 80 km) are predicted to be considerably smaller than for eastern coal-fired power plants supplying energy to major metropolitan areas. The range of estimated premature deaths within 80 km of conceptual commercial 20,000-bbl/d surface and in situ facilities were calculated for exposed populations of 300,000 and 30,000 people, respectively, and appear in Table 7. The former census figure is representative of populations within 80 km of possible commercial surface tar-sand activities expected in California and the latter census figure is representative of populations expected within 80 km of a potential in situ tar-sand project in Utah.

Adverse ecological impacts from atmospheric pollutants emitted by conceptual 20,000-bbl/d surface and in situ projects have been calculated.¹⁰ A simple linear relationship describing the growth response of vegetation after exposure to concentrations of SO₂ above the tolerance threshold was used in making the calculations.²⁵ The results from applying this relationship suggest that commercial surface tar-sand technologies (i.e., retort and solvent procedures) with 97% control of SO₂ could cause a localized yield reduction in native vegetation of 20%. In comparison, the SO₂ emission rate from a commercial in situ steam-injection process (with 97% control of SO₂) would probably not be high enough to adversely impact

TABLE 7. Estimated potential premature deaths within 80 km of commercial tar-sand facilities from atmospheric emissions of SO₂.

Process	Estimated potential number of premature deaths plant-year
Surface retort system ^a	0 to 0.08
Surface solvent system ^b	0 to 0.06
<u>In situ</u> steam-injection procedure ^c	0 to 0.003
<u>In situ</u> combustion procedure ^d	Additional data needed

^aAssumes a population of 300,000 people reside within 80 km; an annual SO₂ emission rate of about 1000 tons per year after 97% control.¹⁰

^bAssumes a population of 300,000 people reside within 80 km; an annual SO₂ emission rate of approximately 760 tons per year; and the use of low-sulfur fuel without SO₂ emission control technologies.¹⁰

^cAssumes a population of 30,000 people reside within 80 km; an annual SO₂ emission rate of nearly 370 tons per year after 97% control.¹⁰

^dThe estimated potential number of premature deaths per plant-year is presumed to be low for this type of facility. However, the SO₂ emission data from field tests of this system would not support extrapolation to a meaningful range of values.¹⁰

the growth response of native vegetation. Insufficient data on SO₂ emission rates from in situ combustion systems prevented determination of potential ecological impacts from this procedure.

In summary, adverse impacts on public health and ecosystems from airborne effluents released either from commercial surface or in situ tar-sand procedures may occur but are expected to be localized and/or controllable. However, this conclusion is based on preliminary evidence from evolving technologies and more information from additional monitoring and modeling studies is necessary to substantiate the current indications.

Surface-Water Contamination

Practices already commonplace in the chemical industry (e.g., monitoring, maintenance, and spill prevention programs) are expected to prevent direct contamination of surface water from accidentally occurring during the operation of surface and in situ tar-sand systems. Moreover, fluids used or created by these systems will generally be physically contained in either vessels or pipelines or the formation itself so that contact with the ambient environment will be minimal or absent. Therefore, adverse impacts on public health and ecosystems are possible but unlikely to occur. However, the potential for surface-water contamination will increase substantially if planned recycling, injection, and underground disposal procedures for process waters are not feasible.

Ground-Water Contamination

Leaching of substances from storage piles of raw and spent ore, and from the operating and backfilled mine areas of commercial surface tar-sand facilities can result in the contamination of ground water. In addition, detection of significant quantities of metals, nutrients, and organic compounds in product waters from in situ combustion and steam-injection field tests²⁶ suggests that ground-water contamination might result from commercial application of in situ technologies. The potential problem of ground-water contamination from in situ processes is further emphasized by the fact that monitoring studies following underground coal-gasification demonstrated that vapor-transported organic materials could be conducted to ground water 250 ft (76 m) away from the combustion zone.²⁷ This distance will depend on the geochemical and physical characteristics of the geologic formation. However, the slow movement of ground water combined with natural attenuation of pollutants by soil, indicate that effects may occur but will be localized and/or controllable.

