LA-8378

R547

An Integrated Environmental Control Technology Approach to Oil Shale Commercialization

MASTER

University of California

LOS ALAMOS SCIENTIFIC LABORATORY
Post Office Box 1663 Los Alamos, New Mexico 87545

This work was supported by the US Department of Energy, Division of Environmental Control Technology.

Edited by Elaine Stanlick
Photocomposition by Chris West

UNITED STATES
DEPARTMENT OF ENERGY
CONTRACT W-7405-ENG. 36

LA-8378

UC-91
Issued: October 1980

An Integrated Environmental Control Technology Approach to Oil Shale Commercialization

E. J. Peterson
E. F. Thode*
P. Wagner
P. L. Wanek

---

*Visiting Staff Member. Department of Management, New Mexico State University, Box 3DJ, Las Cruces, NM 88003.

CONTENTS

AN INTEGRATED ENVIRONMENTAL CONTROL TECHNOLOGY APPROACH TO OIL SHALE COMMERCIALIZATION

by

E. J. Peterson, E. F. Thode, P. Wagner, and P. L. Wanek

ABSTRACT

A literature search was conducted to evaluate information about the chemistry, behavior, and distribution of environmentally hazardous water contaminants produced during extraction (above and below ground) and upgrading of shale oil, and to assess research in oil shale environmental control technology. This report details the literature pertinent to environmental control technology research. Air quality, water quality, potential surface disruption, and potential problem areas are assessed, research needs are identified, and where applicable, environmental control technologies and future research areas are indicated. The concerns discussed in this report will be guidelines for future environmental control technology research at the Los Alamos Scientific Laboratory.

I. INTRODUCTION

During the past three years, the EPA (Environmental Protection Agency) and the DOE (Department of Energy) have published reports on environmental impacts and environmental control technology for oil shale commercialization.[1,2] In addition, ongoing studies in the laboratory[3] and in the field[4,5] have revealed problems not previously considered. Environmental control measures for coping with these problems are being studied at various laboratories.

Environmental control technologies for oil shale commercialization fall into three categories: (1) airborne pollutants including gases, mists, and particulates; (2) liquid discharges and leachates affecting the water environment; and (3) solid waste disposal. Some of the control technologies overlap. For example, the manner of storage of spent shale can affect both air by fugitive dust emissions and water by leaching.

The oil shale resource can provide a significant energy supply of petroleum-like liquids—up to 25% of current foreign imports—but industrialization is just beginning. Many environmental concerns are unresolved because of the (1) immaturity of the industry, (2) incomplete research required to define potential problems, (3) lack of identification of suitable environmental control technology systems, and (4) uncertainties related to the transfer of similar environmental control technology from similar industries. This status requires objective approaches so that we neither overstate nor understate the potential effects of the industry. For example, the operative word in the doctrine of "significant deterioration" is the word "significant." As an illustration, the national short-term ambient air quality standards are regularly exceeded in the Western oil shale region because of high winds that disperse fine particulates from poorly vegetated areas (Ref. 2, p. 97). Mining dust may not contribute enough additional particulates to cause significant deterioration.

Also, surface disruption will be very difficult to avoid with certain processes. However, in the areas in which these processes are to be installed, some surface disruption may not cause any significant deterioration of aesthetic values. These concerns require a clear balance between control systems and acceptable risks.

However, such problems as water consumption placing an upper limit on the scale of commercialization will not disappear. The potential for degradation of aquifers by bridging, leaching, etc. must be clearly defined and then, if necessary, solved, even at an uncertain cost. Finally, the operation is immense, producing tons of waste per pound of product. The only close precedent commercial experience is open-pit copper mining. The overall scale of full commercial operations at 10^6 barrels per day of product shale oil is without parallel in the energy extraction industries.

Sections II, III, and IV, on control of air, water, and solid pollution, deal with existing Federal and State regulations, capabilities of existing environmental control technologies, and major uncertainties and critical problem areas. A summary of uncertainties and critical problem areas is presented in Table I.

II. CONTROL OF AIRBORNE POLLUTANTS

Our definition of airborne pollutants includes gaseous materials, vapors, mists, aerosols, and particulate suspended solids. Some unresolved environmental health hazards may exist within the battery limits of the plant; three potentially serious airborne pollutant problems have been identified that may not be amenable to existing environmental control technologies. These are (1) fugitive gaseous emissions from leaking underground MIS or TIS (modified *in situ* technology and true *in situ* technology) retorts or burning above-ground raw shale piles, (2) particulate emissions of (untreated) oil shale from the TOSCO II above-ground process, and (3) the unknown fate of mercury in surface and *in situ* retorting. The last item may or may not be a problem, considering the low concentration of mercury in most oil shales and the possibility of removal during the sulfur removal process. The second can probably be handled by rigorous application of existing control technology. However, the first item poses a problem of unknown complexity at present.

Following is a summary of regulations, their match with existing control capabilities, and an analysis of unresolved problems. We emphasize that the huge scale of oil shale extraction operations presents problems not previously encountered in energy extraction technologies.

A. Federal and State Regulations

The overall goal of Federal air pollution control regulations, as exemplified by the succession of Congressional acts, the Air Quality Act of 1967, Clean Air Amendments in 1970, 1973, 1974, and twice in 1977, is to control the Nation's air resources so as to promote the public health and welfare, and to allow for growth of the Nation's industrial capacity in a way that is not economically stifling. Congress has specified maximum limitations for only two pollutants; sulfur dioxide and particulate matter. It has, however, directed the EPA to propose guidelines to control atmospheric levels of NO_x, HC, CO, and photochemical oxidants. The EPA has also been given authority to set standards for arsenic, cadmium, and polyaromatic hydrocarbons (PAH), if they are judged to be a danger to the public health.

The regulations to control atmospheric pollutants have evolved from several directions. As an attempt to control gross pollution by newly constructed, potentially large "point sources," the New Source Performance Standards (NSPS) were adopted, which set maximum allowances for any specific operation on a pollutant-by-pollutant basis. In a more area-wide control effort, the National Ambient Air Quality Standards (NAAQS) were set up to assure that the total concentration of pollutants of any "average air mass," encompassing a combination of both point and diffuse sources, does not reach a level harmful to the public health or welfare. The Multimedia Environmental Goals (MEGs), an interim set of guidelines adopted by the EPA to index the existence or degree of the pollution problem, deal with the area-wide picture, as do the NAAQS, but have indicated human and ecosystem toxicity levels for some 200+ "priority pollutants."

