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RETORT ABANDONMENT -- ISSUES AND RESEARCH NEEDS

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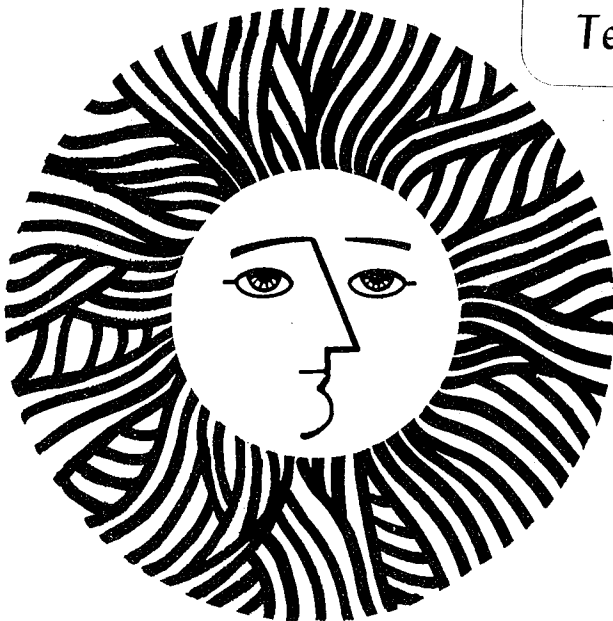
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J.P. Fox, P. Persoff, P. Wagner, and E.J. Peterson

August 1980

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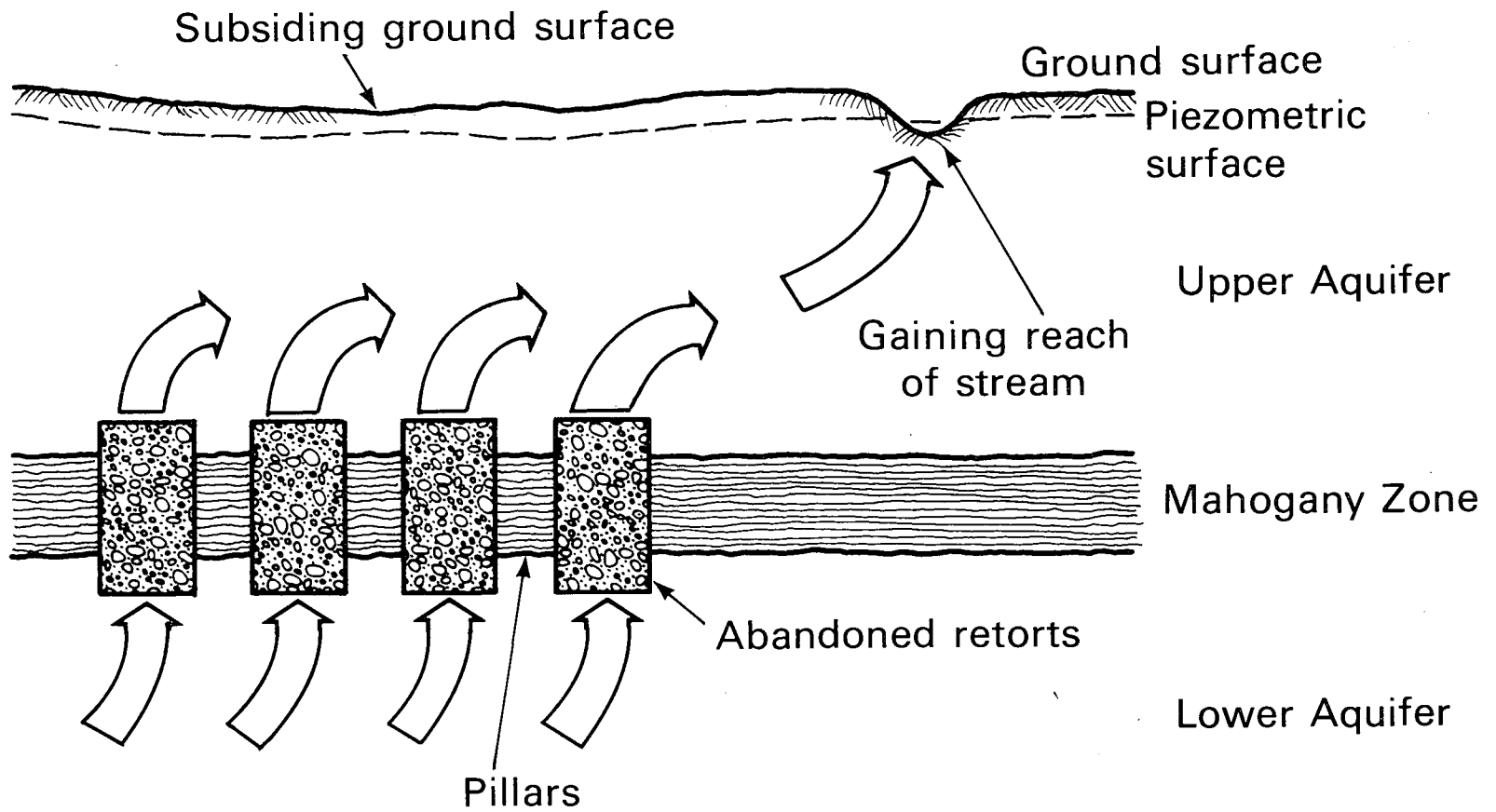
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INTRODUCTION

Vast resources of oil shale--more than 600 billion barrels of recoverable syncrude--exist in the Green River Formation in Colorado, Utah, and Wyoming. The richest of these deposits, those scheduled for early development, are located in the Piceance Creek Basin of western Colorado. The Mahogany Zone and adjacent oil shales, the target of commercial development, are largely impermeable and separate layers of fractured leaner shale which act as confined or unconfined aquifers.

