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CONTROL STRATEGIES FOR ABANDONED IN-SITU OIL SHALE RETORTS

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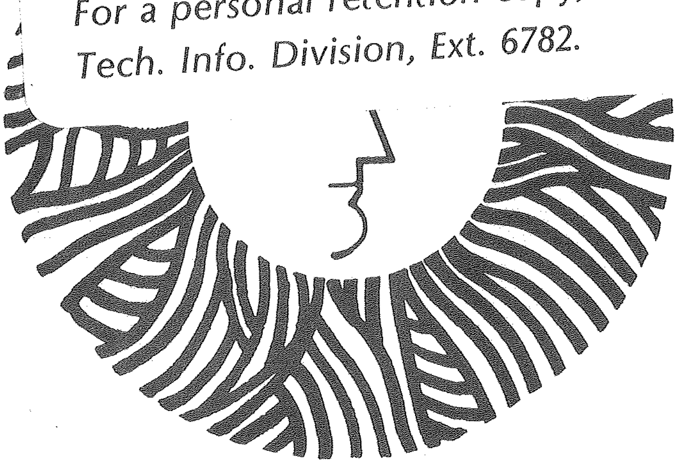
October 1979



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DISCLAIMER

LBL-8780

CONTROL STRATEGIES FOR ABANDONED IN-SITU OIL SHALE RETORTS

TASK REPORT

Prepared for the

U. S. Department of Energy
Division of Environmental Control Technology
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by

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CONTENTS

INTRODUCTION

The purpose of this report is to identify control technologies which may prevent or mitigate certain environmental impacts that are unique to in-situ oil shale production. Literature from related areas (reservoir and civil engineering and deep coal mining), was consulted to answer as completely as possible unresolved technical questions associated with each candidate control technology. Where possible, approximate cost data are presented.

This study focuses on in-situ leaching and addresses subsidence and resource recovery as peripheral issues. Although the vertical modified in-situ process (VMIS) is emphasized, most of the control technologies discussed are equally applicable to other in-situ technologies such as horizontal modified in-situ retorting or true in-situ retorting. Only the oil shale resources in the Green River Formation are considered.

This section discusses in-situ oil shale technologies and their unique environmental problems. It also briefly outlines some of the control strategies that may mitigate these impacts.

IN-SITU PROCESSES

Thermal conversion of oil shale in its original geologic formation is referred to as in-situ processing. This involves creating permeability in the formation through mining or fracturing followed by thermal conversion. In-situ processes are considered to be either "true" or "modified," and entail retort preparation, retorting, product recovery, and product upgrading. Since oil shale is a relatively impermeable material, porosity must be developed to permit the flow of air, gases, and liquids. This is accomplished by either removing a portion of the formation and rubblizing the balance (modified processes) or by creating void space by surface or in-situ disturbance (true processes). In the modified process, an amount of shale equal to the required void space, 20 to 40 percent of the in-place shale, is removed through shafts, adits, and drifts. This material may be processed in a surface retort or stockpiled. The rock left behind is drilled and blasted into the space created by the drifts. This procedure produces a retort filled with rubble. In the true processes, no mining occurs and permeability is created by explosive fracturing, by electro-linking, by solution mining of saline deposits, or by surface uplift.

When adequate permeability has been achieved, the shale in the retort is thermally decomposed by direct or indirect processes. Only the direct processes, in which heat for pyrolysis is supplied by combustion, are of commercial interest and will be discussed. A schematic of this concept is shown in Figure 1. The retort is air blown and the top of the rubblized shale is ignited by an external heat source, such as a gas burner. After ignition, the process is self-sustaining, and the burner is shut off. Initially, the carbon, oil, and gas from the shale are combusted; and the oxygen is depleted. This creates a pyrolysis zone in front of the combustion zone. In the pyrolysis zone, kerogen is thermally distilled without combustion. The pyrolysis zone is driven down the shale bed by incoming air, and