Land Subsidence and Induced Seismicity

Land subsidence and induced seismicity are impacts associated exclusively with in situ operations. The land use surrounding a site will determine the magnitude of the impact should any subsidence occur. For the most part, subsidence is a localized effect that can be limited by proper site selection and operating practices. Induced seismic events can occur from high-pressure injection of fluids and resulting lubrication of geologic fault planes, and from thermal stresses introduced into the formation. Unless unusual conditions are present in a tar-sand reservoir, potential environmental impacts from induced seismic effects are unlikely.

Land-Surface Contamination

Land-surface contamination could be a significant problem associated with commercial surface systems due primarily to the large areas involved in the mining activities. However, careful reclamation and restoration of the mine area should reduce the magnitude of the impacts associated with mining. The release of hazardous substances onto the ground from any surface extraction process should be minimized by such mitigating measures as spill prevention programs, maintenance practices, and monitoring procedures. Thus, effects may occur but are likely to be localized and/or controllable.

Contamination of the land from in situ procedures is generally related to leaks or accidental spills from storage vessels and pipes, although drilling and pumping activities may also contribute to the problem. Current oil-field practices are expected to be sufficient to minimize any impacts that might result from in situ procedures. Therefore, land surface contamination, while possible from in situ technologies, is unlikely to occur.

Worker Health

The potential for morbidity and injury to workers operating commercial surface or in situ tar-sand processes may be significant. Facts concerning worker health problems in other industries such as oil-refining, foreign

shale-oil production, coking, and coal conversion indicate that worker exposure to compounds similar to those expected to be associated with tar-sand oil extraction can lead to toxic, mutagenic, or carcinogenic effects.

An estimate of the potential maximum risk of excess cancer-deaths per plant-year for commercial tar-sand technologies is approximately 0.03. This figure was calculated based on carcinogenic risk estimates for coke and oil-refinery workers.²⁸ This is probably a very conservative figure as the exposure in a modern tar-sand facility should be much lower than past exposure in the reference industries due to the availability and increasing use of protective devices (e.g., respirators and protective clothing).

Evidence from studies performed by Syncrude, Inc., to evaluate the carcinogenicity of products from its commercial surface tar-sand facility in Alberta, Canada, have led to the institution of precautionary measures to protect the work force from exposure to possible carcinogenic substances.²⁹ Other problems detected at the same facility for which mitigating measures are being taken include exposure of workers to an H₂S concentration of 1 ppm and to the odor of mercaptan compounds.²⁹ Due to the fact that there are nominal similarities among several properties of bitumen in Canada and the U.S.,^{30,31} there is a strong possibility that problems like those discovered by Syncrude, Inc., might develop at a surface tar-sand facility in the U.S. and require mitigation.

Occupational health risks may also develop from repeated long-term exposures to subacute concentrations of toxic chemicals released by tar-sand facilities. For instance, H₂S emissions were detected during in situ combustion field tests. If uncontrolled, these emissions can create a potentially significant problem, as illustrated by the following two examples. First, H₂S was implicated as the chemical agent responsible for chronic poisoning of workers in the Swedish shale-oil industry during the 1940s.³² Secondly, residents in the vicinity of The Geysers Geothermal Power Plant in California have appeared at hearings conducted by the California Public Utilities Commission to complain of headache, nausea, and sinus congestion attributable to the presence of H₂S (in concentrations probably as low as 0.1 ppmv) produced during geothermal energy production.³³

Based on current knowledge about the evolving tar-sand petroleum-extraction systems in the U.S., it appears at this time that worker health problems are more likely to occur at commercial surface petroleum-extraction facilities than at in situ facilities. This can be attributed to the fact that surface systems not only produce products that may represent occupational hazards, but also require the use of reagents that may additionally jeopardize the health and safety of workers. Alternatively, the environmental-control measures that could be used for in situ tar-sand technologies are routinely used effectively for thermal in situ heavy-oil extraction procedures. Thus, because these two in situ methodologies are so similar it is presumed that such environmental protection measures will be just as effective during in situ oil-extraction from tar sand.