Current industrial plans call for the development of this resource by vertical modified in-situ (VMIS) retorting. Figure 1 shows a schematic of the relative positions of the Mahogany Zone, aquifers, and VMIS retorts. Large chambers of rubblized shale, about 300 to 750 feet high and 100 to 200 feet square in plan, will be formed in the Mahogany Zone and surrounding oil shale from 500 to 2000 feet below the surface. Vertical pillars, representing nearly 50 percent of the in-place shale, will be left between the retorts to support the overburden. The retort chambers will be pyrolyzed vertically from the top to the bottom by propagating a reaction zone down the packed bed of shale using air and steam. Oil, water, and gaseous products will be pumped to the surface for processing. Following processing, the retorts will be abandoned and large underground chambers of retorted shale left behind.

This type of oil shale processing may result in a number of environmental impacts including aquifer disruption, subsidence, and low resource recovery (Figure 1). During processing, the surrounding aquifers are dewatered. This will alter groundwater quality and reduce the flow in local springs and streams. On abandonment, groundwater will reinvade the area, leaching retorted shale and transporting leached material into the aquifers where it may be withdrawn in wells or discharged into springs and streams that feed the Colorado River system. Additionally, formerly separated aquifers will now be in communication, permitting waters of different quality to mix. There is considerable concern that the large overburden and high void fraction presently under consideration will result in overburden cracking and subsidence over the retorts. Finally, resource recovery in VMIS retorting is poor. About 50 percent of the richer oil shale is left in place as pillars



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Figure 1. Schematic of in-situ retorts and aquifers in Piceance Creek Basin, showing potential for subsidence and spent shale leaching.

to support the overburden, and leaner shales above and below the retorts are not recovered. Thus, primary extraction of a small fraction of the resource considerably complicates secondary extraction of the material left behind.

The purpose of this paper is to identify the key issues in the area of retort abandonment and to assess research needs and priorities based on the current state of knowledge. The paper focuses on the Piceance Creek Basin of western Colorado and the VMIS process because these are presently emphasized by an intense RD&D program by both government and industry. Retort abandonment, as used here, is the process of returning a retorted area to a state of environmental acceptability; it refers to a set of safeguards--procedures, strategies, and technologies--that would be applied prior to, during, or following retorting in order to mitigate undesirable environmental impacts.

ISSUES

Retort abandonment is a new and technically complex field which has only recently been recognized. The first research program in this area was sponsored by the developers of lease tract C-a in 1977. Thus, research in this area is in its infancy, and there are many unresolved issues which range from problem definition to technical details of specifically proposed control technologies. Work in this area is presently being sponsored by the U.S. Department of Energy; the U.S. Bureau of Mines; and the industrial developers of lease tracts C-a and C-b. Some of the major retort abandonment issues are summarized in Table 1. Each of these is briefly discussed below.

PROBLEM DEFINITION

The VMIS process may result in structural, hydrologic, and water quality problems which must be solved before a large-scale commercial industry is developed. Solutions to these problems hinge on an adequate definition and understanding of the problem to be solved and sufficient scientific and engineering data to design and implement control strategies. There is presently little agreement among scientists and engineers on the list of problems which should be considered and their nature, extent, and severity. Thus, there is imminent need for accelerated research in this area. The issues, state of knowledge, and research needs and priorities in each of these areas are reviewed here.

Structural Issues

The structural problems associated with VMIS retorting include overburden cracking, subsidence, and low resource recovery. Subsidence and overburden cracking are common in virtually all mining and tunneling operations where the elevation of the land surface above the underground openings is decreased due to the compression of the structural support members, usually pillars, in the underground works and the deformation of the overlying strata. Vertical modified in-situ retorting will be no exception and, in fact, presents an unprecedented subsidence design problem. The target resource, the Mahogany Zone, is deep. Overburden thickness, which varies throughout the Basin, is typically from 500 to 1000 feet. Present industrial plans call for the removal of 20 to 40 percent of the in-place rock. These factors could lead to subsidence of the land surface over a field of retorts. The resulting overburden cracks and fractures could allow retorting gases to escape to the

Table 1. Summary of retort abandonment issues, research status, needs, and priorities.

ISSUE	STATUS OF RESEARCH	RESEARCH NEEDS	PRIORITY ^a
PROBLEM DEFINITION			
<u>Structural Issues</u>			
Long-term stability, subsidence, and low resource recovery need to be put into perspective.	Calculations have been initiated to assess subsidence potential and methods of improving resource recovery.	More refined computational techniques need to be developed and applied to assess retort stability. Field measurements of in-situ stresses need to be made. Physical properties of large samples need to be determined. Effect of thermal regime on structural calculations should be investigated.	2
<u>Hydrology Issues</u>			
There are inadequate hydrologic data to assess and predict impacts, the geohydrology of oil shale regions is unclear, and most numerical models are not appropriate for unsaturated flow in fractured aquifers.	Scattered field measurements are available for a few oil shale sites. A regional groundwater model has been developed by the USGS and quasi site-specific models by others.	A field program to determine key hydrologic variables at several active oil shale sites is required. Existing models should be expanded to include unsaturated flow and fractured media. The geohydrology of the oil shale region needs to be determined by intensive field studies.	1
<u>Water Quality Issues</u>			
The leaching characteristics of in-situ spent shales, pollutant transport in fractured oil shale aquifers, and the regulatory framework need to be defined.	A number of studies have been conducted on the leaching of spent shales from simulated retorts under laboratory conditions. A regional water quality model that predicts TDS concentrations has been developed by the USGS.	Representative samples of field in-situ spent shales need to be leached under conditions that closely simulate those in the field. The physics, chemistry, and kinetics of leachate formation and transport should be studied. The existing water quality model should be expanded to include additional parameters. A field monitoring program to study leachate composition and transport should be developed. The governing regulatory framework should be defined.	1

^aThe highest priority is assigned a "1" and the lowest a "3".

