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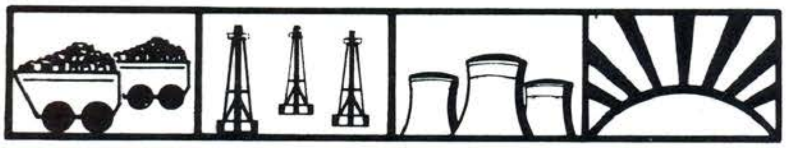

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THE ENVIRONMENTAL IMPACTS OF EXPLOITATION OF OIL SHALES AND TAR SANDS

April 1985

THE ENVIRONMENTAL IMPACTS OF EXPLOITATION OF OIL SHALES AND TAR SANDS

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PREFACE

One of the main objectives of the activities of the United Nations Environment Programme in the area of energy is "to promote the understanding of the environmental impacts of production and use of energy". To achieve this objective, the United Nations Environment Programme has undertaken a series of studies on the environmental impacts of production and use of different sources of energy (fossil fuels, nuclear energy, renewable sources of energy, expanded coal utilization, comparative assessment of the environmental impacts of different sources of energy, etc).

At the United Nations Conference on New and Renewable Sources of Energy convened in Nairobi in 1981, the potential of harnessing new and renewable sources of energy to meet the increasing world energy demand was highlighted. Among the different sources of energy discussed at the Conference, oil shales and tar sands received considerable attention. It has been recommended that special efforts be devoted to solve the various techno-economic problems pertaining to the development of such sources of energy and that detailed assessment of the environmental impacts of oil shales and tar sands exploitation should be undertaken to find ways and means of reducing any potential hazards to acceptable levels.

In addition, at the UNEP's Governing Council Session of Special Character in 1982, the Governing Council identified the environmentally-sound exploitation of new and renewable sources of energy as priority area for UNEP.

To implement these recommendations outlined in the Nairobi Programme of Action for the Development of New and Renewable Sources of Energy and to contribute to the achievement of the objectives of UNEP's activities in the area of energy, as formulated in the Medium-Term Plan, a project entitled "The Environmental Impacts of Exploitation of Oil Shales and Tar Sands (FP/2103-82-04)(2384)" was initiated in October,1982. The main purpose of the project has been " to review the environmental impacts of exploitation of oil shales and tar sands, with the target of providing up-to-date information that should help in the environmentally-sound exploitation of such energy resources ". The project was implemented by the Institut für Geochemie, Petrologie und Lagerstättenkunde, Frankfurt/M., FRG (Prof.K.von Gehlen).

The present report on " The Environmental Impacts of Exploitation of Oil Shales and Tar Sands " is the outcome of the above-mentioned project.

It is hoped that the present report has consolidated our current knowledge on the environmental impacts of oil shales and tar sands and will form a useful reference to scientists, planners and decision-makers on this subject. It is hoped, as well, that gaps of information in this area which were identified in several places could attract more work and efforts from scientists and engineers for further studies and investigations

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Nairobi, March, 1985

FOREWORD

The present report deals with the environmental impacts of exploitation of oil shales and tar sands. In undertaking this review, a great deal of information had to be gathered and scrutinized. In many cases, data had to be re-calculated to standardize the environmental impacts presented, on the basis of production of 50,000 barrels/day of syncrude, which is the general capacity of plants under construction or planned.

It should be noted that the environmental impacts reviewed in this report are those discussed in the literature as derived from pilot plant studies or small-scale industrial operations. In many cases these impacts cover one, and seldom more than one, aspect and the whole spectrum of the environmental impacts of exploitation of oil shales and tar sands- from extraction of the raw material to the processing and upgrading into a refinery feedstock- had to be put together in a systematic way to cover the complete cycle. No attempt has been made to discuss the environmental impacts of utilization of the syncrude or the refinery products since these will be comparable to those impacts of normal crude oil and its distillation products which have been discussed in detail in other UNEP reports.

From the present study it has become clear that there are several inadequacies in our knowledge of the environmental impacts of exploitation of oil shales and tar sands. Such inadequacies require special attention, if the environmentally-sound exploitation of these resources is to be achieved.

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PART I

GENERAL CONSIDERATIONS

PART I

GENERAL CONSIDERATIONS

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CHAPTER 1

INTRODUCTION

The world commercial energy consumption has increased more than three-fold over the past three decades (Table 1). Most of the world's commercial energy consumption has been met by fossil fuels, which were cheap and considered plentiful. In the 1970s, however, most countries have realized that fossil fuels (especially oil) are finite in extent and that other sources of energy should be developed to meet future demand.

Table 1. World Commercial Energy Consumption (in million tonnes oil equivalent).

Year	Total Energy Consumption	Solid fuels	Liquid fuels	Natural gas	Hydro- & Nucl.
1950	1670	1028	450	164	28
1955	2172	1215	663	255	39
1960	2843	1478	910	398	57
1965	3493	1511	1310	594	78
1970	4433	1488	1950	889	106
1975	5122	1550	2349	1070	153
1980	5892	1803	2599	1282	208

Source : United Nations (1976, 1983).

Recently, it has been illustrated that after 1985 the world demand for energy is likely to outstrip supply (World Bank, 1979); the supply of oil has been predicted to fail to meet increasing demand before the year 2000 (WAES, 1977).

The future shortage in oil supplies has implications for the whole world. But it is the developing countries, with less financial resources, that will lose in the worldwide scramble for energy resources, as the supply constraint increasingly becomes a reality. This is particularly alarming since the domestic energy requirements of developing countries are growing, and are expected to grow in the future, with increasing pace of industrialization and development. How to ensure energy supplies for development, therefore, becomes in the long run a question of critical importance for the developing countries themselves as for the world as a whole.

In view of the difficulties to be faced in meeting world energy demand, technological developments will be increasingly necessary to maintain sufficient energy supplies. Alternatives include both new technologies and existing ones that become economic as energy prices increase. Improvements could occur not only in actual exploration and production techniques, but also in electric utility operations, direct fuel consumption, energy conversion , and efficiency levels. Determining the impact of various methods is complicated because each may penetrate the market at a different time, with varying implementation and success rates. Among the technologies expected to be competitive before the year 2000 are the development of new and renewable sources of energy (El-Hinnawi, 1983).

The energy problem over the current and the next two decades should, therefore, be seen as one of transition, in which countries should try to ensure the rational and non-wasteful use of energy and to diversify their sources of energy, establishing an appropriate and environmentally-sound energy mix to meet their incremental needs.

The development of any source of energy has a number of environmental impacts that should be thoroughly asssessed before final decisions are made. Of the many environmental impacts associated with any energy technology, some are substantial and others small; some are important and others with long-term effects; some might be adverse and others beneficial and they might occur in different geographic areas and might affect different communities in different ways. A distinction should be made between the assessment of the nature, scale and geographic distribution of the impact, and the evaluation which is concerned with its value or importance. For many environmental changes which are identified as impacts, the state of knowledge and technology will often only permit a qualitative assessment. Only in a few cases it is possible to evaluate an impact quantitatively. Decisions must ultimately be made on the basis of combination of cost/benefit analysis, other quantifiable inputs and qualitative information.

CHAPTER 2

ENVIRONMENTAL IMPACT ASSESSMENT *

Pollution is generally defined as the introduction by man into the environment of substances or energy liable to cause hazards to human health, harm to living resources and ecological systems, damage to structures or amenity, or interference with legitimate uses of the environment. The important concepts in this definition are (Holdgate, 1979) :

1. Pollution is caused by substances or energy.
2. It has a source or sources, and they are created by man. Natural inputs of the same substances are excluded. Thus pollution is an increment added by man to biogeochemical cycles.
3. Pollution acts in the environment, as a result of these discharges, and follows a pathway, leading to the exposure of structures or organisms.
4. The significance of the pollution is related to its effects on a range of targets (or receptors), including man and the resources and ecological systems on which he depends.
5. Pollution is judged by its impact on social values as well as environmental components: if there is damage to structures or amenity, or interference with legitimate uses of the environment, the substances causing the effect are by definition, pollutants.
6. Quantification of the scale of the hazard or damage or interference is important, and the basic question is one of acceptability of the consequences of the release of the substances or energy.

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* This chapter was written on the basis of material given in the final draft of UNEP's report on "The Environmental Impacts of Production and Use of Energy", Part IV, soon to be published in this series.

Once released from a source, pollutants generally follow different pathways as they spread within the environment. The concentration a pollutant attains at a point is the result of the rate of input to the environment, the dispersion characteristics determined by the properties of the pollutant and those of the medium, and the rate of removal from the environment at all points along the pathway, whether caused by physical, chemical or biological agencies. Fig. 1 develops the pathway model in detail (Holdgate, 1979). It is essentially linear : the amount of pollutants reaching the target is a function of the amount emitted, diminished by dilution and removal or enhanced by environmental accumulation factors. The pathway model is a simple transport system in which, except for anomalies such as bio-accumulation or accumulation in small and unusual regions of the environment, the concentration of pollutants steadily diminishes. Such anomalies of local accumulation can be looked on as closed loops from which material later re-enters the environment when an accumulator organism dies or a sediment is remobilized.

The interaction of target and pollutant results in some kind of effect, and it is the nature, scale and significance to man of this effect that is at the heart of the whole pollution value judgement. The prediction of how effects will change in nature, number or severity with time, is an equally essential part of the process of risk estimation (Holdgate, 1979).
In assessments like this we commonly discriminate between acute damage, defined as an adverse effect on a target that follows directly from exposure to a pollutant and is generally clear-cut, could be fatal, and rarely reversible, and chronic damage that commonly develops long after exposure, or after prolonged exposure to low doses, is less clear-cut, and may be reversible.

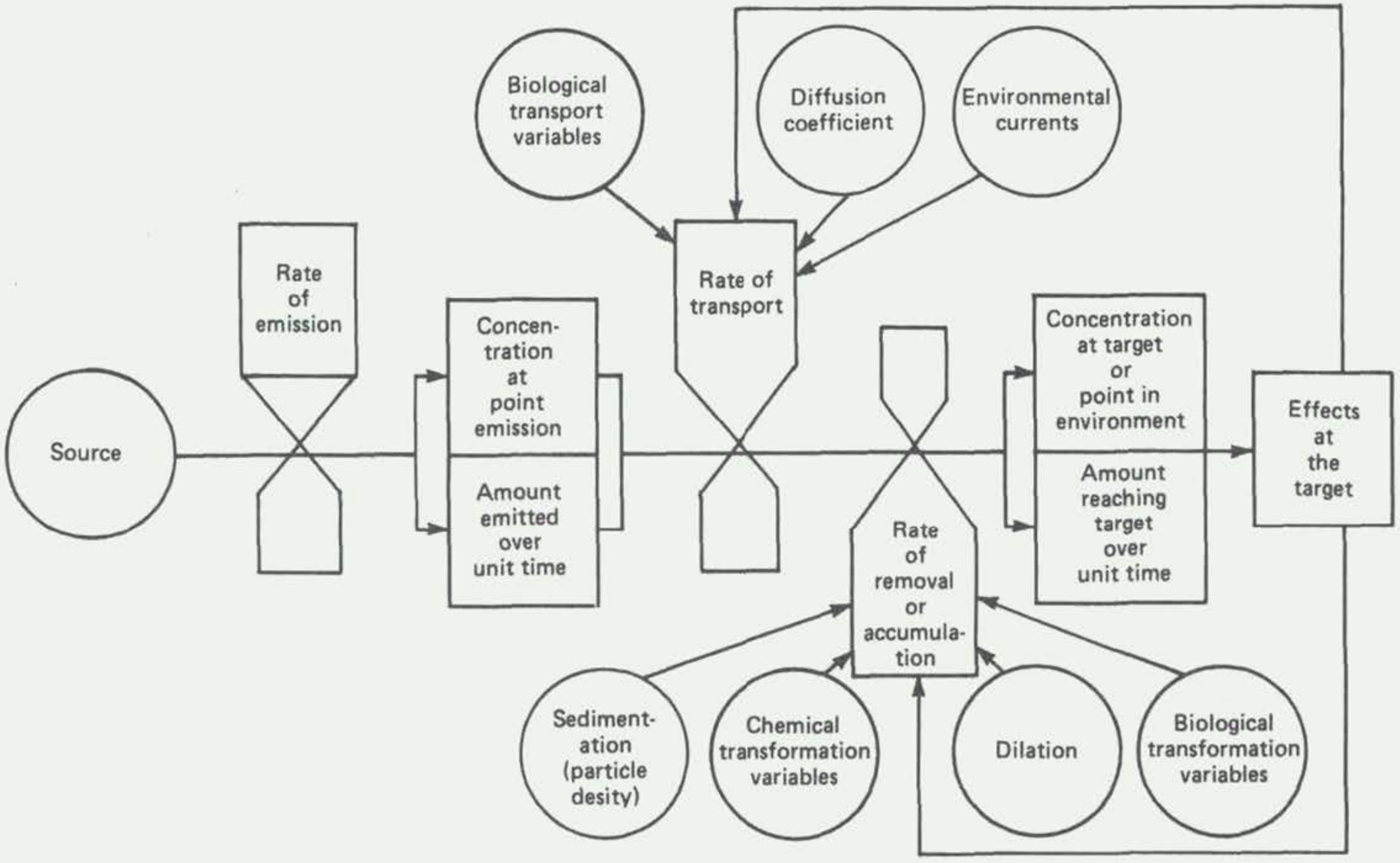

Fig. 1. A pollutant pathway (after Holdgate, 1979)

It should be noted that although the primary concern is to protect man from direct pollution hazards, pollutants,(or consequent environmental degradation) could seriously affect the ecological systems (for example, soil fertility, productivity of seas, water quality, etc.) and man may be affected circuitously.

The classical toxicological dose-response curve is non-linear (Fig. 2). It includes a threshold below which no effect is detectable (Ehrenberg and Lofroth, 1979). This type of dose-effect relationship is often confirmed by occupational health statistics (i.e. at relatively high pollutant levels). As a consequence, attempts have been made to derive safety standards and " clean-up " procedures for pollutants in the various environmental media of air, water, soil, food, etc., so that they ultimately deliver a dose to man below a " safe " level, thus avoiding a significant degree of harm. However, apart from acute and sub-acute effects caused by relatively high pollutant doses, there are longer-term effects on living organisms (including man) usually associated with smaller doses, e.g. chronic illness; carcinogenic, mutagenic or teratogenic effects. All these may appear much later on in the life-cycle or even be delayed until later generations. Such genotoxic effects are generally linearly dependent on the dose at low doses.

2.1. Environmental Impact Assessment

An environmental impact assessment is an activity designed to identify and predict the impact of an action on the bio-geophysical environment and on man's health and well-being, and to interpret and communicate information about the impacts (SCOPE, 1979). In this definition, it is important to recognize

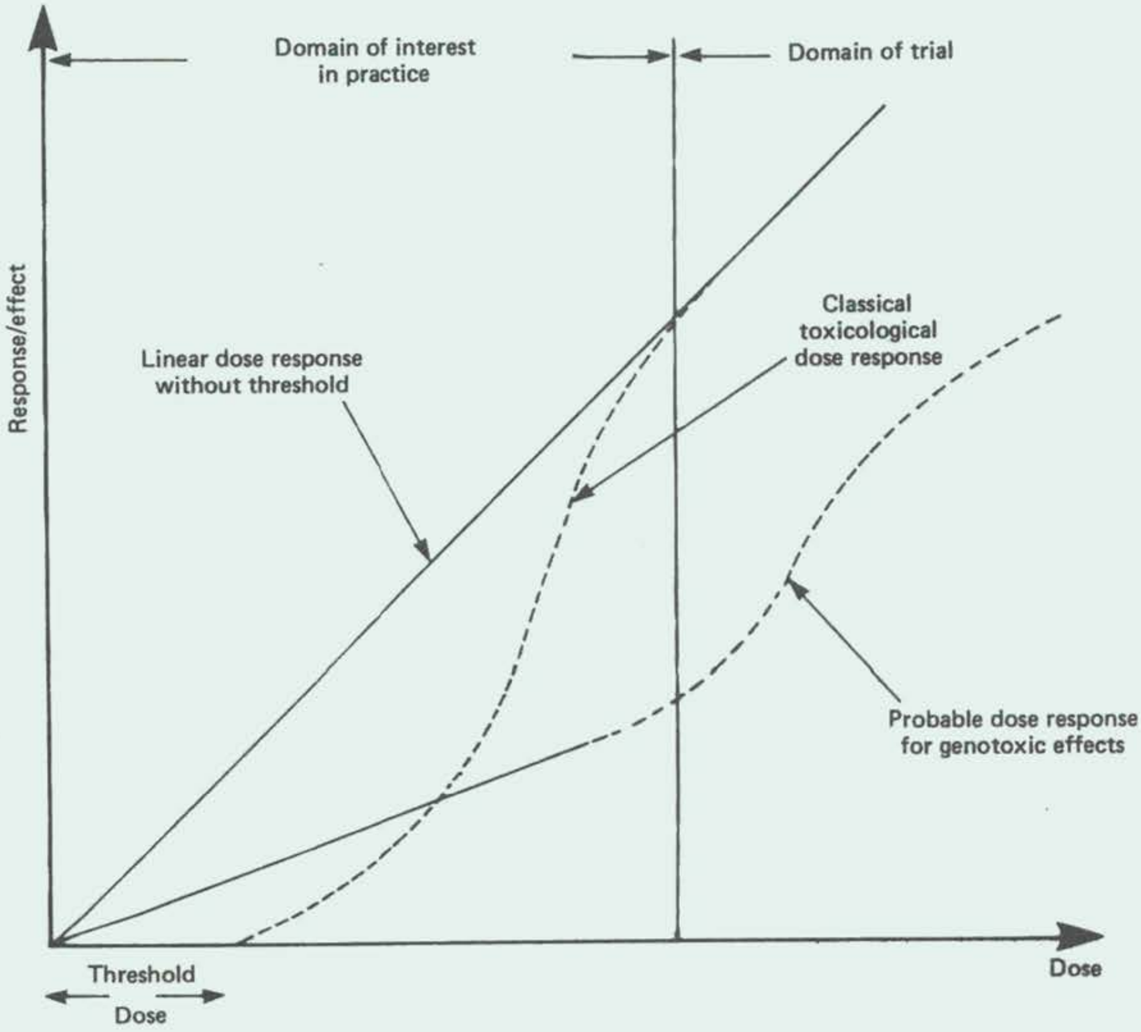

Fig. 2 Dose-Response Relationship
After : Thedeen (1979) and Ehrenberg and Lofroth (1979).

that impacts on ecosystems, biogeochemical cycles, and the like are intimately related through complex feedback mechanisms to social impacts and economic considerations. Environmental impact assessment forms an indispensable part of the planning of environmentally-sound development. When a project (e.g. construction of a power station)is undertaken, it sets in motion a chain of events that modifies the state of the environment and its quality. Anticipation of such changes through environmental impact assessment during the planning of the project makes it easier and cheaper to deal with possible environmental disruptions than to redress them after they had occurred.

The environmental impacts of energy technologies fall into three broad categories : (a) those that are quantifiable and amenable to comparisons among different technologies; (b) those that are quantifiable but difficult to compare from one technology to another; and (c) those that are difficult or impossible to quantify. Some of the parameters that can be quantified cannot be given a price tag. For example, economists have long debated the question of how best to quantify the value of a life. The traditional economic approach has been to equate the value of a life with the value of a person's expected future earnings. Many problems with this index are readily apparent. For one, it undervalues those in society who are underpaid and places no value at all on people who are not in income-earning positions (let alone the differences between earnings in high-income and low-income countries). In addition, it ignores the interpersonal effects of a death which make the loss suffered much greater than any measurable financial loss (Fischhoff et al., 1979). Other examples that cannot be given a price tag are often deployed when landscapes or historic monuments are threatened (see, for example, Ashby, 1978; Holdgate, 1979).

Discussion of the environmental impacts of various energy strategies has, in the past, tended to focus more attention on short-term aspects, such as occupational and public health and direct impacts on the physical environment, than on the long-term socio-economic and environmental consequences. However, there is now a growing disposition to analyze these long-term impacts which may range from those for which substantial data exist and around which there is a fair degree of certainty as to the risks involved, to those which are rather speculative in nature and for which very little data are available.

The biosphere consists of different organisms, plants and animal life supported by a number of physical characteristics such as topography, soils, climate, air, water supply and drainage. For a given development, these physical characteristics and hence the biosphere may be affected. Whenever pollutants are released, the analysis of the environmental impact of these pollutants requires the knowledge of the :

1. quantity and types of pollutants released,
2. dispersion of these pollutants in the environment;
3. ecological pathways followed by the pollutants;
4. relationships between the pollutants and the damage to man and his environment; and
5. the extent of the damage including its cost (where it is possible to make this assessment).

The total impact of some pollutants may depend on positive or negative synergistic effects. Although standards have been formulated for " acceptable " levels of several pollutants, it is prudent to assume that for exposure to many pollutants there is a controversy as regards to the presence of a threshold and that effects can occur at very low exposures. A further feature is that many pollutants may remain in the environment (and accessible to the food chain) long after the action releasing them has been discontinuied. Attempts to assess the long-term impacts of these pollutants, although difficult, should be made taking into consideration the different pathways, biogeochemical cycles and fate of these substances in the environment.

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PART II

THE ENVIRONMENTAL IMPACTS OF EXPLOITATION OF OIL SHALES

PART II

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CHAPTER 3

THE MINERALOGY AND CHEMISTRY OF OIL SHALES

There is no geological or chemical definition of an oil shale. Any sedimentary rock yielding oil in commercial amounts upon pyrolysis may be considered as an oil shale (Tissot and Vandenbroucke, 1983). The composition of the inorganic fraction of oil shales may vary from a shale where clay minerals are predominant, such as the Lower Jurassic shales of Western Europe (for example in France and the Federal Republic of Germany), to carbonates with subordinate amounts of clay and other minerals, such as the Green River Shales of Colorado, Utah and Wyoming, USA. The organic fraction of oil shales is mainly an insoluble solid material known as kerogen. Little is known about the structure of kerogen. One theory is that it is a highly cyclo-paraffinic polymer with a molecular weight of more than 3,000 and with closely associated aromatic, heterocyclic, hydroxylic, carboxylic and related groups (Schriesheim and Kirshenbaum, 1981). When heated to about 450 to 600°C, kerogen undergoes destructive distillation, thereby producing about 38 to 150 litres of a crude oil per tonne of feed shale, depending on the grade of the shale. The amount of kerogen in the shale varies from a few per cent in low-grade shale to more than 40 % in shale that will yield more than 280 litres of oil per tonne.

There are three general depositional frameworks in which oil shales form : shallow seas on continental platforms and shelves (e.g. the Miocene shales of California), small lakes, bogs, and lagoons associated with coal-forming swamps (e.g. Kinderlick, Kazakhstan,USSR), and large terrestrial lake basins (e.g., the Green River Formation, USA).

3.1. Mineralogy of Oil Shales

The mineralogy of oil shales is very variable. The inorganic constituents of oil shales may be divided into detrital, biogenic, and authigenic minerals. The detrital material is composed principally of quartz, feldspars and clay minerals; biogenic minerals are primarily amorphous silica and calcium carbonate, but are not generally abundant. Authigenic minerals are pyrite and other metal sulphides, carbonates (calcite, dolomite, siderite), chert, phosphates, and saline minerals such as trona, dawsonite, halite and others. In the Green River Formation, over 70 authigenic minerals have been identified (Shanks et al., 1976).

Generally speaking, one can say that oil shales consist mineralogically of two main varieties : typical " shale ", and carbonate-rich rocks. Table 2 gives the mineralogical composition of these two main varieties of oil shales. Other shales from other areas may be similar to these, or have a mineralogical composition in-between.

Table 2 Mineralogical Composition of Oil Shales

	Cleveland[1]	Green River[2]	Dawsonite Shale[3]
Carbonates	Minor	50	28
Feldspar	Minor	19	22
Illite clays	59	15	-
Quartz, silica	30	10	16
Analcime	Traces	5	-
Pyrite	5	1	1
Chlorite	6	-	-
Nahcolite	-	-	20
Dawsonite	-	-	13

1/ After Robl et al (1983).

2/ After Wefing and Noack (1979).

3/ After NAS (1979 b). Dawsonite oil shale occurs in the Eocene Green River Formation, USA. Nahcolite and Dawsonite are potential sources of soda ash and aluminium. This shale contains 19 % kerogen.

3.2. Inorganic Chemistry of Oil Shales

The chemical composition of oil shales varies considerably from one deposit to another; even within the same formation the composition may vary widely according to the mineralogical composition and alteration products. Table 3 gives the analyses of the two main varieties of oil shales indicated in Table 2. It should be noted that these analyses are " illustrative " and do not represent " average" composition of such shales.

Table 3 Chemical Composition of Oil Shales

	Cleveland[1]	Queensland[2]	Green River[3]	Israel[4]
SiO_2	66.6	61.2	27.8	16.9
Al_2O_3	16.4	16.3	6.8	6.8
Fe_2O_3	6.8	9.7	2.7	2.8
CaO	0.6	6.1	15.4	34.2
MgO	1.3	2.6	5.3	0.6
Na_2O	0.5	1.2	2.0	0.3
K_2O	4.3	1.6	1.7	0.4
TiO_2	0.9	0.8	0.3	0.3
P_2O_5	0.2	0.3	ND	1.6
CO_2	ND	ND	23.0	33.5

1/ After Robl et al (1983). Average oil yield 51 l/t.
2/ After Lindner (1983) for Brick Kiln Stuart oil shale. Average oil yield 14-195 l/t.
3/ After Tuttle et al (1983). Average oil yield 110 l/t.
4/ After Shirav and Ginzburg (1983) for Ef'e oil shale. Average oil yield 59 l/t.