RECOMMENDATIONS AND CONCLUSIONS

While no project or facility can be made completely free from hazard, early results from field tests of representative surface and in situ tar-sand technologies indicate that cautious development toward commercialization can yield environmentally acceptable processes and facilities that are reasonably safe places to work.¹⁰ However, because technologies to extract oil from tar-sand deposits in the U.S. are presently just evolving, uncertainties still exist regarding the operation of systems that are currently being considered for widespread commercial application.

The following conclusions have been drawn from an assessment of the currently available data¹⁰:

- Surface Extraction Technologies
 - Occupational health problems, including those related to worker exposure to carcinogenic and other hazardous substances, are likely to occur.
 - Public health and/or ecosystem effects from airborne effluents, ground-water contamination, and land-surface contamination may occur but will be localized and/or controllable.
 - Public health and/or ecosystem effects from surface-water contamination are possible, but unlikely to occur.
 - Land subsidence and induced seismic effects are not applicable to surface extraction techniques.

- In Situ Processes
 - Occupational health problems, including those related to worker exposure to carcinogenic and other hazardous substances, may occur but will be localized and/or controllable.
 - Public health effects from airborne effluents, (particularly SO₂ and H₂S) and ground-water contamination may occur but will be localized and/or controllable.
 - Ecosystem effects from airborne effluents and land subsidence may occur but will be localized and/or controllable.

- Public health and/or ecosystem effects from surface-water contamination and land-surface contamination are possible, but unlikely to occur.
- Induced seismic effects are possible, but unlikely to occur.

Early consideration of these potential problems will promote the development of environmentally acceptable tar-sand technologies in the U.S.

For tar sand to make a significant contribution to domestic oil production within the next 20 years expanded research and development efforts are being advocated.^{9,10} This research should (1) more accurately define the resource; (2) improve and advance production methods, especially in situ procedures; (3) identify and resolve environmental impacts and possible institutional constraints on a site-specific basis, particularly issues concerning emissions to air, land, and water; water availability; and land- and water-use conflicts; (4) precisely determine the environmental, health, and safety risks associated with product manufacture, distribution, and utilization; and (5) provide the best available procedures for minimizing impacts and ensuring worker health and safety.

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APPENDIX A

ENVIRONMENTAL CONTROL TECHNOLOGIES THAT MAY BE SUITABLE FOR APPLICATION WITH COMMERCIAL TAR-SAND PROCESSES

ATMOSPHERIC EMISSIONS CONTROL

Table A-1 presents candidate atmospheric emission-control technologies for reducing criteria-pollutant and hydrogen-sulfide emissions from commercial oil-shale processes. Such systems are considered applicable for use with tar-sand oil-extraction procedures. The cost of a typical atmospheric emission-control system for a commercial tar-sand facility that could reduce fugitive dust by 92.2%; particulates by 99.5%; SO₂ by 99.0%; NO_x by the maximum amount (using combustion control); and HC and CO by 50.5 to 89.0% would be \$0.92 to \$1.16 per barrel of product oil (based on predictions for oil-shale procedures).³⁴ For commercial in situ steam-injection, exclusively, a non-vented high-pressure downhole steam generator, that is now being field-tested, may be applicable.¹⁰ Ideally, such a system could eliminate atmospheric emissions associated with steam generation because the system operates entirely within the formation. Preliminary cost analysis for a 10-MBtu/h non-vented downhole steam-delivery system suggests a capital cost over \$1.1 million, and an annual operating cost that may exceed \$1.2 million; however, the precision of these estimates probably ranges from "-35% to +25%."³⁶

WATER POLLUTION CONTROL

Water-pollution-control techniques for removing contaminants from either oil-shale or tar-sand processes have not been tested specifically on these systems. However, potentially suitable water-pollution control technologies for commercial oil-shale facilities have been projected and are likely to be the same for commercial tar-sand projects. These systems are presented in Table A-2. The estimated cost range for a complete water-treatment system used for a commercial tar-sand facility will be similar to that predicted for a commercial oil-shale project: \$0.25 to \$1.25 per barrel of syncrude produced.³⁴