Table 1. Summary of retort abandonment issues, research status, needs, and priorities. (Continued)

ISSUE	STATUS OF RESEARCH	RESEARCH NEEDS	PRIORITY ^a
<u>CONTROL TECHNOLOGY</u>			
<u>Site Selection</u>			
There are inadequate data to determine whether VMIS retorts can be completely contained in dry zones and what fraction of the resource can be recovered with this strategy.	None	An intensive field investigation is required to define the location of aquifers. Existing core hole logs and hydrologic data should also be evaluated. See also hydrology issues.	1
<u>Intentional Leaching</u>			
The engineering feasibility of this strategy needs to be demonstrated and integrated into an overall water management plan.	Work has been initiated to develop a mathematical model of the leaching process. Preliminary experiments suggest that pore diffusion may limit the application of this technology and that leachate demineralization will be required.	Data must be developed on the availability of water for leaching, the quality of leachate, the kinetics of leachate formation, and the volume of water that must be treated. Ongoing work on modeling of leachate formation and treatability of leachate should be continued.	1
<u>Modification of Retort Operating Conditions</u>			
The effect of retort operating conditions on leachate composition needs to be established.	Studies have shown that the concentration of some constituents in leachates produced in field in-situ retorts may be lower than those produced in laboratory retorts. Other work has shown that leachate composition depends on retort operating conditions.	Laboratory and field studies need to be conducted using representative field samples to determine if proposed operating conditions will be adequate to control water quality problems. Laboratory studies need to be conducted to determine the effect of a range of variables on major and minor constituents; field conditions need to be simulated in these studies.	2

^aThe highest priority is assigned a "1" and the lowest a "3".

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PROBLEM DEFINITION			
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<u>Hydrology Issues</u>			
There are inadequate hydrologic data to assess and predict impacts, the geohydrology of oil shale regions is unclear, and most numerical models are not appropriate for unsaturated flow in fractured aquifers.	Scattered field measurements are available for a few oil shale sites. A regional groundwater model has been developed by the USGS and quasi site-specific models by others.	A field program to determine key hydrologic variables at several active oil shale sites is required. Existing models should be expanded to include unsaturated flow and fractured media. The geohydrology of the oil shale region needs to be determined by intensive field studies.	1
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^aThe highest priority is assigned a "1" and the lowest a "3".

hydrosphere and atmosphere and affect the hydrologic properties of aquifers. The structural integrity of aboveground structures could be impaired. Structural instabilities could lead to failure and collapse of tunnels, adits, drifts, or the retorts themselves, leading to serious worker health and safety problems.

Recent calculations of the potential for subsidence suggest that the ground surface should be vertically displaced less than 1 cm over a properly designed retort and that industry plans will provide adequate protection (Ratigan, 1980; Ratigan and Goodman 1981a, 1981b). However, considerable concern still exists over the long-term stability of a field of abandoned retorts because of the lack of field experience and the limitations of numerical models. Thermal effects and discontinuities in the shale could lead to greater subsidence and instabilities in the underground mine. Conventional computational techniques are inadequate to predict subsidence and other structural instabilities, and there are presently no field data available to assess this problem because field experiments have consisted of single, small retorts while commercial operations will use many hundreds of very large retorts. Numerical methods are limited by: (1) absence of adequate field data; (2) unprecedented size and complexity of proposed operations and attendant lack of methods and experience to analyze these operations; and (3) failure of existing models to incorporate prevailing state of in-situ stress, thermal/structural effects, and discontinuities from joints and fractures. Improved computational techniques need to be developed and applied to determine the effect of various mine design scenarios on retort stability. Field measurements of in-situ stresses need to be made, physical properties need to be determined on large samples that are representative of field materials, and long-term investigations at a large-scale in-situ oil shale plant should be conducted. The effect of the thermal regime and discontinuities on the stability of a field of VMIS retorts should be investigated in fundamental laboratory studies and in numerical analyses. Methods to locate and characterize discontinuities in the field should be developed and applied, and the use of a water quench to eliminate instabilities due to the thermal regime should be investigated. Additionally, the effect of subsidence and overburden cracking on the hydraulic properties of aquifers should be addressed.

Resource recovery, on the other hand, is an economic and social issue. Underground mining methods have historically left a significant portion of the resource in place. This is common practice in room and pillar mining of coal in the United States where 42 percent of the resource is left in place as pillars. However, the resource recovery issue in fossil fuels may become controversial in the future due to the requirement of PL 95-87 to maximize resource recovery and because the nation is acutely aware of its finite fossil fuel resources, their present scarcity, the environmental consequences of multiple extractions, and the costs inherent in unplanned development. Poor resource recovery may lead to future operations at the same site, thus resulting in a double assault on the environment and added costs.

This is a particularly important issue for VMIS retorting where 25 to 50 percent of the resource is left in the ground as pillars to support the overburden. Resource recovery could be improved if the pillars could be retorted, which would be possible if the abandoned retorts could be strengthened to serve as new pillars. The amount of strength required would depend on local

geological conditions and individual mine designs. This possibility needs to be evaluated in laboratory experiments and will be discussed in the "Control Technology" section.