In addition to the major chemical constituents indicated in Table 3, oil shales contain a large variety of trace constituents. These trace elements are considered to exhibit three main associations (or affinities) : those elements having an affinity to organic matter (e.g. copper, vanadium,etc); those having an affinity for sulphur (e.g. cobalt, zinc,etc) and those having a silicate and/or carbonate affinity (e.g. barium, strontium, etc). Table 4 gives examples of the trace elements that are commonly found in oil shales.

Table 4 Distribution of Trace Elements in Oil Shales (in ppm)

	Cleveland [1]	Green River[2]	Dawsonite Shale[3]	Israel[4]
As	-	7-40	24	34
B	-	82-140	-	-
Ba	619	32-450	-	250
Be	-	35	-	-
Cd	-	0.14	-	-
Co	21	9-39	< 9	5
Cr	159	34-49	43	280
Cu	91	15-32	38	112
F	-	1700	968	-
Hg	-	< 0.1	-	0.2
Mo	94	5-22	< 25	26
Ni	125	11-16	< 25	138
Pb	-	10-28	-	10
Sr	-	69-790	335	-
Th	-	0.77	-	-
Tl	-	0.14	<0.4	-
U	20	0.99	4	27
V	760	29-83	120	110
Zn	444	13-77	35	310

1/ After Robl et al (1983).
2/ After Cook (1973) and Tuttle et al (1983).
3/ After NAS (1979 b).
4/ After Shirav and Ginzburg (1983).

3.3. Organic Chemistry of Oil Shales

The organic composition of oil shales is very complex. The insoluble kerogen (which is the main organic constituent of oil shales) is built up by a linear network of saturated cyclic rings of methylene groups. Associated with these are some long chains and aromatic structures with the entire system being held together by short methylene inter-connections and crosslinks to oxygen bridges. The empirical formula of the Green River kerogen may be represented as follows : $C_{215}\ H_{330}\ O_{12}\ N_5\ S$.

The soluble bitumen, which constitutes about 10 % of the organic matter in oil shales, consists of a wide variety of compounds : alkanes, aromatics, resins and insolubles. More than 50 cyclic alkanes were separated and identified from the bitumen fractions of the Green River oil shale (Anders and Robinson, 1971).

For the purpose of the present report attention will be mainly given to the oil yield of oil shales and the composition of kerogen. Table 5 gives the characteristics of some of the common oil shales. From this Table it can be concluded that the higher the specific gravity of the oil shale, the the lower its oil content (and heating value) will be.

Table 5 Characteristics of Some Oil Shales

	Oil content (l/t)	Specific gravity (Shale)	Heating value (MJ/kg)	Organic carbon %	Ash %
Australia	346	1.60	19.0	40	52
Thailand	298	1.61	15.5	31	56
New Zealand	276	1.46	21.4	46	33
Spain	196	1.80	12.6	26	63
S. Africa	190	1.58	19.3	44	43
Brazil	119	1.70	8.2	17	77
France	108	2.03	8.9	19	71
USA (Colorado)	102	2.23	5.1	11	67
Scotland	93	2.22	5.9	12	78
Sweden	58	2.09	9.1	19	72

Source : Rühl (1982).

The elemental composition of kerogen is very variable ; the following ranges and average are given by Rühl (1982) as compared to crude oil.

Element	Range (Oil Shale)	Average (Oil Shale)	Crude oil
C %	67-85	79.5	82-87
H %	7-13	9.3	11-15
O %	2-17	8.3	---
N %	0-3	1.3	0-1
S %	0-11	1.6	0-10

Table 6 gives the composition of organic matter in oil shales indicated in Table 3 .

Table 6 Composition of Organic Matter in Some Oil Shales (in %)

	Cleveland	Queensland	Green River	Israel
C	82.4	74.7	80.5	64.9
H	10.1	9.9	10.3	8.0
N	0.8	1.7	2.4	2.8
S	2.8	1.2	1.0	9.1
O	3.9	12.5	5.8	15.2

Source : See under Table 3.

Tissot and Welte (1978) distinguished three types of kerogen on the basis of the atomic ratios of H/C and O/C. The first type (Kerogen I) is characterized by a high H/C ratio and low O/C. This kerogen has a large yield of volatiles and the percentage of conversion of organic matter to oil is high (65 to 70 %). Kerogen II lies between Kerogen I and III and for this class, the percentage of conversion of kerogen to oil varies from 26 to 66 %. Kerogen III has a low H/C and a high O/C ratio. This class yields less than 20 % of oil from the kerogen.

CHAPTER 4

OCCURRENCE AND ENERGY POTENTIAL OF OIL SHALES

Oil shales were commercially exploited since the 18th century, especially in Europe, Canada, USA and Australia. Oil retorted from oil shales reached a peak in production during the early 1940s, but soon production declined sharply after the discovery of the vast oil fields in the Middle East and the flow of cheap light crude oil into international markets. The increases in the prices of energy in the 1970s and the general realization that conventional crude oil resources are limited in nature have triggered a renewed interest world-wide in oil shales and other " non-conventional " sources of energy. The World Energy Conference (1980) and the United Nations Conference on New and Renewable Sources of Energy convened in Nairobi in 1981 have focussed attention on the importance of accelerating research and development to exploit oil shales, among other sources of energy, to meet increasing national energy demands (El-Hinnawi et al., 1983).

4.1. Occurrence of Oil Shales

Oil shales occur virtually in all countries of the world. The following is a description of the main occurrences hitherto discovered and described. Future geological surveys will undoubtedly lead to the discovery of more deposits and to more accurate evaluation of reserves to be economically exploited (see later).

4.1.1. Oil Shales in Europe

In Great Britain, the Lothian oil shale deposits around Edinburgh, Scotland have been successfully exploited since the last century. These deposits were mined continuously from

1859 until 1963, reaching a peak of activity during World War II when 3.3 million tonnes of shale were retorted to produce 1,000,000 tonnes of oil annually. Production only ended when vast quantities of light crude oil from the Middle Eastern Fields began to saturate the market and depress oil prices. There are other small deposits in Great Britain, especially in Central England, where thin beds of shale containing 13-18 % organic matter hold reserves of 75 million tonnes of oil (UK, 1981).

The main oil shale resources in France are located in the Massif Central at Autun, St. Hilaire, Telot and Surmoulin. The Autun shales cover about 400 km^2, are 12 m thick and contain 50 to 100 l oil/ tonne. Surface operations at Autun started in 1838. At St. Hilaire (Aumance Basin), the shales lie 250 m deep, and the recoverable shales total about 150 million tonnes (Rühl, 1982).

In the Federal Republic of Germany, there are several oil shale deposits, in particular in the North (e.g. at Schandelah near Braunschweig). At present, the workable reserves are estimated at 110 million tonnes of shale oil. This is about more than twice the amount of established crude oil reserves of the Federal Republic of Germany. Domestic oil shales are estimated to replace about 2 to 3 per cent of the German mineral oil imports in the years to come (FRG, 1981). In the past,in particular during the two world wars, Germany built several plants for the conversion of oil shale by means of pyrolysis. During the same period, initial experiments were made for underground conversion. At present, the quantity of oil shale processed in the FRG is negligible. The only commercial plant in operation (at Dotternhausen) uses oil shale as an energy raw material utilizing the residues for the production of cement. In recent years, the annual consumption of oil shales at the plant has been estimated at 320,000 tonnes.

Sweden began exploiting its resources of oil shales, estimated at 600 million tonnes of shale oil in the 1920s. Oil shale made an important contribution to Swedish industry during World War II when that country was under a tight naval blockade. After World War II Sweden had a vigorous and profitable oil shale industry until the cheap Middle Eastern crude forced them to close down operations in 1962 (Sweden, 1981).

In Spain, the Puertollano oil shale deposit 200 km South of Madrid was worked for over 40 years. The shale lies 300 m deep in an area of 20 by 4 km, and has an oil content of 10 % by weight. The resources are estimated at 100 million tonnes of shale oil (Spain, 1981; Rühl, 1982).

In the Tyrolian region of the Austrian Alps , oil shales occur at about 100 locations in layers of 0.15 to 1.0 m thick. The oil shale has up to 15 % oil by weight and has been mined for over 200 years to produce Ichthyol and other medicinal products (Rühl, 1982).

Oil shale reserves in the USSR have been estimated at 2000×10^9 tonnes. The largest oil shale deposits are the Baltic shale basin, the Volga shale basin, the Timano-Pechora basin and the reserves of the Domanikovy shales located in the area of the Southern Timan and along the western slope of the Urals. The yield of oil from these shales amounts to 10-20 % by weight. Oil shales have been directly combusted in power plants to produce electricity. At present, over 70 per cent of the oil shale mined in the USSR is used to generate electricity (the Baltic and the Estonian State Regional thermal power plants with a combined design capacity of 3224 MW). The experience gained by the USSR in the field of using oil shales for electricity production is unique and can be of much interest to countries with reserves of low-cost shales poor in kerogen content. About 25 per cent of the oil shale mined in the USSR is subjected to thermal decomposition in shaft generators at temperatures of 480-700°C, resulting in liquid and gaseous products (USSR, 1981).

Oil shales have been also found in Bulgaria (20 to 200 million tonnes shale oil in place), Italy, Yugoslavia (30 to 130 million tonnes shale oil in place) and Roumania (Rühl, 1982).

4.1.2. Oil Shales in North America

The United States of America has some 245 X 10^9 tonnes of oil in oil-bearing shales (the Green River Formation) in three Western States : Colorado, Wyoming and Utah. About one-third of this oil from shale is believed recoverable from 43,000 km^2 of these lands. The shales range in quality from about 40 to more than 300 litres of oil per tonne of rock. The richest layers of the deposits are more than 30m thick; together, lean and rich sequences of shales are over 500m thick in Colorado. Exploitation activities include the development of four 2,100 ha prototype tracts in Colorado and Utah. One tract, the site of an in-situ pilot project since October, 1980, is being developed by Rio Blanco Oil Shale Project, a joint venture of Standard Oil of Indiana and Gulf Oil Company. Rio Blanco hopes to develop a large open-pit mine with surface retorts which will produce 78,000 barrels of shale oil daily by 1987. The second Colorado tract, being co-developed by Occidental Petroleum and Tenneco, provides a testing ground for the modified in-situ technology. It has a 1986 production target of 57,000 barrels of shale oil per day. Other developers of Colorado shale include Exxon USA and Tosco (46,000 barrels per day), Union Oil of California (9,000 barrels per day), and Multi Mineral Corporation, which is extracting secondary shale oil and alumina in a nahcolite mining operation (USA, 1981).

In Eastern States, oil shales are known to cover vast areas from New York to Texas. Such shales are estimated at 150 X 10^9 tonnes of oil in place, 5 % of which can be recovered by open pit mining (Rühl, 1982). The shale contains up to 100 l oil/ tonne shale.

Canada has an estimated total reserves of 23 X 10^9 tonnes of shale oil located in Nova Scotia, Ontario, Quebec, Newfoundland, and Manitoba. Oil shale development is unlikely in Canada in the foreseeable future, although there is currently some significant activity for resource evaluation (Canada, 1981).

4.1.3. Oil Shales in Latin America

Brazil has very large reserves of oil shales (672 million tonnes oil), most of which are found in the Itari area which extends for over 1,600 km from the State of Sao Paulo to the frontier with Uruguay. Although the Irati shales are lean, 11 % oil by weight, the Brazilians have been mining them since the late 1800s. A prototype pilot plant has been built in Sao Mateus do Sul, Parana State, using the PETROSIX process, fully developed in Brazil. This plant has been running for some years, having already fulfilled its basic purposes, i.e. to demonstrate the viability of the relevant Brazilian-developed technology (PETROSIX PROCESS) and to gather information for the basic project of a large scale industrial plant, which will also be located in Sao Mateus do Sul and should start production in 1985, with an initial capacity of 25,000 barrels of oil per day, together with other marketable by-products (Brazil, 1981; Costa Neto, 1983).

4.1.4. Oil Shales in Asia and the Pacific Region

Oil shales occur in three states in Australia : New South Wales, Tasmania and Queensland. The proven reserves of shale oil in Australia amount to 500 million tonnes (Australia, 1981).

In China, oil shales occur in the provinces of Honan, Guangdong, Jilin and in other provinces as well. The shales have been exploited since decades; shale oil refineries were established in Liaoning and Guangdong provinces. The present annual production of shale oil in China amounts to 300,000 tonnes. The proven recoverable reserves of oil shale in China amount to 120 X 10^9 tonnes, with an average oil yield of about 5.5 % (China, 1981; Rühl, 1982).

The recoverable reserves of oil shales in Israel are estimated at 4.4 X 10^9 tonnes; the average kerogen content of these shales is about 15 %. These known reserves could potentially produce over 200 million tonnes of oil with additional quantities of gas and other products. The commercial exploitation programme in Israel aims at producing about 20,000 to 40,000 barrels per day by 1990 (Israel, 1981).

Abundant oil shale deposits are known to occur in Jordan. The estimated total reserves in the country are about 30 X 10^9t. The largest deposits of oil shales are at El-Lajjoun about 100 km South of Amman, where the total proven reserves have been estimated at 1.2 X 10^9 tonnes of bituminous marls, with an oil content of 10 %. Studies are underway to use the oil shale either for direct combustion (to generate electricity in a 300-400 MW power plant) or for production of 50,000 barrels of oil per day by retorting (Jordan, 1981).

4.1.5. Oil Shales in Africa

Oil shales are known in many African countries, e.g. in Algeria, Libya, Egypt, Ghana, and other countries, but few details have been given on the potential of these deposits.

In Morocco, two major oil shale deposits are known : one at Timahidit (10 X 10^9 tonnes) and the second at Tarfaya (200 X 10^9 tonnes). Both shales are of low grade, with Timahidit and Tarfaya averaging 74 and 55 l/t, respectively. Plans are underway to develop a 20,000 t/d open-cast mine designed to feed a 10,000 bbl/d "batch" retort consisting of four 2,500 bbl/d modules (Mining Magazine, September, 1982, p.172). There are also plans for an oil shale fed power plant of 250 MW to be in operation in 1986 (Rühl, 1982).

4.2. The Energy Potential of Oil Shale Resources

4.2.1. Resource Terminology

In discussing resources it is necessary to define two key terms : reserves and resources. According to the U.S. Geological Survey/Bureau of Mines classification (USGS, 1974), reserves are identified deposits of minerals known to be recoverable with current technology under present economic conditions. On the other hand, resources include reserves as well as minerals that have been identified but cannot now be extracted because of economic or technological limitations, as well as economic or sub-economic materials that have not as yet been discovered.

There are three main categories of reserves :

1. Measured reserves are identified reserves from which an energy commodity can be economically extracted with existing technology and whose location, quality, and quantity are known from geologic evidence supported by engineering evidence.
2. Indicated reserves are reserves based partly on specific measurements, samples, or production data and partly on projections for a reasonable time period on the basis of

geological evidence.

3. Inferred reserves are reserves based upon broad geologic knowledge for which quantitative measurements are not available. Such reserves are estimated to be recoverable in the future as a result of extensions, revisions of estimates, and deeper drilling in known fields.

The World Energy Conference (WEC, 1980) used the expression " Proved Recoverable Reserves " to indicate measured reserves, and " Additional Resources " to include both indicated and inferred reserves as defined above.

Although some oil shales have been geologically appraised in detail, many others have been only partly described. This situation, besides the loose usage of the terms resources and reserves, has created great difficulty in knowing the actual oil shale reserves in the world. The U.S. Geological Survey (USGS, 1973) and the World Energy Conference (WEC, 1975) gave the following estimates for oil shales having higher yields than 40 l/t :

	USGS (1973)	WEC (1975)
Identified Reserves[1]	450 X 10^9 t oil	460 X 10^9 t oil
Hypothetical Reserves	1268 X 10^9 t oil	1416 X 10^9 t oil
Speculative Reserves	46000 X 10^9 t oil	51244 X 10^9 t oil

1/ include measured, indicated and inferred reserves. 10^9 t= Gt

The World Energy Conference (WEC, 1980) gave a value of 339 X 10^9 t oil for identified reserves of oil shale in the world. Table 7 gives estimates of oil shale reserves in the world.

Table 7 Oil Shale Reserves (WEC, 1980)
(in million tonnes of recoverable oil)

	Proved Recoverable Reserves	Additional Resources	Production (1978)
USA	28,000	236,000	
Australia		490	
New Zealand	1		
Thailand	2,015		
USSR	6,820	49,180	37
Brazil	84		
Jordan	800	7,000	
Morocco	7,400		
FRG	250		
Sweden	880		
Spain	12		
Total	46,262	292,670	37

Based on additional data presented in different national papers submitted at the United Nations Conference on New and Renewable Sources of Energy (1981), the proved recoverable reserves of oil from oil shales are estimated at about 52,000 million tonnes.

The consumption of shale oil in 1981 has been estimated at 68 million tonnes (UN Conference on New and Renewable Sources of Energy, 1981), i.e. about 1.2 % of the total commercial energy consumption in the world in that year (see p.1-2 of this report). The United Nations Conference estimated that by accelerated development of the oil shale industry, about 4000 million tonnes of shale oil could be utilized by the year 2000. This would constitute about 33 % of total commercial energy demand in that year (assuming that the average commercial energy demand in the world will be about 12,000 million tonnes of oil equivalent in the year 2000, which is a realistic figure; see estimates given on p.2). IIASA (1981) expects that synthetic crudes would constitute 40 % of total liquid fuels needed by the world in the year 2030.

CHAPTER 5

OIL SHALE TECHNOLOGY

Oil shale can be used directly as fuel, or can be processed by retorting (pyrolysis in a retort) with subsequent oil and gas production. The present Chapter gives a brief description of the different technologies of oil shale exploitation.

5.1. DIRECT COMBUSTION OF OIL SHALE

Oil shale has been used extensively in the USSR to fire power stations. About 60 % of the oil shale mined in Estonia (heating value 8.4 to 12.6 MJ/kg) is used as fuel for two 1600 MW power stations (USSR, 1981).

In the Federal Republic of Germany, oil shale has been used to produce both electricity and cement in an integrated complex (at Dotternhausen, using the Lurgi-Rohrbach process). Combustion of the oil shale (heating value 4 MJ/kg) takes place in the power station to generate electricity (Fig. 3). The electricity is used to provide power for the cement works, making it more or less independent of the public grid. The combustion residues are delivered to the cement works where they are ground together with cement clinker which is conventionally burnt in a rotary kiln, using standard raw materials. In this way oil shale has a dual function, i.e. source of energy and raw material for cement production. More than 30,000 tonnes of oil shale cement are produced annually, in addition to other building materials (e.g. mortar binders for road construction). Fig. 3 shows also the possibility of extracting valuable metallic compounds from the residues obtained in the power station; oil shale often contains metals such as uranium and/or vanadium.

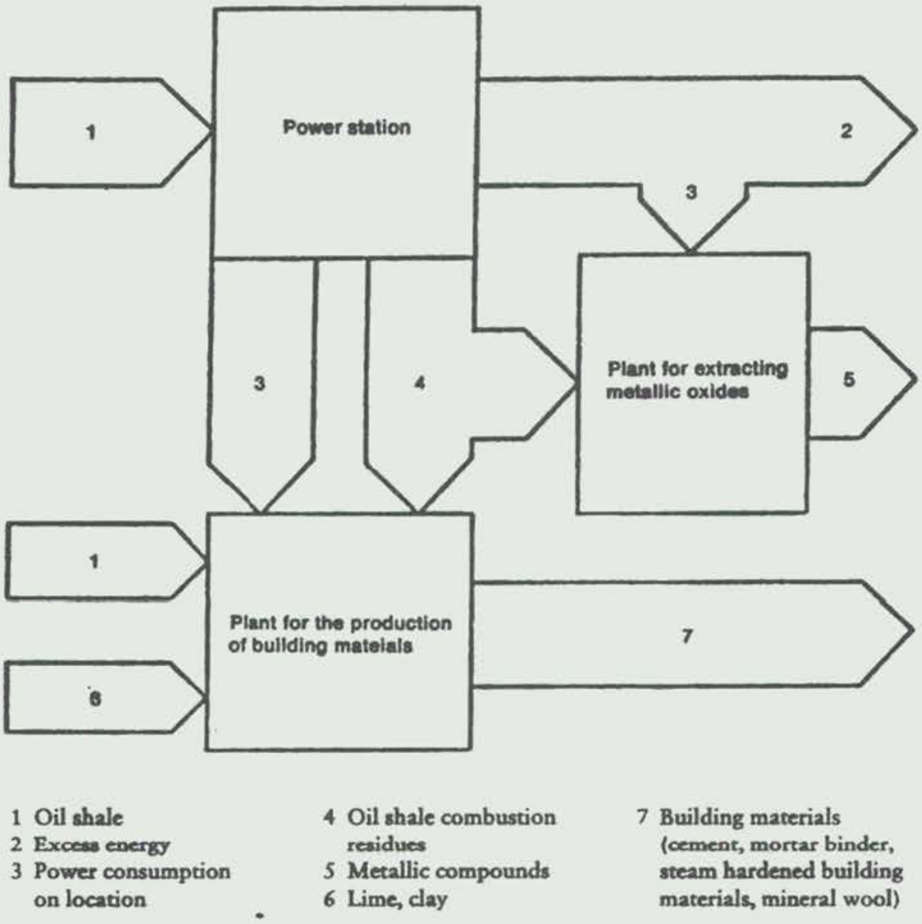

Fig. 3 Schematic Diagram of the Rohrbach Process (after Wefing and Noack, 1979).

5.2. OIL SHALE RETORTING

The extraction of oil from oil shale is accomplished by retorting for which two generic methods have been developed : (a) on the surface in a retort vessel and (b) in the earth (in-situ retorting).

Surface retorting of shale involves extraction by mining, crushing to retortable size, heating in a retort, and disposal of the waste shale produced. In-situ retorting requires fracturing the shale in the ground to permit some fluid heat transfer agent (e.g. hot gases) to retort the shale. The released oil then flows by gravity or pressure to some collection sump from which it can be removed. Both surface and in-situ retorting will produce a heavy oil that will have to be upgraded to improve oil flow to complete refining into standardized liquid fuels.

5.2. 1. Surface Retorting

Fig. 4 is a flow diagram illustrating the main processes encountered in surface retorting of oil shales. Oil shale retorts are classified according to whether they are directly or indirectly heated. In directly heated processes, heat is supplied by burning a fuel, which may be recycled retort offgas with air (or oxygen) within the bed of shale. Depending on the flow conditions, some portion of either the coke residue or the unretorted organic matter may be burned as well. In many designs, most or even all the heat is provided by combustion of the kerogen or coke residue. In the indirectly heated processes, a separate furnace is used to raise the temperature of a heat transfer medium that is then injected into the retort to provide heat. Two subclasses of indirectly heated retorts arise according to whether

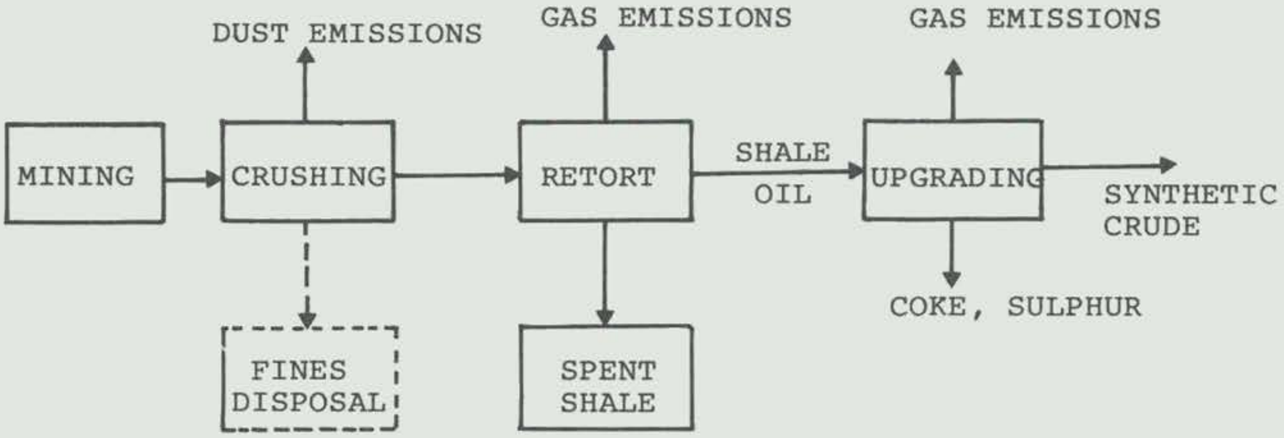

Fig. 4. Flow Diagram for Surface Retorting of Oil Shales.

a solid or gaseous heat transfer medium is used. In the case of a gas, the shale is heated by gas-to-solid heat exchange as is always the case in directly heated retorts. If a solid is used, heating is accomplished by solid-solid exchange. The furnace may be fired with retort offgas or crude shale oil. If retorted shale is used as the heat carrier, then the energy content of the coke residue is partly recovered by its combustion in the furnace. The three heating methods are illustrated in Fig. 5.