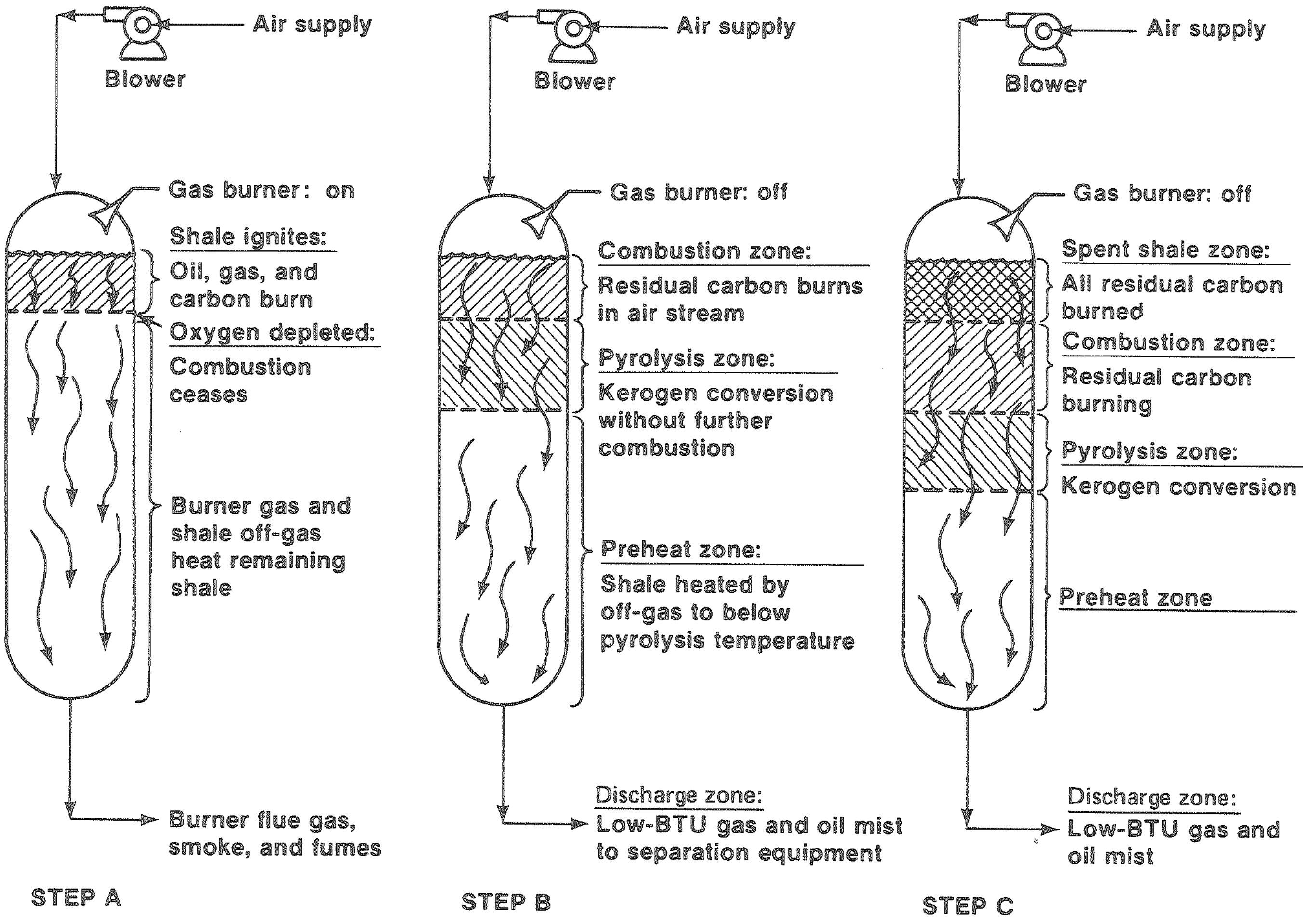

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Figure 1. Direct-mode, vertical in-situ retorting. Source: Sladek, 1974.

combustion is sustained by the carbon left on the pyrolyzed shale. The hot pyrolysis products move ahead (co-current) or behind (countercurrent) of the reaction front.

This same basic process occurs irrespective of the specific technology involved. For example, modified processing may proceed in the vertical or horizontal mode or in the co-current or countercurrent mode. In each case, however, the process fundamentals are the same. A pyrolysis zone followed by a combustion zone is moved through a shale bed by incoming gases. Products move out of the reaction area, and spent shale is left behind as the reaction front passes.

True In-Situ Processes

In these processes, porosity is created by surface or in-situ disturbance or solution mining rather than hard-rock mining. There are presently (Oct. 1979) three active true in-situ experiments, which are being conducted by Laramie Energy Technology Center (LETC), Geokinetics, and Equity Oil. The LETC experiments have included rubblization by well-bore springing and hydraulic and explosive fracturing of the shale. Combustion was initiated at an injection well and forced into recovery wells located in a pattern around the injection well. These experiments have not been successful due to inadequate fluid-flow properties caused by insufficient permeability and inadequate redistribution of available void. The results of these experiments indicate that successful true in-situ retorting is dependent on the development of methods to introduce initial void volume into the shale bed and to uniformly distribute that void.

Geokinetics is investigating a horizontal process in Uinta County near Vernal, Utah. Surface uplift by explosive fracturing is used to create adequate permeability, and retorting involves moving the combustion zone horizontally. The process is designed for oil shale deposits in thin beds with shallow overburden.

Equity Oil is pursuing a true in-situ process which uses solution mining to create the necessary void space. High pressure, high temperature steam is injected into the permeable leached zone of the Green River Formation to transfer heat to oil shale. The process is designed specifically for the 550-foot-thick leached zone in the Green River Formation.

Modified In-Situ Processes

In these processes, 20 to 40 percent of the in-place shale is removed and the void volume distributed by blasting. This concept is being pursued by Occidental Oil Shale, Inc. and the Rio Blanco Oil Shale Project (Gulf Oil Corp. and Standard Oil Co. of Indiana). In both processes, air and steam are injected into the top of the retort and combustion started at the top of a rubblized bed. Retorting proceeds vertically downward, and residual carbon is consumed for fuel. Steam is used to control retorting temperature and to improve the Btu content of the offgas through the char-steam reaction. Products drain to a bottom sump from which they are pumped to storage. This type of process is shown schematically in Figure 2.