Hydrology Issues

Western oil shales are known to be laced with groundwaters (Weeks et al., 1974; NAS, 1980; Robson and Saulnier, 1980). The physical presence of water in the oil shale formation poses several problems for the oil shale industry. First, the water must be removed before large-scale mining and underground combustion can occur. Massive dewatering, requiring long-term pumping rates of from 2,300 to 21,800 gpm at tract C-a and 7,600 to 14,200 gpm at tract C-b, may be required (Mehran et al., 1981). This may result in alteration of local water quality, drying up of wells and springs, and the loss of considerable water from local streams such as the Piceance Creek and Yellow Creek. Recent calculations indicate that 30 years of dewatering at the C-a tract may lower the phreatic surface by as much as 102 feet beneath waters tributary to the Yellow Creek and that 60 years of dewatering at the C-b tract may lower it by 328 feet beneath the Piceance Creek (Mehran et al., 1981). Groundwaters will slowly reinvade the retorted site upon abandonment, flowing through mined-out and/or retorted areas. Soluble organic and inorganic constituents may be leached from these areas, transported in local aquifers, and discharged into wells, springs, and streams that drain into the Colorado River system (Figure 1).

The probable occurrence, severity, and extent of these hydrology-related problems--dewatering and reinvasion--are poorly understood at the present time although a number of studies have investigated them (Weeks et al., 1974; Fox, 1979; Robson and Saulnier, 1980; Brown et al., 1977; Mehran et al., 1981). There are presently inadequate hydrologic data to assess and predict impacts; and the hydrology of the Piceance Creek Basin and other areas is uncertain. Model simulations have been inadequate due to: (1) uniqueness and complexity of hydrogeology; (2) neglect of unsaturated flow; (3) use of porous media rather than fractured media simulations; and (4) use of nonrepresentative geometry to describe the physical system. These studies have generally concluded that these large dewatering flow rates will result in the loss of water from streams and that groundwaters will reinvade retorting sites decades to centuries after abandonment. However, the magnitude of these effects is uncertain. Large ranges for dewatering and reinvasion rates have been reported by various investigators, and there is little agreement on the geohydrology and geographical extent of aquifers. The aquifer system in the western oil shale region is highly heterogeneous and anisotropic (the primary source of permeability is faults, joints, collapse breccia, and solution cavities which are poorly mapped), and there are very few field measurements of key hydrologic variables such as the storage coefficient and transmissivity. This has resulted in the use of a very few site-specific measurements of a heterogeneous system to characterize large areas, from one to hundreds of square miles.

Pre- and post-development geohydrology of the Piceance Creek Basin and other areas is not adequately understood and is presently controversial. Coring (Smith, 1980) and recent hydrologic investigations on lease tracts C-a and C-b have revealed that the aquifer system is far more complex than the simplistic model originally proposed by Weeks et al. (1974). In the Weeks

model, the groundwater system was conceptualized as an upper and lower aquifer separated by the relatively impermeable Mahogany Zone; local streams were assumed to be recharged, amounting to some 80 percent of their flow, by water from the upper aquifer. This type of scenario could result in groundwater reinvasion and leaching the abandoned retorts and leachate discharge into the Colorado River system. Because the Mahogany Zone is only 200 feet below the surface at its thickest point and because commercial oil shale retorts will span 300 or more feet of continuous oil shale including this zone, it has been variously proposed that the retorts will act as conduits connecting the upper and lower aquifers (Fox, 1979; Amy, 1981). However, recent work suggests that the system consists of a complex tier of aquifers and aquitards. Smith (1980) has indicated that, on the Naval Oil Shale Reserves, the oil shale horizon from the top of the B-Groove to several hundred feet above the top of the Mahogany Zone is dry and not connected with surrounding aquifers. These new results suggest that retorts could be wholly contained in dry zones where groundwater might not invade an abandoned site. Additionally, recent analyses of water quality data suggest that local streams may receive flow from the alluvial aquifer rather than, or in addition to, flow from the upper aquifer. This would tend to lessen the impact of dewatering and leachate discharge on local streams.

Even less is known about site dewatering and post-abandonment geohydrology. Initial conditions for post-retorting flow will be determined by the dewatering operation, which is not clearly understood at this time. Mehran et al. (1981) recently completed parametric studies and long-term simulations for the proposed developments at tracts C-a and C-b. This study demonstrated that higher porosities, lower residual saturations, higher hydraulic conductivities, and isotropy will tend to increase mine inflows. These investigations indicate that the desaturation process and associated permeability variations have important effects on dewatering and reinvasion which had previously been overlooked (Weeks et al., 1974; Robson and Saulnier, 1980; Tipton and Kalmbach, 1977; Brown et al., 1977; Banks et al., 1978). Dewatering will initiate unsaturated flow, that is, when water is withdrawn from a medium by pumping, it is replaced by air and the medium is said to "desaturate." This reduces permeability and affects local flow properties. Mehran et al. (1981) have shown that desaturation will increase pumping rates required to dewater the formation by an order of magnitude or more and decrease reinvasion rates into the abandoned site. These new results could adversely affect the economics of oil shale recovery (due to high dewatering flows) or lead to less serious impacts from reinvasion (due to lower rates).

Relatively little work has been completed on groundwater reinvasion of abandoned retorts. These calculations encounter the same difficulties that exist in other hydraulic simulations, i.e., inadequate field data and description of baseline geohydrology. They are additionally complicated by: (1) the strong (and undefined) influence of the thermal regime; (2) lack of knowledge on the state of saturation at abandonment; and (3) effect of hysteresis. Mehran et al. (1981) have estimated that reinvasion rates on tract C-b may be 10 ft/yr. These low rates could have favorable environmental consequences by providing sufficient time for control technologies to be implemented.

An adequate definition of the occurrence, extent, and severity of hydrology problems will require an extensive hydrologic data base obtained

from field tests and the refinement of existing hydrologic models. In-depth hydrologic studies are required to define the geohydrology of oil shale sites that are being considered for early commercialization. Aquifer locations need to be mapped and flow directions determined. Key hydrologic parameters, including transmissivity, permeability, storage coefficients, and the relationship between saturation and hydraulic conductivity, need to be determined for each aquifer over a sufficiently large geographical region.