The Paraho Direct Retorting *

Fig.6 illustrates the Paraho direct retorting. Raw shale, crushed to 5-75 mm, is fed into a hopper at the top of the retort and spread evenly onto the shale bed by a rotating distributor system. The shale is heated by the rising hot gases as it descends from the preheating zone into the retorting zone, where the kerogen is pyrolyzed to produce the oil and gas products. The rising gases carry the products out of the retort through the gas withdrawal manifold. Because the gases are cooled by the incoming shale, much of the oil product condenses and leaves the retort as a mist. The retorted shale, which still contains 20 to 25 % of the original organic matter as coke residue, next descends into the combustion zone, where the coke is ignited in the oxygen-containing, air/recycled gas mixture. About half the coke residue is burned, and this provides most of the heat required for pyrolysis. Little recycled gas is burned during combustion of the coke; it serves mainly as a diluent for temperature control to limit carbonate decomposition, shale-ash sintering, and clinker formation. The gas distributors are cooled with circulating water.

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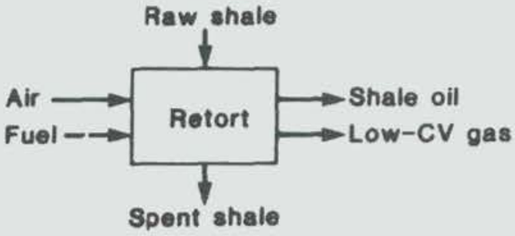
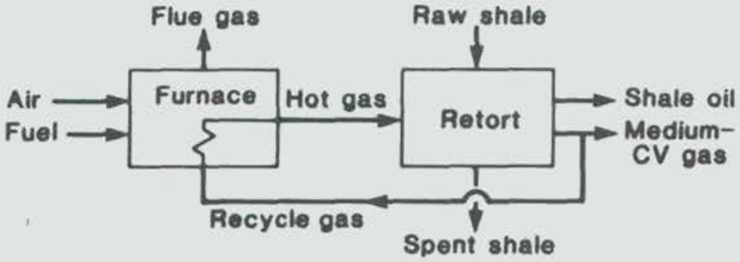
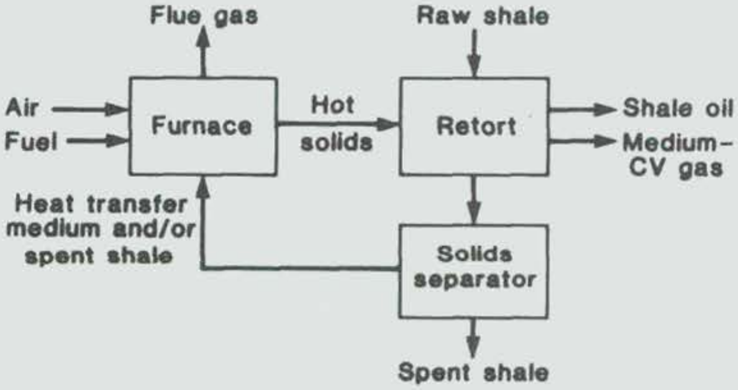
* Developed by Paraho Development Corp., a consortium of 17 companies. The word " Paraho " is derived from the Portuguese " para homem " , meaning " for mankind ".



(a) Directly heated retort

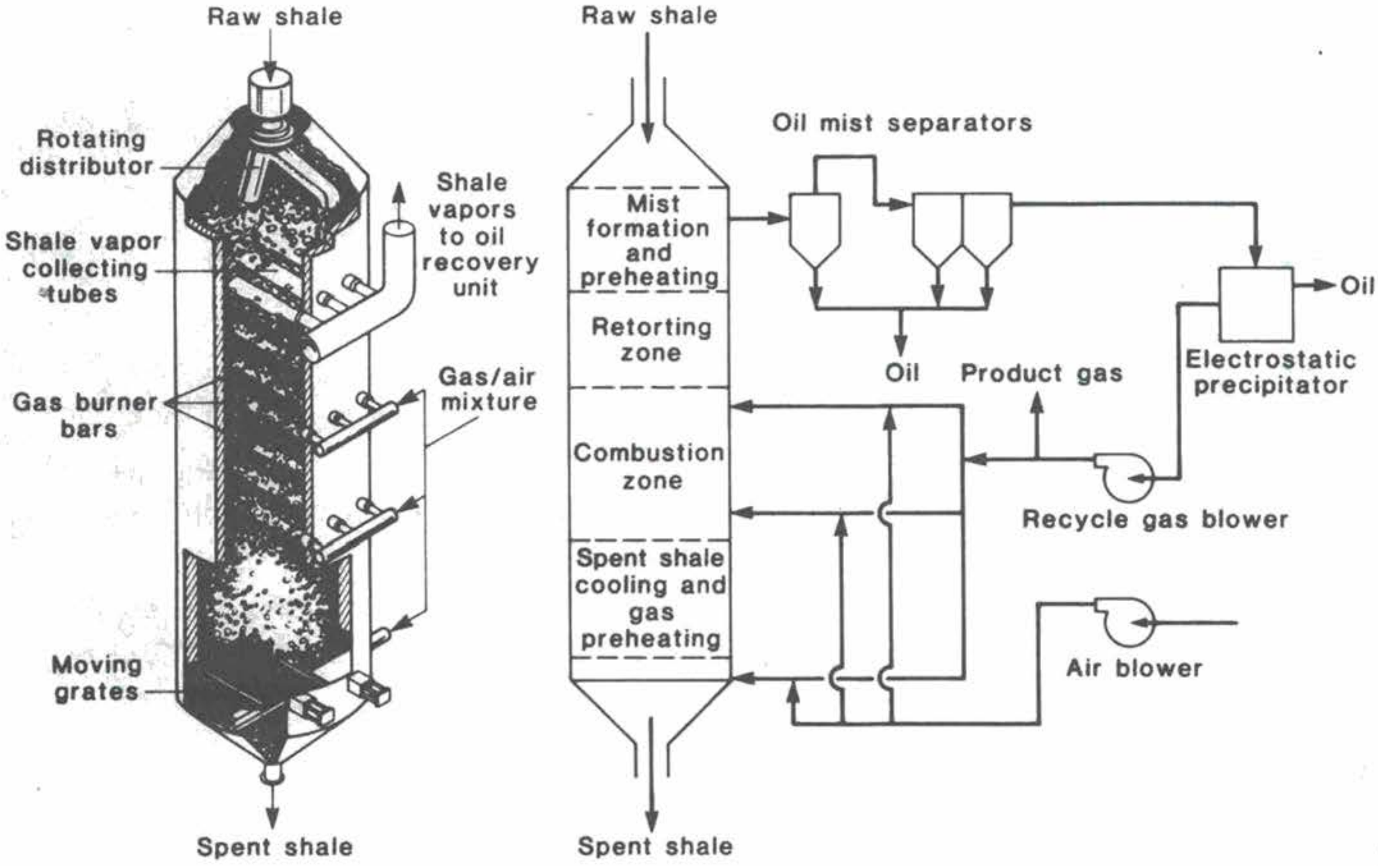


(b) Indirectly heated retort, gas-to-solid heat exchange



(c) Indirectly heated retort, solid-to-solid heat exchange

Fig. 5 The Three Heating Methods for Oil Shale Retorting (Probstein and Hicks, 1982)



Retort

Directly heated mode flow scheme

" <u>Oil " refers to Shale Oil</u>

Fig. 6 The Paraho Retorting Process
(after Probstein and Hicks, 1982).

The Union B Retort

This retorting process has been developed by Union Oil of California. Here, the shale is charged into the lower and smaller end of a truncated cone and is pushed upwards by a piston referred to as "rock pump", countercurrent to the air, which enters, preheated by the spent shale, at the retort top. The retorting occurs in the lower part, and at the bottom hot gas and liquids preheat the entering shale, which forms a vertical pile during upward movement (Fig. 7).

The TOSCO II Retort

The above-mentioned retorts, whether operated in the direct or indirect mode, heat shale by contact with a hot gas. As shown in Fig. 5 in indirectly heated retorts this gas-to-solid heat transfer may be replaced with solid-to-solid heat transfer by mixing a preheated solid with the shale. The hot solid may be recycled spent shale, or may be a special-purpose material introduced into the system specifically for heating the shale. An example of this is the TOSCO II (The Oil Shale Corporation, USA) process, shown in Fig. 8, in which 13mm diameter ceramic balls are used as the heat transfer medium.

Crushed shale of less than 13mm in size is preheated by pneumatically conveying the shale upward through a vertical pipe concurrently with hot flue gases from the ball heater. The flue gas is cooled during this process and the cooled gas is passed through a venturi wet scrubber to remove shale dust before venting to the atmosphere, at a temperature of about 50 to 55°C. The ceramic balls are heated in a vertical furnace and then fed along with the preheated shale, which has been separated from the flue gas in settling

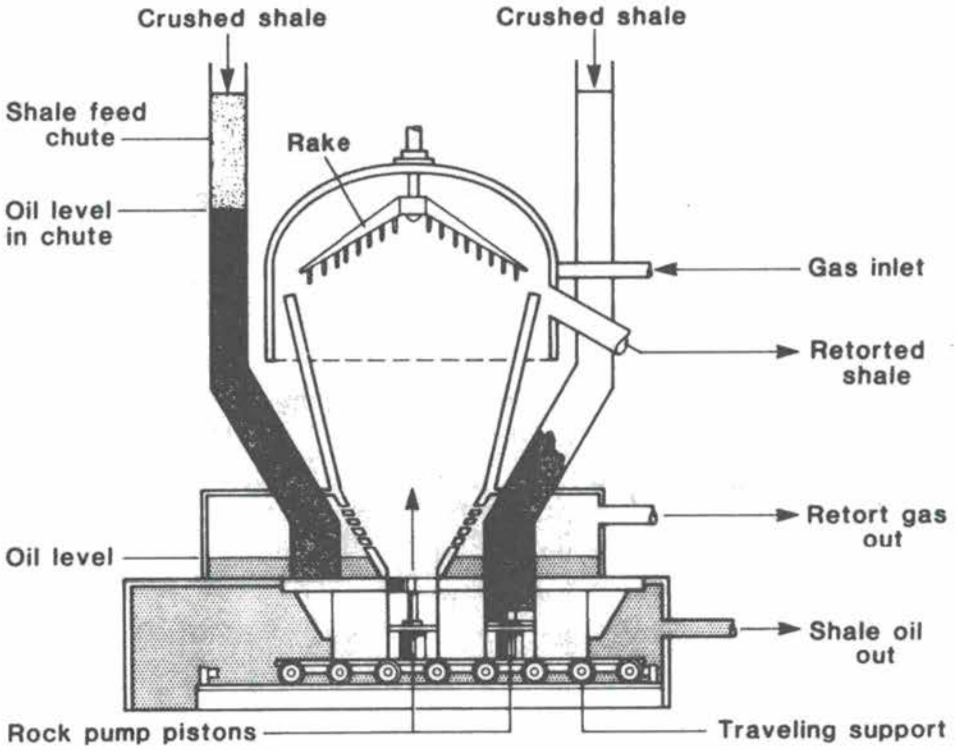


Fig. 7 The Union B Retort (after Probstein and Hicks, 1982).

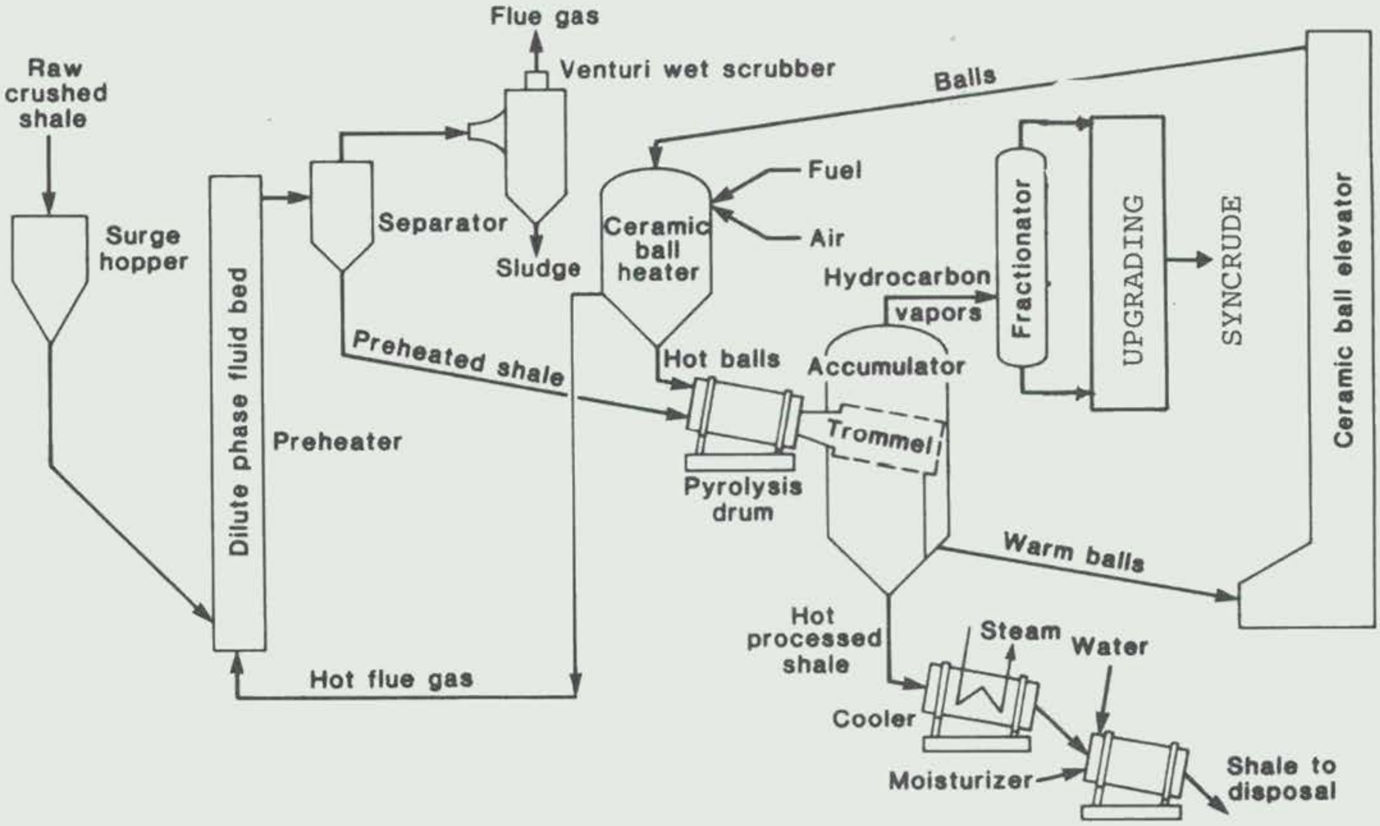


Fig. 8. The TOSCO II Retorting Process (after Probstein and Hicks, 1982).

chambers and cyclones, into a horizontal rotating kiln where the pressure is slightly above atmospheric. The mixture of balls and shale flows through the kiln, bringing the shale to a rotating temperature of about 510°C through conductive and radiative heat exchange with the balls. The resulting hydrocarbons and water vapours are drawn off and fractionated, leaving behind a mixture of balls and processed shale. The ceramic balls are separated by size from the fine-powdered spent shale by passage through a trommel, a heavy-duty rotating cylinder with many small holes punched in its shell. Warm flue gas is used to remove residual dust from the ball circulation system. The dust is removed from the flue gas with a venturi wet scrubber. With a bucket elevator, the balls are then circulated back to the ball heater for reheating by burning some of the product gas. The processed shale is cooled in a roating drum steam generator, then moistened to about 14 % (moisture content) in a rotating drum, after which it is transported by a conveyor belt for disposal. The steam and processed shale dust produced in the moisturizing process are passed through another venturi scrubber to remove the dust before discharge to the atmosphere. The importance of the moisturizing is that addition of the water to the TOSCO-type processed shale, at pre-determined shale temperature, appears to lead to cementation of the shale after proper compaction. A disadvantage of the indirect heating processes is that there is a significant loss of heat with the flue gases, and thermal efficiencies can consequently be expected to be lower than for the direct heating processes. Efficiencies of 76 % and 73 % have been estimated for the TOSCO II and the Paraho indirectly heated retorts, respectively (Probstein and Hicks, 1982).

The Lurgi-Ruhrgas Process

The Lurgi-Ruhrgas process has been developed commercially for the processing of sub-bituminous coal and the cracking of liquid hydrocarbons. Units suitable for the retorting of 4500 tonnes/day are presently in operation for cracking naphtha. In the oil shale retorting version of the process (Fig. 9) spent shale is mixed with the incoming raw shale in a sealed screw-conveyor, which acts as the retort. All of the material is discharged into a surge bin. The vapour stream is drawn off to a condenser to produce the gas and liquid fractions. Some spent shale is withdrawn from the surge bin as waste and the remaining solids are transferred to the end of a lift pipe. Here they are heated by combustion of the carbonaceous residue on the spent shale (and by burning supplemental fuel if needed). The hot solids are then used once again for retorting.

The Petrosix Process

The Petrosix retort (Fig. 10) was developed by Petrobras of Brazil. The system is very similar to that of Paraho. One difference is that the spent shale in the Petrosix system is discharged into a water bath, as is the case for the Union retort. In the Paraho retort, the shale is discharged dry. A 5.5m diameter demonstration unit designed to handle 2000 t/d of shale has been operated in Brazil since mid-1972. Construction of a 6.8×10^6 l/d commercial facility based on twenty 11m diameter Petrosix retorts is currently being considered by the Brazilian government.

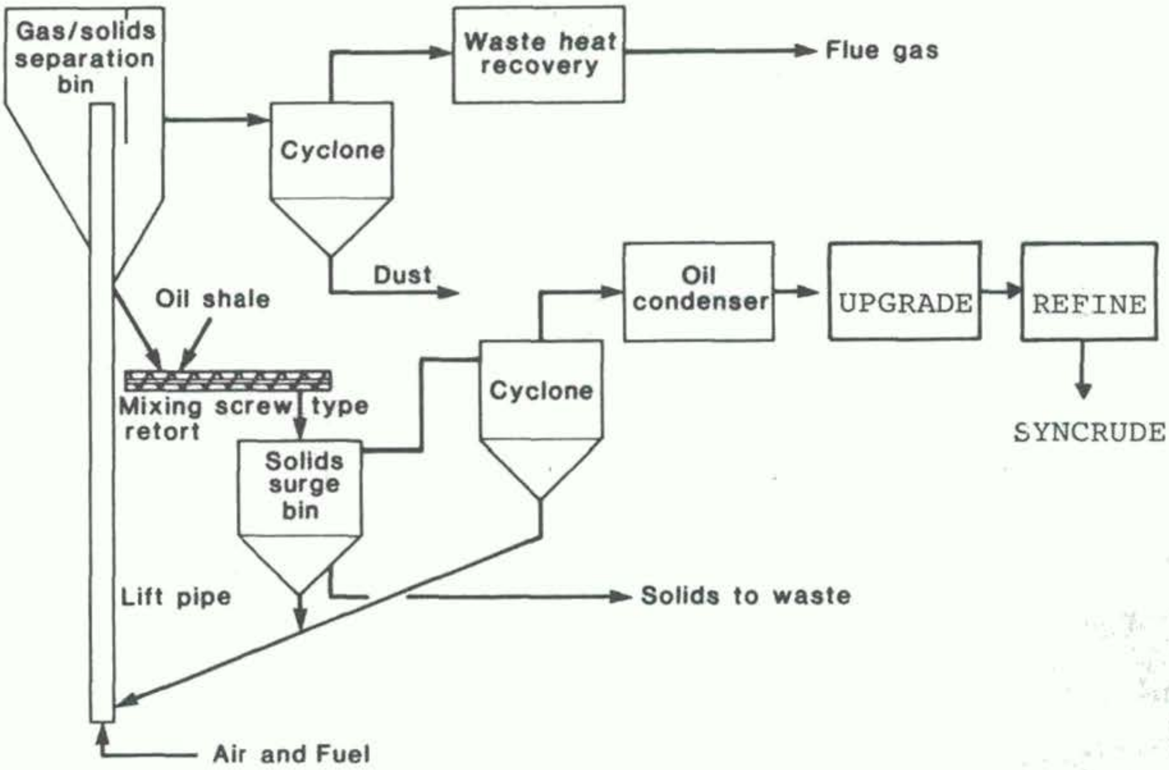


Fig. 9. The Lurgi-Ruhrgas Retorting Process (after Probstein and Hicks, 1982).

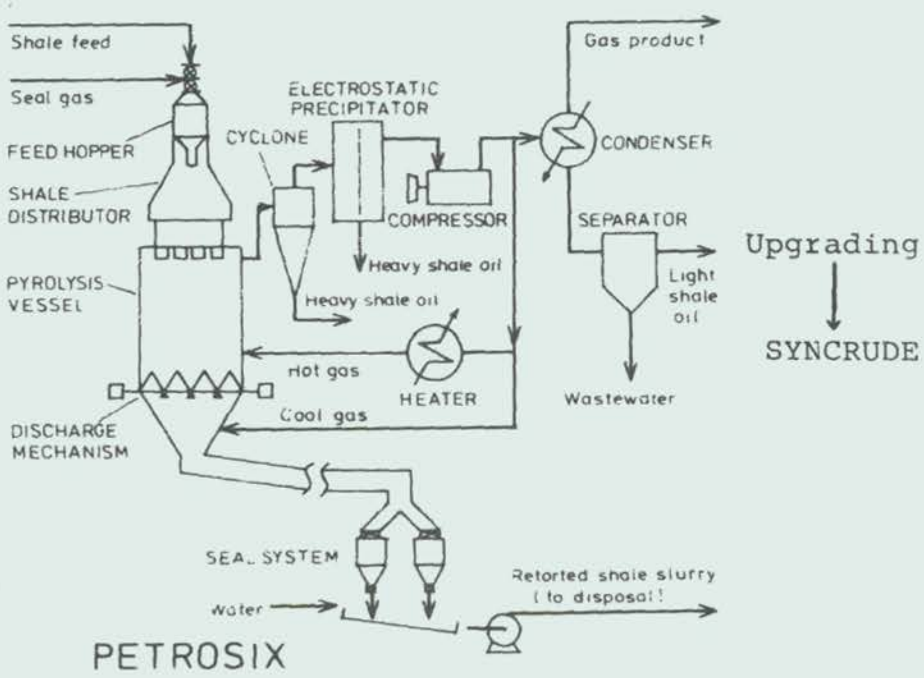


Fig. 10 The Petrosix Retorting Process (after Rühl, 1982).

5.2.2. In-Situ Retorting

In-situ retorting offers the possibility of eliminating the problems associated with the disposal of the large quantities of spent shale that occur with surface retorting. In addition, mining costs are largely reduced or eliminated, so that recovery of lower-grade shale down to 40 l/t becomes a possibility. A major problem arises with in-situ retorting if the oil shale deposit is associated with groundwater. Aquifers are found both above and below shale zones in some oil shale formations. In such cases the deposit to be retorted in-situ must first be dewatered, the water disposed of, and a means provided to ensure that the groundwaters are not contaminated by contact with the organic residue remaining after retorting is completed.

True in-situ (TIS) retorting :

This process involves fracturing the shale in place, igniting the fractured shale, feeding in air to sustain the combustion for pyrolysis, and pumping out the product oil and gas. Oil shale is not porous and generally does not lie in permeable formations, so adequate flow paths are difficult to create. The result is that the gas flow is very difficult to control and the oil yields are low.

Modified in-situ (MIS) retorting.

In this procedure, some portion of the shale is mined out using conventional techniques, and the remaining shale is " rubblized" by exploding it into the mined void volume. The resulting oil shale rubble constitutes the retort. Occidental Oil Shale, Inc., a subsidiary of Occidental Petroleum Co. has been particularly active in developing MIS retorting.

Each commercial-size retort in the "Oxy" system may measure 60m X 60m X 95m high. About 25 per cent of the shale in this block is mined out according to a pattern designed to give a uniform voidage distribution on explosion. After the retort is formed, connections are made to the surface for withdrawing the oil and gas, and for pumping down air and steam. The completed retort is illustrated in Fig. 11. Retorting is started at the top of the rubble pile, which is ignited by injecting air, and burning fuel gas. Heat from the burning zone is carried downward and pyrolyzes the shale in lower layers. The combustion zone advances vertically down the retort, preceded by the pyrolysis zone. The fuel gas is required only to initiate combustion; thereafter, the residual carbon remaining in the pyrolyzed shale is sufficient to supply the required heat. The oil vapours and gases are swept down by the overall gas flow to the lower regions of the retort. The oil and some water vapour condense out in the cooler lower regions and then percolate down to the sump at the bottom of the retort, from where they are pumped to the surface. The underground process operates as a packed-bed, directly heated batch retort.

5.3. SHALE OIL UPGRADING

Crude shale oils produced by the different retorting processes described above (sometimes referred to as "retort oil") should be refined and upgraded into a syncrude (refinery feedstock) suitable for conversion to distillate liquid fuels. Crude shale oils are more viscous than high-quality petroleum crudes and contain high amounts of nitrogen, particulates and arsenic compounds. Table 8 gives the properties of crude shale oils as compared to Arabian crude oil. There are several degrees of upgrading of shale oil as illustrated in Fig. 12.