To allow industrial expansion, and because pollution levels were not being lowered to proposed standards by proposed deadline dates, the Clean Air Act Amendments of 1977 established area classes. Class I areas, such as national parks, were to be preserved in their present pristine state. So long as emission regulations were met, Class II areas were to be allowed moderate development, and Class III areas were to be allowed more intensive

TABLE I

UNCERTAINTIES AND CRITICAL PROBLEM AREAS IN ENVIRONMENTAL CONTROL TECHNOLOGY FOR OIL SHALE COMMERCIALIZATION OPERATIONS

Concern	Pollutant	Technology	Status[a]	Current Assessment	Delay
				AIR QUALITY	
Atmosphere	Particulates, including fugitive dust emissions	Surface	ETA	Dust and particulates produced by mining, hauling, and crushing shale should be readily controlled by existing technology. Techniques include surface wetting, baghouse filters, and various wet scrubbing schemes.	Possibly slight due to scale-up.
		MIS	U	Surface problems from processing of mined shale were discussed above. Dust and particulates from *in situ* rubbling should be contained in the retort area if geology and geohydrology have been properly chosen and manipulated.	Minimal.
	SO_2, CO, NO_x, and NH_3	Surface	ETA	Existing technology for control of these emissions includes process control under reductive conditions, end-use combustion, gas recycle, scrubbers, and precipitators.	Minimal, but concern related to technology transfer.
		MIS	U	Control as fugitive emissions is unresolved. The problem has not been assessed, existing control technology has not been applied, and thus, additional work is needed.	Unknown, but should be a controllable problem.
	Mercury	Surface MIS	U	The fate of mercury in processing is unknown. Retort studies have resulted in very poor closure on Hg elemental balances. It is believed that about half the Hg escapes in the gases in a dilute form. (For surface processing, this might be alleviated by a sulfur removal unit.) Reliable data on the form and concentrations of Hg species released to the atmosphere do not exist. This could be a serious environmental problem because of the toxicity of various Hg compounds. Control technology is presumably not a problem but assessment of the nature of the Hg problem must be made.	Medium possibility of delay until problem is assessed.

---

[a] ETA = Existing technology available.
U = Uncertain at present; presumed to be technologically controllable at some cost, perhaps a very high one.
P = Potential impediment to shale oil development. Proven control technology does not exist. Not possible to predict cost of proposed technologies.

Table I (continued)

Concern	Pollutant	Technology	Status^a	Current Assessment	Delay
Atmosphere	Other volatile trace elements, e.g., arsenic, fluorine	Surface MIS	U	Comments for Hg are applicable, but this is not considered a critical problem compared with the potential major health effects of Hg—compound contamination.	Unknown, needs to be assessed.
	Hydrocarbon vapors	Surface	ETA/U	In general, controllable by existing technology unless non-deterioration requirements are rigidly applied. (However, see comment on burning raw shale piles.)	Minimal, but other control strategies should be studied.
		MIS	P	Fugitive emissions from burning raw shale piles and from underground processing could cause violation of standards. The extent of these circumstances is not known and could lead to serious difficulties. Assessment of the dangers in this area is needed.	Potential problem must be addressed.
	Polynuclear aromatics (PNAs on particles)	Surface	ETA	Suspected carcinogens can be controlled by existing technology.	None.
		MIS	U	Comments under fugitive dust emissions are pertinent. Should not be a major problem if the overburden is not extensively damaged during rubbling (this may not be true for TIS process). However, this is by no means certain and the assessment of on-site problems may be difficult.	Minimal, but careful processing will be very important. Process-dependent problem.
				WATER QUALITY	
Retort water	Organics	Surface	ETA/U	Retort water is known to contain up to 4000 ppm of organic contaminants, some of which are carcinogens. Control technology to clean up retort water is still in the research stage. Existing technology from the organic chemicals industry may apply but will likely be expensive. Less expensive routes, such as using spent shale as a contaminant absorbent, need to be investigated.	Dependent upon environmental control technology chosen.
		MIS	U	Above comments should be applicable unless re-use of the water for steam generation or cooling of retort radically alters the contaminant concentrations or distributions in various media (spent shale, groundwater, etc.). At this time, these aspects have not been assessed. Amounts of waste water to be processed will affect the costs.	Uncertain.

Table I (continued)

Concern	Pollutant	Technology	Status[a]	Current Assessment	Delay
Retort water	Inorganic major and trace elements	Surface	ETA	Retort water composition will be site-specific. Since the water will be retained within the battery limits, it should be controlled by existing technologies. However, the magnitude of the contamination needs to be assessed.	Minimal.
		MIS	U	Composition of the water will be site-specific. Research into the quantity and quality of retort water needs to be continued. The potential for groundwater contamination by retort water needs to be assessed. As with organics, compositional changes due to re-use of retort water for processing need to be understood.	Uncertain.
Process water	Organics	Surface	U	Same as retort water	Uncertain.
		MIS	U	Same as retort water	Uncertain.
	Inorganics	Surface	U	Same as retort water	Uncertain.
		MIS	U	Same as retort water	Uncertain.
Spent shale leachates	Organics	Surface	U	Leaching rates of organics and stabilization of shale piles are major questions. Environmental control technology for disposal and stabilization of rubbled mineral wastes may be applicable, but effectiveness for organics is not certain. PNAs may be a major problem if not properly isolated. See comment concerning groundwater contamination by organics. Changes in form and toxicity of organics may occur due to microbial action. This needs to be assessed. Also, further development of flash flood protection is needed with specific attention to mud-slide dangers.	Uncertain.
		MIS	P	Backflooding of spent *in situ* retorts and subsequent contamination of subsurface water may occur by mobilization of organic residues or leaching of unretorted organic materials. The nature and the magnitude of this problem must be assessed. Retorting conditions will be a major variable. The dangers of these pollutants need to be understood.	Critical problem area; uncertain until assessed.

Table I (continued)

Concern	Pollutant	Technology	Status[a]	Current Assessment	Delay
Spent shale leachates	Inorganics	Surface	U	Conventional environmental control technology may suffice, but assessment and evaluation is needed before this situation is clear. B, F, As, Se, and Mo leaching could present difficulties but probably are solvable problems. Comments above about leaching rates and shale pile stabilization (including flash flood protection) are applicable here.	Unknown, but should be controllable.
		MIS	P	This, along with the organic contaminants, is potentially the most serious problem facing *in situ* processes because of the possibility of underground water contamination. Large amounts of inorganic trace elements will be available and could be solubilized by backflooding of the spent retort. Insufficient information is available for assessment of the problem. The relationships of retorting conditions and raw shale composition with amounts of leachable inorganics are only beginning to be understood. This information is extremely important because adequate assessment of the problem depends on the high-temperature chemistry taking place during retorting. The magnitude of the problem will also depend on the hydrology and geohydrology of the region. The nature and rate of groundwater contamination by spent shale leachates is extremely site-specific, not only because of the hydrology, but because of the absorbing and attenuating characteristics of the surrounding rock medium. Even if the problem were assessed, control technologies for backflooding and subsequent groundwater contamination are only in their infancy. Much more research with regard to assessment and control technology development is necessary.	Critical problem area which needs to be assessed and controlled.
Groundwater (other than by retort or leachate waters)	Organics	Surface		None	
		MIS	P	Fugitive emissions produced during underground retorting, such as volatiles or organic liquids, could contaminate subsurface waters. This is a critical unresolved problem. The spent shale in the retort may have sufficient absorptive capacity to take care of the PNAs and PHAs, but this issue must be resolved. Research is needed.	Uncertain until assessed, but comments for leachates probably apply.