New modeling studies should not be undertaken until the data deficiency has been resolved. Existing models are already more sophisticated than available data warrant. These existing tools should be used in parametric and sensitivity analyses in the short term to identify important field variables. Further simulations of hydrologic impacts of VMIS retorting should await an improved data base. In the interim, the existing regional groundwater model of the Piceance Creek Basin (Robson and Saulnier, 1980) should be extended to include unsaturated flow, fractured media, and more realistic geometry, as appropriate, and used to study additional field sites.

Because of the potential importance of hydrologic impacts, both from an economic and environmental standpoint and because of the relative disarray of the field, it would be worthwhile to conduct a carefully planned workshop in which field scientists and computationalists bring together their expertise to assemble a more physically realistic model of the system. Areas in which critical data are lacking and field work is required should be identified. Without this type of integrated effort, further computation efforts will lack credibility.

Water Quality Issues

The water quality problems associated with VMIS retorting are linked to the hydrology issues discussed in the previous section and encompass the degradation of local surface waters and groundwaters by in-situ leachate and by the mixing of waters of different qualities. Since water quality ultimately depends on the volume of water in which a constituent is dissolved, the water quality problems are constrained by the same set of factors discussed under hydrology.

In in-situ retorting, large chambers of retorted shale and allied mining works, including shafts, adits, and drifts, are left underground where they might act as sources of pollution. If the retorting site is located in a wet region, groundwater may enter the site following abandonment and leach soluble organic and inorganic constituents from this raw and spent shale. These materials may then be transported in local aquifers, withdrawn in wells, or discharged into local springs and streams. Additionally, in some areas of the Green River Formation, such as on lease tract C-b, water quality in adjacent aquifers is of widely differing qualities and pockets of highly saline water exist. If in-situ retorting connects these aquifers and/or saline pockets, local groundwaters may be degraded by mixing with poorer quality water.

The problems of aquifer and eventual surface stream pollution by leaching of VMIS retorts on lease tracts C-a and C-b have been studied by Fox (1979) and Robson and Saulnier (1980). Fox concluded that it could take centuries before significant groundwater degradation would occur, due to the low flow

velocities in many areas of the Piceance Creek Basin. However, the report pointed out that the potential long-term effects could be serious due to the critical issue of salinity in the Colorado River system and the slow self-purification properties of groundwater aquifers. Leachates could result in salinity increases of from 2 to 56 mg/l in the Colorado River at Lees Ferry and of from 1,740 to 46,100 mg/l in the Piceance Creek at White River (Fox, 1979) several centuries after site abandonment. Robson and Saulnier (1980) similarly concluded that the discharge of leachate from in-situ retorts would adversely affect the quality of local surface waters and groundwaters. For tract C-b, they predicted a 750 to 1,750 mg/l increase in TDS of Piceance Creek after 60 years of leaching and a 20,000 mg/l increase near the mine. Similarly, for tract C-a, they predicted minimal changes in water quality in Yellow Creek following 60 years of leaching, due to low flow velocities and long transit distances, and an increase in excess of 40,000 mg/l near the mine. Little attention has been focused on the issue of mixing of dissimilar waters.

However, as noted previously for hydrology problems, the probable occurrence, severity, and extent of these problems are poorly understood at the present time. The major uncertainties are related to the underlying hydrology (previously discussed), leaching characteristics of in-situ spent shales, pollutant transport in fractured oil shale aquifers, and the controlling regulatory framework.

Although a large number of studies have been conducted on the leaching of in-situ spent shales (Parker et al., 1976, 1977, June 1978, Sept. 1978; Amy, 1981; Amy and Thomas, 1977; Jackson et al., 1975; and Kuo et al., 1979), the composition of these leachates is still uncertain due to the absence of representative field samples and inadequate laboratory simulations of field conditions. The majority of this work was conducted using spent shales produced by simulated in-situ retorts, laboratory reactors designed and operated to simulate as nearly as possible actual field conditions. Industrial developers and Smith et al. (1978) argue that leachates from field in-situ retorts will differ chemically from those produced by simulated in-situ retorts and that most dissolved constituents will occur at lower concentrations in field leachates. This argument is based on the fact that field retorting will probably produce relatively insoluble silicate mineral phases such as members of the akermanite-gehlenite series rather than the more leachable oxides often observed in simulated retorts. This is due to the higher temperature and longer residence times that are anticipated for the hot spent shale within field retorts. These views are supported by the work of Kuo et al. (1979) in which core samples from an Occidental field retort were leached under laboratory conditions; these leachates had a lower concentration of TDS, many inorganic ions, and a lower pH than leachates from simulated in-situ spent shales. However, these perceptions and experiments address only salinity, pH, and certain major ions while an equally critical environmental issue is the solubilization and mobilization of toxic trace elements that have been observed in spent shale leachates. A recent DOE study (U.S. DOE, 1980), in which core material from an Occidental field retort was leached with distilled water, revealed that concentrations of Al, As, B, F, Mo, Se, and V were sufficiently high to warrant further investigation. It is not at all clear whether the trace elements of environmental concern are less soluble or less

mobile as a result of field retorting conditions. At this time, the data to resolve these issues and an understanding of the controlling chemical processes are inadequate to predict the composition of field leachates. Thus, the question of the relationship between retorting conditions and the nature and magnitude of any ensuing environmental concerns is as yet unresolved.