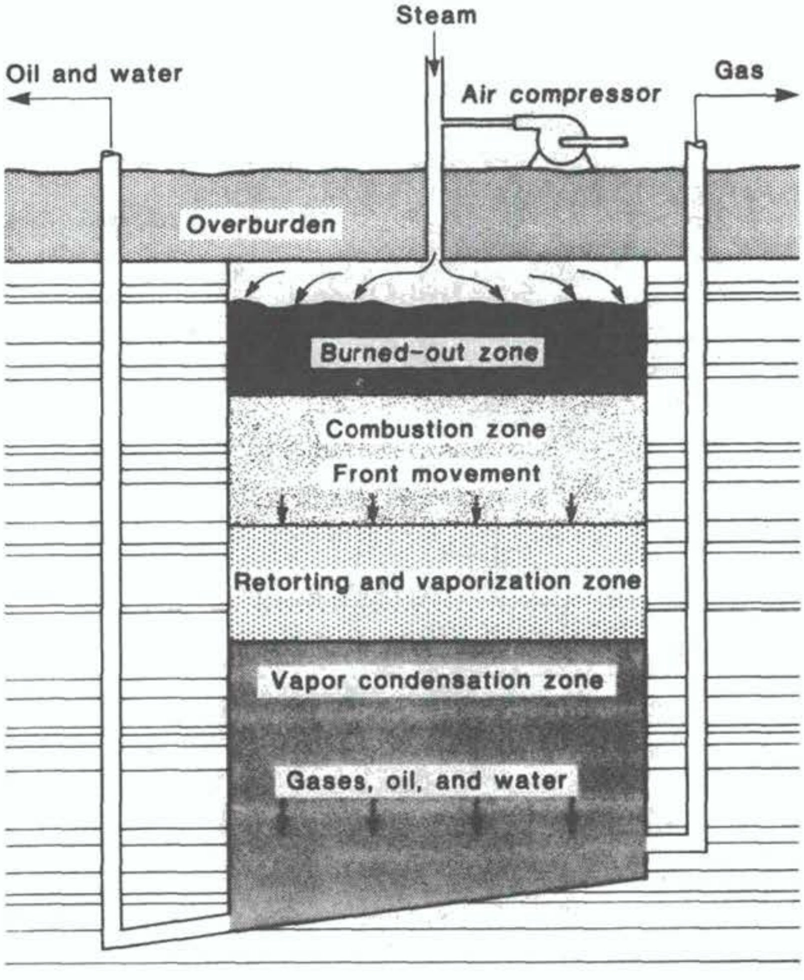


Fig. 11 Schematic Diagram of MIS Retorting (Oxy retort). After Probstein and Hicks (1982).

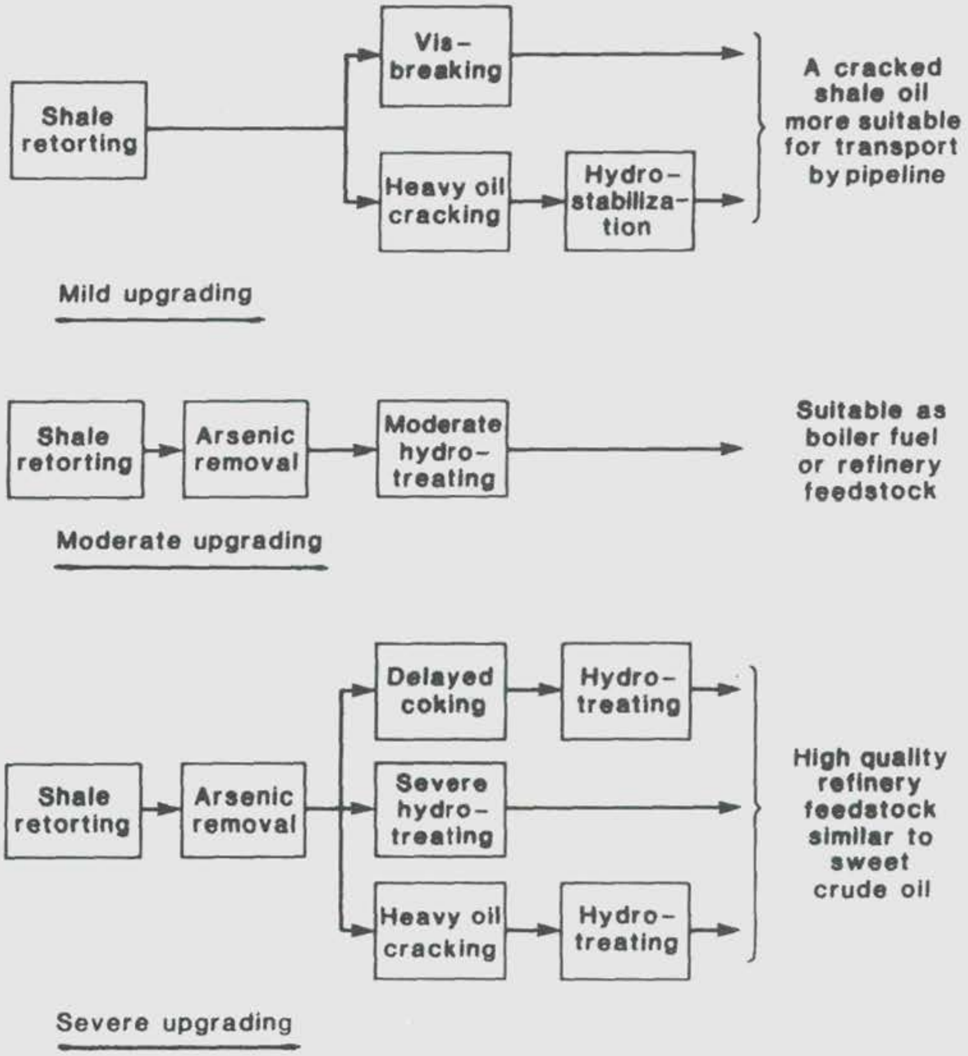


Fig. 12 Upgrading of Shale Oil
(Probstein and Hicks, 1982)

Table 8. Properties of Crude Shale Oils Compared to Arabian Crude Petroleum.

	Crude Shale Oils				Arabian Crude Petroleum
	Paraho	Union B	TOSCO II	Oxy	
Specific Gravity (g/cm³)	0.94	0.92	0.93	0.91	0.85
Viscosity (cSt at 38°C)	78.5	98.0	27.1	15.8	5.5
Pour Point(°C)	-15	-10	+27	+10	-25
Sulphur %	0.71	0.90	0.67	0.64	1.7
Nitrogen %	2.0	2.0	1.85	1.5	-
C/H ratio	7.1	7.3	7.3	7.7	6.2
Distillation %					
155°C	-	6.0	7.1	1.3	23
260°C	6.8	12.8	13.9	14.0	21
565°C	84.2	67.6	61.4	80.2	42
Residue	9.0	13.6	17.6	4.5	14

Source : Rühl (1982). Shale oil from Green River oil shale.

Crude shale oil contains particulates (largely shale fines) and arsenic. Oil soluble arsenic (varies from 18 to 52 μg/g) is the most troublesome trace element in shale oil, as it rapidly deactivates certain refinery catalysts (Probstein and Hicks, 1982). Removal of particulates is carried out by water washing and by electrostatic de-ashing which also removes about half of the arsenic. The arsenic content is further reduced by treatment with alumina catalysts and absorbents in the presence of hydrogen at moderate pressure at a temperature of 230-250°C.

After the solids and arsenic removal steps are done, the oil is hydrotreated to reduce the nitrogen content. The hydrotreating, which is done using a high activity denitrogenation catalyst, is carried out at pressures of 1500 to 2500 psig and temperatures of 370-390°C to give a syncrude containing 600-800 ppm nitrogen (Hartley et al, 1980). The hydrotreating also removes the last of the arsenic, reduces sulphur and oxygen contents to very low levels, hydrogenates olefins, and lowers the carbon/hydrogen ratio. Table 9 gives the properties of crude shale oil and upgraded shale oil (syncrude) as compared to Arabian light crude petroleum.

Table 9 Properties of Crude Shale Oil, Upgraded Shale Oil and Arabian Crude

	Shale Oil		Arabian Light Crude Petroleum
	Crude	Upgraded	
Gravity (gm/cm³)	0.92	0.86	0.85
Nitrogen (%)	1.8	0.08	0.08
Sulphur (%)	0.8	0.0018	1.70
Oxygen (%)	0.9	<0.01	-
C/H ratio	7.3	6.5	6.4
Pour Point (°C)	15	27	-25

Source : Calculated from Hartley et al (1980). Green River shale.

It should be noted that neither the crude shale oil nor the upgraded syncrude could be transported in unheated pipelines. Because of its high pour point the shale oil would not be acceptable as a compatible crude in an existing common carrier pipeline. Thus, processing of the crude shale oil at or near the shale retorting site to yield pipelineable products will have to be done.

5.4. ASSUMPTIONS FOR THE ASSESSMENT OF THE ENVIRONMENTAL IMPACTS OF OIL SHALE DEVELOPMENT

Oil shale development will have a number of impacts on land, water, air and on different biota. The magnitude of these impacts will vary from one place to another and will depend on the grade of the oil shale, the technology ot its exploitation and the size of the processing plant. Two options exist for oil shale development; the main steps encountered in both options are as follows :

1. Surface Retorting
    - Oil shale mining and crushing
    - Surface retorting (direct or indirect retorting)
    - Upgrading of crude shale oil
    - Refining of the syncrude

2. In-situ Retorting
    - Oil shale fracturing
    - In-situ retorting
    - Upgrading of crude shale oil
    - Refining of the syncrude

To be profitable, an oil shale retorting operation should yield 50,000 barrels (bbl)/ day * of syncrude (Eddlemon and Tolbert, 1983). In discussing the environmental impacts of the different steps of the oil shale fuel cycle (i.e. from the extraction of the oil shale to retorting, upgrading and refining), the production of 50,000 bbl/day of syncrude has been taken as a basis for the quantification of resources required and of the different environmental impacts. The oil shale referred to in the calculations is assumed to yield 100 l of oil / tonne of shale, which is the "average" grade of shale encountered in many countries. For shales with different oil yields and/or

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* i.e. about 8000 m^3/day (1 bbl = 159 litres).

for different production rates of syncrude, the values given in the present report can be easily scaled up or down. Table 10 summarizes the basic figures and assumptions used for quantification of information presented in the following chapters.

Table 10 Figures and Assumptions *

Oil yield of shale : 100 l/t

Heating values :

- oil shale : 5.1 MJ/kg
- crude shale oil : 43.1 MJ/kg
- syncrude : 46.9 MJ/kg
- crude petroleum : 45.2 MJ/kg **
- coal : 28.5 MJ/kg **
- liquefied natural gas : 50.0 MJ/kg **

Retort conversion efficiency :

- Paraho Direct : 86 %
- Paraho Indirect : 73 %
- TOSCO II : 76 %
- In-Situ (Oxy) : 60 %

Efficiency of crude shale oil upgrading : 90 %

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* Recalculated from data given by : Probstein and Gold (1978), Penner et al (1981) and Probstein and Hicks (1982).

** Data given for comparison with shale oil

CHAPTER 6

ENVIRONMENTAL IMPACTS OF OIL SHALE MINING

Oil shale can be mined, according to its geological setting by a variety of methods, the most common of which are : surface mining (open-pit or strip-mining) and underground mining (e.g. room-and-pillar technique). Recovery factors of 100 per cent are not possible in practice; at present the average recovery factor for surface mining in general is 80-90 % and for underground room-and-pillar mining it is about 35-50 %. The amount of oil shale to be mined depends on the quality of the shale (oil yield), the retort conversion efficiency and the size of the retorting operation. Fig. 13 illustrates the material flow in the oil shale fuel cycle to produce 50,000 bbl/day of syncrude. It should be noted that because the Paraho retort cannot accept fines, about 5 per cent more shale must be mined than can be used (Probstein and Gold, 1978). The amounts of oil shale to be mined each day are much higher than, for example, those of coal used for production of the same amount of syncrude (about 15,000 tonnes of coal are required to produce 50,000 bbl/day of syncrude through liquefaction). For a 20 year lifetime of an oil shale plant, the amount of oil shale to be mined varies from 780 million to 950 million tonnes. Mining this huge amount of shale will undoubtedly have several potential environmental impacts. These are discussed in the following.

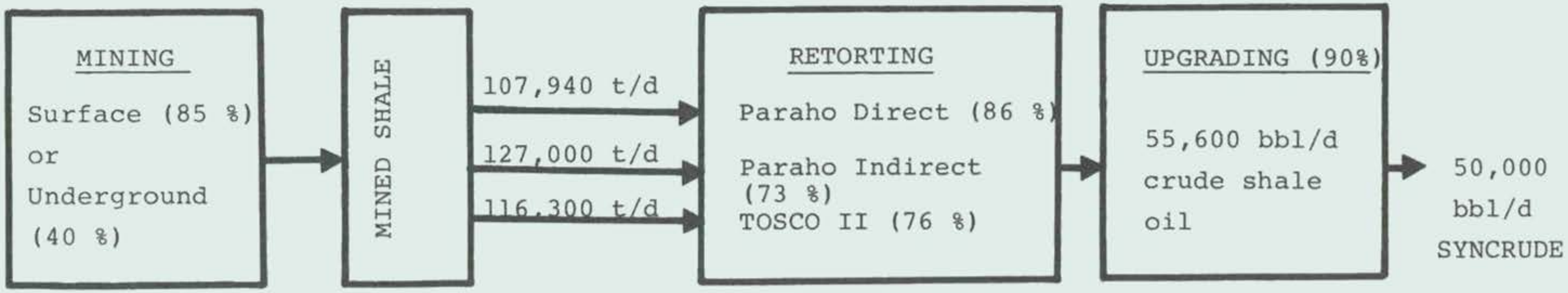

Fig. 13. The Oil Shale Fuel Cycle

Percentages refer to recovery (conversion) efficiencies.
Shale grade : 100 l/t.
Values of mined shale for Paraho retorting include an additional 5 % (see text).

6.1. Impact of Oil Shale Mining on Land

Surface mining has a more potential impact on land than underground mining. The amount of disrupted land varies from one place to another, depending on the geological occurrence of the oil shale formation and its characteristics. Weaver (1974) estimated the land requirements of an oil shale plant producing 50,000 bbl/day at 80-100 ha/year (for open-pit mining) and at 4 ha/year (surface area for underground mining). These figures do not include land needed to support population, infrastructure or solid waste disposal; such land would vary up to several thousands of hectares.

Where surface mining is carried out near population centres, it will have a direct effect on human settlements and the total infrastructure of the area. Construction of new settlements, roads, etc is necessary if mining operations are to move towards uninhabited areas. Reclamation of strip-mined areas would become a necessity to restore land and to prevent acid drainage (see later).

6.2. Impact of Oil Shale Mining on Water

In the extraction and handling of oil shale for delivery to the conversion plant, dust is generated at different stages. Although the use of dry or wet dust collectors is common to control dust in underground mines, crushing and storage facilities, water sprays are used to hold down dust, especially in the open (e.g. in surface mines, partially-closed storage and crushing facilities, etc). The amounts of water required to control dust in mining and crushing operations vary from one plant to another. Probstein and Gold (1978) estimated the water consumed for these purposes as follows:

	Water consumption (m^3/hour)*
Paraho Direct	115
Paraho Indirect	132
TOSCO II	126

* For the production of 50,000 bbl of syncrude/day.

The following ranges of water consumption in shale mining and handling have been calculated from the data given by Penner et al (1981) :

	Water consumption (m^3/hour)
Direct surface retort	61-195
Indirect surface retort	133-305
In-situ retorting	27-82

Mining of oil shale may have a number of potential impacts on aquatic ecosystems in the area (surface and groundwaters). Suspended solids and sedimentation will occur to some extent in water bodies receiving runoff or discharges from shale development sites. Impacts to aquatic ecosystems from sediment addition include reduced light penetration and consequent inhibition of photosynthesis and primary production, interference with food acquisition, reproduction, and habitat selection, and physical abrasion of aquatic biota (Eddlemon and Tolbert, 1983), Impacts from sediment addition may also alter community structure through reductions in fish population densities or even destruction of individual species. Increased intensity of runoff as the result of vegetation removal reduces the variety and abundance of stream fauna. This occurs as the result of resuspension of benthic organisms and substrate particles in the water column, abrasion of individuals, and alteration of the stream-bed habitats by the scour. Eddlemon and Tolbert (1983) pointed out that the combination of increased runoff and increased sediment transport into streams, as the result of surface mining disturbances, was the primary factor responsible for significant changes in community structure, including reductions in the numbers of individuals and species.

Some oil shales contain high amounts of pyrite (FeS_2). Pyrite-bearing shale is a potentially serious hazard to aquatic ecosystems because it oxidizes on exposure to air and water to form ferric sulphate and sulphuric acid. On dilution (as in a stream), ferric sulphate may hydrolyze to form more sulphuric acid and a ferric hydroxide precipitate called " yellow boy " (Hutchinson, 1957). This precipitate forms a layer over the substrate, inhibiting photosynthesis and altering aquatic habitats. In some instances, low oxygen content of the water caused by oxidation of ferrous ions may contribute to alterations in community structure (Hynes, 1970). The sulphuric acid formed from the oxidation of exposed pyrite surpasses ferric hydroxide as a hazard to aquatic communities because it not only alters the pH of water to levels possibly incompatible with the survival of some species, but it also may mobilize certain trace elements in the shale or stream bed.

Although species composition and biomass of most aquatic communities have been shown to be severely altered by acid drainage, research is needed to determine whether the principal agents of change in a given aquatic ecosystem are acid drainage itself, or acid mobilization of trace elements, or both. Because considerable quantities of potentially harmful substances may occur in raw shale, acid leaching of these substances would probably mobilize certain trace elements (and possibly other toxic, carcinogenic, or mutagenic substances). Although the nature and intensity of impacts on aquatic ecosystems will vary from site to site, the immense quantities of shale and the size of the processing operations involved suggest the likelihood that some fraction of the leachable contaminants may enter area streams, conceivably in sufficient quantities to adversely affect aquatic communities.

Different control measures are known to minimize the detrimental effects of acid mine drainage. Such measures include drainage control in the mine area, proper disposal of sulphur-bearing materials to ensure that pyritic refuse does not come in contact with water, sealing-up abandoned mines to prevent water from entering the sulphur-bearing soil and chemical treatment of acid mine drainage. The latter consists essentially of treatment with various alkaline neutralizing agents, including limestone, lime, and caustic soda. Such treatment is designed primarily to treat solution acidity and remove those ions whose solubilities are sensitive in the acid to neutral range. New methods of treating acid mine drainage utilizing ion-exchange technology, reverse osmosis, and flash distillation reduce acidity and a substantial part of the dissolved ions. In some countries, stringent control measures are being implemented to avoid the hazards of acid mine drainage associated with coal mining. Such control measures apply also to oil shale mining.

6.3. Occupational Hazards

Oil shale mining, like any other large-scale mining operation, will have a number of occupational hazards. The risk of death from accidents in underground mining has been estimated at 1.5 X 10^{-3} per person per year (Pochin, 1976), or about 0.5 deaths per 1 million tonnes of mined rock (assuming an average productivity of 3000 tonnes per worker per year). This accident fatality rate is about the same as that in underground coal mining (UNEP, 1981). In surface mining, the accident fatality rate is much lower, and has been estimated at 0.1 deaths per 1 million tonnes of mined rock. The rate of accidental non-fatal disabling injuries would be similar to that encountered in coal mining. This has been estimated at 30 per 1 million tonnes of mined rock for underground mines and at 5.5 per 1 million tonnes of mined rock for surface mines. Using these values of risk, Table 11 gives the calculated estimates of accidental deaths and disabling injuries that would result from mining oil shales for the production of 50,000 bbl of syncrude.

Table 11. Estimates of Deaths and Injuries from Accidents in Oil Shale Mining *

	Deaths	Disabling Injuries
Underground Mining		
Paraho Direct	0.05	3.2
Paraho Indirect	0.06	3.8
TOSCO II	0.06	3.5
Surface Mining		
Paraho Direct	0.01	0.6
Paraho Indirect	0.01	0.7
TOSCO II	0.01	0.6

* For production of 50,000 bbl of syncrude.

These values are much higher than those associated with the production of 50,000 bbl of crude petroleum (estimated accidental deaths, 0.0001 and disabling injuries, 0.012 as calculated from risk values quoted by UNEP, 1981), or with the production of coal to produce the same amount of syncrude by liquefaction (the amount of coal to be mined is 15,000 tonnes and by using the same risk figures given above, the estimated deaths from mining accidents would be 0.0075 for underground mining and 0.0015 for surface mining. Disabling injuries would be 0.45 and 0.08, respectively). The high rates of accidental deaths and injuries in oil shale mining (for the production of 50,000 bbl of syncrude), as compared to coal is due to the much lower heating value of oil shale which makes it necessary to mine much greater amounts of the rock than in the case of coal.

In oil shale mining, as in other mining operations, workers are exposed to dusts during the extraction of the rock and during the crushing operations. The first concern of industrial hygienists is normally the free silica content of the dust, which can lead to speculation about fibrotic lung diseases. With a material such as oil shale, however, the presence of free silica and other mineral components must be considered along with the presence of the organic matrix. The combination of components capable of eliciting a pneumoconiotic response with complex organic material could lead to synergisms resulting in more complex lung diseases. Human silicosis has been described in rats exposed to shale dust (Holland and Jackson, 1983), and oil shale pneumoconiosis or "shalosis" may occur from silica or kerogen found in oil shales (Wright and Rom, 1980). Lung cancers have been reported in Scottish oil shale miners after lifetime exposures (35-40 years), and hypertrophic rhinitis was observed in Estonian oil shale miners (Holland and Jackson, 1983).

The risk of death from ill health resulting from exposure to dust and silica in underground mines has been estimated at 5×10^{-4} per person per year (Pochin, 1976), or 0.16 deaths per 1 million tonnes of mined rock (assuming productivity of workers to be 3000 tonnes/person/year). The incidence of chronic respiratory diseases is about 12 times this figure (UNEP, 1981). Using these figures, the estimated occupational deaths and cases of chronic respiratory diseases in underground oil shale mining would be as follows :

	Occupational deaths *	Chronic Respiratory Diseases *
Paraho Direct	0.017	0.204
Paraho Indirect	0.020	0.240
TOSCO II	0.019	0.228

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* For production of 50,000 bbl of syncrude.

It must be pointed out that all the above-mentioned estimates for mining accidents and for occupational hazards are only approximate values that serve as an "indication" of the magnitude of the hazard involved. Such values will vary from one place to another, depending on the mining technology, the safety measures implemented, the scales of production, etc.

Another occupational hazard in oil shale mining is the exposure to noise produced by the mining equipment. Hurck (1978) pointed out that in the Federal Republic of Germany, about 61 % of workers in underground mines were exposed to a maximum noise level of 90 dB(A), which is considered safe according to regulations used in FRG; about 31 % were working at noise levels of 91-100 dB(A) and about 8 % of the workers were exposed to 101 dB(A). Several techniques are being developed to reduce the level of noise of the mining equipment.

CHAPTER 7

ENVIRONMENTAL IMPACTS OF OIL SHALE RETORTING

7.1. AIRBORNE EMISSIONS

Oil shale retorting results in a number of airborne effluents in addition to the crude oil produced. The composition of the gaseous effluents depends on the composition of the shale, the retort temperature, and the composition of the air used to support combustion. The different important airborne emissions encountered are discussed in the following.

7.1.1. Sulphur Oxides

Oil shale technologies have the potential for emitting large quantities of SO_2 and, therefore, efficient environmental control systems will be required for sulphur reduction. The source of SO_2 emissions is from reduced sulphur gases, predominantly H_2S, in that part of the retort gas to be used as fuel gas. The H_2S is evolved during the retorting from inorganic and organic constituents in the oil shale mineral matrix. If not removed by environmental control technologies, the sulphur would be released as SO_2 following oxidation of the fuel gas. Table 12 gives estimates of SO_2 that would be emitted from different retorting technologies.

Non-H_2S sulphur compounds comprise 1% to 8 % of the total sulphur measured in several retort offgases (Fruchter et al, 1983). Thus, they may make a significant contribution to fugitive emissions, and may contribute, through oxidation, to SO_2 emissions. The main non-H_2S sulphur compounds emitted during oil shale retorting include carbonyl sulphide (COS),

Table 12 Sulphur Emissions from Oil Shale Retorting *

Retort	Unabated Sulphur emissions (tonnes/d)	Unabated SO_2 emissions (tonnes/d)	SO_2 emissions after control (tonnes/d) **
Paraho Direct	55	110	6
Union B (Indirect)	78	156	8
TOSCO II	178	356	18
In-Situ (MIS)	305-1440	610-2880	31-144

* For production of 50,000 bbl/d syncrude.
** 95 % sulphur removal.
After Fruchter et al (1983), with modification.

carbon disulphide, thiophene, methylthiophene, dimethyl sulphide, ethyl mercaptan, dimethyl disulphide, etc.

To remove sulphur compounds contained in the retort gases, two options exist : (1) to remove the reduced species, e.g., H_2S, COS, etc before oxidation of the fuel gas (using, for example, the Stretford H_2S removal process); or (2) to remove SO_2 by scrubbing the flue gas after oxidation (flue gas desulphurization, FGD). The Stretford process is a direct, liquid phase process which removes H_2S before offgas combustion. Although the method is highly efficient (H_2S removal of up to 99 %) and is not expensive, some serious operational problems have been encountered (Fruchter et al, 1983). In addition, minor sulphur compounds in the retort gas, e.g. SO_2, COS, etc may escape removal or cause degradation of the Stretford liquids. In the flue gas desulphurization (FGD), the retort offgas is combusted (usually for power production), oxidizing sulphur compounds to SO_2. The latter is then scrubbed from the resulting flue gas. FGD is a relatively expensive technique for sulphur removal and, in addition, may generate fine particles as sulphur is removed, causing an additional environmental and health concern (Daum et al, 1982). Using FGD with sulphur removal efficiency of 95 % , Table 12 shows the values of SO_2 that would be emitted from different retorting facilities. The Paraho Direct and Union -B (indirect heating) will give values of SO_2 emissions that are in compliance with the Colorado Air Quality regulation which limits oil shale facilities to 0.14 kg SO_2 emitted per barrel of crude shale oil produced (Daum et al, 1982). A 50,000 bbl/day syncrude facility would give 7.8 tonnes SO_2/day, accordingly. The TOSCO II and in-situ retorts will give rise to SO_2 emissions much higher than those specified in the regulation.