TABLE A-1. Air-pollution-control systems potentially suitable for reducing emissions of criteria pollutants (i.e., TSP, SO₂, NO_x, HC, and CO) and H₂S from commercial tar-sand projects.^a

Air-pollution-control system	Efficiency (% emissions reduction)	Readiness of the technology	Other considerations
POLLUTANT: Total suspended particulates (TSP)			
Water sprays	80 to 98 for particles >5 μ	High	Additives such as wetting agents and chemical binders improve efficiency
Cyclone separators	Up to 90 for large particles, and Up to 50 for particles <10 μ	High	
Scrubbers	93.6 to 99.8 for particles <5 μ	High	Little maintenance
Baghouse filters	Up to 99 for particles \geq 1 μ	Medium	Moderate maintenance
Electrostatic precipitators	Up to 99.9	Low to medium	Little maintenance
POLLUTANT: Sulfur dioxide (SO ₂)			
Wellman-Lord process	About 90 ^b	Medium	Sludge disposal
Double alkali	Greater than 99 for [SO ₂] <10 ppm	Medium	Sludge disposal
Nahcolite-ore process	50 to 80	Low	Experimental technology. Efficiency is a function of flow rate and ratio of Nahcolite to SO ₂ .
POLLUTANT: Hydrocarbon (HC) and carbon monoxide (CO)			
Combustion control		High	Use of excess air for complete combustion easily accomplished, but careful maintenance necessary.
Evaporation control		High	Floating roof tanks accommodate high vapor pressure without need for venting.
Control of fugitive emissions		Low	Difficult due to large number of dispersed sources.

TABLE A-1. (concluded) Air-pollution-control systems potentially suitable for reducing emissions of criteria pollutants (i.e., TSP, SO₂, NO_x, HC, and CO) and H₂S from commercial tar-sand projects.^a

Air-pollution-control system	Efficiency (% emissions reduction)	Readiness of the technology	Other considerations
POLLUTANT: Nitrogen oxide (NO _x)			
Combustion control	Can achieve compliance with regulations	High	Supplemental gas cleaning systems can be added if necessary.
Diesel-exhaust control	Can achieve compliance with regulations	Medium	Recirculation of exhaust gases can produce maintenance problems.
POLLUTANT: Hydrogen sulfide (H ₂ S)			
Stretford process	Up to 99.9	Medium	High chemical make-up costs. If COS, and CS ₂ are present, then pretreatment will be necessary to remove them to prevent their interference with H ₂ S removal.
Selexol and other physical absorption processes	Greater than 98	Medium	
Claus process with a tail-gas cleaning system (e.g. Shell Claus off-gas treating (SCOT), Beavon, or Institute Francais du Petrok (IFP) process.	Greater than 98	High	Long experience by industry but downtime and maintenance problems exist and back-up units are required.

^aData taken from Ref. 34, pp. 269-276

^bFrom Ref. 35, p. 210.

Table A-2 Water-pollution control technologies potentially suitable for removing contaminants from wastewater streams produced by commercial tar-sand oil-recovery processes.^a

Contaminant	Technology	Removal efficiency (%)	Relative reliability	Relative adaptability
Oil and grease	Dissolved air flotation	90	Very high	Very high
	Coalescing filter	99	High	High
	Clarification	80	Very high	Very high
Dissolved gases	Air stripping	80	High	High
	Steam stripping	95	Very high	High
	Flue-gas stripping	95	High	Medium
	Biological oxidation	High	Medium	Medium
Dissolved organic compounds	Activated sludge	95 BOD ^b /40 COD ^c	High	Medium
	Trickling filter	85 BOD	High	Medium
	Aerated lagoon	80 BOD	Medium	Medium
	Rotating contactor	90 BOD/20 to 50 COD	High	Medium
	Anaerobic digestion	60 to 95 BOD	High	Medium
	Wet air oxidation	64 BOD/74 COD	Medium	High
	Photolytic oxidation	99 BOD	Medium	Very high
	Carbon adsorption	99 BOD	Medium	High
	Chemical oxidation	90 BOD/90 COD	Very high	Very high
	Electrolytic oxidation	95 BOD/61 COD	Medium	Very high
Suspended solids	Clarification	50	High	High
	Pressure filtration	95	High	High
	Multimedia filtration	95	Very high	High
Dissolved solids	Clarification	Low except for metals	High	Medium
	Distillation	99	Medium	Low
	Reverse osmosis	60 to 95	Medium	Medium
	Ion exchange	High	High	Low
	Electrodialysis	10 to 40	Medium	Medium
Sludges	Thickening	Product 6 to 8 solids	Very high	High
	Anaerobic digestion	Low	High	Medium
	Vacuum filtration	Product 20 to 35 solids	High	High
	Sludge drying beds	Product 90 solids	Medium	Low
	Evaporation basins	Product 95 solids	Very high	Low
	Filter press	Product 35 solids	Very high	High
	Aerobic digestion	Low	Low	Low