The actual composition of field leachates is further obscured by the lack of field experience and the difficulty of obtaining reasonable simulations of the leaching process under laboratory conditions. Past leaching studies used distilled water at ambient temperatures and pressures, contact times between the shale and leach water of 30 days or less, and a uniform and small particle size range to define equilibrium conditions. Although this is a key first step in understanding leachate chemistry, it must be expanded and combined with other approaches to model the complex leachate-groundwater system actually encountered in the field. In the field, relatively large nonuniform particles of hot spent shale will be leached by slowly moving groundwater, a few feet per year, with a high TDS; initial leach water temperatures and pressures will be greater than ambient; and contact times may be on the order of one to ten years. Trapped retorting gases will be dissolved by invading waters, and the bottom section of a field retort may act as a source of contamination. This section is exposed to different conditions than the rest of the retort. It will contain a plug of partially retorted shale, wet with oil, condensed material, and other retorting byproducts; and it will chemically behave very differently from the rest of the retort. Therefore existing data, including those developed using field spent shales, may not accurately describe field leachates. Some laboratory experiments are being planned to investigate time-temperature effects, surface area effects, and local leach water. These studies will allow us to understand and model the equilibrium (thermodynamic) and time-dependent (kinetic) influences of leachate formation under conditions that simulate actual field retorts.

The ultimate impact of leachate on local water quality will depend on its attenuation during aquifer transport. The ability of the aquifer media to attenuate through dilution, pH adjustment, sorption mechanisms, or ion-exchange processes is perhaps the single most important aspect of leachate generation and transport. Although these topics have been discussed by Fox (1979) and have been considered in a regional chemical transport model (Robson and Saulnier, 1980), the quantitative data needed to substantiate the views of these authors do not exist.

Finally, the actual existence of a water quality problem depends on the uses to which a water is put and the quality requirements for those uses. These requirements are specified in a complex set of state and federal regulations which govern the quality of waters. Regulations which may apply to an in-situ oil shale industry include the Federal Water Pollution Control Act (PL 92-500), the Surface Mining Control and Reclamation Act (PL 95-87), the Resource Conservation and Recovery Act (PL 94-580), the Safe Drinking Water Act (PL 93-523), Colorado River Basin Salinity Control Forum Standards, and water quality criteria and effluent limitations set by the states of Colorado, Utah, and Wyoming. However, many uncertainties surround these regulations because specific standards for an in-situ oil shale industry have not been established.

An adequate definition of the occurrence, extent, and severity of water quality problems will require the resolution of the above discussed issues, namely, leaching characteristics of spent shale, pollutant transport in fractured oil shale aquifers, and the controlling regulatory framework. This will require an extensive field monitoring program coupled to a laboratory program. The physics, chemistry, and kinetics of leachate formation and transport should be explored in fundamental laboratory studies in which representative field samples are leached under approximate field conditions. The effects of retort operating conditions and leaching conditions on leachate composition need to be evaluated. Important variables include leach water composition and temperature, in-situ pressures, shale temperature, groundwater flow velocities, and contact time between the shale and water. The effect of the bottom plug and dissolved in-situ gases should also be evaluated in laboratory studies. Experimental results should be used to develop a water quality model of the system to predict impacts for a range of retorting scenarios. Dispersion coefficients, which will be dependent on both leachate concentrations and flow velocities, need to be determined for oil shale media. The results of the computer simulations and laboratory studies should be corroborated in field leaching studies in which abandoned retorts are flooded with local groundwater and the surrounding aquifers are monitored over several years. Attention needs to be focused on the proper location and completion of monitoring wells in fractured aquifers. Finally, the regulatory framework needs to be clarified so that the degree of control required, if any, to preserve environmental integrity can be determined once the proposed problems are adequately defined.

CONTROL TECHNOLOGY

Solutions to the structural, hydrologic, and water quality problems discussed in the previous sections must be determined before a large-scale commercial oil shale industry can develop. These solutions or control technologies may consist of management strategies or hardware options to lessen the impacts of large-scale dewatering, invasion of retorted sites by groundwater, in-situ leaching, subsidence, and low resource recovery. These strategies should be developed in parallel with retorting technology, and close coordination and liaison with technology development should be fostered.

A number of strategies, including site selection, retort grouting, intentional leaching, modification of retorting conditions, and use of a grout curtain, have been proposed and laboratory and computer simulations of these options are in progress (Persoff and Fox, 1979, 1980; Fox and Persoff, 1980). However, as discussed previously, this research has been in progress for less than three years, and the problems that such technology would have to solve and the criteria that would have to be met are largely undefined. Therefore, there are many unresolved technical issues and uncertainties, and considerable additional research is required. Each proposed control technology is reviewed below in the framework of what is currently known and recommendations made for additional research.

Site Selection

The purpose of this strategy is to locate VMIS retorts in groundwater-free zones. This would minimize or eliminate in-situ leachate formation and transport and represents the most desirable condition for protecting ground-

water from degradation. There are presently inadequate data to determine with certainty whether or not VMIS retorts can be completely contained in dry zones and, if so, what fraction of the resource can be recovered using this control strategy. It is recommended that an in-depth study of site selection techniques be completed. Existing core hole logs and hydrologic data should be reviewed to determine the fraction of the resource that can accommodate in-situ retorting in dry zones. This should be supplemented with new field data, as required. This survey should form the basis of further selection of sites for experimental and commercial programs.

Intentional Leaching

Leachate formation and transport can be minimized by intentionally leaching the retorts, recovering the leachate, treating it, and either disposing of it or reusing it for further leaching. Several laboratory investigations have shown that the concentration of organics and inorganics in leachates decreases rapidly with leaching flow (Amy and Thomas, 1977; Amy, 1981; Kuo et al., 1979; Persoff and Fox, 1980). Thus, it has been proposed that treating a finite volume of leachate may be sufficient to remove enough of the leachable material in spent retorts to protect groundwater quality (Persoff and Fox, 1980). However, recent work by Hall and Selleck (1981), directed at developing a mathematical model for the leaching of organic carbon, indicates that there are two separate leaching mechanisms. The first, the rapid removal of carbon from the surface of shale particles, has been noted by many investigators and is well documented. However, the second, the slow transfer of carbon from internal pores, has not previously been investigated and could have significant implications for an intentional leaching strategy. Because this second mechanism may persist through many pore volumes and if the concentration of organics and other constituents in these waters is sufficiently high, it may not be feasible to control leaching by intentional leaching.