Table I (continued)

Concern	Pollutant	Technology	Status[a]	Current Assessment	Delay
Groundwater (other than by retort or leachate waters)	Inorganics	Surface		None	
		MIS	P	Comments above apply to volatile inorganics such as Hg compounds. The extent of these problems needs to be assessed. Another potential for inorganic contaminants comes from aquifer bridging where fresh water in an upper aquifer is polluted by saline water from a lower aquifer. Major control technology is probably careful selection of retort site to ensure the maintenance of a sufficient barrier between aquifers. Plugging or sealing of spent retorts may be of use. The economics of these solutions are uncertain.	Uncertain until assessed, but comments for leachates probably apply.
				SURFACE QUALITY	
Raw shale storage	Organics and inorganics	Surface MIS	U	The extent of leaching of organics and inorganics from raw shale piles is not well known, but it is not considered to be a major problem.	Minimal.
	Volatiles	Surface MIS	U	Uncontrolled burning of raw shale piles could cause serious air pollution. Technology from the coal industry may be applicable.	Minimal.
Spent shale storage	Organics and inorganics	Surface MIS	U	Pile stability is a question. Erosion protection is a question. Success of revegetation on the scale proposed is not certain. Wetting of the shale with retort water and compacting is not a demonstrated technology, and thus, requires further investigation.	Minimal.
Subsidence and surface disruption	--	Surface MIS	U	This has not been considered a major problem for either technology. However, especially for MIS, local spalling of ceiling or floor material could increase the possibility of aquifer bridging. Also, worker safety is always a concern and will be affected by considerations such as mine stability and migration of toxic gases from active retorts to adjacent mining operations. Careful choice of *in situ* or mining areas will help.	Unknown.

growth. To prevent economically deleterious consequences to industry, the best available technology (BAT) was to be used to clean up noncompliance areas, and an area containing a source that still could not comply with regulations was to be declared a nonattainment area if pollutant accumulations exceeded NAAQS. Each case was to be given a review with time extensions given to reach regulation levels, and a requirement to produce alternate site plans if that source could not meet the extended deadline date by the BAT. The philosophy of preventing significant deterioration of the Nation's air resources was to be held foremost throughout.

Although oil shale operations are not specifically mentioned in the provisions of the Clean Air Act, rules for upgrading petroleum refineries and storage and transfer facilities probably would apply. The oil shale production areas are included in the large Class II designation, in which moderate development will be allowed, but it is not clear what level of pollution will be tolerated.

Colorado has adopted standards for air pollution control specific to the commercial oil shale industry (those producing more than 1000 bbls/day), whereby a limit of 0.3 lb SO_2/bbl may be produced from the recovery operation and a like amount from the refinery operation. Utah enforces the numeric allowances regulated by the Federal law.

Air quality of the occupational environment in the oil shale industry is directed more specifically by the Occupational Safety and Health Administration (OSHA) and through the Toxic Substances Control Act (TSCA). Permanent levels for beryllium, mercury, asbestos, and vinyl chloride emissions have been established to prevent health hazards to workers.

B. Relation of Present and Predicted Air Quality to Existing Standards

Crawford et al. (Ref. 1, pp. 99-112) have thoroughly reviewed the air quality impacts of oil shale extraction and processing. They are critical of the modeling studies for predicted air quality performed up to 1977 because of lack of precise meteorological data for many of the sites and the use of a rather simplified air diffusion model that does not take into account the turbulent conditions in mountainous regions. They point out that, for various causes not attributable to (local) human activity, Federal particulate ambient air standards and nonmethane hydrocarbon standards are often exceeded. Thus, shale oil process plants could cause further degradation of natural air quality.

In spite of their doubts about prior modeling studies, the authors believe that the environmental controls assumed in these modeling studies would not be sufficient to meet the significant deterioration and SO_2 standards. However, they are optimistic that taller stacks, improved control technology, restricted plant size and proper siting (in view of meteorological factors) will permit standards to be met. Additional research being conducted could place these opinions on a firm base.

C. Application of Existing Technologies to Airborne Pollution

1. Application to Above-Ground Retorting. The basic technology to control dust and particulates produced by mining, hauling, and crushing of shale is well known, although direct application to the large volumes of particulates expected to be produced in a commercial oil shale operation may require some development time in order to complete the technology transfer. Particulates from oil shale operations have not been completely characterized and may contain harmful constituents that would require more stringent control. The gaseous emissions produced during surface retorting include pollutants (NO_x, SO_2, CO, and HC) for which air quality standards have been established and for which existing control technologies from other areas will be applied (Ref. 2, pp. 75ff). The question of the applicability of such controls to a fully developed commercial shale oil operation introduces the unknowns associated with the enormous tonnage of materials (estimated at 21 000 000 tons/yr for a 50 000-bbl/day plant) being handled and treated, and any peculiarities to oil shale processing that interfere physically or chemically with control systems operations.

2. Application to Underground Retorting. Concerns about emissions of gaseous, aerosol, and particulate matter produced during subsurface retort preparation are similar to those already discussed with regard to mining and shale preparation for surface retorting. Dusts and gases produced during rubbling are intended to be contained within the retort. However, during the actual retorting operation, direct atmospheric venting and/or fugitive emissions released through fissures in the overburden may present an environmental disturbance. Although this circumstance can be largely avoided by the proper choice and development of retort sites, the potential for unexpected releases of environmentally unacceptable airborne matter must be considered as finite. This is especially true for TIS processes with associated surface uplifts.

The seriousness of such emissions from MIS and TIS operations has not been studied in detail and existing control technology has not been applied to this problem. Thus, additional work is needed.

3. Occupational Health Problems Within Battery Limits. The degree of ventilation required within *in situ* mines has not been established. Individual dose monitors for the uncharacterized organic residuals are not available. Guidelines for hygiene programs have not been established. Analyses of risks have not been performed. Technology transfer for inhalation protection from other industries has not yet occurred; however, these problems are currently being addressed by the Los Alamos Scientific Laboratory (LASL) Health and Occupational Medicine Groups. Note that the severity of the problem is increased by the proposed methods of operation on a commercial scale; that is, retorting in one block will be proceeding at the same time as mining and preparation operations in adjacent blocks. Leaks from an active retort into an adjacent retort being prepared are possible, although the probability is unknown. Such leaks would expose workers to health hazards ranging from carbon monoxide poisoning to long-term toxic effects. Careful planning and management, along with mine atmosphere monitoring, should prevent these problems.

D. Critical Problem Areas and Uncertainties

1. General. Despite the fact that many of the problems related to control of point-source airborne contaminants have been resolved in related technological areas, technology transfer to the oil shale industry is uncertain. This is primarily because of unique problems in supply and materials handling, especially in large-scale activities. The climatic conditions at the site, including the low amount of precipitation and its uneven distribution over the year, also raise a series of unresolved issues. Characteristics of retort gases that may cause problems in application of conventional controls are (1) large volumes of gases that will require clean-up, (2) high concentrations of particulates and toxic vapors in the gases, and (3) some substances may interfere with the control systems, for example, conventional baghouses for removal of particulates are likely to be uneconomical or ineffective in dealing with oily dust. Complete assessment is required in these areas to determine if there is a problem, how serious the problem is, and whether it can be controlled within acceptable limits.

2. CO_2 Emissions. It has been estimated that the atmospheric concentration of CO_2 could reach several times its present value in the next 100 years with possible adverse effects as a result of meteorologic interactions. There are indications that this increase is related to fossil fuel combustion, and retorting of oil shale could add to the severity of the problem. Carbon dioxide emissions are not regulated, but growing awareness of the problem could result in such regulations. These regulations will affect all fossil fuels, but if the CO_2 problem proves to be serious, the extent of impact on an oil shale industry will be greater because of the large amount of CO_2 release (up to 4 times greater) from the oil shale fuel cycle.