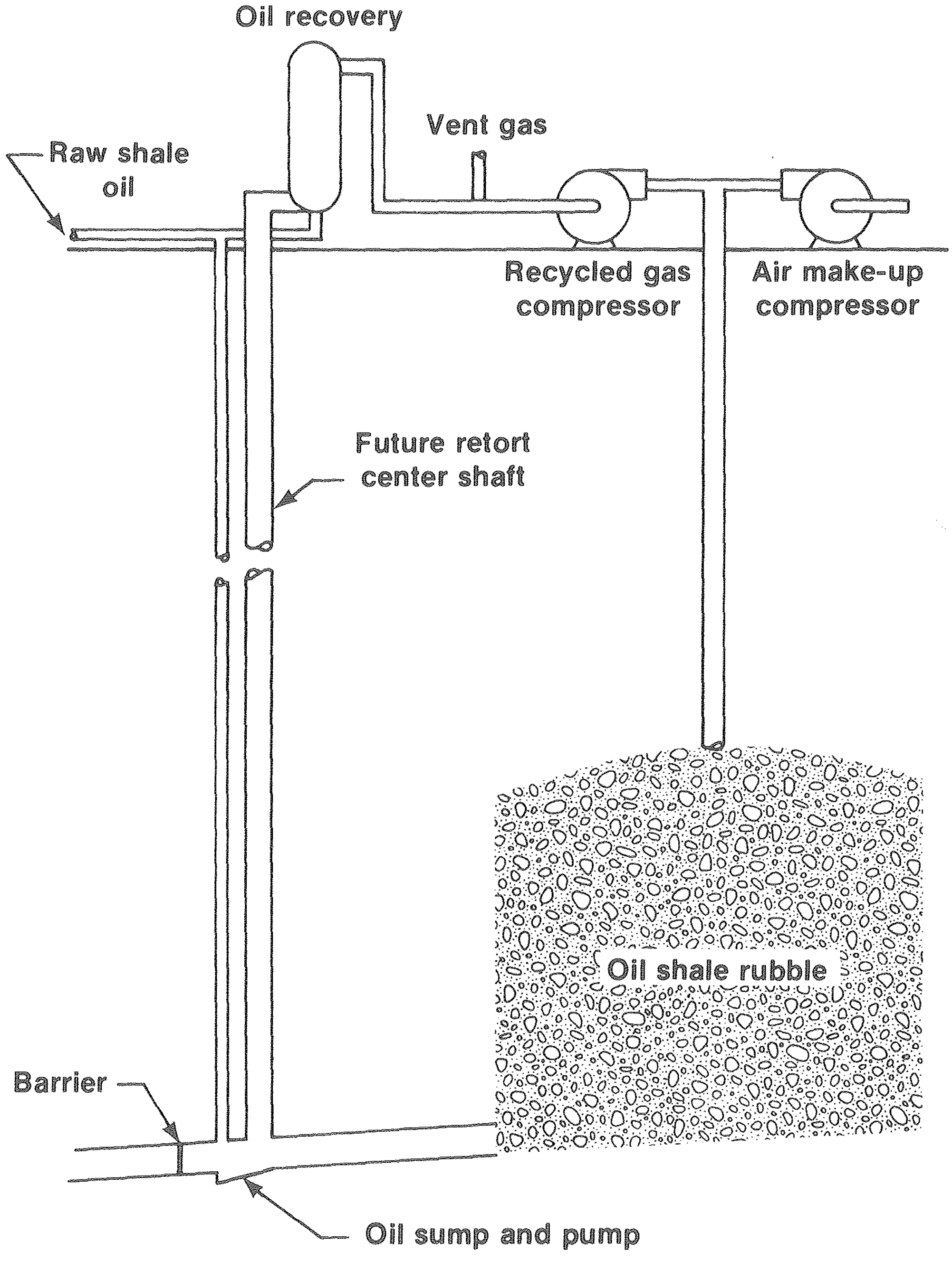

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Figure 2. Occidental oil shale process retort operation. Source: McCarthy, 1976.

The Occidental and Rio Blanco processes differ primarily in the mining methods used and the specific operating conditions employed. The Occidental process uses a modified room and pillar mining method while the Rio Blanco process uses a sub-level caving method. Additionally, Rio Blanco plans to use a relatively rapid retorting rate at positive retort pressure with a 40 percent bed void volume; the Occidental process uses a slower retorting rate at slightly negative pressures with about 20 percent void volume.

This study will focus on the vertical modified in-situ process (VMIS) because it is believed to have the most serious water problems and because it is presently the subject of an intensive research and development effort by both the Department of Energy and industry.

Simulated In-Situ Retorts

These are surface retorts designed and operated to simulate in-situ conditions. Much of the data presented in this study was developed using products from these retorts. These retorts typically consist of a stainless steel tube fitted at the top to allow a gas to flow through and at the bottom to collect products. The tube is filled with crushed shale, and pyrolysis is initiated as previously described for in-situ processes. The principal simulated in-situ retorts are those operated by LETC and LLL. LETC operates two retorts with capacities of 10 tons and 150 tons of shale, and LLL operates two retorts with capacities of 125 kg and 6000 kg of shale.

RETORT ABANDONMENT ENVIRONMENTAL ISSUES

Large cavities of spent shale remain in the underground environment after oil is extracted from an in-situ retort. These cavities of spent shale, referred to as "abandoned in-situ retorts," pose several serious environmental hazards. Abandoned retorts may cause groundwater contamination or they may subside, creating surface disturbance. Additionally, about 50 percent of the resource must be left in place as pillars to support the overburden. These issues--groundwater disruption, subsidence, and resource recovery--are discussed individually. Figure 3 shows in simplified form the relative positions of the target oil shale layer, the Mahogany Zone, fractured oil shale artesian aquifers, and a VMIS retort.

Groundwater pollution may result from abandoned in-situ retorts intersecting aquifers adjacent to the oil shale resource. During development and retorting, aquifers are dewatered. Following abandonment, groundwater will re-invade the aquifers and fill the retorts, leaching spent shale. The leached material, which includes many organic and inorganic compounds, can be transported in the aquifers and ultimately discharged into streams and springs or pumped into wells. Local streams which receive groundwater inflow are tributary to the Colorado River system where salinity is already a national and international concern.

If a retort penetrates one aquifer, there will be a hydraulic gradient in a horizontal direction across the retort, causing horizontal flow through the retort, which will transport leached material into the aquifer. If a retort penetrates more than one aquifer and the aquifers are at different heads, there will also be a vertical hydraulic gradient causing flow through the retort from one aquifer to the other. This condition could be more serious