Environmental Impacts of SO_x Emissions :

Although sulphur has a natural global biogeochemical cycle, the impact of man-made emissions of sulphur are sufficiently large to interfere significantly with this cycle. Man-made sulphur dioxide (SO_2) is emitted on a global scale, with fossil fuel combustion producing about 80 per cent of all SO_2 emissions. Global man-made emissions of SO_2 from all sources are about 127 million tonnes per year, of which over 90 per cent is produced in the northern hemisphere (Global-2000, 1981).

Man-made SO_2 emissions are globally distributed, not only because of the multitude of individual sources but because such emissions are made via tall stacks which, though reducing SO_2 levels close to source, make the emissions available for long-range transport. The emitted SO_2 can travel hundreds or even thousands of kilometers from the original sources and thus cross national boundaries creating trans-national environmental problems.

Sulphur dioxide can be oxidized to form various sulphate-containing compounds, including sulphuric acid and ammonium sulphate. It is this heterogeneous mixture that produces the various health and environmental effects in many areas. Exposure to SO_2 and sulphate aerosols results in respiratory ailments in humans particularly in urban areas (WHO, 1979).

The oxidation of SO_2 to produce sulphuric acid aerosols and their subsequent washout in precipitation (acid rain) is of growing concern. Acid rain often falls many hundred or thousands of kilometres from the source of SO_2, and sometimes causes considerable damage in aquatic ecosystems. Lakes with limited buffering capacity are being acidified at an alarming rate : many Canadian lakes have experienced a change of one pH unit (a ten-fold increase in hydrogen ion concentration) in the past ten years (NRCC, 1981). Several thousand lakes in northern Europe and North America have been damaged. A marked decline in the diversity and density of aquatic plants and animals has been linked to acidification of lakes as have declines in many fisheries (Dickson, 1975; UNEP, 1982; UNEP, 1983). Aluminium is leached out from soils and lake sediments during the acidification process and, due to its toxic effect on fish, is considered to be a major cause for fish kills. Concentrations of mercury in fish appear to be enhanced in acidified lakes. Mobility of metal ions in soil will also increase under acid conditions. This can result in elevated cadmium concentrations in terrestrial plants, and subsequently in grazing animals (UNEP, 1983, 1984). The impact of acidification in raising aluminium and other metal concentrations in groundwater poses a threat to human health where drinking water is obtained from wells. Acid rain also affects buildings and monuments : India's Taj Mahal and the Parthenon in Athens are only two examples of the human cultural heritage seriously threatened.

Sulphur dioxide and sulphate damage to vegetation takes place via deposition and fumigation and also indirectly via changes in soil chemistry. Damage to leaves is a result of high concentration of SO_2 , and is probably less important than chronic effects on vegetation where there is no visible damage. Chronic exposure to SO_2 may result in considerable reductions in yield, which is of great importance in forestry and agriculture. Recent evidence indicates that forest damage in over one million hectares in central Europe may be related to acid precipitation. In the Federal Republic of Germany it was estimated that 560,000 ha, or approximately 7.7 per cent of the forest area had been affected by acid rain (of this area about 35,400 ha are severely damaged) and other air pollutants (Tomlinson, 1983).

The health effects of SO_2 have been recently reviewed by WHO (WHO, 1979). It has been demonstrated that the effects of SO_2 are augmented by other pollutants in the air, especially by particulates (oil shale retorting results in the emission of 0.82 to 8.9 tonnes of particulates per day from a plant producing 50.000 bbl/d of syncrude; see. Raufer and Yates, 1980). Three categories of human disease appear to be influenced by atmospheres containing sulphur dioxide and associated pollutants : increased prevalence of lower pulmonary disease in children; increased frequency of severity of asthmatic attacks; and increased prevalence of chronic respiratory disease.

During the so-called air pollution episodes that occurred in some urban areas, an increased mortality has been observed in susceptible groups, e.g. persons with heart and lung diseases, and the aged. Moreover, high concentrations of sulphur dioxide and particulates have been associated with acute morbidity. WHO (1979) developed guidelines for the protection of the health of the public from exposure to SO_2 and associated pollutants. The concentration of SO_2 in the atmosphere should not exceed 100-150 $\mu g/m^3$ for 24 hours, and the annual mean should not be more than 40-60 $\mu g/m^3$. The interim guidelines formulated for suspended particulates are : 150-230 $\mu g/m^3$ for 24 hours, and 60-90 $\mu g/m^3$ for annual means.

7.1.2. Nitrogen Oxides

Oil shale retorting will yield a number of nitrogen compounds in retort gases. Nitrogen oxides (NO_x) can be formed in two basic ways : (i) nitrogen in the combustion air will combine with the oxygen in the air during the retorting process to produce NO, most of which is later oxidized to NO_2 ; (ii) combustion of nitrogen-containing organic compounds and ammonia in the retort offgas. The latter is considered the major source of nitrogen oxides in offgas. Table 13 gives estimates of ammonia content in gases from different retorting processes.

Table 13. Estimates of Ammonia Content in Retort Gases *

	tonnes NH_3/day (uncontrolled)
Paraho (Direct)	42.2
Union-B (Indirect)	2.5
TOSCO II	155.7

* After Fruchter et al (1983), with modification. For production of 50,000 bbl/day of syncrude.

A portion of the ammonia emitted is to be recovered from the offgas for sale as fertilizer and, therefore, it is difficult to estimate the actual amounts of NH_3 that would contribute to NO_x emissions. Raufer and Yates (1980) estimated the uncontrolled annual emissions of NO_x from oil shale retorting (on the basis of production of 50,000 bbl/day of syncrude) as follows :

Surface retorting	600-6400	tonnes/y
In-situ retorting	2300	tonnes/y

A number of trace nitrogen compounds has been identified in retort offgas; the most common compounds include : hydrogen cyanide, acetonitrile, acrylonitrile, propionitrile, isobutyronitrile, pentanenitrile, pyridine and benzylamine (Fruchter et al, 1983). The concentration of these compounds is generally less than 100 ppm in the retort offgas.

Environmental Impacts of NO_x Emissions :

Oxides of nitrogen from natural and man-made sources are present in the atmosphere. Natural production, estimated at about 500 million tonnes per year is derived mainly from bacterial action in soil and from forest fires. Man-made emissions arise from the combustion of fossil fuels. This produces about 50 million tonnes per year localized mainly in centres of population (NAS, 1977 ; SCOPE, 1983).

Nitrogen oxides can undergo various reactions in the atmosphere to form aerosols of nitric and nitrous acids, and nitrate and nitrite salts. Under certain conditions NO_x and other primary pollutants can react to form secondary pollutants referred to as photo-chemical oxidants, the major components of which include NO_x, ozone and peroxyacetylnitrate (PAN) which, together with many other organic compounds, form photochemical smog (NAS, 1977; WHO, 1978). NO_x and photochemical oxidants can be transported in air for long distances.

Nitrogen oxides may have adverse effects on plants, at least in urban areas (Mansfield and Freer-Smith, 1981). However, there is little data available on the background concentrations of NO_x or of possible effects on plants, either singly or in combination with SO_2. In contrast, it is known that PAN and ozone are very phytotoxic and are known to injure plants in most, if not all, major urban areas in North America and Mexico and probably throughout the world (NAS, 1977).

Nitrogen oxides are responsible for about 30 per cent of the acidity in acid precipitation (Environment Canada, 1981) but the nitric acid aerosol formed is only of minor influence in lake acidification and may have a fertilizing effect in soils, at least in the short term. However, if the trend of increasing NO_x emissions and nitrate deposition continues, then nitric acid will assume an increasingly important role in the acidification of soils and freshwater systems.

The different photochemical smog components, including NO_x, differ in their toxicity. The human health effects associated with NO_x and photochemical oxidants are of importance in urban areas where the highest concentrations are found. The rapid growth of urban population in developing countries, combined with the increasing volume of traffic in the cities, has already resulted in problems with "smog". Such problems are likely to increase as vehicle numbers rise. Indeed, current trends indicate that NO_x and oxidant emissions are increasing in urban areas throughout the world. There is evidence of increased respiratory disease, decreased lung function and frequent eye irritation in some urban populations as a result of exposure to NO_x and photochemical oxidants. The situation is complicated by the ubiquitous presence of SO_2 , suspended particulates and other air pollutants, thus making it more difficult to determine whether health effects are caused by NO_x , photochemical oxidants or a combination of these and other pollutants (WHO, 1977,1978). A nitrogen dioxide concentration of 940 µg/m³ has been selected as an estimate of the lowest level at which adverse health effects due to short-term exposure to nitrogen dioxide can be expected to occur. By adopting a minimum safety factor of 3-5, WHO (1977) pointed out that a maximum one hour exposure of 190-320 µg/m³ should be consistent with the protection of public health and that this exposure should not be exceeded more than once per month.

7.1.3. Hydrocarbons

Hydrocarbon species, especially C_1 through C_6 , have been found in the offgases of various retorts. Other aliphatic and aromatic hydrocarbons also occur, but in lower concentrations. Methane (CH_4) constitutes the bulk of hydrocarbons emitted from different retorting processes. Table 14 gives estimates of total hydrocarbon emissions encountered.

Table 14 Estimates of Hydrocarbon Emissions in Retort Gases.

	Uncontrolled Emissions (t/d)
Surface Retorting *	3.8-11.0
In-Situ Retorting *	2.7
Paraho Direct **	2.1
TOSCO II **	7.6

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* After Raufer and Yates (1980).
** After Fruchter et al (1983).
\- Calculated for production of 50,000 bbl/d syncrude.

The estimates given in Table 14 show that for Paraho (Direct) and in-situ retorts the emissions of hydrocarbons are lower than those encountered in indirectly-heated retorts. The higher the temperature of retorting, the lower the emissions of hydrocarbons will be (most of the hydrocarbons will dissociate to CO, CO_2, water vapour, etc).

7.1.4. Carbon Monoxide

Carbon monoxide (CO) is a product of incomplete combustion of carbonaceous fuels and is formed whenever carbon-bearing materials burn, if the oxygen furnished is less than that required to form carbon dioxide. Table 15 gives estimates of carbon monoxide emitted from different retorts.

Table 15. Estimates of Carbon Monoxide Emissions in Retort Gases.

	Carbon Monoxide Emissions (t/d)
Surface Retorting	0.82- 9.9
In-Situ Retorting	0.19

After Raufer and Yates (1980) for plants producing 50,000 bbl/d syncrude.

Environmental Impacts of CO Emissions:

The health significance of carbon monoxide as a contaminant of air is largely due to the fact that it forms a strong co-ordination bond with the iron atom of the protohaem complex in haemoglobin forming carboxyhaemoglobin (HbCO) and thus impairs the oxygen-carrying capacity of the blood. The dissociation of oxyhaemoglobin is also altered by the presence in blood of carboxyhaemoglobin so that the suppply of oxygen to tissues is further impaired. The affinity of haemoglobin for carbon monoxide is roughly 240 times that of its affinity for oxygen; the proportions of carboxyhaemoglobin and oxyhaemoglobin in blood are largely dependent on the partial pressures of carbon monoxide and oxygen. Carbon monoxide is absorbed through the lungs and the concentration of carboxyhaemoglobin in the blood at any time will depend on several factors. When in equilibrium with ambient air, the carboxyhaemoglobin content of the blood will depend mainly on the concentrations of inspired carbon monoxide and oxygen. However, if equilibrium has not been achieved, the carboxyhaemoglobin concentration will also depend on the time of exposure, pulmonary ventilation, and the carboxyhaemoglobin originally present before inhalation of the contaminated air. In addition to its reaction with haemoglobin, carbon monoxide combines with myoglobin, cytochromes, and some enzymes; the health significance of these reactions is not clearly understood but is likely to be of less importance than that of the reaction of the gas with haemoglobin (WHO, 1979).

There is general agreement that any individual should be protected from exposure to carbon monoxide that would result in carboxyhaemoglobin levels of 5 % for any but transient periods, and that especially susceptible persons ought not to be subjected to concentrations giving carboxyhaemoglobin levels exceeding 2.5 % (WHO, 1979).

7.1.5. Carbon Dioxide

Carbon dioxide is produced during oil shale retorting. The main source of CO_2 released is the carbonate minerals present in the raw shale. Low-temperature indirect retorting processes operate at temperatures near 500°C, which is not high enough to significantly calcine the carbonate minerals. On the other hand, high-temperature direct retorting processes operate at temperatures of 700°C to 1100°C - high enough to calcine carbonate minerals and liberate appreciable quantities of CO_2. In addition to creating the potential for carbonate decomposition, oil shale retorting releases CO_2 from the combustion of organic carbon (Coburn, 1983).

The amount of CO_2 produced by oil shale retorting varies widely depending on variations in the mineralogy and organic content of the shales and on the retorting technique. Shales rich in carbonate minerals will yield more CO_2 than carbonate-poor shales for the same retorting process. Fruchter et al (1983) estimated the amounts of CO_2 released during the retorting of the Green River Shales (carbonate-rich shales) as given in Table 16.

Table 16. Rates of CO_2 Released During Retorting of Oil Shales

	CO_2 (kg/bbl)	CO_2 (t/d)
Paraho Direct	154	7700
Union-B (Indirect)	72	3600
TOSCO II	49	2450
In-Situ Retorting	415-525	20750-26250

After : Fruchter et al (1983). Second column for 50,000 bbl/d.

Sundquist and Miller (1980) compared the amount of CO_2 generated by retorting oil shale and burning the produced syncrude with that generated by burning crude petroleum, natural gas and coal to give a fixed amount of usable energy (Table 17). The data given in that Table mean that, in general, one barrel of shale oil produced and burned produces twice the amount of carbon dioxide released from burning one barrel of crude petroleum. The production and consumption of 1 million barrels of shale oil per day would release 0.22×10^9 t to 0.62×10^9 t of CO_2 per year, while burning 1 million barrels of crude petroleum per day would release 0.15×10^9 t of CO_2 per year.

Table 17. Carbon Dioxide Emitted From Production and Use of Shale Oil as Compared to Other Conventional Fuels*

	CO_2 Emitted (kg/1 million kJ)
Oil Shale :	
- Oil produced by low-temperature retorting	110
- oil produced by high-temperature retorting	257-400
Crude Petroleum	77
Natural Gas	55
Coal	92

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* Recalculated from data given by Sundquist and Miller (1980). Oil shale referred to is Green River Shale (rich in carbonate minerals).

Environmental Impacts of Carbon Dioxide Emissions:

Carbon dioxide (CO_2) is a natural trace constituent of the Earth's atmosphere. The present mean concentration of CO_2 is around 340 ppm by volume (Kellogg, 1980). Carbon dioxide has a critical role in the global heat balance in that it is essentially transparent to the incoming solar radiation but absorbs the infra-red radiation emitted by the earth. This radiation trap causes a warming of the lower atmosphere which is known as the "greenhouse effect".

The global nature of the CO_2 problem arises from the combustion of fossil fuels which are being used at an increasing rate. From the mid-nineteenth century until 1977, CO_2 emissions have grown by 4 % to 5 % per annum and since 1977 have probably slightly slowed down to some 2 % per annum because of a slow down in fossil fuels consumption. Currently about

20 X 10^9 t of CO_2 are emitted annually from fossil fuel combustion compared to natural emissions of the order of 900 X 10^9 t (Bjorkstrom, 1979; Munn and Machta, 1979).

The impact of these emissions has been a steady increase in the atmospheric concentration of CO_2 from an estimated 260-300 ppm, to around 340 ppm in just over one hundred years- an increase of 12% to 30%. This corresponds to about half that expected if all the CO_2 stayed in the atmosphere and it is believed that the remainder enters the oceans. The trend of increasing CO_2 concentration has been recorded in many locations since the late 1950's. With the continued increase of CO_2 in the atmosphere it is estimated that the concentration will double within the next 70-80 years (Kellogg, 1980). The general effects of this doubling on the Earth's climate have been established through models, but there is uncertainty as to the exact magnitude and distribution of these effects. Calculations with three-dimensional, time-dependent models of the global atmospheric circulation indicate that a doubling of the CO_2 level will cause an average global warming of 1.5°C- 4.5°C with greatest increases predicted for the higher latitudes of the northern hemisphere (UNEP, 1984).

These increases in temperature may lead to effects such as altered precipitation and evaporation regimes, which could affect agriculture and the distribution of food resources. Effects on the oceans may also be significant, as changes in wind circulation would affect ocean currents, causing the relocation of nutrient-rich areas leading to the redistribution of marine organisms and the consequent elimination of some commercial fisheries. Ocean warming and ice cap melting may raise the sea level by the order of one metre (NAS, 1983).

Currently there is no evidence that there has been a CO_2-induced increase in the global temperature. The detection of such an effect is made difficult by the inherent variability in climate. In addition, predictions of the time when a global warming will be detectable are highly dependent on the assumed rate of heat exchange between different parts of the oceans.

Several approaches to control the CO_2 problem have been proposed (NAS, 1983; EPA, 1983; UNEP, 1984). The technical fixes which involve the collection and disposal of CO_2 are not considered to be practical or economical. Alternative energy systems which do not emit CO_2 might be developed to reduce the reliance on fossil fuels although such actions are currently considered to be of limited effectiveness and prohibitively expensive. Energy conservation is considered to be an important means of reducing CO_2 emissions from fossil fuels.

The relationship between oil shale development (as well as other synthetic fuels) and the global carbon dioxide problem should, therefore, be carefully assessed before embarking on large-scale development projects. The present rate of production of carbon dioxide from conventional fuels is about 20×10^9 t per year. If one million barrels of shale oil are produced and consumed each day in addition to present consumption of conventional fuels, the annual global production of CO_2 from fossil fuels would increase by 1 to 3 percent. If one million barrels of shale oil were substituted each day for the same amount of conventional oil in the present world-wide fuel mix, the corresponding increase in CO_2 production would be 0.5 to 2.5 per cent of the present annual global flux of CO_2 from utilization of fossil fuels (Sundquist and Miller, 1980). This increase in the global CO_2 budget would be accelerated if large-scale development of oil shale would take place using in-situ and/or high-temperature retorting.

7.1.6. Trace Elements and Compounds

The retorting of oil shale by surface or in-situ methods releases a number of trace elements and compounds in the gaseous phase, the most important of which are discussed in the following.

Arsenic :

Arsenic occurs in retort gases mainly as As_2O_3 and AsH_3 (Fruchter et al, 1983). The observed levels of arsenic trioxide and arsine range from 2 to 40 µg/m³ and from < 0.03 to 0.4 µg/m³, respectively. These levels correspond to daily releases in the untreated offgas of 1 to 20 g of As_2O_3 and from < 0.02 to 0.2 g of AsH_3 (for plants producing 50,000 bbl/d of syncrude).

Such levels of arsenic in the working environment may give rise to acute, subacute, and chronic effects. The adverse health effects of arsenic may involve the respiratory, gastro-intestinal, cardiovascular and nervous systems (WHO,1981). Arsenic has been associated with pulmonary cancer in some industries; it has been estimated that exposure to airborne arsenic levels of about 50 µg/m³ for more than 25 years would result in a nearly 3-fold increase in mortality due to lung cancer over the age of 65.

Mercury :

The retorting of oil shale by surface or in-situ methods will volatilize most of the mercury present in the oil shale. Fruchter et al (1978) have demonstrated that volatilization could be near 100 % for experimental retorts. A 50,000 bbl/d commercial operation, processing about 100,000 tonnes of shale per day containing 0.1 ppm mercury will volatilize 10 kg of mercury per day if the loss is complete (Klusman and Matoske, 1983). The fate of this mercury is somewhat speculative. Widespread dispersion in the atmosphere is possible depending on local weather conditions. Considerable adsorption of mercury by atmospheric particles and soils is most likely to occur. The impacts of such mercury emissions will be determined by a number of factors : availability of soil-adsorbed mercury, ability of plants to adsorb mercury, pathways taken by mercury and the possibility of synergistic and/or catalytic effects (in relation to other pollutants). Bio-transformation of mercury is particularly important in determining effects on man and other organisms (UNEP, 1981; El-Hinnawi and Hashmi, 1982).

Radon :

Raw oil shale contains the naturally occurring radionuclides of the Th-232, U-238 and U-235 decay series as well as K-40 and Rb-87. Of these, only the Th-232 and U-238 series are dosimetrically significant. It is reasonable to assume that until the raw shale is processed, the radioactive daughters of Th-232 and U-238 are in secular equilibrium, so that their concentrations can be computed from the concentrations of U and Th in the shale, the well-known abundances of Th-232 and U-238, and the appropriate decay constants. The emissions of uranium and thorium from oil shale processing are projected to be low because only a small amount of U- and Th-bearing particulate material escapes the retort vessel, and because much less penetrates the offgas processing systems.

Radon, however, is a noble gas trapped in shale. Upon grinding and retorting, all of the Rn-222 contained in the shale may be liberated. Given an average concentration of 4.7 ppm of U in shale, a processing rate of 1.02×10^6 g/sec for a 50,000 bbl/d plant, and the specific activity of U-238 (3.33×10^{-7} Ci/g), the activity release rate for the Rn-222 in equilibrium with U-238 is 1.6 µCi/sec (Fruchter et al, 1983).

The radioactivity released from a coal-fired power plant has been estimated at 1500 µCi per 1 MW(e)y (see, Chadwick and Lindman, 1982). Recalculated, this gives 0.047 µCi for 1 million kJ. Using the above-mentioned values given by Fruchter et al (1983), the radioactivity released to produce 1 million kJ from oil shale would be 0.46 µCi, which is about 10-times the amount emitted by burning coal. Although these figures will vary according to the type of coal or shale, processing, and burning technologies, etc, they illustrate that oil shale development could contribute radioactive emissions higher than coal for the same amount of produced energy.

Toxic and Geno-toxic Organic Compounds :

Polycyclic aromatic hydrocarbons (PAHs), their nitrogen heterocyclic analogues, and aromatic amines exist in the vapour phase at the temperatures of the retorting and combustion zones and, upon cooling, become associated with oil mist droplets, soot, and spent shale particles suspended in the retort offgas. To date, the available experimental data indicate that toxic organic compounds, including PAHs, are readily found in incinerated offgas from oil shale retorts. Ondov et al (1981) and Nautsch (1981), for example, made positive identification of over 75 compounds in 10 class groups in extracts of aerosol particles discharged into the atmosphere.

Removal of toxic and carcinogenic compounds such as benzo-a-pyrene (BaP) in retort offgas is dependent on the efficiency pf particulate and product oil collection devices, and on the efficiency of destruction in incinerators, flares or combusters. Current recovery schemes include condensors, electrostatic precipitators, cyclones, and mist eliminators. However, it is doubtful that the combined efficiency of particulate and product oil recovery can exceed 99.9 %. The remaining fraction of BaP will escape in a fine aerosol of oil droplets, soot, and spent shale particles.

7.2. LIQUID EFFLUENTS

7.2. 1. Wastewater

From the point of view of water management, the type of oil shale retort is quite important. One reason is that large quantities of water are evolved when shale is retorted, the actual amount depending on how the retort operates. A second reason is that some retorting processes require little or no cooling, while others must be cooled. The basis for the first reason lies in the fact that if the retort is heated directly, the water recovered from the retorting will be composed of the shale surface moisture, the thermal decomposition products of the carbonate minerals, and the water produced in the combustion. On the other hand, with indirectly heated retorts, the water in the combustion products is generally lost up the furnace stack (Probstein and Gold, 1978).

Relatively large quantities of foul process wastewater are produced when oil shale is retorted to produce shale oil. At surface retorting processes, wastewater is produced at about one-third the oil rate, while at in-situ operations it may be produced at as much as twice the oil rate (Table 18).

Table 18. Quantities of Process Wastewater Generated by Oil Shale Retorting

	bbl/bbl crude oil	m^3/day *
Surface retorting	0.3	2385
In-situ retorting	2.3 **	18285

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* For plant producing 50,000 bbl/d syncrude

** Of these, 1.6 bbl are gas condensates and 0.7 bbl retort water.

Recalculated from data given by Hicks and Probstein (1983).

The wastewater produced is contaminated with a range of potentially harmful contaminants that have proved difficult to control using conventional treatment technologies. Considerable effort has consequently been directed at developing processes to clean these waters, and it is now conceivable that with extensive treatment the water could be cleaned and rendered suitable for discharge or re-use at the oil shale plant (for example, for the management of spent shale; see later). Table 19 gives the chemical composition of process water resulting from a TOSCO II retort. It should be noted that the composition of the wastewater will vary according to the type of raw shale retorting temperature, etc. The values given in Table 19 show the high loads of organic compounds in the wastewater. A number of polycyclic aromatic hydrocarbons (PAHs) has been detected in retort wastewater; the most common include : pyrene, fluoranthene, benz-a-anthracene, chrysene, triphenylene, benzo-a-pyrene, benzo-e-pyrene and perylene. The concentration of PAHs varies up to 450 ppb (Coomes, 1980).