Inadequate experimental work has been conducted on this control technology to determine if it is indeed feasible and, if so, how to optimize and implement it. However, related work on leachate composition, formation, and transport is underway. Before intentional leaching can be adequately evaluated as a control method, data need to be developed on the availability of water for leaching, the quality of leachate, the kinetics of leachate formation, the volume of water that must be treated, and methods of leachate treatment. A large amount of water is needed for leaching. Estimates indicate that 10 to 14 MGD of water would be required for two pore volumes of leaching per 50,000 barrel-per-day capacity (Persoff and Fox, 1980). Detailed estimates of water availability for this purpose should be made. A plan for handling, storing, and reusing leachate and disposing of the brine streams from treatment must be developed. The volume of leachate that must be treated needs to be defined so that treatment costs, which are nearly proportional to leachate volume, can be determined. This will require the further development and use of a kinetic model of the leaching process (Hall and Selleck, 1981). Methods of treating the produced leachate must be selected and tested in laboratory- and pilot-scale treatability studies conducted using field spent shales, and the result of this work corroborated in larger scale field tests. Water quality requirements for treated leachates, dependent upon the reuse or disposal option, must be determined.

Modification of Retort Operating Conditions

Several studies (Amy, 1981; Parker et al., 1978) have shown that the leachability of spent shale depends upon retort operating conditions. This work suggests that leaching is minimized by combustion retorting to burn off char; use of sweep gas to remove CO₂; high temperatures, about 1000°C, to promote silication reactions; steam retorting; and a slow retorting rate. However, the relationship between retorting conditions and the leachability and mobility of many environmentally important trace elements has not been defined. If these conditions are used, it may be possible to produce a spent shale with adequate strength and a sufficiently low leachability to minimize water quality and structural problems of in-situ retorts. However, it is presently uncertain whether these conditions are adequate to mitigate all leaching problems. The relationship between operating conditions and leachability is complex and inadequately understood at present. Related issues, namely composition of the leachate, pollutant transport, and the controlling regulatory framework, which were discussed in a previous section, need to be addressed.

Additional research is required to further explore the effect of retorting conditions on the solubility of a broader range of constituents, including trace organic and inorganic compounds. The effect of shale composition, retorting temperature, retorting rate, input gas composition, and particle size on the solubility of major and minor compounds needs to be determined for conditions which span those anticipated for commercial development. Tradeoffs between oil production and leachability need to be explored in economic studies.

Grouting

The three principal environmental problems associated with VMIS retorting--contamination of surface waters and groundwaters, subsidence, and low resource recovery--may be alleviated by filling the abandoned in-situ retorts with a grout made from surface spent shale. This grout would fill some of the voids, reduce the permeability of the retorts, and provide protection against subsidence by increasing retort stiffness and strength. If adequate strength could be developed in the retorted mass, it might be feasible to retort some of the pillars, thus improving resource recovery. A cheap material, such as spent shale, would have to be used as the basis of such a grout because 9 to 12 ft³ of voids must be filled for each barrel of oil recovered. Thus, conventional grouting materials are too costly for this application (Fox et al., 1978).

The successful application of this proposal requires the development of grouting criteria, formulation of an adequate grouting recipe, and development of methods to successfully distribute the grout within the retort. Work to date has focused on the development of a grout; little research has been conducted on grouting criteria and grout distribution. Experimental work has consisted of exploratory laboratory research focused on the development of a grout from spent shale. Three types of processes, which produce a range of compressive strengths and permeabilities, have been investigated: modification of operating conditions of the surface retort (Mallon, 1979); heat or chemical treatment of as-received surface spent shale (Mehta and Persoff, 1980); and direct use of as-received surface spent shale (Nevens et al., 1977). Others

have measured geotechnical properties of surface-retorted spent shale which are relevant to grouting (Culbertson et al., 1970; Holtz, 1976; Peterson, 1978; Farris, 1979). The relative merits of these approaches depend on a wide range of factors including grouting criteria, cost and availability of technology and raw materials, and properties of raw materials. There is presently inadequate information to select from the proposed methods, because additional experimental work is required to demonstrate feasibility and determine design criteria. These processes were recently reviewed by Fox and Persoff (1980) who concluded that as-received, untreated surface spent shale may be used to control in-situ leaching and subsidence and that a higher strength grout, such as that proposed by Mehta and Persoff (1980) or Mallon (1979), would be required for additional resource recovery.

Grouting of in-situ retorts will require large quantities of water to prewet the spent shale and to slurry the grout. Recent estimates indicate that from 90 to 150 gallons of water per barrel of oil may be required for this operation (Persoff and Fox, 1980; Nevens et al., 1979). These quantities of water are larger than projected water consumption for all other water uses at an in-situ plant (Fox, 1980) and may significantly limit the application of this technology. The quantity and quality of water required for prewetting and slurring need to be determined by laboratory investigations, and the available water supply at in-situ sites needs to be examined to determine if the required water is available. Because the lack of adequate water supply could hinder the commercial use of the grouting technology, this issue should receive top priority and be resolved early to prevent unnecessary grout development work.

The development of a suitable grout has been hindered by the absence of grouting criteria--engineering standards that must be met in order to achieve environmental goals. Very little research has been conducted in this area. Specific design criteria will depend on the goals of the grouting operation--alleviation of aquifer disruption, subsidence control, and/or enhanced resource recovery--and the geological and hydrologic conditions of specific sites. Qualitatively, as a minimum, a candidate grout should meet the following criteria:

- The grout must be fluid enough to penetrate nearly all voids in the retort.
- The setting time must be long enough to allow the grout to fill nearly all voids.
- The permeability of the grouted retort must be low enough to keep transport of leachate within acceptable limits.
- The grouted retort must have sufficient strength and stiffness to satisfy structural requirements vis-a-vis subsidence and, if possible, increase resource recovery.
- The grout must retain its properties permanently, or degrade so slowly that objectives are met.