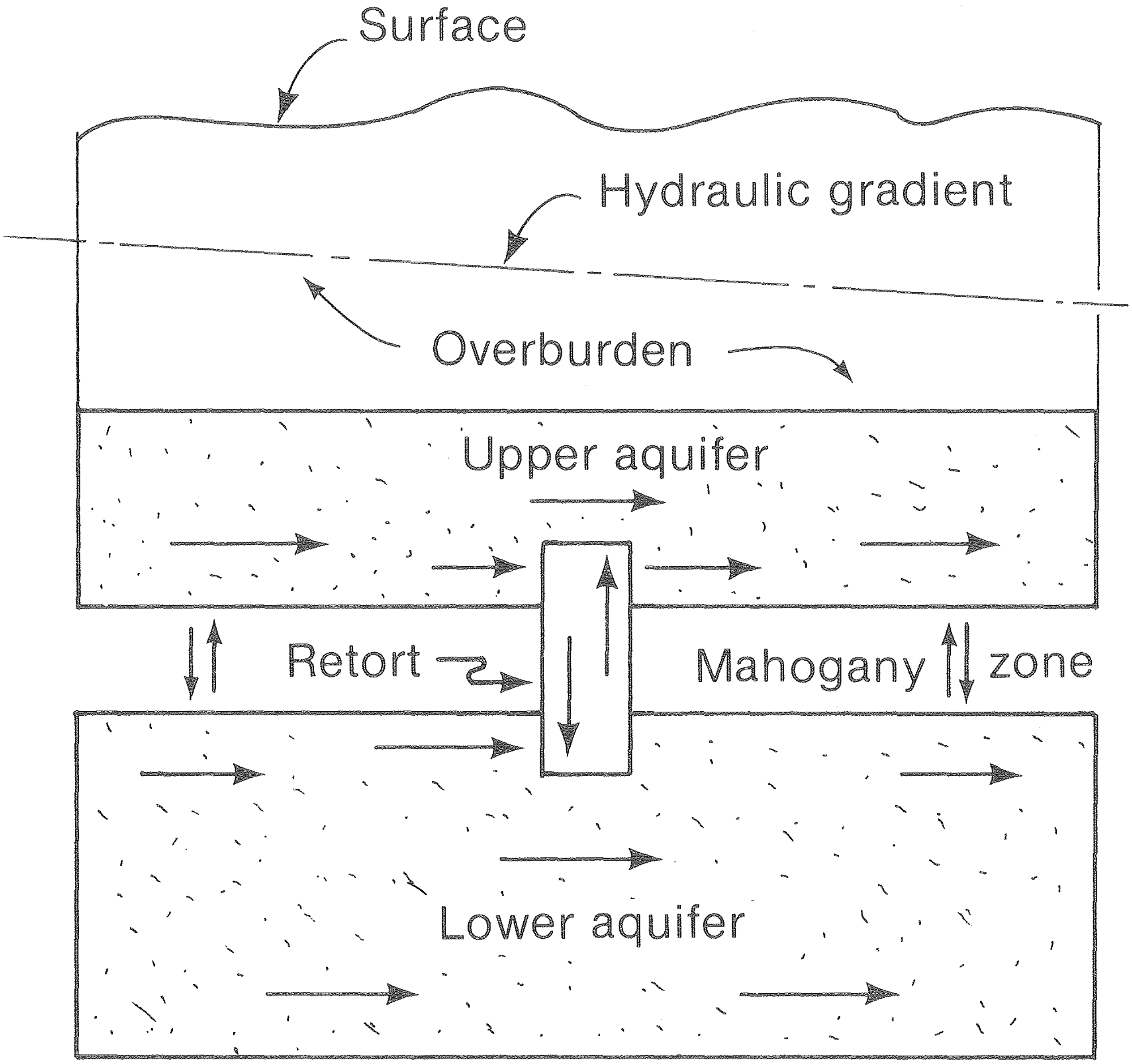

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Figure 3. Schematic of retort-aquifer configuration in the Piceance Creek Basin.

because the vertical gradient resulting from this condition could be greater than the horizontal gradient; thus the rate of flow through and leachate transport away from the retort would be greater.

The problem of aquifer and eventual surface stream pollution by leaching of vertical modified in-situ retorts in the Piceance Creek Basin has been quantified by Fox (1979). This study 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 in the Colorado River at Lees Ferry, Arizona, of from 0.3 to 50 mg/l (Fox, 1979). A TDS increase of 50 mg/l in the Colorado River would have a significant economic impact upon irrigated agriculture. Kleinman (1974) estimates the total economic loss due to Colorado River salinity increases to be $200,000-$400,000 per year per mg/l (1974 dollars). Additionally, elevated concentrations of certain toxic or carcinogenic organic materials may occur in aquifers or surface streams. If these waters were used for municipal supply or stock watering, local health problems might result.

In some areas of the Piceance Creek Basin, water quality of the lower aquifer is much worse than that of the upper aquifer. In these cases, contact between the two aquifers created by the retorts would permit degradation of the upper aquifer in the absence of leaching.

Resource recovery in VMIS retorting is poor. Oil recovery is low and 25 percent to 50 percent of the developed area must be left intact as pillars between retorts to support the overburden. If sufficient strength could be developed in abandoned retorts, it might be possible to design a retorting system so that pillars could be retorted and resource recovery improved.

Finally, considerable concern exists over the long-term stability of abandoned retorts. Computational techniques are inadequate to predict incidences of subsidence, and there are presently no field data available to assess this problem because field experiments have consisted of single, small retorts while commercial operations may use many hundreds of very large retorts. The target resource, the Mahogany Zone, is deep. Overburden thickness, which varies throughout the Basin, is typically from 500 to 1000 feet. Recent field experiments suggest that high void volumes, about 40 percent, may be required to achieve efficient oil recovery. At the lower void volumes used in early experiments, about 20 percent, the abandoned retort provided some overburden support because shale exfoliates during retorting, providing contact between the horizontal pillar at the top of the retort and the spent shale. At higher void volumes, there will be no contact between this horizontal pillar and the spent shale, and the abandoned retort thus will not contribute to overburden support.

The purpose of this report is to seek solutions to the first of these environmental problems: in-situ leachate formation and control. Solutions to the other issues--mixing of dissimilar waters, subsidence, and resource recovery--will be addressed as benefits which accrue when the first problem has been solved. In other words, some solutions to the in-situ leaching problem, such as filling the retort with a grout, may simultaneously provide protection against subsidence and provide the opportunity for improved resource recovery.

SUMMARY

Prevention of groundwater pollution resulting from in-situ oil shale development will require a novel control technology. Based upon information available regarding the problem and related technologies, certain candidate control technologies appear technically and economically feasible. These technologies and their projected costs are listed in Table 1. Pending verification of certain assumptions, it appears possible to prevent pollution of groundwater for about $0.59-$0.67 per barrel by recovering leachate and treating it on the surface; for about $0.74-$2.85 per barrel by placing a grout curtain around an entire block of retorts; or for about $0.35-$1.30 per barrel by backfilling abandoned retorts with a grout of surface-retorted spent shale. These cost projections are preliminary and subject to change as experimental data are generated and as design criteria are developed. The technical feasibility of these technologies has not been demonstrated, and many uncertainties remain concerning technologies as well as site-specific issues. Therefore, these cost projections are initial approximations which may not reflect actual costs at any specific site. Nevertheless, the projections are useful for RD&D decision-making. Detailed cost projections for each control technology are provided later in this study (see page 78).

SITE SELECTION

Site selection is the location of retorts where they will not be leached by groundwater. Although some oil shale deposits in Utah and Wyoming are located above the water table and would not be flooded on abandonment, much of the Mahogany Zone in the Piceance Creek Basin is surrounded by aquifers. Since most of the thick rich deposits which are the target of VMIS retorting are located there, site selection would eliminate many suitable VMIS sites. Consequently, site selection could impede development of VMIS oil shale retorting, and other environmental control technologies should be considered to facilitate development of the rich Piceance Creek Basin oil shale deposits.

GROUTING ABANDONED RETORTS WITH SPENT SHALE

Abandoned retorts may be filled with a grout to reduce their permeability and provide stiffness and strength. If the grout is manufactured from on-site waste products, such as spent shale, and if grouting is technically feasible, groundwater pollution may be controlled at a cost of about $0.35-$1.30 per barrel of oil produced. The large volume of grout required to completely fill an abandoned retort eliminates from consideration all commercially available grout materials. Unresolved technical questions

Table 1. Comparison of projected costs for various control technologies for abandoned in-situ retorts.