Table 19. Chemical Composition of Process Wastewater from TOSCO II Retort

Component	Concentration (ppm)	kg/day *
Calcium	280	667
Magnesium	100	239
Sodium	670	1598
Ammonia	15	36
Zinc	5	12
Arsenic	0.015	0.035
Chromium	2	4.7
Carbonate	360	859
Bicarbonate	100	239
Sulphate	850	2029
Thiosulphite	90	215
Phosphate	5	12
Chloride	570	1359
Cyanide	5	12
Phenols	315	751
Amines	410	978
Organic acids	1330	3172
Oil	960	2290

* For plant producing 50,000 bbl/d syncrude.
Pb,Mo, Se, Cu, Ni, Co, Fe, Mn, Hg may be present in amounts less than 1 ppm.
Recalculated from data given by NAS (1979 A).

The major classes of organic compounds that have been reported in shale oil wastewaters have a high vapour pressure and limited water solubility indicating a potential for their emission from a wastewater into the atmosphere. Unless shale oil wastewaters are treated to remove these volatile contaminants before reuse or disposal, these emissions could result in a source of air pollutants that is difficult to control, particularly if the wastewaters are widely distributed as in proposed co-disposal in open fields with retorted spent shale. Hawthore and Sievers (1984) have recently found that exposure of untreated shale oil wastewaters to sufficient amounts of air will result in the emission of large quantities of aromatic nitrogen-containing compounds (accounting for 40-78 % of the total emitted organics from wastewater), ketones (3-13 %), phenols (2-11 %) and nitriles (2-6 %). By contrast, wastewaters stored in closed systems emit approximately 3 orders of magnitude lower amounts of organic compounds into the static air above the wastewater.

7.2.2. Oil Spills

Oils derived from shale are generally richer in phenols, aromatic amines and other water-soluble organic classes than petroleum products. Spills of shale oil from pipelines, storage tanks, retort vessels, or transport vehicles may affect aquatic ecosystems differently and more severely than would spills of conventional oils. Giddings and Washington (1981) showed that the water-soluble fractions of shale oil were more toxic to algae than petroleum products, but less toxic than coal-liquefaction products.

Crude shale oil stands chemically between crude petroleum and coal tar. Its carcinogenicity is also in an intermediate position, being less carcinogenic than tar and more carcinogenic than petroleum. Coomes (1980) pointed out that crude shale oil contains a number of polycyclic aromatic hydrocarbons (PAHs), which are known to be carcinogenic. Table 20 gives the concentration of the main PAHs in crude shale oil and compares the concentration of benzo-a-pyrene (BaP) in shale oil with that of crude petroleum and coal.

Table 20. Concentration of PAHs in Shale Oil *

Compound	Concentration (ppb)
Pyrene	14,500 - 22,000
Fluoranthene	3,700 - 6,900
Benz-a-anthracene	2,000 - 4,500
Chrysene	5,350 - 6,850
Triphenylene	1,250 - 2,050
Benzo-a-pyrene	3,100 - 7,250
Benzo-e-pyrene	1,350 - 2,000

	Benzo-a-pyrene (BaP) (ppb)
Crude shale oil	3,200
Libyan Crude petroleum	1,320
Coal	4,000
Asphalt	10,000 to 100,000

* For TOSCO II, after Coomes (1980).

The carcinogenicity of Scottish shale oil was demonstrated in experimental animals as early as 1922. In the same year, a high incidence of skin and scrotal cancer was found among oil shale workers (Zone, 1980). Such incidence of cancer is parallel to the well-documented cutaneous effect of coal tar and pitch (see also Kahn, 1979).

Crude shale oil contains a number of trace elements, the most important of which include As, B, Cr, Co, Cu, Pb, Mn, Mo, Ni, Se, V, Zn, and Hg. The concentration of these elements varies markedly according to the type of raw shale and the retorting technology. Table 21 gives the concentration of some trace elements in crude shale oil produced by TOSCO II retort.

Table 21. Trace Elements in Shale Oil (ppm)

As	50
B	10
Cr	16
Cu	4
Hg	3
Pb	1
Ni	18
V	27
Zn	130

After NAS (1979 A).

7.3. SOLID WASTES

Oil shale retorting results in huge amounts of solid wastes, mainly as retorted or spent shale. Approximately 80 to 85 % of the raw shale remains as spent material after retorting. Table 22 gives the quantities of solid wastes generated from oil shale retorting.

Table 22. Solid Wastes Generated from Oil Shale Retorting *

Process	Mined Shale (t/d)	Solid Wastes (t/d)	
		Shale fines	Spent shale
Paraho Direct	107,940	5,000	87,500
Paraho Indirect	127,000	6,000	103,000
TOSCO II	116,300	-	98,000

* For plants producing 50,000 bbl/d syncrude.
Recalculated from data given by Probstein and Gold (1978).

Because of the expansion of the shale volume during retorting (the volume increases by 10 to 25 %; see NAS,1979 A), only part of the spent shale can be disposed of at the mine site, whether it is an underground or surface outcrop mine. The remaining shale must be disposed of above ground at suitable sites.

7.3.1. Properties of Spent Shale

The spent shale from the retorting process will vary in composition and texture, depending on the mineralogy and texture of the raw oil shale and on the retorting process. Spent shale may vary from a lumpy ash-like material resembling dry chunky peanut butter to a fine ash-like substance with a carbon residue that looks like grey talc powder. Table 23 gives the physical and chemical characteristics of spent shale (for TOSCO II process) as compared to normal soil.

Retorted shale contains nominal quantities of compounds, which range from soluble (e.g. sodium salts) to slightly soluble (e.g. calcium and magnesium compounds). The conversion of largely insoluble carbonates and other minerals to the more soluble forms depends on the retorting temperature.

Table 23. Physical and Chemical Characteristics of Spent Shale.

	Spent Shale (TOSCO II)	Soil
Clay %	17	29
Silt %	69	32
Sand %	14	39
pH (in paste)	8.6	7.7
Calcium (mmol/l)*	10	2
Magnesium ,,	38	0.7
Sodium ,,	212	0.6
Potassium ,,	20	0.5
Carbonates ,,	0.0	0.0
Bicarbonates ,,	4.2	5.2
Sulphates ,,	159	0.3
Chlorides ,,	5.5	0.5

* in saturated extract.
After Berg et al (1983).

Carbonates begin to decompose at 320°C, and at 850°C conversion is largely complete; heating rate and time are also important factors. Spent shale contains generally the same trace elements found in raw oil shale; most elements tend, however, to be more enriched in the spent shale with the exception of volatile ones, especially mercury (see Table 24).

As in the case of inorganic components, the concentrations of organic compounds in spent shale depend upon the characteristics of the raw oil shale, retorting temperatures, oxygen concentration, and reaction kinetics. Generally speaking, the concentration of organic material in spent shale will be much lower than that in the raw oil shale, although some compounds may remain unchanged or even become enriched in the spent shale. The latter is illustrated by the concentration of polycyclic aromatic hydrocarbons in raw oil shale and in the spent shale produced from TOSCO II retorting (see Table 25).

Table 24. Trace Elements in Spent Shale *

	Raw Oil Shale (ppm)	Spent Shale (ppm)
As	60.0	60.0
Be	1.0	1.2
B	63.3	54.0
Cd	1.3	1.5
Cr	41.7	53.8
Co	6.5	8.0
Cu	47.5	55.0
Pb	29.3	34.5
Hg	0.2	0.0
Mo	30.0	37.7
Ni	23.9	27.5
V	57.1	70.6
Zn	65.0	76.0

* For TOSCO II , after NAS (1979 A). Green River oil shale.

Table 25. Polycyclic Aromatic Hydrocarbons in Spent Shale (ppb) *

	Raw Oil Shale	Spent Shale
Pyrene	64	61
Fluoranthene	33	23
Benz-a-anthracene	13	27
Chrysene	36	30
Triphenylene	22	13
Benzo-a-pyrene (BaP)	14	28
Benzo-e-pyrene	16	18
Perylene	3	6

* For TOSCO II, after Coomes (1980). Green River oil shale.

7.3.2. Environmental Impacts of Spent Shale

The management of spent shale will have several impacts on land and water resources. Weaver (1974) indicated that about 20 to 35 ha per year will be required for permanent disposal of spent shale produced from a plant producing 50,000 bbl/d of syncrude. The water requirements for dust control and vegetation of spent shale have been estimated by different authors as shown in Table 26.

Table 26. Water Requirements for Spent Shale Management (in 1000 m^3/d) *

Probstein and Gold (1978)	
Paraho Direct	12.7
Paraho Indirect	4.9
TOSCO II	15.2
Penner et al (1981)	
Surface Retorting (Direct)	4.2-10.2
Surface Retorting (Indirect)	8.3-16.7
In-Situ Retorting	3.0- 5.3
Hicks and Probstein (1983)	
Surface Retorting	4.4-11.0
In-Situ Retorting	3.4

* For plants producing 50,000 bbl/d syncrude.

In spent shale management, concern has centered around the long-term physical and chemical stability of waste embankments and the impact on water quality from surface runoff, failure or leaching of waste embankments and subsequent effects of particulates, pH changes, salts, potentially toxic minor elements, and organic compounds. Adverse aquatic effects can occur from acid, trace element, organic, or sediment-laden runoff from strata exposed at the disposal site during spent shale disposal and reclamation. Some shales contain large quantities of saline minerals such as dawsonite, nahcolite, halite, etc. These salts are not removed during retorting, but remain in the spent shale, and represent in several ways a potential environmental problem during vegetation efforts (Fransway and Wagenet, 1981). Salts present in excessive amounts have adverse effects on plant establishment and growth, especially when concentrated in the root zone by evaporative fluxes of water. Adding excess water to the spent shale could leach the salts below the plant root zone, but if the water is improperly managed, it is possible that large quantities of soluble salts could be introduced into the groundwater system.

It has been suggested that a layer of soil be used as a surface cover over the spent shale. Successful implementation of this method requires that the net movement of water be downward to avoid transport of salts from the spent shale to the overlying soil. George et al (1981) found that cheatgrass (Bromus tectorum L.) plants are better grown on soil covering the spent shale. When soil and spent shale were mixed, cheatgrass growth was more successful than on spent shale alone. Topsoiling of spent shale may, however, be expensive. Berg et al (1983) estimated the cost for 30 cm topsoiling to be about \$ 0.02 to \$ 0.1 per barrel of syncrude produced from oil shale.

Reclamation of spent shale in arid and semi-arid regions faces several challenging problems. Shallow topsoil, harsh climate and limited water supply and low suitability of spent shale as a plant growth medium must be addressed if any reclamation plan is to be successful (McKell et al, 1984).

Kilkelly and Lindsay (1982) studied the distribution of boron, molybdenum, arsenic, selenium and fluorine in plants grown on spent shale. They found that the boron content of western wheatgrass grown on spent shale was significantly elevated compared with boron levels in plants grown on normal soil. The concentration of boron in western wheatgrass grown on spent shale, especially TOSCO retorted shale combined with other factors such as salinity and drought, could significantly affect the reclamation of retorted oil shales. The combination of molybdenum and copper levels in fourwing saltbush growing on retorted shale would make this shrub unsuitable as forage for ruminants. The concentrations of arsenic, selenium and fluorine in plants grown on spent shale are minimal and appear to be of little environmental significance.

On the other hand, Schwab et al (1983) studied the concentration of several potentially toxic elements (F, B, Mo, Pb, Ni, Co, Cd, Cr, Hg, Se and As) in plants grown on various depths of soil covering retorted (Paraho) shale. The concentrations of Mo and the Cu/Mo ratios in the plants indicate that molybdenosis could be expected with livestock grazing on revegetated plants. Increasing the depth of soil cover reduced the Mo levels, but a year later it was found that increasing the soil depth may only temporarily reduce the potential molybdenosis problem.

CHAPTER 8

THE ENVIRONMENTAL IMPACTS OF CRUDE SHALE OIL UPGRADING AND REFINING

Although physico-chemical properties vary with the type of retorting process used, all crude shale oils tend to be heavier than petroleum. Shale oils have pour points, viscosity and nitrogen content significantly higher than most crude petroleums. Thus oil shale plants would have upgrading facilities to reduce the viscosity and pour point of the crude shale oil, and to eliminate or reduce the sulphur, nitrogen and other undesirable components. In other words, upgrading would transfer the crude shale oil into a suitable feedstock (syncrude) for refineries.

Wastes from upgrading plants would be similar to those produced by similar plants associated with the petroleum industry. However, some differences might exist in the type and quantities of wastes, especially solid ones. The National Academy of Sciences (NAS, 1979 A) estimated the quantities of wastes generated from upgrading plants (for production of 50,000 bbl/d of syncrude) as follows :

Spent catalyst wastes	715 t/y
Diatomaceous earth	429 ,,
De-activated carbon	429 ,,
Caustic wash	875 ,,
Coke	300,000 ,,
Arsenic	105 ,,

These wastes may be mixed into and dispersed with spent shale (coke may be used in plant or sold). Upgrading produces also commercially valuable sulphur and ammonia.

Hicks and Probstein (1983) estimated the wastewater (sour water) produced by upgrading of crude shale oil at 0.4 bbl for each barrel of syncrude produced. In other words about 3000 m^3 of sour water are produced each day for a plant producing 50,000 bbl/d syncrude. No information is available about the composition of this sour water or techniques for its treatment and disposal. However, the composition would generally be similar to wastewater produced from similar facilities in the petroleum industry.

Giddings and Washington (1981) pointed out that upgrading of crude shale oil reduced its toxicity to algae; the toxicity of syncrude would be more or less similar to that of crude petroleum.

Upgrading of crude shale oil reduces also its carcinogenic potency (Coomes, 1980). The concentration of polycyclic aromatic hydrocarbons in crude shale oil and in upgraded oil (hydro-treated) is shown in Table 27. Most of the PAHs were greatly reduced, especially the ones known for their potentially carcinogenic effects (e.g. benzo-a-pyrene, BaP).

Table 27. Concentration of PAHs in Upgraded shale oil (in ppb)

	Crude Shale oil	Upgraded oil
Pyrene	14,500	17,500
Fluoranthene	6,900	980
Benz-a-anthracene	2,700	-
Chrysene	5,600	915
Triphenylene	1,250	-
Benzo-a-pyrene (BaP)	3,100	690

After Coomes (1980).

Environmental Impacts of Syncrude Refining

Syncrude produced by upgrading of shale oil will be similar in properties to crude petroleum, and could be refined in petroleum refineries. Therefore, the environmental impacts will be similar to those of petroleum refineries; these have been recently reviewed by UNEP (1981).

Refineries are large industrial installations with air and water emissions, large water requirements for processing and cooling and safety problems due to risks of explosion and fires. A 50,000 bbl/d refinery requires about 85 hectare of land for direct use and an additional 85 ha as exclusion zone (this is the area that surrounds the plant site where no resident population is allowed for safety - related reasons).

Table 28 gives the main airborne and liquid effluents resulting from a refinery processing a 50,000 bbl of syncrude per day.

Table 28. Emissions from Oil Refinery *

Airborne Effluents:	
Sulphur oxides	5.8 t
Organic compunds	6.3 t
Nitrogen oxides	5.0 t
Carbon monoxide	1.2 t
Ammonia	0.6 t
Liquid Effluents (3.8×10^4 t) containing:	
Chlorides	6.6 t
Grease	0.2 t
Ammonia Nitrogen	0.2 t
Suspended solids	0.5 t
Dissolved solids	28.0 t
Trace metals	0.005 t

* Recalculated from data given by UNEP (1981), for a 50,000 bbl.

It should be noted that technologies are available to reduce different emissions from refineries, and hence their environmental impacts. Such environmental protection measures must be taken, and continuous monitoring be implemented at and around refineries to serve as warning measures in case of leaks or emergency situation that require immediate attention.

Odour can be a potential nuisance in and around a refinery. The principal malodorous compounds existing in crude oil or formed during its processing into products are hydrogen sulphide and mercaptans. Should any of these escape from a refinery there is a risk of smell in the neighbourhood. Ethyl mercaptan has a perceptible smell when present in a concentration of only one part per thousand million; thus even a very small loss can create an unpleasant smell downwind under certain meteorological conditions.

Accidental spills at refineries can occur from stored crude oil or refined products. Such spills can affect different ecosystems in the vicinity of the refinery. It should be noted here that refined products are more toxic to aquatic organisms than crude oil (Giddings and Washington,1981). Some refined products are also more hazardous to health of humans than crude oil (WHO, 1982).

SUMMARY AND RECOMMENDATIONS

In the preceding chapters of Part II of this report a review of the environmental impacts of exploitation of oil shales has been given, on the basis of existing scientific information. The main findings of the review together with the research and development priorities identified are summarized in the following.

1. Oil shales occur in many countries and constitute an important source of energy that has, hitherto, been neglected. The proved recoverable reserves of oil from oil shales are estimated at about 52,000 million tonnes; the additional resources are estimated at about 300,000 million tonnes. The consumption of shale oil in the world was about 68 million tonnes in 1981 and by accelerated development of the oil shale industry, it could reach about 4000 million tonnes by the year 2000 (or about 33 % of the total commercial energy demand in that year). As a matter of fact, several studies indicate that synthetic crudes would constitute about 40 % of the total liquid fuels needed by the world in the year 2030.

2. Oil shales can be used directly as fuel, or can be processed by retorting (pyrolysis in a retort) with subsequent oil and gas production. Retorting can be carried out on the surface in a retort vessel or in the earth (in-situ retorting). Several technologies exist for both methods, the most common of which have been outlined in the present report.

3. Crude shale oil produced by different retorting processes are more viscous than high-quality petroleum crudes and contain higher amounts of nitrogen, particulate matter and arsenic compounds. Shale oils should, therefore, be upgraded into a syncrude (refinery feedstock) suitable for conversion to distillate liquid fuels. Upgrading units will constitute parts of integrated oil shale plants.

4. Oil shale development will have a number of impacts on land, water, air and on different biota. The magnitude of these impacts will vary from one place to another and will depend on the grade of the oil shale, the technology of its exploitation and the size of the processing plant.

5. The oil shale industry will require mining of huge amounts of oil shale. About 780 million to 950 million tonnes of shale (depending on the oil content of the shale) should be mined over a period of 20 years to feed a plant producing 50,000 bbl/day of syncrude. The area of disrupted land from mining operations will vary from one place to another, depending on the geological occurrence of the oil shale formation and its characteristics. The land requirements for a 50,000 bbl/day oil shale plant have been estimated at 80-100 ha/year (for open-pit mining) and at 4 ha/year (surface area for underground mining). The water consumption in shale mining and handling operations has been estimated at 27-305 m^3/hour depending on the technology of retorting to be used.

6. Mining of oil shale will have a number of potential impacts on aquatic ecosystems in the area (surface and groundwaters). Suspended solids and sedimentation will occur to some extent in water bodies receiving runoff or discharges from shale development sites. The addition of

such sediments to aquatic ecosystems will have a number of detrimental impacts on water quality and aquatic life. Pyrite-bearing shales will cause acidification of water (effects will be similar to those of acid drainage associated with coal), which in turn will cause the mobilization of some trace elements and affect aquatic life.

7. Oil shale mining will have a number of occupational hazards. The number of accidental deaths and disabling injuries has been estimated at 0.05 and 3.5 for a 50,000 bbl/day syncrude production if shale is extracted by underground mining. In the case of surface mining, the figures are 0.01 and 0.6 respectively. These values are much higher than in the case of production of 50,000 bbl of crude petroleum or in the case of mining coal to produce the same amount of syncrude through coal liquefaction. The high rates of accidental deaths and injuries in the case of oil shales are attributed to the fact that much larger amounts of oil shales are needed to produce the same amount of syncrude. A number of occupational diseases will be encountered in oil shale mining. Silicosis and oil shale pneumoconiosis (or shalosis) are of primary concern. Lung cancers and hypertrophic rhinitis were observed in some oil shale miners.

8. Oil shale retorting involves complex processes between solids, liquids, and gases and their mechanical, physical and chemical properties. A great deal of basic information and fundamental understanding is missing on many components of these complex processes. The detailed determination of the mineralogical, physical and geochemical properties of shales will give information that would lead to more efficient management of resources, and process control under environmentally acceptable retorting operations.

9. Oil shale retorting produces a number of air-borne emissions that should be controlled. Large quantities of SO_2 are produced mainly from the oxidation of H_2S and organic sulphur compounds that are emitted during retorting. If uncontrolled, such SO_x emissions will cause a number of undesirable effects in the environment in the vicinity of the oil shale plant. In addition, the long-range transport of SO_x and their oxidation to sulphuric acid aerosols and their subsequent washout in precipitation (acid rain) is of growing concern. Acid rain has caused acidification of fresh-water lakes in many countries (with consequent detrimental effects on aquatic life), destruction of vegetation and forests, soil degradation, damage of buildings and historical monuments,etc. Nitrogen oxides, hydrocarbons and carbon monoxide are also emitted during oil shale retorting. Their environmental impacts have been outlined in the present report.

10. Carbon dioxide is produced during oil shale retorting. The amount of CO_2 produced will depend on the composition of the shale and the retorting technique. High-temperature retorting (e.g. Paraho Direct) and in-situ retorting produce more than double the CO_2 amount produced by low-temperature retorting (e.g. Union-B or TOSCO II). In general, one barrel of shale oil produced and consumed produces twice the amount of carbon dioxide released from burning one barrel of crude petroleum. The relationship between oil shale development and the global carbon dioxide problem should, therefore, be carefully assessed before embarking on large-scale development projects. The present rate of production of carbon dioxide from conventional fuels is about 20×10^9 t per year. If one million barrels of shale oil are produced and consumed each day in addition to present consumption of conventional

fuels, the annual global production of CO_2 from fossil fuels would increase by 1 to 3 per cent. If one million barrels of shale oil were substituted each day for the same amount of conventional oil in the present worldwide fuel mix, the corresponding increase in CO_2 production would be 0.5 to 2.5 per cent of the present annual global flux of CO_2 from utilization of fossil fuels. This increase in the global CO_2 budget would be accelerated if large-scale development of oil shale would take place using in-situ and/or high-temperature retorting. The increase in global CO_2 concentration may cause world-wide climatic changes with subsequent wide environmental implications.

11. The retorting of oil shales releases also a number of trace elements and compounds in the gaseous phase. Arsenic, mercury, polycyclic aromatic hydrocarbons and aromatic amines are of particular concern. Research should focus on the transport and chemical transformation of these and other airborne pollutants which emanate from oil shale plants as they interact with other pollutants, catalysts, moisture, and sunlight within the ambient environment. The fate of such pollutants should be accurately determined to safeguard the environment.

12. Relatively large quantities of foul process wastewater are produced when oil shale is retorted. The wastewater produced contains a number of inorganic and organic compounds which are potentially hazardous. Research should focus on the detailed nature of these compounds and their persistence in the environment. Special attention should be devoted to develop technologies to reduce the amount of these contaminants in wastewater to acceptable levels, so that the wastewater could be disposed of or re-used (for example in the management of spent shale) without causing environmental deterioration.

13. Oils derived from shale are generally richer in phenols, aromatic amines and other water-soluble organic classes than petroleum products. Spills of shale oil from pipelines, storage tanks, retort vessels, or transport vehicles may affect aquatic ecosystems differently and more severely than would spills of conventional oils. Crude shale oil is more carcinogenic than crude petroleum, and a high incidence of skin and scrotal cancer was found among oil shale workers. Upgrading crude shale oil to a refinery feedstock reduces its carcinogenic potency.

14. There is a considerable lack of information on the health implications of oil shale development. Research is needed to characterize process streams and end products. The toxicity and carcinogenicity of different products should be studied in detail through animal testing. Dose-effect relationships need to be established to determine relative potency for various workplace chemicals as well as the mechanisms for activation, metabolism, and movement of pollutants on and across the skin barrier. Epidemiology is an important discipline with regard to occupational exposures. In addition to the development of epidemiological data bases in analogous technologies such as coke production, coal cleaning and processing, and oil refining, prospective morbidity studies need to be initiated utilizing information on existing workers in synthetic fuel facilities as the beginning of a registry. Standardized non-biased methods for analysis of epidemiological data need to be developed. As new syncrude plants are sited, an epidemiological data base should be initiated to assess whether the general public surrounding these plants face higher health risks than the population at large.

15. Oil shale retorting produces huge amounts of retorted or spent shale. In spent shale management, special attention should be devoted to ensure the long-term physical and chemical stability of waste embankments and the impact on water quality from surface runoff, failure or leaching of waste embankments and subsequent effects of particulates, pH changes, salts, potentially toxic minor elements and organic compounds. Adverse aquatic effects can occur from acid, trace elements, organic, or sediment-laden runoff from strata exposed at the disposal site during spent shale disposal and reclamation. Of critical concern is the effect of long term, chronic exposure of natural biota and agricultural crops to low levels of pollutants unique to the spent shale, especially to biotic systems (e.g. semi-arid desert biota and grass lands) which usually have not been stressed by man-induced pollutants. Several experiments have been undertaken to reclaim spent shale by growing certain species of plants directly on spent shale or on a soil layer covering the shale. It has been found that the growth of several species of plants is enhanced when the spent shale is covered by a soil cover. However, it has also been found that plants grown became enriched in certain trace elements, especially boron and molybdenum. The latter renders such plants unsuitable as forage.