These parameters need to be quantified using numerical methods and laboratory studies so that candidate grouts can be tested against a set of criteria and several grouts selected for field testing. Preliminary calculations and investigations suggest that pillars, as presently designed, should provide adequate protection against overburden cracking and subsidence without post-retorting grouting (Ratigan, 1980; Ratigan and Goodman, 1981a, 1981b). More definitive statements must await the existence of field data. However, if resource recovery is to be improved, grouted retorts will have to be substituted for pillars. Calculations indicate that 100 percent extraction can be realized if the grouted retorts have a strength of about 1000 psi and a stiffness (tangent modulus at zero strain) of 500,000 psi (Fox and Persoff, 1980; Ratigan and Goodman, 1981b). Additionally, estimates by Brown et al. (1977) indicate that a permeability of 3×10^{-6} cm/sec in the grouted retort will be required to keep the incremental salt loading to Piceance Creek less than 100 mg/l per 30,000 barrel-per-day production. These estimates are based on preliminary calculations in the absence of adequate laboratory and field testing. An improved finite element computer model should be used to determine the structural requirements for grouted retorts that would satisfy various levels of overburden support, i.e., to prevent subsidence or to allow various degrees of increased resource recovery. Similarly, a numerical groundwater flow and chemical transport model should be used to estimate the permeability requirements for a grouted retort.

In addition to developing a suitable grouting material at reasonable cost, the problem of distribution of grout in the abandoned retort must be solved. This is critical because, if grout cannot flow freely in the rubble of an abandoned retort, numerous injection holes will be needed to insure uniform and complete filling of voids. Because VMIS retorts are located 1000 to 2000 feet below ground surface, the cost of drilling injection holes will add significantly to or outweigh the cost of manufacturing and injecting the grout.

There are presently inadequate data to answer the critical question of grout distribution--the spacing of grout injection holes to achieve uniform grout penetration. Classical grout penetration theory is inadequate to predict penetration distances of non-Newtonian grouts, such as spent shale grouts, and yield erroneously high penetration distances (Thomsen, 1980), thus underestimating the cost of grouting. Consequently, available estimates (Mallon, 1979) may be in error by an order of magnitude or more. Prediction of penetration distance depends on both the properties of the rubble (particle size distribution and void ratio) and the rheological properties of the grout (viscosity). A workable mathematical description of the flow of a non-Newtonian fluid, e.g., spent shale grout, through a rubble bed should be developed and tested in laboratory experiments. Pertinent physical properties of the rubble bed and candidate grouts should be measured in laboratory and field experiments and used in the mathematical model to predict grout penetration. These predictions should be verified in field experiments. Some work of this nature has recently been initiated (Thomsen and Persoff, 1981).

Grout Curtain

A possible control technology to prevent groundwater from leaching abandoned retorts would be construction of a grout curtain to route flow around the retorting site. The use of a grout curtain to stop groundwater

flow is not a novel concept. However, there are special conditions of this proposed application that may make it difficult or expensive.

The first of these is the depth at which the curtain must be constructed. In order to form a continuous curtain, holes must be drilled through about 1000 ft with very small deviations. This may be difficult to achieve. A second problem arises because the formations which are to be grouted (the aquifers) are of very low permeability; and it may be difficult to inject grout, especially a suspension grout such as portland cement, into so tight a formation. The selection of a grout for this application will depend upon the distribution of fracture sizes in the formation to be grouted. If permeability is due to a few large fractures (> 0.025 inch), these may be satisfactorily grouted by portland cement. However, if permeability is due to the presence of many small fractures, a more expensive chemical grout would be needed. The amount and cost of grout material needed would be determined by the porosity of the formation.

Little information is currently available to answer any of these questions, and there are no oil-shale specific investigations on this control method. Exploratory drilling and a test grouting program will be necessary to assess the feasibility of this control technology. A groundwater flow model should be used to evaluate the efficacy of a grout curtain. Groundwater quality and leachate transport should be studied as a function of curtain location, thickness, and permeability. If these results are encouraging, field studies should be conducted to determine engineering feasibility. Geological exploration will be required to determine the fracture size distribution and density.

SUMMARY

This paper has identified key issues in the area of retort abandonment and has addressed research needs in the context of our present state of knowledge.

Retort abandonment for VMIS shale oil recovery is an environmentally sensitive research area that has received recognition only within the past five years. Thus, experimental data and information are, in general, limited. In addition, there is presently a wide spectrum of unresolved issues that range from basic problem definition to technical details of potential control technologies. This situation is compounded by the scale of the problem and the absence of a commercial industry. The problems involve large numbers and will require engineering on a gigantic scale. Abandoned retorts are large--up to 700 feet deep and several hundred feet in cross section. They will exist in huge blocks, several square miles in area, which are inaccessible at several thousand feet below the surface. The processes that will ultimately be used to extract the oil are undefined. The technology is in transition, and representative samples of materials have not been available for research.

Research efforts in this area have concentrated on basic studies on the nature and magnitude of environmental problems resulting from VMIS oil extraction. These investigations have used laboratory reactors to generate spent shales and modeling studies to predict water quality and hydrologic impacts. The technology for retort abandonment is just now being developed, using engineering analyses to identify promising environmental control options and laboratory and modeling studies to determine feasibility. We expect that,

as the environmental problems are better defined and understood, conventional control technologies will prove to be adaptable to a majority of the problems associated with this new process and that laboratory and modeling research on problem definition will be refocused on technology development and field experiments.

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