Technology	Cost per Barrel of Oil, $	
	Tract C-a	Tract C-b
Site Selection	a	a
Retort grouting		
Air level drilling	0.49	0.35
Ground level drilling	0.65	1.30
In-situ precipitation of calcite	1.88	1.15
Grout curtain	0.74	2.85
Hydraulic bypass	0.46	1.76
Cap rock	b	b
Recover and treat leachate	0.67	0.59
In-situ treatment by adsorption and ion exchange	c	c
Modify operating conditions	d	d
Reverse wettability	c	c

[a] Requires individual case assessment.

[b] Not applicable.

[c] Prohibitively expensive and uneconomical.

[d] No increase in cost of retorting.

include the ability of a spent shale grout to flow in a retort, the degree of permeability reduction which is possible, and the development of adequate cementing properties.

IN-SITU PRECIPITATION OF CALCITE

Formation of precipitates within pores of an abandoned retort may be effective in sealing these pores. Precipitates of calcite may be formed by placing lime in an abandoned retort and reacting it with CO_2, but costs require that this method be restricted to filling about 10 percent of the voids in a retort. This may, however, be useful in combination with some other control technology.

GROUT CURTAIN SURROUNDING BLOCK OF RETORTS

Construction of a grout curtain around an entire block of retorts would protect the groundwater by preventing communication between the aquifers in the retorting area and the aquifers in the rest of the basin. Cost of this control technology is projected to be about $0.74 to $2.85 per barrel of oil produced. This assumes that a large number of retorts can be surrounded by a grout curtain and that the cost per square foot of curtain is not much greater than costs for grout curtains under dam foundations. In principle, this technique should be feasible and effective. Presently unknown factors, however, may have a major effect on the cost. The size of open fractures in the aquifers will determine whether a suspension grout or a more expensive chemical grout is required, as well as necessary spacing of grout injection holes. The porosity of aquifers will determine how much grouting material is actually needed. The costs indicated assumed a single row curtain using cement grout with holes drilled at five foot centers. Other unresolved technical issues here are the integrity and the long-term stability of the grout curtain. Formation shifts related to the retort block or sulfate attack of the curtain could result in leakage and eventual failure.

HYDRAULIC BYPASS

It may be possible to design retorts or retort blocks to minimize flow of groundwater through retorts or to intentionally create zones of high permeability to transport groundwater away from or around spent retorts. This may cost from $0.46 to $1.76 per barrel of oil.

CAP ROCK

Leaving intact and water-free oil shale rock in place between retorts and aquifers would reduce flow through retorts. This would restrict the size of retorts, possibly making them uneconomical, as well as leaving rich resources unrecovered.

RECOVER AND TREAT LEACHATE

Leachate collection, treatment, and disposal may cost about $0.59-$0.67 per barrel of oil. The major unresolved technical question is the rate at which material is leached from spent shale and, hence, the total volume which must be treated before it is considered safe to permit all further leachate to enter aquifers. If large spent shale particles expected under field conditions are leached much more slowly than the small particles used in laboratory experiments, the volume of leachate to be treated and attendant costs may be much higher than those projected. No treatment technology has yet been demonstrated, but this is considered to be a solvable problem if the volume to be treated is not too large.

MODIFY RETORT OPERATING CONDITIONS

Leachability of spent shales is less if they are well burned, retorted in a steam environment, and exposed to high temperatures for long periods of time. Experimental materials from field retorts are required to determine if these conditions do produce a sufficiently non-leachable spent shale.

Accurate control of rubblizing and retorting will be essential if this is to be used as a control technology.

OTHER METHODS

Use of conventional grouting materials such as portland cement or chemical grouts is too expensive to consider. Exotic techniques such as reversing the wettability of spent shale or precipitating polymers in place appear technologically and economically remote. In-situ treatment of leachate with adsorbents and ion exchange resins is also too expensive because of the large amount of dissolved salts that must be removed from the leachate.

CONCLUSIONS AND RECOMMENDATIONS

Review of available data on retort-aquifer hydrology and the properties of spent shale indicates that a retort abandonment control system will be needed to protect Piceance Creek Basin groundwater from the potentially harmful effects of the in-situ retorting. Examination of several candidate control strategies showed that some appear to be cost effective and technically feasible. These are summarized with projected costs in Table 1. Specific conclusions and recommendations follow.

USE OF COST PROJECTIONS

Complete reliance upon the cost projections developed in this report as the sole guide for determining future study and analysis should be avoided. In many instances, cost projections have been based upon data resulting from laboratory tests (comparable data from field tests were not available) or upon assumptions made in the absence of data. Costs may be much lower or much higher than those projected. More accurate cost estimates, based upon actual field tests, are needed before cost projections can be used as a determining factor for further field testing or for the adoption of a final control system for any specific site.

No conclusions are made concerning the cost-desirability of one control strategy compared to another. This is necessitated because, again, the cost projections for some control strategies were derived from data based upon laboratory work rather than upon field testing. Furthermore, some of the control methods, which appear to be more economical, fail to provide full protection against adverse environmental impacts. For example, although leachate collection and treatment has a low cost per barrel of oil produced, from $0.59 to $0.67, this strategy would provide no protection against subsidence, and it would not provide for additional resource recovery. Comparison of one control strategy with others must be based, not only upon cost estimates, but also upon the relative degree of control provided.

USE OF AVAILABLE MATERIALS

Several of the control strategy costs examined in this report--grouting abandoned retorts, for example--are based upon the use of locally available materials such as spent oil shale. The large volume of grout required to completely fill an abandoned retort eliminates use of commercially available grout for this purpose because of cost. If spent oil shale could be used to manufacture grout for retort filling, costs would be low enough to make this control strategy economically feasible. Similar comparisons apply to some other control measures. Further testing and study of the use of locally available materials, under both laboratory and field conditions, are required.

METHODS USED BY OTHER TECHNOLOGIES

The processes used in production of oil shale have not been developed sufficiently, from the standpoint of commercial utilization, to provide adequate data for a comprehensive study of control strategies. However, methods used by other industries, such as coal mining and construction, are similar to those envisioned for some control strategies. Therefore, further studies concerning control measures should use appropriately modified data from allied fields and industries, until adequate data for oil shale processes become available.