3. Particulates, SO_x, and NO_x. Controls for criteria pollutants from processing and upgrading of shale oil, as well as emissions from waste dumps, ponds, etc., are established technologies. The applicability of these controls has the uncertainties associated with a major new industrial development, as well as uncertainties in the costs involved in adapting existing controls to the arid, windy, high country of the Green River formation. Particulate controls present problems because of the mixture of powders, dusts, and hydrocarbon liquids. Here, the concern is the effectiveness of the control methods, considering the unprecedented amounts of gaseous and particulate matter expected from shale oil recovery.

4. Trace Elements. Both point and fugitive emissions of small amounts of Hg, As, Se, COS, H_2S, and NH_3 may come from several sources,[6] including retorting operations, solid and liquid recovery, disposal systems, process machinery, and truck traffic. The site and shale oil recovery process will be the major determinants of the applicable environmental control technologies. At present, some sites and technologies seem to provide reasonable environmental protection, except for mercury contamination. Others require further study.

Mercury may be a problem because its fate in the retorting process is unknown. Experiments are in progress[7] to identify this problem, but studies to date have resulted in very poor closure of mercury element balances. Although up to half the mercury may escape with the gases as very dilute vapor in direct mode, its fate in MIS is less clear. Reliable data on the form and concentration of mercury release do not exist. Mercury may cause very little problem, in any event, because of its inherently low concentration in most raw shale. However, because mercury contamination and toxicity of mercury compounds are serious, this potential problem needs to be assessed thoroughly.

5. Polynuclear Aromatic Hydrocarbons. Both kerogen and bitumen in raw shale contain condensed-ring hydrocarbons, mostly in polymer form. Pyrolytic decomposition of the kerogen into raw shale oil produces several hydrocarbon fractions; one is a class of polycyclic hydrocarbons and their sulfur and nitrogen-containing derivatives. These compounds are referred to in the oil shale literature as POMs, PHCs, or PNAs. A preferred indicator compound for these materials is benzo-(a)-pyrene, a material suspected (but not proven in humans) of carcinogenic activity. Raw shale oil contains considerably less of this compound than coal tar, but about the same amount as in asphalt or cracked crude residuum (Ref. 1, p. 92). Thus, the amount of potential carcinogen is relatively high, but the bioavailability and carcinogen effects are not known. There are small amounts of POMs in some types of spent shale. Application of spent shale to the skin of mice showed no carcinogenic activity in short-term tests (Ref. 2, pp. 152-153); however, the internal effects from inhaling spent shale dust are not completely known at present.

Raw shale presumably releases some PNAs in the crushing process because of mechanical and thermal degradation of kerogen. Thus, workers should be protected from inhalation of raw shale oil aerosol or raw shale dust or from repeated skin contact with raw shale oil.[8] Conventional environmental control technology should prevent these airborne materials from crossing the battery limits of the plant. Further controls may be implemented if the battery limits are crossed by airborne pollutants.

6. Summary. Point-source emissions of criteria pollutants should cause difficulties only because of the vast quantities that may be released. For the noncriteria pollutants and for fugitive emissions in general, assessment of the degree of hazard for a given production level will probably be site- and process-specific.

III. CONTROL OF WATER POLLUTION

Above-ground oil shale operations will not produce water outflow from the battery limits, so in that sense, the technical problems are internal to the particular operation. However, spent shale piles from above-ground retorting may present serious water pollution problems. Although the control technologies for these are considered well established by some writers (Ref. 2, pp. 153-159), their adequacy is challenged by others.[9]

Special problems are possible with either underground process and definitive answers are not available yet. Two principal problems associated with the MIS process are groundwater contamination resulting from aquifer bridging and that from leaching of waterflooded retorts. Aquifer bridging, the cross flow of water from one aquifer to another, may pose a problem when an aquifer with water unfit for plant or human consumption connects with another aquifer of potable purity. The severity of this problem is likely to be site-specific. The extent of the groundwater contamination problem that results from the leaching of abandoned (spent) retorts has not been fully defined, but various control technologies have been discussed and may be applicable if needed.[10] Because of the lack of data on flooded spent retorts and their leaching properties, controls that have been considered for retort abandonment are conservative. An example is the grouting or filling of a spent retort with an insoluble matrix to prevent transport of trace elements and undesirable organics beyond the retort boundaries. Among other control technologies being considered is backflooding the spent retort (by groundwater intrusion or flushing from the surface, or a combination of the two), removing the leachate, treating it on the surface, and either reinjecting the water into the retort or making some other use of it. Such a control should be implemented only after verification of groundwater contamination in the abandoned retort. This possibility, and the fact that the treated water can be fully characterized after purification and before use, holds promise that the level of treatment and the economics of retort abandonment may be realistic.

Increased salinity may be a socioeconomic factor. Because any kind of water, let alone usable surface and groundwater, is scarce in this region, some upper limit of shale oil production capacity may be established by the available water.

A. Federal and State Regulations

1. Surface Waters. In general, the rationale of water pollution standards parallels that of air pollution controls. It is a stepwise attempt to improve the quality of existing point-source effluents, to maintain area-wide levels for undesirable constituents below those defined as being dangerous to the public or ecosystems, and ultimately, an attempt to prevent pollutants from entering the waterways.

Relevant Federal regulations for controlling surface-water quality include the Federal Water Pollution Control Act (FWPCA), Safe Drinking Water Act (SDWA), Clean Water Act (CWA), and the Toxic Substances Control Act (TSCA). The "Water Quality Criteria," drafted by the EPA in 1975, were guidelines to be achieved by the best practicable technology (BPT) for point-source effluents and regulated only pH. In 1976, the National Commission on Water Quality concluded that the requirements of the 1977 target date for "fishable and swimmable" waters, and the 1983 target date for no pollutant discharge, could not be met by the BPT. Cases were reviewed individually and time extensions were given. General planning programs, such as the River Basin Plan and the Area-Wide Waste Treatment Management Plan, were organized to facilitate compliance with regulations. Permit programs, such as the National Pollutant Discharge Elimination System (NPDES) also involved a phase scheduling of compliance for regulations regarding navigable waters. Although not directly regulatory, various interim guidelines, including the Water Quality Criteria, and especially the MEG/MATE methodology to model the relative hazards of pollutants, are part of the evolutionary picture of clean water controls. For fossil-fuel-related effluents, permanent regulations have been set by the EPA for only pH, total dissolved solids (TDS), iron, and manganese. There are also permanent standards for polychlorinated biphenyls (PCBs), benzidine, aldrin/dieldrin, DDT, DDE, DDD, endrin, and toxaphene in water.

Utah has established minimum standards for Class C waters, that is, those that could be used for livestock watering, aesthetics, fish and wildlife propagation, recreation (except swimming), for irrigation without treatment, or for drinking water with treatment. These standards are equal to or more stringent than the Federal standards for like constituents. Utah has no permit program.

Colorado's water quality standards are set forth in the Colorado Water Control Act, administered by the Colorado Department of Health, which also administers the NPDES program. Colorado is also attempting to establish a means of complying with minimum salinity standards for the Colorado River as it enters Mexico, which is of international concern.

2. Groundwater. Aquifers containing less than 10 000 ppm TDS are defined in Federal regulations to be underground drinking water sources, and therefore, are subject to surface drinking water regulations. Utah specifically includes groundwaters, underground contamination, and aquifer disturbances in its water pollution act, though there is no TDS limit. Colorado, by the Colorado Water Quality Control Commission, regulates the reinjection of water into underground disposal wells. Again, numeric standards for TDS have not been established; however, this issue is being studied.