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PART III

THE ENVIRONMENTAL IMPACTS OF EXPLOITATION OF TAR SANDS

PART III

THE ENVIRONMENTAL IMPACTS OF EXPLOITATION OF TAR SANDS

CONTENTS

CHAPTER 9

OCCURRENCE AND ENERGY POTENTIAL OF TAR SANDS

9.1. Definition of Tar Sands

Many attempts have been made to define tar sands, but there is no full consensus on the resources relevant to this term. Tar sands, oil sands, bituminous sandstone, oil-impregnated sandstone, etc. have been used to describe resources in different countries. The World Energy Conference (1980) defined tar sands (or bituminous sands) as those deposits of sand and sandstone that contain a high concentration of bituminous hydrocarbons, from which oil can be recovered by heating or other extraction process. Deposits of heavy oils and bitumens of higher density and viscosity that are not economically recoverable by conventional methods due to insufficient natural reservoir energy are also included.

However, the United Nations Conference on New and Renewable Sources of Energy (1981; document A/CONF.100/PC/26) defined tar sands as being any material such as unconsolidated sand, sandstone, limestone or other sedimentary rock containing oil with a viscosity greater than 10,000 centipoises under its underground conditions. The in-place oil has a very low mobility, and no significant primary production of it can be achieved. The density of the oil is usually 1.0 g/cm^3 or more (API gravity-about 10 degrees or less). Such oil is also known as " tar " or extra-heavy oil (Rühl, 1982). For comparison, normal crude oil has a specific gravity normally less than 0.900 g/cm^3 (API gravity higher than 25 degrees) and a viscosity less than 10,000 centipoises (Crabble and McBride, 1979).

In the present report, tar sands are defined according to the definition of the UN Conference on New and Renewable Sources of Energy (1981), but bituminous limestones have been excluded since most tar sands in the world consist of sandstones. Tar sands differ from oil shales by the fact that the organic matter is essentially soluble in petroleum solvents, while the kerogen of oil shales is insoluble.

9.2. Major Deposits of Tar Sands

From the geological point of view, the majority of the world's known large tar sands deposits are of Cretaceous and early Tertiary age. They were mainly formed in deltas or environments very near the shore; most tar sands are found in fluvial sandstone (UN Conference on New and Renewable Sources of Energy, 1981).

Numerous deposits of tar sands are known to exist in many countries, for example in Albania, Argentina, Ecuador, Egypt, France, Federal Republic of Germany, India, Indonesia, Iran, Italy, Madagascar, Nigeria, Romania, Senegal, etc., but data are very limited to allow reliable estimation of the tar sands resource base in the world. Major accumulations of tar sands that have been studied in detail are those of Canada, USA and Venezuela. These deposits are claimed to account for about 90 per cent of the tar sands deposits in the World (WEC, 1980; UN Conference on New and Renewable Sources of Energy, 1981). These deposits are described in the following :

9.2.1. Tar Sands in Canada

The tar sands deposits in the Province of Alberta in Canada are perhaps the largest in the world. They cover an area of about 50,000 km² and have a thickness of up to 60 metres. The overburden can be as thick as 700 m. There are four main deposits (UN Conference on New and Renewable Sources of Energy, 1981) :

	Oil in place (10^9 tonnes)
Athabasca	116
Cold Lake	25
Wabasca	6
Peace River	10
	157

About 10 per cent of the oil in place can be recovered economically by present technology. This is equivalent to about 16 X 10^9 tonnes oil. Rühl (1982) gave a range of 5 to 20 X 10^9 tonnes for recoverable oil from the Alberta tar sands. Heron and Spady (1983) indicated that the initial established oil reserves in tar sands were about 3.4 X 10^9 tonnes, of which cumulative production until the end of 1981 amounted to 40 X 10^6 tonnes (production in 1981 alone was 6.5 million tonnes). Two plants are currently operating in Canada to extract syncrude from tar sands : Suncor, Inc., with a production capacity of 57,000 barrels (about 8000 tonnes) per day and Syncrude Canada, Ltd, with a production capacity of 129,000 barrels (about 18,000 t) per day (Heron and Spady, 1983).

9.2.2. Tar Sands in the U.S.A.

In the U.S.A., substantial deposits of tar sands have been identified at about 500 locations in 22 States. The U.S.A. deposits (primarily in California, Utah, Kentucky, New York, New Mexico and Texas) are estimated to contain more than 5 X10^9 tonnes of oil. Utah deposits alone contain some 3.7 X10^9 tonnes of oil, of which about 0.7 X10^9 t are believed to be recoverable (U.S.A., 1981).

9.2.3. Tar Sands in Venezuela

The Orinoco Tar Belt, which is now called " Heavy Oil Belt " , is situated at the southern edge of the East Venezuelan Basin and measures 700 by 70 km in extension. The total belt area comprises 54,000 km². The tar sands deposits are not well evaluated but appear to lie at a depth varying between 200 and 1100 metres with sand thickness of about 30 metres (UN Conference on New and Renewable Sources of Energy, 1981). It should be noted that the specific gravity of the oil varies from 1.014 g/cm³ (i.e. extra-heavy oil) at the southern edge of the Belt to 0.965 g/cm³ (i.e. heavy oil) in greater depths and towards the north. This has led to variations in resource estimates. Values as high as 450 $X10^9$ tonnes of oil in place have been given for both extra-heavy and heavy oils (UN Conference on New and Renewable Sources of Energy, 1981; Rühl, 1982). But it is believed that the extra-heavy oil attributable to tar sands is mainly located at Cerro Negro; the oil in place is estimated to be 20 $X10^9$t.

9.3. The Energy Potential of Tar Sands Resources

Although some tar sands have been geologically appraised in detail, many others have been only partly described. This, besides the fact that there has been some confusion between what is really meant by tar sands (in some cases extra-heavy oils are confused with heavy oils not related to tar sand deposits) and asphalt deposits, etc has created great difficulty in estimating accurately the tar sands deposits in the world. Table 29 gives the known estimates of oil in place from different tar sands deposits in the world. By oil in place is meant total resources. The amount of oil to be recovered from such resources depends on the geology of the deposits, grade of the tar sands, technology used for oil recovery, etc. Recovery rates have

Table 29. Estimated Oil in Place from Tar Sands Deposits.

Deposit	Oil in place (10^9 tonnes)
Canada	
Athabasca	116
Cold Lake	25
Wabasca	6
Peace River	10
U.S.A.	5
Venezuela (Cerro Negro)	20
Nigeria	0.16
Malagasy	3
Jordan	0.70
USSR (Volga/Ural)	23
Total	208.9

Source : compiled from data given by WEC (1980); UN Conference on New and Renewable Sources of Energy (1981) and Rühl (1982). Heavy oils and asphalts are not included.

been estimated from 3 to 10 per cent of the oil in place. In other words, about 6.3 $X10^9$ t to 21 $X10^9$ t oil can be recovered from the known oil in place (208.9 $X10^9$ t as given in Table 29). It should be noted that this is the minimum amount of oil that could be recovered. It is possible that much higher quantities could be recovered, and this depends on development of technologies and on discovery of potential deposits of tar sands.

The United Nations Conference on New and Renewable Sources of Energy (1981) estimated that at present the total consumption of oil extracted from tar sands deposits amounts to about 28 million tonnes (about 0.5 per cent of the total world commercial energy consumption in 1981). By the year 2000, oil from tar sands may constitute up to 0.9 per cent of the total world commercial energy consumption (assuming that the total consumption in the year 2000 will be about 12,000 million tonnes of oil equivalent).

9.4. Mineralogical and Chemical Properties of Tar Sands

Tar sands consist mainly of fine-grained quartz sand and subordinate amounts of feldspar grains, clay minerals and accessory heavy minerals (e.g. garnet, amphiboles, etc). Pyrite and nodular marcasite are common in Athabasca tar sands, where iron oxidation products stain and indurate thick beds in many localities (Rühl, 1982).

Normally tar sands are unconsolidated, with their mechanical properties governed by the slightly interlocking nature of the grain contacts. However, in some deposits from U.S.A., the tar sands may be consolidated forming a sandstone, or a marly sandstone. An important feature of most tar sands is their high porosity, typically from 25 to 35 per cent, in contrast to the relatively impermeable character of oil shale.

In the Athabasca deposits of Canada, the sand grains are all in direct contact with one another, and wet with a thin layer of water a few micrometers thick that forms a continuous sheath. Filling the void volume among them is the bitumen, which forms a continuous phase through the pores. The bitumen is not in direct contact with the sand grains, being separated from them by the water layer. This hydrophilic nature of the sand grains renders the extraction of bitumen by hot water extraction easy (see Chapter 10). On the other hand, most deposits in the U.S.A.

do not have the water layer around the sand grains so that the bitumen adheres directly to the grains, a characteristic of importance in defining the extraction method.

Tar sands contain varying amounts of bitumen. Sands with bitumen in excess of about 10 per cent (by weight) are classed as good grade, while sands containing less than 5 per cent bitumen are not considered to be economically recoverable by present mining and extraction techniques (Humphreys and Schutte, 1978). The amount of bitumen in Alberta tar sands covers a range up to 18 per cent by weight. The largest and richest tar sands in the United States (Utah) have a bitumen concentration of up to 17 per cent.

Table 30 gives the chemical composition of bitumens from different tar sands.

Table 30. Composition of Bitumens from Tar Sands.

	C %	H %	N %	O %	S %
Athabasca	84.0	10.2	0.7	2.0	4.6
Peace River	81.7	10.0	0.1	2.1	5.6
Cold Lake	83.9	10.9	0.2	0.9	4.7
Wabasca	82.4	10.3	0.4	0.8	5.5
Utah Triangle	84.0	10.1	0.5	1.1	4.4
Venezuela	84.7	10.4	0.6	0.5	4.2
Crude Oil	82-87	11-15	0-1	---	0-10

Source : Rühl (1982); Probstein and Hicks (1982)
Heating value of Athabasca bitumen 41.3 MJ/kg.

Bitumens contain several trace metals. In the tar sands of U.S.A., the nickel content varies from 75 ppm to 120 ppm, and the vanadium content from 130 ppm to 500 ppm. In the bitumens of Venezuela, the nickel content varies from 50 to 140 ppm while the vanadium varies from 200 to 1,000 ppm (Rühl, 1982). Chromium, copper, molybdenum, magnesium and iron are also common traces in bitumens.

The bitumen that makes up the organic component of tar sands is of the petroleum family, and when separated from the sand, its decomposition by pyrolysis is similar to the cracking of petroleum crude. Slow thermal pyrolysis of Athabasca bitumen at 600°C produces an ultimate yield of about 77 per cent liquids, 16 per cent coke, and 7 per cent gaseous material. The corresponding values for a typical bitumen from the Tar Sand Triangle of southeastern Utah are 73, 22 and 5 per cent. The higher liquid yields are associated with bitumens of higher hydrogen content. These yields depend on the pyrolysis temperature and fall off sharply below about 425°C. The distillate is mainly paraffinic and the hydrocarbon gases are predominantly C_3 and C_4 compounds. The sulphur levels in the crude may be too high to be acceptable for conventional refining, and hydrocracking may be required.

CHAPTER 10

TAR SANDS TECHNOLOGY

Two options exist for the recovery of oil from tar sands: (1) mining of the tar sands followed by above-ground bitumen extraction and upgrading to a refinery feedstock; and (2) in situ extraction, in which the bitumen is released underground by thermal and/or chemical means and then brought to the surface for upgrading and processing (see, for example, Thomas, 1981; Probstein and Hicks, 1982; Penner et al, 1982; Heron and Spady, 1983). These options are described in the following.

10.1. Surface Recovery of Bitumen From Tar Sands

10.1.1. Mining of Tar Sands

Because tar sands deposits are generally unconsolidated, they are not structurally competent, and conventional underground mining methods are precluded. As a consequence, tar sands mining is carried out almost entirely above ground, although some underground hydraulic fracturing techniques to form a slurry which is then pumped to the surface have been investigated (Probstein and Hicks, 1982).

The economic feasibility of mining tar sands is dictated mainly by the overburden that must be stripped away to expose the tar sands for mining, and the thickness of the tar sand zone. Where the overburden is soft and unconsolidated, as in the Canadian deposits, surface mining is considered practical when the overburden thickness is 45m or less and the ratio of the overburden to tar sand zone thickness is less than 1 (Probstein and Hicks, 1982).

There are two schools of thought regarding the selection of mining equipment for tar sands mining. One approach is to use numerous small-scale units of a conventional design; the other is to use few specially designed, very large-scale equipment. Both the Suncor facility and the Syncrude Canada operations in Alberta, use speciality equipment. Suncor uses huge bucket-wheel excavators, and Syncrude uses giant electric draglines (Cox and Baughman, 1980). The amount of tar sands to be mined depends on the quality of the tar sands (bitumen content), but roughly two tonnes of raw ore must be mined for each barrel of synthetic crude produced.

10.1.2. Recovery of Bitumen

10.1.2.1. Hot Water Extraction

The hot water extraction process for the recovery of bitumen from tar sands was pioneered and developed by K.A. Clark in the 1920s (the method is sometimes referred to as the Clark Hot Water Extraction Process). Fig. 14 is a simplified flow diagram of this method. The tar sands feed is first conditioned with hot water to form a pulp of 60 to 85 per cent solids at about 90°C. Sodium hydroxide and chemical conditioners are added to control the pH and facilitate the subsequent separation of the bitumen from the sand. The conditioning is carried out in a horizontal rotating drum heated by steam. The layers of tar sands disintegrate in this process from the heat and mechanical action, the warmed layers sloughing off and exposing the cooler inner layers. The resulting slurry is screened to

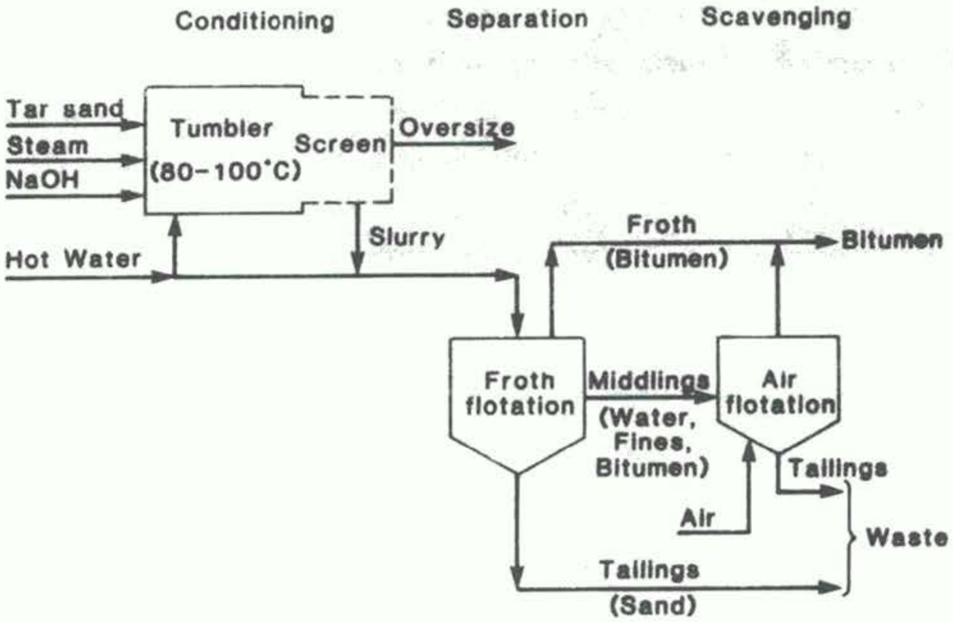

Fig. 14. Simplified Flow Diagram of Hot Water Extraction Process (after Probstein and Hicks, 1982).

remove rocks, clay, and lumps of oil sand, then pumped into separation tanks in which most of the bitumen rises to the surface as a froth. The sand sinks to the bottom of the tanks and is pumped away along with the excess water. Between the floating bitumen froth and the clean sand on the bottom is a mixture of clay, bitumen, and water called " middlings ". These are drawn off and put through a second froth flotation treatment to extract most of the remaining bitumen. The total recovered bitumen is then heated and diluted with naphtha to make it flow more readily, and put through two stages of centrifuging to remove coarse solids and clay and the remaining water. The clean bitumen is withdrawn from the centrifuge, run through a diluent recovery unit to remove the naphtha, then stored in heated tanks to await upgrading into synthetic crude oil. The recovered naphtha is returned to the process and added to more raw bitumen. The sand, clay, water and small amounts of bitumen remaining are called " tailings ". They are pumped to tailings ponds where the solids are allowed to settle out and the clear water is recycled.

At present, the hot water extraction process is used on a commercial scale in two plants in Canada (Suncor and Syncrude, Ltd.). At both plants, approximately 93 per cent of the bitumen originally in the tar sands is recovered by the hot water extraction process (Thomas, 1981; Probstein and Hicks, 1982; and Heron and Spady, 1983).

10.1.2.2. Cold Water Extraction

Because of the large energy requirement for heating in the hot water extraction process, a cold water extraction process would be desirable. In this procedure, the tar sand is broken up, kerosene is added in equal mass to the bitumen, and then water is added in an amount 2 to 3 times the mass of bitumen. After the addition of chemicals for pH control and a wetting agent to enhance separation, the mixture is agitated and the sand is separated from the bitumen by the shearing action that takes place. This method has been tested only at the pilot scale (Probstein and Hicks, 1982).

10.1.2.3. Solvent Extraction

In this procedure, the bitumen is dissolved by mixing a light hydrocarbon solvent with the tar sands and then draining the resulting mixture from the sands. The mixture is then pumped to a vessel where the solvent is recovered by distillation and recycled. The principal limitation of the method is that the solvent has a higher value than the bitumen so that a large fraction of it must be recovered if the process is to be economical. Separation of the solvent from the bitumen by thermal stripping is straightforward, although it can be energy intensive. The recovery of the residual solvent physically entrained in the waste sand interstitial void volume is considerably more difficult. The solvent that is not drained from the sand is usually a volatile hydrocarbon and can be driven off and recovered by heating the sand. This results in a substantial energy loss because of the need to heat the waste sand itself, from which it is not possible to recover all of the heat. Solvent extraction processes have been tested on small pilot plant scale on both Canadian and U.S. tar sands. However, because of the high solvent recovery requirements it is unlikely that a pure solvent extraction process is economically viable (Probstein and Hicks, 1982).

10.1.2.4. Direct Coking (Fig. 15)

A method for recovering the bitumen from tar sands that is most similar to the retorting procedures for shale oil recovery is that of direct coking. The method has the advantage that in a single, relatively simple pyrolysis operation an upgraded synthetic crude product is produced directly. One procedure employing indirect heating, that has been tested in Canada, is the fluidized-bed coking technique. In this method, the tar sand is pyrolyzed in the coker at 480°C with the heat supplied by clean sand from which the coke has been burned off. In the coker, the volatile matter is distilled from the tar sand with coke being deposited on the sand grains by thermal cracking. The coked solids are then fluidized with air and transferred to the burner, which operates at about 760°C. Part of the hot sand (20 to 40 per cent) is rejected, with the remainder transferred to the coker and fluidized by the pyrolysis off-gases. The principal disadvantage of this technology is the need to handle a large quantity of solids in relation to the bitumen pyrolyzed. A mass ratio of sand to oil in the coker is reported to be about 35. This value results from the need to have a large re-circulation rate of hot sand to the coker to raise the coker temperature. A pyrolysis process using indirect heating that has been suggested as being applicable to the direct coking of tar sands is the Lurgi-Ruhrgas process used for oil shale retorting.
Since direct coking processes do not require water, they should be most appropriate for processing Utah tar sands which are not water-wet and which are found in arid regions (where there would be lack of water for the hot water extraction process). Although pilot experiments have been carried out on direct coking of tar sands, the technology

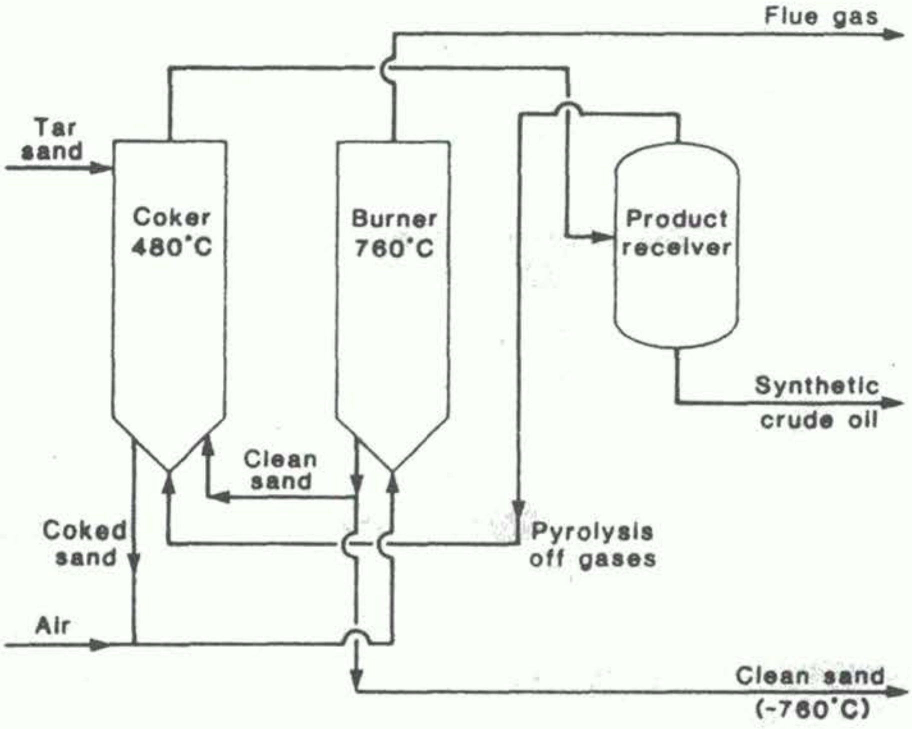

Fig. 15. Direct Coking of Tar Sands
(after Probstein and Hicks, 1982).

is still far from being commercially viable (Penner et al, 1982; Probstein and Hicks, 1982).

10.2. In-Situ Recovery of Bitumen from Tar Sands

Recovery of the bitumen from deep tar sands deposits requires the use of in-situ methods. These methods are generally considered appropriate where the overburden depth is greater than 200 to 300 m. In the recovery operation to drive out the bitumen, a minimum depth is necessary to contain the pressurized fluids injected. The tar sands zone should also be of a minimum thickness in order that the recovery operation be economical; the tar sands zone should be more than 15m thick (Probstein and Hicks, 1982).

Because of their depth, the exploitation of much of the U.S.A. and Canadian tar sands (and also other deposits) will undoubtedly require the development of in-situ technologies. No commercial plant is presently in operation, although ESSO Resources Canada, Ltd, is proposing to build an in situ plant in Alberta's Cold Lake deposit to produce 140,000 barrels per day of synthetic crude oil.

In-situ methods for the recovery of tar sands bitumen are for the most part similar to those employed in the enhanced recovery of conventional crude oil. Most of the current approaches involve heating and pressurizing the deposit. Heating reduces the bitumen viscosity until at 120 to 150°C it will flow freely, so with pressurization it can be easily driven out of the deposit. The thermal methods include injecting steam into the deposit alone or in conjunction with hot water, and combustion of the tar sands. Solvent extraction may also be used to reduce the bitumen viscosity in place, although solvent losses in the deposit generally make this procedure economically unacceptable as is the case in above-ground processing, though solvent extractants may be used as aids in thermal processing. The tar sands formations have porosities of 25 to 40 per cent, so they are sufficiently porous to enable fluids to flow through them under relatively small pressure gradients. At reservoir conditions, however, the permeability is greatly reduced because of the immobility of the bitumen filling the void spaces (Cox and Baughman, 1980; Probstein and Hicks, 1982).

10.3. Upgrading of Bitumen Into a Refinery Feedstock

Crude bitumen recovered from tar sands has a high viscosity and pour point. It cannot be transported by pipelines and must be upgraded into a suitable refinery feedstock. Existing tar sands plants include units for upgrading bitumen.

Many alternative schemes for upgrading bitumen have been investigated and developed. Most follow the same general pattern. The first upgrading step is to convert the non-distillable residue to a distillate which can be further processed. The second step, generally hydrogen treating, converts the distillate to an acceptable product mix and removes objectionable sulphur and nitrogen compounds. The final products are then recombined as synthetic crude oil (refinery feedstock). Both of the operating Canadian plants (Suncor and Syncrude) and most of the proposed ones employ coking followed by hydro-treating to upgrade bitumen.

Two different methods of coking are employed in the two commercial tar sands plants currently in operation in Alberta. These are described in the following (see Thomas, 1981; Heron and Spady, 1983).

10.3.1. Delayed Coking

Delayed coking is the process used by Suncor, Inc., Canada, for upgrading bitumen into a syncrude suitable as a refinery feedstock. Suncor uses three conventional delayed coker units in its upgrading plant. Each consists of a heater and a pair of drums. Bitumen is introduced into the drums and retained for seven hours at thermal cracking temperatures. The heat cracks the molecules into vapours and solid coke. The coke is deposited in the drum, along with much of the sulphur and virtually all of the trace metals. After the process is completed, the coke is removed from the drum by high pressure water jets. Bitumen is then reintroduced into the drum and the process begins again. The coke that has been removed is dumped into a hopper, crushed, and moved by conveyor belt to the boiler plant to be used as fuel. Surplus coke is stored on site for sale. The vapours from the coking action pass overhead into a fractionating tower where they are separated by distillation into four main components : (a) light process gas; (b) naphtha, the portion that can be upgraded into gasoline; (c) kerosene, which produces jet fuels and (d) gas-oil, the heaviest component which is used as a heating fuel or which may be further upgraded. The three liquid products of the coker still contain sulphur and nitrogen which are removed by treatment with hydrogen in " Unifiners ". The hydrogen combines with the sulphur and nitrogen to form gases that are drawn off, leaving purified naphtha, kerosene and gas-oil. These products are then stored separately until they are blended later for shipment as synthetic crude oil.