This study has indicated, however, that adequate information is not readily available in literature concerning some allied fields. For example, although backfilling coal mines has been standard practice in Europe for decades, it is only now being considered for use in the United States. Consequently, detailed technical data are not readily available in English-language literature. Direct liason with users of an allied technology of this nature might provide more detailed information of value in adopting these methods to oil shale control. Discussion with industries using similar techniques might also provide much useful information. For example, discussions with civil engineers specializing in grouting the foundation layers below a dam site might provide additional data based upon their field experiences.

FIELD TESTING

Much of the data used in this report has been derived from reports of various laboratory tests and experiments. As a result, the cost projections cited may be lower than costs that might be expected for a field in-situ process. More information is needed concerning actual field conditions in order to enable more accurate cost estimates to be made. Although additional laboratory testing is required for many facets of various control strategies discussed in this study, such testing should be supplemented by field tests at the earliest possible time. These field tests might be incorporated as part of in-situ field retort testing currently underway.

APPLICATION TO OTHER OIL SHALE DEPOSIT AREAS

This study has been restricted to the oil shale resources of the Green River Formation in general and to those of the Piceance Creek Basin in particular. Consequently, many of the technical conclusions drawn in the body of this report apply primarily to this area. It is possible that some technologies considered to be technically or economically undesirable for the Piceance Creek Basin might be both technically sound and less costly if used elsewhere. For example, the use of cap rocks and reversing wettability as control measures in the Piceance Creek Basin appear to be prohibitively expensive. The use of cap rocks is technically undesirable because of the relatively shallow depth of rich dry oil shale compared to the height of the vertical retort required for efficient and economic VMIS processing. This might not be true in other areas. The application of the control strategies discussed in this report to other areas should be based upon suitability for those areas and not upon their feasibility in the Piceance Creek Basin.

However, the basic technologies discussed and the cost estimates projected for the various control strategies are equally applicable to areas other than the Piceance Creek Basin. Case-by-case analysis is required in adapting any specific control measure, as discussed in this report, to another area.

COMBINATIONS OF CONTROL STRATEGIES

Several of the control strategies reviewed in this study fail to fully meet requirements to prevent or mitigate adverse impacts upon the environment. It is possible, however, that combining two or more strategies as a cohesive control measure might meet preventitive goals within economic limits. This study did not consider combinations of control strategies, although several combinations were readily apparent. Further studies should consider combinations of strategies as well as investigating additional single control methods.

ADDITIONAL STUDY REQUIRED

The problems concerning the development and use of various control strategies discussed in this report make it clearly apparent that additional study is required. As already indicated, data are required from field testing of various control methods. Data must also be developed concerning the application of technologies used by other industries to oil shale production because these data would make possible better analyses of the various control strategies as well as providing more accurate cost estimates. Comparative studies contrasting two or more control strategies, preferably tested under field conditions, would provide more accurate information upon which to base final selection of a strategy or strategies for industrial implementation.

Retort grouting, intentional leaching, grout curtain, and hydraulic bypass all should be evaluated by laboratory and computer studies. A Piceance Creek Basin-wide hydrologic model should be used to determine the effectiveness of each of these technologies and to compare them on a uniform basis. Independent recognized construction and grouting contractors should be consulted to assess the feasibility of grout curtain and hydraulic bypass construction.

Field tests should be conducted on those control strategies judged most cost-beneficial. When a selected control system is applied, a long-term monitoring program should be instituted to determine the effectiveness of the project as compared to predicted effects.

ARE CONTROL STRATEGIES FEASIBLE

This study indicates that control strategies can meet requirements for preventing or mitigating the adverse impacts of oil shale processing upon the environment. It is also evident that many of these control methods appear to be economically feasible, especially in the Piceance Creek Basin whose oil shale resources were used as the basis for this study. The basic technologies involved in various strategies are technically feasible; and most of the strategies are economical within useable limits.

CONTROL STRATEGIES

This study identifies a number of strategies or technologies that would mitigate the aquifer disruption problem. Some of these also address the issues of subsidence and resource recovery. These technologies are based on retort plugging, hydrogeologic modifications, leaching, and various physical and chemical processes that render the spent shale less soluble.

The retort plugging strategies seek to minimize the flow of groundwater through abandoned retorts by filling them with a cementitious material to reduce permeability. The amount of leachable material present in the retorts would not be changed, but the rate of transport of leachable material into the environment would be reduced by controlling the amount of water penetrating the retort. The purpose of these strategies is to keep the concentration of pollutants in the leachate leaving the retort within acceptable limits. Technologies to plug abandoned in-situ retorts include sealing with a grout manufactured from surface spent shale and in-place precipitation of calcite.

The hydrogeologic modification strategies seek to alter local geological and hydrological conditions to minimize the flow of water into the retorted area. This may be accomplished by constructing a large underground wall, called a grout curtain, around a large block of retorts. This wall could divert most of the groundwater flow around the retorted area. This could also be achieved by constructing the retorts with an impervious layer, or cap rock, between the retort and adjacent aquifers or by surrounding a retorting site with a series of wells. This latter option would increase the permeability on the periphery of a retorted area, routing flow around the retort site rather than through the retorts.

The purpose of the leaching strategies is to reduce the amount of leachable material remaining in place and to meter out the balance so that the resulting concentrations are within environmentally acceptable limits. This could be accomplished by intentionally leaching the retort with mine dewatering effluents and pumping the leachate to a surface treatment plant for upgrading and final disposal. Analogously, an adsorbent or exchange resin could be pumped into the retort as a slurry to trap leachables as they form and meter them out over a period of time.

The in-situ leaching problem may also be mitigated by physically or chemically modifying the in-situ spent shale to reduce its leachability. This may be accomplished by operating the retort to produce inert silicate minerals or by using a wetting agent to reduce the wettability of the spent shale.

HYDRAULIC ISOLATION BY 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 groundwater from degradation. There are presently inadequate data to determine with certainity 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. However, available hydrologic and geologic data suggest that only a very small fraction of the resource may be adaptable to this type of isolation strategy (Weeks et al., 1974).