Underground water supplies are inherently difficult to monitor, and data resulting from a monitoring program are difficult to interpret. Thus, the identity of upstream sources that contribute to statistically significant salinity differences in a large basin area will probably be uncertain. The regulations do state, however, that the hydrology of the area must be well understood before development can take place. Such regulations may be subject to a variety of interpretations.

B. Capabilities and Limitations of Existing Control Technologies for Surface and Groundwater.

1. Application to Above-Ground Retorting.

a. Control Technologies for Surface Water. Surface waters can be contaminated by any combination of mining, processing, or disposal of the oil shale. Of these, the two major sources of contamination are waters associated with oil shale processing and that caused by leaching of spent shales that are exposed to weathering and precipitation.[11]

Water produced during oil shale retorting may contain organic and inorganic contaminants, each in concentrations as high as 20×10^3 μg/mℓ.[12-14] Product water separated from the product oil is a complex mixture that often contains suspended solids or greases as well as dissolved contaminants. Often the retort water is biologically unstable, as evidenced by the formation of algae growth.[15] Most research on retort water control technology is still in its infancy, and efforts thus far have not been highly successful.

A recently released study on control costs of a surface retorting operation assumes a worst-case conceptual design of a water effluent treatment system that should handle this complicated problem, but the authors know of no experiments to verify the effectiveness of this design (Ref. 16, pp. 5-9 to 5-12). At present, it is not clear that such an expensive and elaborate system is required because the separation characteristics of the effluent have not been extensively studied, nor have such studies been performed on all the available alternatives.

Many abatement procedures that have cleaned up contaminated municipal and industrial effluents can presumably be applied to the treatment of retort and product waters.[17,18] Current ideas combine these procedures into a multistep process for removing the various classes of contaminants in stages.[16] Individual procedures include steam stripping, bioaccumulation, biodegradation, oxidation, the use of adsorbents (spent shale, other carbonaceous soils, clays, soils, and synthetic resins), chelation, ion exchange, and reverse osmosis. Several of these techniques are being investigated in various laboratories, but more intensive research is needed. The control methods that should be emphasized must account for the chemical character and the volume of the water, secondary effects of residue disposal, and the projected end use for the water. For example, some workers believe that adsorption on spent shale will suffice for partially processed retort water that is not to be discharged or reused. However, disposal of spent shale used as an adsorbent may be a problem when RCRA (Resource Conservation and Recovery Act) criteria are considered.

Other contaminated process waters associated with shale oil extraction (coolants, blowdowns, etc.) are expected to have much lower contaminant concentrations than product retort water and to be amenable to treatment by conventional industrial effluent control technologies.

Water contaminated by contact leaching of shale waste disposal sites may be an impediment to the shale oil industry. Such contamination may occur when surface or groundwater passes through raw shale (mine spoils) or retorted (spent) shale disposal areas. Both organic and inorganic constituents are present in raw or spent shale leachates; however, more than likely, not in the quantities contained in retort or product waters. General control methods include immobilization or removal of the contaminants before disposal of the shale wastes, calcining or preleaching with aqueous solvents, or the application of cements, sealants, attenuating agents, or sorbents to the waste materials at the dump site to retain aqueous contaminants within the confines of the site. Application of many of these techniques would be easier for surface shale wastes than for abandoned underground retorts because the waste is exposed and the disposal site is readily accessible.

It may also be feasible to treat contaminated water directly as it emerges from the waste disposal areas, but it is extremely difficult to guarantee that all of the water draining from the site is being collected, so that none is escaping into the surrounding environment. Control techniques for direct treatment of shale waste leachates should include the use of adsorbents or attenuating agents, evaporation, steam stripping, and bioaccumulation, along with other techniques such as reverse osmosis and ion exchange.

b. Groundwater. Plans filed for the various above-ground sites make an effort to protect groundwater from process waters and spent shale drainage, however, if the proposed procedures are inadequate, contamination of upper aquifers is possible. Weathering effects, such as cycles of intense freezing in the winter followed by thawing of the impervious linings of catchment ponds, have not been adequately studied. Finally, the effects of large-scale operations on aquifer drawdown and concomitant increases in forces tending toward contamination from various sources have not been adequately studied using even simple hydrologic models. Drawdowns for sanitary and other uses by an increased population have been discussed but not accurately calculated.[19]

2. Application to Underground Retorting. At this time, the most attractive underground retorting strategy is the MIS method, which probably will be used in the shale oil extractions at lease tracts C-a and C-b. MIS retorting is considered to be developmental (as opposed to above-ground being ready for commercialization), but comparison of the logistics of the two methods indicate that MIS technology has the advantage if major shale oil production is begun. Since this underground retorting technique brings with it uncertainties as to the seriousness of the potential water contamination, we considered it in some detail despite the fact that it is not yet ready for commercialization.

a. Control Technologies for Surface Water. Since 20-50% of the oil shale is mined and stored above ground in the MIS process, the possibility that an MIS operation would be accompanied by a surface-retorting extraction facility must be considered (this is the planned method of operation at C-a and C-b). The environmental control strategies for surface water, discussed in Sec. III.B.1.a., have identical application here. Worst-case technology is discussed in Ref. 16, pp. 4-13 through 4-15.

b. Control Technology for Groundwater. Contamination of groundwater by retort products and spent shales as the water backfloods through abandoned underground retorts may be a serious environmental problem. Uncertainties exist as to the magnitude of the problem and the control technology requirements.[11, 20-22] Optimum control of process parameters is more difficult to achieve underground than with surface retorting, and leachable organic and inorganic residues will probably remain in many of the *in situ* retorts at the completion of the oil extraction process. The Green River oil shale formation contains a complex system of aquifers of varying quality; groundwater could backflood into the abandoned retort (perhaps very slowly) and become contaminated by solubilizing organic and inorganic contaminants. Leachates of this type would probably contain much lower concentrations of contaminants than the water produced during the retorting process.[22] It is not known whether large quantities of oil shale pollutants can be transported into local aquifers.

Many possibilities will have to be considered in any study whose goal is preventing contamination of subsurface waters by spent *in situ* retorts. These include immobilization or removal (by pumping or flushing) of the contaminants before abandonment of the retort, addition (slurry backfilling) of adsorbents, attenuating agents, and cementing agents to the spent retort, and physical isolation of contaminated aquifers.

Immobilization or removal of the organic and inorganic contaminants from spent retorts is highly desirable because there would be no possibility of subsequent contamination of subsurface water. Immobilization of waste contaminants might be accomplished by calcining (high-temperature treatment) either during or after shale oil extraction to produce an inert mass of the shale residues consisting mainly of silicated materials. Another means of immobilizing the contaminants in spent underground retorts is to apply grouts or sealants to an entire retort or perhaps to its exterior. Retort sealing agents may include various blends of spent shale, Portland cement, concretes, pozzolanic agents, clays, silicate materials, and carbonate and silicate cements. The removal of contaminants from a spent retort before abandonment may be accomplished by steam stripping or by flushing the retort with detergents or surfactants.