10.3.2. Fluid Coking

Fluid coking is used by Syncrude, Ltd, Canada, to upgrade bitumen into a synthetic crude oil. The coke produced in the Syncrude operation has the consistency of very fine sand that permits it to flow between the two units of the fluid coker- the reactor and the burner. Heated coke from the burner moves to the reactor where it forms a bed of hot particles at 520°C. Preheated bitumen is sprayed onto the hot coke bed. The heavy molecules crack, producing light molecules and more fluid coke. About 40 per cent of the coke produced in the process is used in the coker burner and the remainder is withdrawn and stockpiled. The light molecules in the form of vapour are cleaned of coke and heavy hydrocarbons as they leave the coker. As at Suncor, they are then separated in a fractionator. Syncrude's fluid coking process produces only three fractions-process gas, naphtha and gas-oil. Process gas is treated with hydrogen to remove sulphur and nitrogen, then used as a fuel. The liquid products-one-third naphtha and two-thirds gas-oil- are cleaned of sulphur and nitrogen in catalytic hydro-treating units. Although fluid coking yields 10 per cent more liquid products from the bitumen than does delayed coking, they are heavier and require more severe hydrotreating to ensure their stability and to prevent them from forming more viscous compounds.

Table 31 gives the characteristics of crude bitumen separated from Athabasca tar sands and the syncrude produced from the bitumen by upgrading using delayed coking.

Table 31. Properties of an Athabasca Bitumen and Synthetic Crude Oil from Suncor Plant, Inc.

	Original Bitumen	Synthetic Crude Oil
Elemental Analysis (Wt %)		
Carbon	83.4	86.3
Hydrogen	10.4	13.4
Nitrogen	0.5	0.02
Sulphur	4.5	0.03
Oxygen	1.2	--
Hydrocarbon Type (Wt %)		
Asphaltenes	19.0	--
Resins	32.0	--
Aromatic oils	30.0	21.0
Aliphatic oils	19.0	79.0
Trace Metals (μg/g)		
Vanadium	250	0.01
Nickel	90	0.01
Iron	75	--
Copper	5	0.02
H/C atom ratio	1.50	1.86
Gravity (°API)	6.5	37.6
Specific Gravity	1.025	0.837

Source : Probstein and Hicks (1982).

10.4. Assumptions for the Assessment of the Environmental Impacts of Tar Sands Development

Tar sands development will have a number of impacts on land, water, air and on different biota. The magnitude of these impacts will vary from one place to another and will depend on the grade (bitumen content) of the tar sands, the technology of its exploitation and the size of the processing plant.

In discussing the environmental impacts of the different steps of the tar sands exploitation (i.e., from the mining of the tar sands to the extraction, upgrading and refining of the syncrude), the production of 50,000 bbl/day of syncrude has been taken as a basis for the quantification of resources required and of the different environmental impacts. Fig.16 gives the material balance for the production of 50,000 bbl/day (or 6944 t) of syncrude from tar sands using the hot water extraction process.

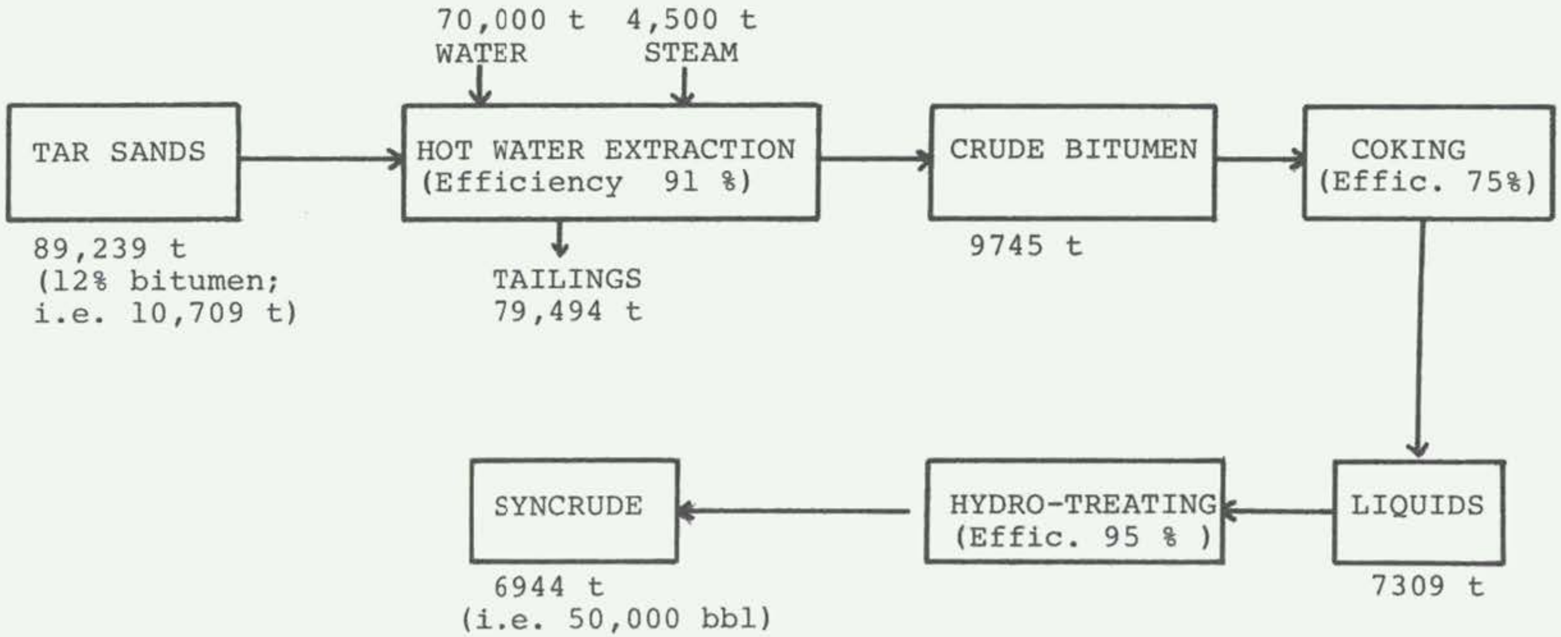

Fig. 16. Material Balance for Production of 50,000 bbl of Syncrude from Tar Sands using Hot Water Extraction Process (Calculated from Data Given by Probstein and Hicks, 1982 and Rühl, 1982).

Heat Content of Crude Bitumen : 39 MJ/kg
Heat Content of Syncrude : 42.5 MJ/kg

CHAPTER 11

ENVIRONMENTAL IMPACTS OF TAR SANDS MINING

The amount of tar sands to be mined depends on the quality of the tar sands (bitumen content). The size of the mine varies according to the geological setting of the tar sands deposits, especially on the thickness of the overburden to be removed to expose the tar sands formation. In Canada, it has been estimated that about 5 tonnes of tar sands and overburden must be handled on the average for each barrel of syncrude produced (Penner et al, 1982). In other words, a plant producing 50,000 bbl of syncrude would require the handling of 250,000 t of material (about 89,000 t of tar sands and the balance is overburden).

The amounts of tar sands to be mined are much higher than, for example, those of coal used for the production of the same amount of syncrude (about 15,000 tonnes of coal are required to produce 50,000 bbl/day of syncrude through liquefaction). For a 20-year lifetime of a tar sands plant (producing 50,000 bbl/day syncrude), the amount of tar sands to be mined is about 650 million tonnes. Mining this huge amount of tar sands will undoubtedly have several potential environmental impacts. These are discussed in the following.

11.1. Impacts of Tar Sands Mining on Land

Tar sands are mined by open-pit (or surface)mining , and this exerts potential impacts on land. The area of disrupted land will vary from one place to another, depending on the geological occurrence of the tar sands formation and its characteristics (especially the nature and thickness of the overburden). The mining operation at the Syncrude Plant in Canada covers an area of 25 km² ; the overburden thickness is 15 m and the tar sands formation is 42 m deep (Penner et al, 1982). The overburden removed must be dumped somewhere, and reclamation of such strip-mined areas has become a necessity to restore land and minimize environmental damage.

11.2. Impacts of Tar Sands Mining on Water

In the extraction and handling of tar sands for delivery to the bitumen extraction plant, dust is generated at different stages. Water may be required to control such dust. Probstein and Gold (1978) estimated the amount of water to control dust in surface mining of shale to be about 120 m³/hour for mining an average of 100,000 tonnes. In the case of tar sands, if we assume that about 5 tonnes of overburden and tar sands are mined for each barrel of synthetic crude produced (Penner et al, 1982), then the amount of water required to control dust would be about 300 m³/hour for a plant producing 50,000 bbl/day of syncrude.

Mining of tar sands may have some potential impacts on aquatic ecosystems in the area (surface and groundwaters). Suspended solids and sedimentation will occur to some extent in water bodies receiving runoff or discharges from tar sands development sites. Impacts to aquatic ecosystems from sediment addition include reduced light penetration and consequent inhibition of photosynthesis and primary production, interference with food acquisition, reproduction, and habitat selection, and physical abrasion of aquatic biota (Eddlemon and Tolbert, 1983). Some tar sands (or the overburden removed) contain high amounts of pyrite (FeS_2), the oxidation of which on exposure to air and water leads to the formation of " acid drainage " which will affect different ecosystems (increase in the acidity of soils and water bodies, mobilization of trace elements from sediments, toxic effects on aquatic organisms, etc.).

11.3. Occupational Hazards

There are two kinds of occupational hazards that might be encountered in mining tar sands : accidents and occupational diseases. In surface mining, the accident fatality rate has been estimated at 0.1 deaths per 1 million tonnes of mined rock and the accidental non-fatal disabling injuries at 5.5 per 1 million tonnes of mined material (UNEP, 1981). Using these values, and assuming that 250,000 t of material (tar sands and overburden) are mined for the production of 50,000 bbl of syncrude, the estimated accidental fatality rate would be 0.025/50,000 bbl of syncrude, while the estimated accidental disabling injuries would be 1.4/50,000 bbl of syncrude. These estimates are much higher than those associated with the production of 50,000 bbl of crude petroleum (estimated accidental deaths, 0.0001 and disabling injuries, 0.012 ; see UNEP, 1981), or with the production of coal to produce the same amount of syncrude by liquefaction (estimated accidental deaths from surface mining 0.0015 and disabling injuries, 0.08; see UNEP, 1981)

In tar sands mining, workers are exposed to dust during the extraction of the rock. The first concern of industrial hygienists would be the possibility of high rates of incidence of silicosis. Although it might be assumed that the incidence of silicosis may be similar to normal sand quarries, it should be noted that in the case of tar sands, the presence of free silica must be considered along with the presence of the organic content (bitumen). Silicosis is caused by very small particulates (< 5 µm in diameter). The percentage of such particulates in dusts from tar sands quarries might be considerably less than that in dusts from ordinary sand quarries, since in the former most sand particles are adhered together by bitumen and are not easily liberated during mining. This may lead to lower rates of incidence of silicosis in tar sands mining (per unit of produced sands). On the other hand, bitumen could trigger synergistic effects resulting in more complex lung diseases. Bitumen is also known to contain several polycyclic aromatic hydrocarbons which are carcinogenic (WHO, 1982).

CHAPTER 12

ENVIRONMENTAL IMPACTS OF BITUMEN RECOVERY FROM TAR SANDS

12.1. Surface Recovery

It has been pointed out in Chapter 4 of this report that there are several methods for the recovery of bitumen from tar sands. One method, the hot water extraction process, is used on a commercial scale in Canada. A major environmental concern related to this process is the management of the tailings from the extraction plant.

At the Suncor tar sands plant, the extraction plant tailings were disposed in a tailings pond constructed immediately adjacent to the Athabasca River. A starter dyke was constructed along an island in the river and across a small channel. The dyke was subsequently raised with the coarse fraction of the tailings stream to form a structure that would contain sludge and fines. This pond was designed to store tailings until sufficient space became available in the mined-out area to allow for in-pit disposal. Recently, Suncor has commenced disposal of tailings in the pit. A large dyke composed of overburden material was constructed across the pit to form the first in-pit pond. Continued in-pit disposal will be accomplished by construction of a series of overburden dykes as mining progresses. Approximately 1500 litres per second of tailings in the form of water (50 %), bitumen, sand, silt and clay are pumped by multi-stage centrifugal pumps to the disposal area. Clarified water is recycled to the extraction plant for use as make-up water (Thomas, 1981).

Syncrude Canada Ltd. selected a large area within the Beaver Creek Valley north of the plant site for the disposal of tailings. The site covers an area of approximately 2800 ha and has a volume sufficient to contain at least eight years of tailings. When sufficient space becomes available in the pit, tailings will be diverted to the mined-out area. Sludge and water from the in-pit disposal area will be pumped to the main tailings pond in the Beaver Creek Valley. Prior to in-pit disposal of tailings, a portion of the mined-out pit will be used to store overburden. At full production, the Syncrude extraction plant will generate approximately 103 million m^3 of tailings per year of which approximately 48 million m^3 is water to be recycled through the extraction plant (Thomas, 1981).

The disposal of tailings requires large areas of land. In-pit disposal will not be enough and additional areas will be required. This is because in the bitumen extraction process, the volume of tar sands becomes greater. One cubic metre of original tar sands (normally compact) yields 1.4 m^3 of loose sand tailings after the bitumen extraction (Penner et al, 1982; Boehm and Golosinski, 1983).

The large areas of the settling ponds are of major concern. Local micro-climatic effects may be triggered by water evaporated from such ponds. A problem that has been identified in the Athabasca area in Canada is the production of " ice fogs " from the large tailings ponds. These " ice fogs " are generated in very cold environments (-30°C and below) when exposed water surfaces are available, or when water vapour is otherwise released.

It should be noted that the water released from the bitumen extraction plant with the tailings is contaminated with various material. The settling of fine suspended material from the water in the ponds is retarded by the chemical additives and high mechanical energy input to the hot water extraction process. As a consequence, the suspended particles form a deep layer of sludge that limits the volume of clear water; this requires continuous enlargement of the settling volume to accomodate expansion of the sludge layer. New technology is required to eliminate either the tailings pond sludge layer or, preferably, the ponds themselves. One such technology is the dry retorting of tar sands (e.g. the Lurgi-Ruhrgas process), which is largely insensitive to the grade of tar sands feed and is capable of generating dry tailings (Heron and Spady, 1983).

The water from the bitumen extraction plant is also contaminated by a number of inorganic and organic compounds. Sulphur in tar sands bitumen is present mainly as organic sulphur compounds. Also, trace metals in the bitumen are present as complex metallo-organic compounds, e.g., porphyrins and salts of organic acids. In the hot water extraction process, some of these compounds react with the water and become partly hydrolyzed. The effect of this is to make the tailings pond water toxic to aquatic life, and hence unsuitable for discharge into natural water bodies. Furthermore, some bitumen remains in the tailings and a thin slick of bitumen and lighter hydrocarbons form on the surface of the tailings pond. This slick may pose a hazard to water-associated birds that alight on the pond, through bitumen-fouling of feathers.

In a study that involved the discharge of tailings sludge into a small part of a river in northern Alberta, Canada, a 60 % reduction in the standing stock of benthic invertebrates occurred throughout a four-week period in the immediate area of spillage. The material affected the benthic invertebrates and other aquatic life in two basic ways : (1) through the toxic effects due to the organic and inorganic compounds, and (2) by covering breathing, feeding or living surfaces with fine particles (Hupka et al, 1984).

The currently accepted solution to the problem of tailings water is to design " zero-discharge " plants, with the tailings water being impounded and recycled through the bitumen extraction plant to the maximum extent possible. Experiments have shown that natural flocculation and settling of fine particles in a low alkalinity environment is fast and after 10-20 minutes, 90 % of the water can be recycled. The very fine sand remaining in the recycled water is lower than 500 mg/l (Hupka et al,1984). Water recycle had no deleterious effect on the separation efficiency despite the slight increase of dissolved and suspended matter in the recycled aqueous phase. Loss of water from the tailings ponds of such plants may result from evaporation, inclusion of water in deposited sludge on the bottom of the ponds and from seepage through dykes constituting the walls of the ponds or through the ground below the pond. The latter may cause contamination of groundwater in the area.

The spent tar sand (tar sands tailings) consists mainly of sand, silt and clay contaminated with some remaining bitumen and caustic compounds that were used in the bitumen extraction process. The reclamation of such spent tar sands constitutes a major difficulty in the environmentally-sound management of tailings. Some attempts have been made to grow some foliage on spent tar sands after their treatment with fertilizers and additives (Mossop, 1980). Covering the spent tar sands layers with soil (as suggested for reclamation of spent shale after oil shale retorting) could provide a satisfactory solution for growing a variety of plants and, hence, rehabilitation of strip-mined areas and spent tar sands.

12.2. In-Situ Recovery

In-situ recovery of bitumen from tar sands offers much less potential surface impacts than surface recovery. Some vegetation would normally need to be cleared and the ground graded to accomodate equipment installations, but only relatively small areas would be affected. Surface operations can be conducted so as to avoid or minimize interference with concurrent land usages such as livestock grazing or agricultural activities. Produced sand and drilling cuttings would constitute the main solid wastes associated with in-situ operations. The sand that would be produced could be separated from the bitumen and probably discharged into a pit that would later be backfilled. The cuttings produced from the drilling operations could also be disposed of by procedures commonly employed in the oil production industry by burying in a pit and backfilling at the completion of the drilling operations.

Land subsidence and induced seismicity are two potential effects associated exclusively with in-situ operations. The impact of any subsidence produced by commercial in-situ tar sands operations will depend on the land use surrounding the site. For the most part, subsidence represents a localized effect that can be controlled effectively by proper site selection and operating practices. Seismicity may result from the high-pressure injection of fluids and resulting lubrication of fault planes in a tar sands formation. It is also conceivable that thermal stresses in the formation may cause seismic events. Unless unusual conditions exist in the formation, the potential environmental effects from induced seismicity should be insignificant.

Various airborne emissions are associated with in-situ recovery of bitumen from tar sands. The volume of the emitted gases depends mainly on the quality of the tar sands, the production mechanism and the characteristics of the bitumen in place. The airborne emissions would usually contain varying amounts of sulphur compounds (SO_x, H_2S, etc), nitrogen oxides, carbon dioxide, carbon monoxide and hydrocarbons. The environmental impacts of these emissions have been reviewed in detail by UNEP (1981) and in the first part of this study (see report on the environmental impacts of exploitation of oil shales).

The gaseous emissions produced in conjunction with in-situ bitumen recovery from tar sands will probably be very lean and lack sufficient heating value to justify collection and processing for marketing. They might be either vented to the atmosphere or combusted further to completely oxidize the carbon monoxide, hydrogen sulphide, and methane. Other airborne emissions associated with in-situ recovery are the exhaust discharges from diesel or gasoline-powered equipment and dust generated from vehicles travelling the access roads.

12.3. Upgrading of Bitumen

Upgrading operations at a tar sands plant are the primary source of airborne emissions. The compound that has provoked the most active debate in Canada is sulphur dioxide, but particulate matter, hydrocarbons, trace elements (especially vanadium and nickel) and other substances potentially emitted from a bitumen upgrading plant are also of concern.

Rom and Lee (1983) estimated the amounts of emissions from an upgrading bitumen plant as follows (re-calculated for the production of 50,000 bbl of syncrude) :

	kg emitted
Carbon monoxide	900
Hydrocarbons	29000
Nitrogen	16000
Particulates	22000
Sulphur Oxides	5800

12.4. Health Aspects of Tar Sands Development

12.4.1. Occupational Health

The risk of morbidity and injury to workers operating commercial surface or in-situ tar sands plants could be significant. Information from other industries such as oil refineries, shale-oil production, coking, and coal conversion indicates that exposure of workers to chemical compounds similar to those expected from tar sand oil extraction can lead to toxic, mutagenic or carcinogenic effects.

A preliminary estimate of the cancer risk for workers at a tar sands facility was computed using carcinogenic risk estimates for coke and oil refinery workers (Daniels et al,1982). The maximum risk of excess cancer deaths per plant-year (plant producing 50,000 bbl/day) for tar sand technologies based on this calculation is about 0.045. This is probably a very conservative figure as the exposure in a modern tar sands facility will probably be much less than past exposure in the reference industries because of the availability and increasing use of protective devices (e.g. respirators and protective clothing). Other problems detected at tar sands facilities in Canada involved exposure of workers to a hydrogen sulphide concentration of 1 ppm and to the odour of mercaptan compounds. Although H_2S becomes a health hazard at concentrations of over 10 ppm (UNEP, 1981), repeated long-term exposure to minor concentrations of H_2S was the main reason for chronic poisoning of workers in the Swedish shale oil industry during the 1940s (Daniels et al, 1982).

Worker health problems are more likely to occur at surface extraction facilities than at in-situ projects. This difference arises because surface extraction procedures not only will produce products that may represent occupational hazards, but also will require the use of reagents that may jeopardize workers' health and safety. Environmental control measures routinely used for heavy-oil extraction would most likely be effective for in-situ tar sand procedures because the methodologies are similar.

12.4.2. Public Health

An estimate of the magnitude of the public health impacts attributable to air pollution from commercial tar sands facilities was obtained using a health-damage function for SO_2 emissions from coal-fired power plants (Daniels et al, 1982). According to that function the calculated damage is 0 to 0.8 premature deaths per 1000 tonnes of SO_2 emitted*. Daniels et al (1982) used that function to estimate premature deaths from the release of SO_2 from tar sands plants. They found that within 80 km around the plant, the estimated premature deaths would be as

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* Assuming a population of 3 million within 80 km of the power plant.

follows :

Technology	Estimated premature deaths/year*
Surface recovery	0 to 0.12
In-situ recovery	0 to 0.0045

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* Assuming 97 % control of SO_2 emissions at a plant producing 50,000 bbl/day.

SUMMARY AND RECOMMENDATIONS

Part III of the present report reviews the environmental impacts of exploitation of tar sands on the basis of existing scientific information. The main findings of that review together with the research and development priorities identified are given in the following.

1. Tar sands occur in many countries, but detailed geological studies are needed to determine the reserves and characteristics of these deposits. Major accumulations of tar sands that have been studied in detail are those of Canada, USA and Venezuela. These deposits account at present for about 90 per cent of the proven reserves of tar sands in the world. The total reserves of oil in place from tar sands deposits in the world has, hitherto, been estimated at 209 $X10^9$ tonnes. About 10 per cent of these can be recovered with presently available technologies.

2. Two options exist for the recovery of oil from tar sands: mining of the tar sands followed by surface recovery of the bitumen, and in-situ extraction of the bitumen from the tar sands. The hot-water extraction process for the recovery of bitumen from tar sands is the most common method, applied at present on a commercial scale in Canada. Since the bitumen recovered from tar sands has a high viscosity and pour point, it must be upgraded into a suitable refinery feedstock.

3. Tar sands are normally mined by surface mining. About five tonnes of tar sands and overburden must be handled to produce one barrel of syncrude. For a plant producing 50,000 bbl/d of syncrude, about 250,000 tonnes of material must be handled.

The area of disrupted land from such mining operations would be considerable. Runoff or discharges from tar sands piles or overburden will cause detrimental effects on aquatic ecosystems in the area. Pyrite-bearing formations will cause acidification of water bodies in the vicinity of the tar sands development sites (through acid drainage).

4. There are two kinds of occupational hazards that are encountered in mining tar sands : accidents and occupational diseases. The latter is mainly due to exposure to dust. The rate of incidence of silicosis in tar sands mining may differ from that in conventional sand quarries. It depends on the amount of free silica liberated in the dust and on the possible synergistic effects of the bitumen that might be adhered to the grains.

5. The surface recovery of bitumen from tar sands using the hot-water extraction process has a number of environmental impacts, the most important of which is related to the tailings from the extraction plant. The disposal of tailings requires large areas of settling ponds. Local micro-climatic effects may be triggered by water evaporated from such ponds. The water from the bitumen extraction plant is contaminated by a number of inorganic and organic compounds which render the water toxic to aquatic life, and hence unsuitable for discharge into natural water bodies. Furthermore, some bitumen remains in the tailings and a thin slick of bitumen and lighter hydrocarbons forms on the surface of the tailings pond. This slick may pose a hazard to water-associated birds. The currently accepted solution to the problem of the tailings water is to design zero-discharge plants, with the tailings water being impounded and recycled through the bitumen extraction plant to the maximum extent possible.

6. The reclamation of spent tar sands constitutes a major difficulty in the environmentally-sound management of tailings. Some attempts have been made to grow foliage on spent tar sands after their treatment with fertilizers and additives.

7. In-situ recovery of bitumen from tar sands offers much less potential surface impacts than surface recovery. However, land subsidence and induced seismicity may constitute two potential effects associated exclusively with in-situ operations.

8. The present review shows that there is considerable lack of information on the environmental and health impacts of tar sands development. Research is needed to characterize process streams and end products. Special emphasis should be given to quantification of the different effects of exploitation of tar sands on different ecosystems. The toxicity and carcinogenicity of different material and products should be assessed in detail. Epidemiological data bases should be established to assess whether the general public surrounding tar sands plants face higher health risks than the population at large.

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