Dry zones may not be suitable for VMIS retorting. The VMIS process requires a thick, continuous, vertical section of oil shale not interrupted by significant thicknesses of barren rock (Smith, 1978). Based on the commercial designs of industrial developers, it is apparent that about 300 feet of continuous vertical oil shale is required for the process to be economic (Gulf, May 1977; Ashland, 1977). Most of the resources, where necessary geologic conditions exist to support this technology, are in the Piceance Creek Basin of Colorado where confined aquifers penetrate the oil-bearing strata (Weeks et al., 1974). In most of this region, the Mahogany Zone, which is a target of VMIS retorting, is 100 to 200 feet thick. In order to have a sufficiently long vertical section of oil shale, the installed retorts must intersect the stratum immediately above or below the Mahogany Zone where water-bearing zones exist. Therefore, it will be difficult to locate VMIS retorts in completely dry zones without sacrificing the economic feasibility of the VMIS process. Smith (1978) noted that the most suitable basin-wide section for VMIS development in the Piceance Creek Basin consists of the Mahogany Zone from the top of B-groove and overlying oil shale. B-groove was excluded because it is an aquifer in most areas. The developers, however, are extending their retorts through B-groove.

The two active VMIS projects, Occidental Oil Shale, Inc. and Tenneco on lease Tract C-b and Rio Blanco Oil Shale Project on lease tract C-a, are both located in the Piceance Creek Basin of Colorado. Development plans (Gulf, May 1977; Ashland, 1977) for both tracts call for penetration of more than one aquifer.

This report recommends that an in-depth study of site selection be completed. This strategy will not be considered further here due to the lack of data and the fact that most of the resources presently under development are in wet zones, thus requiring some other control strategy.

HYDRAULIC ISOLATION BY GROUTING ABANDONED RETORTS

Grouting is defined as the injection of a fluid material into the voids of a soil formation to stop or reduce water movement or to consolidate and strengthen the soil (Herndon and Lenahan, 1976). The primary purpose, in this case, is to reduce the permeability of abandoned retorts. However, strengthening abandoned retorts by grouting would provide important secondary benefits not obtained from any other candidate control technology: the increased strength and stiffness and reduced voids of the abandoned retort would provide protection against subsidence and the opportunity for increased resource recovery.

Vertical modified in-situ (VMIS) retorts require large pillars for overburden support. These pillars occupy 25 to 50 percent of the area of a retort block and therefore prevent the recovery of much of the oil in a developed area. If grouting gives sufficient strength and stiffness to the abandoned retort, the pillars between retorts could be rubblized later and retorted for additional oil recovery. Such additional recovery has not been included in any of the cost estimates presented herein. Critical problems in grouting operations are the selection of an appropriate grouting material and the distribution of the grout through the formation to be grouted. These problems will be discussed in following sections.

Industry Experience

Grouting has been widely used in a number of industries to reduce the permeability or to increase the strength of materials and structures ranging from soils to ocean sediments to dam and building foundations. Additionally, the concept of returning mining wastes underground is not new for it has been widely practiced in underground coal mines in Europe and has been proposed for surface mining of oil shale (DOE, 1979).

This section briefly surveys the literature from these other fields to provide a foundation for developing a technology for grouting abandoned in-situ retorts with wastes from surface retorting. Grouting and underground waste stowing are widely used in the construction industry, for oil field applications, and in underground coal mining.

Underground Disposal of Coal Mine Wastes. Coal mine waste has been stowed underground in Europe for decades, and the practice is presently being evaluated for use in the United States. Underground stowage methods and their technical and economic feasibility have been reviewed in a report by the National Academy of Sciences (1975). The results of that study are summarized here.

Approximately 25 percent of the coal that is extracted from underground mines in the United States is rejected as waste. In contrast, about 80 percent of the oil shale that is mined would be rejected as waste. In Europe, coal wastes are returned to the underground environment to control subsidence during longwall mining. This is accomplished by returning the wastes to the mine, using either pneumatic or hydraulic transport. These practices have been largely abandoned in Europe due to high costs and their interference with mechanized mining methods. However, they are now being considered in the United States to control surface waste disposal problems regulated by Public Law 95-87.

The National Academy of Sciences study (1975) found that the cost of backfilling abandoned United States and European underground mines ranged from \$3.00 to \$9.00 per ton of waste disposed (1975 dollars). The study estimated that the minimum hypothetical cost of underground disposal in the United States with pneumatic backfilling was \$3.50 to \$5.00 in 1975 dollars per ton of waste; for hydraulic backfilling, it was \$5.00 per ton of waste disposed.

By comparison, in the Bureau of Mines study of the technical feasibility of hydraulic transport of surface-retorted spent shale by slurry pipeline (Link et al, 1975), horizontal transport costs were found to be about \$0.02 to \$0.03 per ton-mile. Conveyer transport was found to be more economical. This cost does not include any slurry preparation costs.

Backfilling abandoned retorts is technically a more difficult problem than backfilling underground mines. The area to be backfilled in underground coal and oil shale mines consists of 100 percent void space while that to be backfilled in VMIS retorts is only 20 to 40 percent void space. Additionally underground coal mines are typically shallower than VMIS retorts, which are located at 1000 to 2000 feet below the surface. These differences probably make the cost of backfilling VMIS retorts higher than the cost of backfilling underground coal or oil shale mines.

Construction. In the construction industry, grouting is used to strengthen or stabilize soil or to impede the flow of water. Typical applications for stabilizing soil include remedial grouting, used when running sand makes excavation difficult, and "mud-jacking" where grout is injected under settling foundations. Grouting to strengthen soil can be permeation grouting, which penetrates through the soil, or compaction grouting, which displaces and compacts the native soil. Grouting to control water movement prevents water from entering excavations or from leaking under and lifting dams. In both types of application, the grout may be selected for temporary or permanent strength, depending on the application. The grouting considered for in-situ oil shale retorts is similar to grouting used in construction since both seek to prevent groundwater flow and to strengthen the pertinent materials.

Oil Field Applications. In oil well completions, cement slurries are pumped into wells to seal the annular space between well and casing. This is done to isolate fluids and pressures from different zones, to protect groundwater quality from degradation by mixing with water from poorer quality formations, and to ensure that the well produces from the desired formation. Cements used for this purpose are usually ordinary or sulfate-resisting portland or portland-like cements (API, 1977).

Oil well cementing has special requirements, due to high down-hole temperatures and pressures and the need to control slurry density, slurry viscosity, time of set, loss of whole slurry or water into formations, and costs. A wide variety of additives are available to tailor cement slurry properties to job requirements (Suman and Ellis, 1977; Parker and Clement, 1977). Among these are accelerators (e.g., calcium chloride), retarders (calcium lignosulfonate), extenders (bentonite, fly ash), weight material to increase density (sand, barite), and lost circulation materials (ground nut shells, cellophane flakes). The examples named are typical but not exhaustive of the list of available additives, many of which have more than one function.