The treatment of spent underground retorts with adsorbents or attenuating agents may be useful if water contaminant immobilization or removal is not feasible or only partly successful. Depending on the accessibility of the retort and the permeability of the spent shale bed, slurries of activated spent shale, clays, soils, lime, or other attenuating agents might be pumped into the retort to retain waterborne contaminants as they are released from the waste materials.

Still another alternative, which may be less expensive than sealing and which might be combined with addition of attenuating agents, is natural leaching. In this approach, the spent retort is allowed to fill gradually with aquifer water and both the retort and exit water pathways are monitored for undesirably high concentrations of indicator pollutants. Appearance of such a concentration of any one indicator in any exit pathway would trigger a complete pumpout of the retort for treatment of the water and use or release at the surface.

If contaminated groundwaters cannot be cleaned up before they escape from the spent retort, it might be necessary to isolate the region (for example, by using a grout curtain around the retort), retaining backflooded water indefinitely in the spent retorts of a field. This is believed to be a "last resort" control with low probability of need.

Aquifer bridging also presents an environmental concern for the oil shale industry. The oil shales of the Green River formation often are bounded above and below by aquifers. Usually, the upper aquifers are of higher quality than the lower aquifers (Ref. 1, pp. 117-121). To disturb the intervening shale strata by mining or *in situ* retorting to the point where aquifers of variable quality could intermix would be undesirable, if not unacceptable. Here, too, the best control technology would prevent contamination by choosing mining or retorting sites with maximum structural integrity, and by exercising care during mining or retort operations. Again, it may be possible to apply some type of sealant or grout to weak areas to prevent the formation of unwanted bridges between aquifers.

C. Critical Problem Areas and Uncertainities

As in the situation concerning environmental controls of gaseous and airborne pollutants, the logistics (especially the materials-handling problems) of shale oil commercialization and the climatology and geology of the location raise questions related to control of water contamination that have not been assessed. To cite one example, the tradeoffs in water usage in the relatively arid* regions of the Green River formation among agricultural needs, human requirements, and ecological and environmental restraints, as opposed to the expected extent of commercialization, have not been integrated or evaluated.

Not all of the pertinent hydrology studies have been completed, but Ref. 1 (pp. 113-123) gives a picture of the known hydrology of the shale oil producing area. In summary, the effect on salinity of the Colorado River *can* be minimized by proper process, siting, and mining procedures. In general, lower groundwater aquifers are of poorer quality, so that inorganic degradation of that resource is presumed to be less serious. However, excessive extraction of water from poor quality aquifers could cause problems, including reduced flow for other uses and increased salinity.

If one considers total water consumption involved in oil shale commercialization, including the needs of those who will move into the area to work on construction, operation, and community support, it is not clear how large an industry can be supported by the water available. Consumption and water degradation will place an upper limit on the possible scale of operations—one estimate is more than 100 000 bbl/day but not more than 2 000 000 bbl/day.[23]

1. **Raw Shale Drainage.** All of the above-ground processes and the MIS process will have piles of raw shale stored above ground. Raw shale leaches very small amounts of inorganic constituents, probably not enough to be a serious pollution problem, and it also is expected to leach a small amount of organics. How much would depend on the size reduction and amount of weathering to which the raw shale had been exposed. Only reasonable precautions to catch rainwater runoff and use it in the process would probably be needed.

2. **Retort Water Treatment.** Retort water is of poor quality. Conventional petroleum technology treatment of the raw product water may be an acceptable option. It is expected that an ammonia stripper, sulfur recovery unit, and API separator would be used as primary in-plant treatment in all units. For MIS technology, the most desirable secondary treatment is still uncertain. One approach is adsorption of retort water on spent shale; however, experiments have not progressed enough to determine the level of secondary treatments that would be required before disposal into exhausted retorts for quenching, sealing, etc.

Specific compounds or elements of environmental concern to the overall hydrologic system would have to be removed or immobilized. Depending on the needs of the plant, one or more conventional secondary treatments will be required in order to use the retort water for cooling and other plant purposes.

3. Spent Shale Drainage.

a. Above-Ground Disposal. Spent shale piles above ground are subject to leaching from rainfall and runoff. The carbonaceous (indirect-mode) spent shales leach much less inorganic matter than do the burned direct-mode residues. Present plans for above-ground spent shale dumps call for compacting the bottom layers of shale or placing impermeable barriers to reduce percolation into surface water aquifers. The plans also call for pile drainage and catchment systems for runoff. Catchment and evaporation ponds are to be clay lined (Ref. 1, p. 127). In some operations, the pile runoff is to be used for dust control on roads and working piles. The major uncertainties are twofold: (1) will usage for dust control on roads cause buildup of salts, which would eventually cause a significant increase in groundwater (surface-water) salinity, and (2) will evaporation ponds operate satisfactorily at high elevations during the long winter freezes? A further question of the integrity of the pond linings under conditions of total icing may also be raised.

b. Shale in Spent MIS Retorts. One major proposal for handling spent shale from the MIS process is that of slurrying that portion of the shale retorted above ground and reinjecting it into the spent retort. This leaves no rainfall leaching problem but does raise questions concerning backflooding and subsequent leakage of leach

---

*Mean annual precipitation in Grand Junction, Colorado is 8.41 in. (Ref. 2, p. 126).

water into a bedrock aquifer. Various technologies have been suggested to seal off the retorts or to reduce the leach rate to a tolerable amount. The technologies for minimizing leaching (bentonite addition, grouting of the individual spent retort, etc.) all pose problems in monitoring the results. Remote monitoring to pinpoint failure of control strategies is a problem that should be studied for possible solutions. Although the technology for complete sealing (grout curtain) may be effective, it may be very costly, and the economics must be assessed for field implementation.

The MIS system, although not ready for commercialization, has many benefits. There is uncertainty about seepage from backflooded retorts, but there is no evidence of increasing solubles in the aquifers significantly above background. Before final decisions on which control technologies are to be used, the magnitude and nature of the problems must be determined.

c. Process Water Treatment. Process water treatment is expected to follow conventional technology. Certain process waters and cooling water blowdowns must be held in stabilization ponds before reuse or further treatment. These waters contain undesirable concentrations of contaminants and it is important that the holding ponds be built with impervious linings to avoid percolation into alluvial aquifers (Ref. 2, p. 127). Also, it is important to contain spillovers from excessive rainfall.

d. Fugitive Releases of Contaminated Water. Fugitive releases of contaminated water are unplanned. We classified as less serious those releases that would affect bedrock aquifers (through overloading of mine sumps, etc.) because natural purification may attenuate certain contaminants. Also, the organic contaminants would be diluted by the long distance traveled and by water added by rainfall, etc. before the water encounters production wells or springs.

More serious would be those releases affecting surface waters and connected aquifers. Two sources of such releases may be expected. One is plant accidents and the other is flash flooding. In the Intermountain West, there is a possibility of contamination from sudden, massive (once in 25 years) flooding. For flash floods of short duration, check dams may be desirable, and they would also catch plant spill. To be effective, their footings would have to extend to bedrock.

e. Aquifer Bridging. The technologies suggested to prevent cross flow through spent MIS retorts between saline and fresh-water aquifers essentially fall into four categories: (1) *plug* the pores and crevasses in the rubbled spent shale so that flow is prevented or minimized, (2) *mine* so as to *leave an impervious caprock* of oil shale at the top of the retort, (3) *divert* the upper aquifer flow around the retort or bank of retorts, using appropriately emplaced piping, and (4) *isolate* an entire bank of retorts by emplacing a grout curtain around the perimeter, extending from the bottom of the lower bedrock aquifer to the top of the upper one. Some combination of 3 and 4 might be necessary if the grout curtain interfered with downstream users of the upper aquifers. At present, it is not known whether any workable plugging treatment can be developed; the caprock is in doubt because it is not known whether fissures will develop when rubbling occurs. The diversion concept is untried and potentially expensive, and likewise, the grout curtain concept is untried and potentially very expensive.