^a Data taken from Table 63, in Ref. 34, p. 306.

^b BOD: Biochemical Oxygen Demand

^c COD: Chemical Oxygen Demand

LAND PRESERVATION AND RECLAMATION

Land preservation and reclamation during tar-sand oil-extraction activities is another category of environmental impacts that requires implementation of mitigating measures. For a 20,000-bbl/d commercial tar-sand surface-mining procedure the entire surface area involved may exceed 2,600 acres; and for a 20,000-bbl/d commercial in situ tar-sand project the surface area involved may exceed 4000 acres.¹⁰ Reclamation activities to avoid, minimize, or repair significant environmental impacts from land disturbance can involve

- Reducing surface-waste disposal by burying waste as backfill or placing it into in situ reservoirs;
- Reducing erosion from waste and spent-ore-storage piles by using biodegradable chemical stabilizers that do not interfere with seed germination and that temporarily bind particles together until revegetation occurs;
- Using revegetation to reduce overland flow of water and sediments, increase water infiltration, provide food and shelter for returning wildlife, and ameliorate microclimatic conditions, wind erosion, and extremes in soil temperatures; and
- Landscaping the terrain to its original or an improved state to minimize impacts on wildlife and restore or perhaps even enhance grazing or agricultural production.

Costs will depend on the extent and complexity of reclamation required and will include the quantity and type of chemical binders and soil amendments that are needed as well as the equipment and manpower demanded. Average cost estimates for oil-shale development range from \$4,000 to \$10,000 per acre; and more specifically, for a 50,000-bbl/d oil-shale project where only surface disposal of waste is used, the cost is estimated to range from 1 to 4 cents per barrel of shale-oil.³⁴ Such costs are likely to be similar for commercial tar-sand projects.

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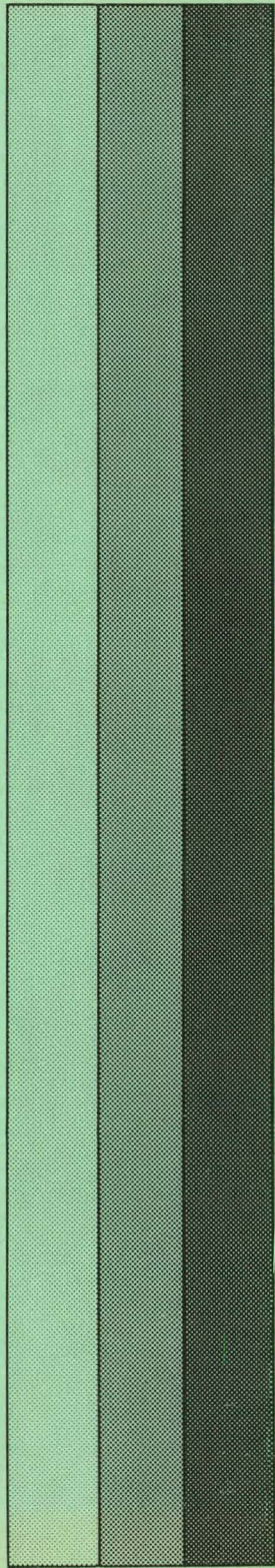
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