From a practical point of view, some combination of use of caprock with plugging of the spent retort using surface burned shale to fill the entire headspace seems most desirable. This would solve three problems: (1) the aquifer-bridging problem, (2) the disposal problem of surface extracted shale, and (3) the problem of possible subsidence over the burned retort. Even more desirable would be to manage the siting and mining so that the integrity of the caprock was assured, using alternatives only when necessary.

IV. CONTROL OF SOLIDS AND SOLID WASTES

The sheer magnitude of the solids to be handled and the solid waste to be disposed of in shale oil production is something never before approached in US energy production. For example, a representative Appalachian coal mining and coal cleaning operation might produce 2 000 000 tons per year of cleaned coal. The BTU equivalent of this coal would be about 12 500 000 barrels per year of shale oil (approximately 34 000 bbl/day). The solid waste from the coal cleaning operation is only 1 000 000 tons per year[24] as compared with the 12 500 000 to 25 000 000 tons of spent shale from the equivalent shale oil operation. The amount of waste from shale oil production is about *fifteen* to *thirty* times the quantity of solid waste from coal cleaning operations.

Analogies with coal mining waste and coal cleaning waste can only be carried to a certain point, because the considerable chemical differences between the two produce different environmental effects. But, insofar as the mechanical properties may be similar, lessons may be derived from the older technology. One of the most serious problems of above-ground raw shale storage is accidental ignition. Control measures similar to those for coal piles or coal-rich waste piles might be adopted. Another potentially serious problem is slumping, sliding, and gullying of waste shale piles, for which control technology learned from the older industry may be of value.

Whether dust control, transportation, piling, stabilization, and other solid waste procedures *can* be successfully conducted on so vast a scale even with the advantage of analogous experience is the major question in control technology for solids in the oil shale production program.

A. Regulations

Indirect contaminating effects of solid oil shale wastes by air (dust) or water (leaching) would be controlled by air or water pollution statutes previously discussed. A more direct effect of solids, generated by the transfer of enormous volumes of materials, is the problem of instability or slippage due to structural defects of waste piles (Ref. 2, pp. 133-141) and visual pollution, due to scarring of the landscape. These problems are accountable in Federal land reclamation statutes, such as the RCRA or the SWDA of 1976, as are problems pertaining to destruction of archaeological or paleontological objects. In essence, reclamation controls seek to maintain both the scenic and functional aspects of the land.

Although not specifically designated for the oil shale industry, provisions of the Surface Mining Control and Reclamation Act of 1977 and the Federal Coal Mine Health and Safety Act (1969), regulating safety standards for coal mines, refuse piles, and impounding structures, will no doubt be adapted to oil shale operations.

Both Utah, by means of the Utah Mined Land Reclamation Act of 1975, and Colorado, through the Colorado Mined Land Reclamation Act of 1976, have established specific requirements regarding statements of prior land use, estimates of current resource potential, and plans for postmining land use. Also required are specifications for topsoil and overburden deposition, grading and compacting, revegetation, and a timetable for returning the land to some semblance of its premined state in order to qualify for permission to develop an area.

B. Capabilities of Existing Control Technologies

Control technologies from the coal mining and mineral concentrating industries and the coal-fired power industry may be applicable to shale oil production, insofar as the chemical and physical properties of raw shale and of spent shale show similarities with coal, coal refuse, and ash. Experience with shale oil development programs will provide more specific information.

1. **Soil and Overburden from Open-Pit Mining.** The technology is well developed in connection with copper and iron mining. The appropriate modifications for rock and soil type and for site considerations have been proposed by the companies involved. Dust control may still be a problem.

2. **Raw Shale Storage.** Above-ground storage of raw shale presents problems analogous to those of raw coal storage and of high-coal-content mine waste piles. Pile construction methods are well known, and the ability to reduce the probability of ignition is built into these construction methods. Their applicability to shale piles is not yet evident. Methods of protection from weathering and dusting by temporary pile sealing are also well established. Complete prevention of raw shale pile ignition from accidents or lightning strikes may be difficult to accomplish but the effects may be mitigated by building many smaller separate piles rather than a few large ones. Pile leaching is not expected to be a problem, but conventional methods of ditching for collection of pile runoff are to be used.

3. Spent Shale Storage and Disposal. To a certain extent, technology transfer is possible from experience with fly ash, bottom ash, and coal-cleaning waste disposal. However, neither the physical nor chemical characteristics of the spent shale particles are directly comparable with any of these materials. The internal angle of repose of spent shale has been measured as 18.5°, and the proposed face angle of the storage piles is to be 14°. Some authors feel that present knowledge of pile-building technology is not adequate to prevent slippage, slumping, and other undesirable mechanical defects in very large spent shale piles.[2] On the other hand, others rely on the cementitious or pozzolanic nature of spent shale to provide a high degree of pile stability. Present knowledge of pile building and monitoring is not sufficient for this new application. The process-specific chemical and physical nature of spent shale must be investigated with regard to these considerations and some work in this area is under way.

4. Recovering and Revegetation. Assuming that spent shale is not classified as a hazardous waste, the technology for recovering and revegetation is well known. The principal obstacle to implementation may be effects of the saline-alkaline nature of the waste combined with the availability of water and top soil.

5. Fugitive Dust Emissions. Water sprays along the conveyor belts and other conventional dust reduction technology used during transporting of spent shale and pile building should control dust emissions. However, because of the very large scale of the operation, a large uncovered nonworking pile area will be susceptible to wind. It is not clear that enough partially treated process water is available for dust control in this large area, or whether spraying would be feasible.

6. Subsidence and Surface Disruption. Subsidence and surface disruption, according to specific existing standards, are of primary concern only if they affect the overall ecosystem or the property rights of others. Thus, interference with surface water or groundwater flow (for example, damming a stream, blocking an aquifer) is the principal concern to shale oil production. It does not seem possible to prevent subsidence with underground retorting, but proper site selection and room construction should minimize interferences with aquifer flow.

C. Critical Problem Areas and Uncertainties

Some of the critical problems of solid waste disposal are air and water pollution problems that were discussed in previous sections, as well as those discussed below. They are discussed here because the applicable environmental control technology focuses on the solid waste rather than on a waste stream of air or water.

1. Storage of Raw Shale. Once ignited, it is virtually impossible to extinguish a fire in a pile of raw shale. Spontaneous combustion, possible if the shale is quite finely divided, it not considered likely. Accidental ignition from some process or operating source or from lightning is more likely. The possibility of these fires becoming a serious problem can be reduced with good management, including restriction of both height and areal extent of each pile and adequate space between piles. It is not known whether lightning rods would be effective.

2. Disposal of Spent Shale. Three major concerns about spent shale disposal sites are (1) general problems of pile stability, especially in significant rainfall, (2) pile erosion in very heavy rainfall and flash flooding, and (3) management problems arising from the sheer magnitude of the waste to be stored. Some authors (Ref.1, p.140) raise general questions about pile stability, which apply to both side-fill and valley-fill techniques, although the valley fill is probably a little more stable. Two characteristics give rise to these uncertainties. One is that varying degrees of compaction are expected within a spent shale pile. The interfaces between more dense and less dense portions of the pile are likely to form planes of easy slippage, especially if lubricated by rainfall. Crawford[1] believes that the pile face angle of 14°, which has been proposed for some of the operations, is too close to the measured internal angle of slip of 18.5° for shale waste. Slumping of a pile can promote considerable water accumulation within the pile with many adverse effects, the least of which would be increased leaching from the pile; the worst would be disastrous pile movement. The second characteristic is pile erosion caused by heavy rainfall. Although adequate provisions are proposed to handle runoff from normal rainfall, control of intense rainfall and flash flooding may be a problem. Two hazards exist: (1) undercutting of the sides of the pile, and (2) gullying of the top of the pile. The first could cause major pile movement; both would result in accumulations of debris outside the designated pile area and result in silting along natural water courses. Various authors comment on the lack of experience with waste piles of the character and magnitude of the expected above-ground spent shale disposal piles. There is no analogy in chemical composition, particle size distribution, total mass to be disposed of, and rate of disposal of this mass in US mining experience.

3. **Revegetation of Spent Shale Piles.** The revegetation of spent shale piles has been studied carefully and the plans seem adequate. However, water of adequate quality to enable soil that holds plants to become re-established may be insufficient. Salinity of the spent shale is the major part of the problem. Possible concentration of boron in plants to a point unsatisfactory for domestic cattle has been at issue, but it may be only a minor problem.

REFERENCES

1. K. W. Crawford, C. H. Prien, L. B. Baboolal, C. C. Shih, and A. A. Lee, "A Preliminary Assessment of the Environmental Impacts from Oil Shale Developments," US Environmental Protection Agency, Industrial Environmental Research Laboratory (TRW Environmental Engineering Division and Denver Research Institute) report EPA-600/7-77-069 (July 1977).

2. N. de Nevers, D. Eckhoff, S. Swanson, B. Glenne, and F. Wagner, "Analysis of the Environmental Control Technology for Oil Shale Development," University of Utah, US Department of Energy report C0014043-1 (February 1978).

3. T. R. Galloway, "Oil Yield Loss Mechanisms in Modified In Situ Retorting of Oil Shale: The Challenge of Efficiently Retorting Very Non-Uniform Beds of Oil Shale Rubble," paper 56e presented at 86th Meeting of the American Institute of Chemical Engineers, Houston, Texas, April 4, 1979.

4. P. Wagner, P. L. Wanek, and J. M. Williams, "Environmental Research on a MIS Process," in Oil Shale Task Force Publication, US Department of Energy report DOE/EV-0078 (May 1980).

5. R. A. Loucks, "Occidental Vertical Modified In Situ Process for the Recovery of Oil from Oil Shale," Occidental Oil Shale, Inc., US Department of Energy report TID-28943 (August 1978).

6. "Environmental Development Plan—Oil Shale," US Department of Energy report DOE/EDP-0051 (November 1979), p. 18.

7. J. P. Fox, K. K. Mason, and J. J. Duvall, "Partitioning of Major, Minor and Trace Elements During Simulated In Situ Oil Shale Retorting in a Controlled-State Retort," Lawrence Berkeley Laboratory report LBL-9030 (April 1979).

8. Denver Research Institute, "EPA Program Status Report: Oil Shale 1979 Update," Environmental Protection Agency report EPA-600/7-79-089.

9. US Department of Energy, "Environmental Readiness Document, Oil Shale, Commercialization Phase III Planning," report DOE/ERD-0016 (September 1978), p. 15.

10. P. Persoff and J. P. Fox, "Control Strategies for Abandoned In Situ Oil Shale Retorts, Twelfth Oil Shale Symposium Proceedings, Golden, Colorado, April 18-20, 1979 (Colorado School of Mines Press, 1979), pp. 72-80.

11. H. W. Parker, R. M. Bethea, N. Guven, M. N. Gazdar, and J. K. Owusu, "Simulated Ground Water Leaching of In Situ Retorted or Burned Oil Shale," American Chemical Society Division of Fuel Chemistry preprint 21 (6), p. 66-76 (1976).

12. J. P. Fox, Lawrence Berkeley Laboratory, "Water Treatment and Disposal," presented at 2nd ERDA Meeting and Workshop on Oil Shale Environmental Research, Richland, Washington, November 1, 1977.

13. "Properties of Retort Water," in *Synthetic Fuels Data Handbook,* Thomas A. Hendrickson, Ed. (Cameron Engineers, Inc., Denver, 1979), p. 101.

14. K. D. Linstedt, E. R. Bennett, and B. Harding, "Characterization and Treatment of Retort Water from In Situ Oil Shale Processing," University of Colorado, Department of Civil and Environmental Engineering final report PL 61683 (September 1976).

15. D. S. Farrier, R. E. Poulson, Q. D. Skinner, J. C. Adams, and J. B. Bower, "Acquisition, Processing and Storage for Environmental Research of Aqueous Effluents from In Situ Oil Shale Processing," Proc. 2nd Pac. Chem. Eng. Congr., 1977, Vol. II, p. 1031.

16. Mitre Corporation, "Environmental Control Costs for Oil Shale Processes," US Department of Energy report DOE-EV-0055 (October 1979).

17. Roy E. Williams, *Waste Production and Disposal in Mining, Milling, and Metallurgical Industries* (Miller Freeman Publications, San Francisco, 1975).

18. "Cleaning Our Environment, the Chemical Basis for Action," a report by the Subcommittee on Environmental Improvement, Committee on Chemistry and Public Affairs (American Chemical Society, Washington, DC (1969).

19. D. W. Hendricks and J. C. Ward, "Environmental Analysis of an Oil Shale Industry in the Upper Colorado Region," in *Developments in Petroleum Science 5: Oil Shale,* T. F. Yen and G. V. Chilingarian, Eds. (American Elsevier Publishing Co., New York, 1976), p. 226.

20. G. Amy and J. Thomas, "Factors that Influence the Leaching of Organic Material from In Situ Spent Shale," Lawrence Berkeley Laboratory report LBL-5974 (1977).

21. J. J. Schmidt-Collerus, Francis Bonomo, and C. H. Prien, "Polycondensed Aromatic Compounds and Carcinogens in the Shale Ash of Carbonaceous Spent Shales from Retorting of Oil Shale," in *Science and Technology of Oil Shale,* T. F. Yen, Ed. (Ann Arbor Science Publishers, Inc., Ann Arbor, 1976) Chap. 9.

22. W. R. Chappell, "Toxic Trace Elements and Oil Shale Production," Proc. 11th Oil Shale Symp., Golden, Colorado, April 12-14, 1978 (Colorado School of Mines Press, 1978), pp. 32-42.

23. Energy Development Consultants, Inc., "Oil Shale in Colorado 1979," Colorado Energy Research Institute report (January 1979).

24. National Academy of Sciences/National Academy of Engineering Committee, *Underground Disposal of Coal Mine Wastes* (National Academy of Sciences, Washington, 1975), pp. 78-79.

☆ U.S. GOVERNMENT PRINTING OFFICE: 1980—777-022/192