Grouting Criteria

The characteristics of a grout used to seal an abandoned in-situ retort will depend on the goals of the grouting operation: alleviation of aquifer disruption, subsidence control, and/or enhanced resource recovery. The specific goals of any abandonment plan will depend on the geologic and hydrologic conditions of the site and societal goals regarding resource recovery. These criteria will have to be determined on a case-by-case basis. However, a few general considerations can be discussed qualitatively.

As noted previously (see "Hydraulic Isolation by Site Selection" page 15) most VMIS sites will be located in areas where aquifers intersect the oil-bearing strata. Therefore, aquifer disruption will be a generic problem, and some protection will be required for most such sites. This means the grout must reduce the permeability of the abandoned retort.

The potential for subsidence, on the other hand, will depend on mine design and geologic conditions of the site. Because of inadequate field experience, there is presently no clear understanding of subsidence potential in the vicinity of VMIS operation. However, there is concern that the recent change from 20 to 40 percent void volume may significantly affect the potential for subsidence (see the discussion on page 7). Subsidence protection will require filling most retort voids and the development of some strength in the rubble column.

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 U. S. where 42 percent of the source is left in place as pillars (NAS, 1975). 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. Enhanced oil recovery is a constant reminder of the consequences of short-sighted planning and poor resource recovery. The issue of resource recovery will become a focal point of energy policy, and eventually be legislated like many other environmental goals.

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 design.

As a minimum, any grout used to seal an abandoned VMIS retort should have the following characteristics:

(1) The grouted area must be impermeable enough to prevent the degradation of local groundwater or surface water.

(2) The grouting material must be chemically stable in the presence of saline groundwater.

(3) The grout viscosity must be low enough and the setting time long enough for the slurry to penetrate a large area.

(4) The grouted area should be able to withstand both hydrostatic and overburden pressures. The hydrostatic pressure is due to natural head differences that exist between the aquifers surrounding the oil shale deposits in some areas and to significant dewatering during retorting.

The specific value for these criteria would depend, as noted above, on hydrologic and geologic conditions, on mine design, and on societal values. These requirements cannot be precisely defined at present due to inadequate information. However, they can be discussed qualitatively.

Permeability. The flow through a grouted retort is proportional to the permeability of the retort. In a commercial operation, many retorts over a large area will become available for leaching at once. Thus, the amount of water that can be allowed to flow through any single retort will be very small. Brown et al. (1977) estimated that an average post-grouting permeability two orders of magnitude lower than the host rock would be required to keep the incremental salt loading to Piceance Creek less than 100 mg/1 per 30,000 barrel-per-day production. The value proposed was 3 x 10^{-6} cm/sec.

Jones (1963) indicates that the limit to which permeability can be reduced by grouting is about 10^{-5} cm/sec, and that it is easier to reach this limit by starting with a rather permeable formation than by starting with a relatively impermeable formation, such as 10^{-3} or 10^{-4} cm/sec. The actual permeability of grouted formations is rarely reported in the literature because any failure is usually traced to an incomplete seal rather than to the inability of the grout to achieve the desired permeability. Such a low permeability has not been required of any grouted formation that has been described in the literature known to the authors. Several reported permeabilities are listed in Table 2. Apparently, the lowest permeability that can be expected for abandoned retorts is about 10^{-4} cm/sec, although the high permeability of the retort before grouting favors achieving low permeability.

Once the required permeability of the grouted retort has been established, a grout must be selected which can achieve this target value. The permeability of a grouted retort will be strongly dependent upon the permeability of the grout used. Subsequent sections of this study propose the use of a spent shale grout. The permeability of various surface retorted and simulated in-situ retorted spent shales are summarized in Table 3. Although the permeability of one spent shale was less than Brown's target of 3 x 10^{-6} cm/sec, excellent penetration of the abandoned retort would be needed for this permeability value to apply to the retort as a whole.

Table 2. Permeability of grouted formations.

Grout Used	Project	Permeability, cm/sec Before grouting	 After grouting
Cement-bentonite followed by deflocculated bentonite	Obra Dam, India[a]	3×10^{-2}	8×10^{-4}
--	Aswan High Dam[a]	---	5×10^{-4}
Cement (Rows 1 and 5) clay-cement (Rows 2 and 4) clay-cement chemical (Row 3)	Karl Terzaghi Dam, Canada[b]	---	2×10^{-4}
Two injections of cement-bentonite followed by sodium-aluminum silicate	Girna Dam, India[a]	10^{-4} to 10^{-2}	10^{-4}
"Black cotton" cement 14:1 with 4% sodium silicate	Kotah Barrage, India[c]	10^{-4} to 1	10^{-4}
Clay-cement in coarse sand, sodium-aluminum silicate in fine sand	d	4×10^{-1}	10^{-4}
3 stages of cement-bentonite, 4th stage sodium aluminum silicate	Mattmark Dam, Switzerland[e]	---	6×10^{-5}

[a] Badappanavar, 1974.

[b] Bowen, 1975.

[c] Greenwood and Raffle, 1963.

[d] Mayer, 1958.

[e] Herndon and Lenahan, 1976.

Table 3. Permeability of spent shales.

Retorting Process	Spent shale size distribution, cm			Permeability, cm/sec		
	10%	50%	90%	Initial	28 day	Reduction %
USBM[a]	0.013	0.18	2.9	3.39×10^{-4}	2.13×10^{-4}	37
TOSCO[a]	0.0015	0.0069	0.03	2.45×10^{-5}	2.23×10^{-5}	9
Lurgi (936°F)[b]	89% through 150 mesh			7×10^{-5}	2.8×10^{-5}	89
Lurgi (993°F)[b]	92% through 150 mesh			2×10^{-4}	$2.5 \times 1\text{-}^{-6}$	99
Lurgi (1040°F)[b]	86% through 150 mesh			2×10^{-4}	1.2×10^{-5}	94
Indirect heating[c]	35% through 200 mesh			0.7×10^{-6} to 5×10^{-6} depending on compaction effort		--
Simulated in-situ[d] retorting	0.14 cm - 0.64 cm			2.3×10^{-2} to 3.3×10^{-2}		--

[a] CSU, 1971.

[b] Nevens et al., 1977.

[c] Peterson et al., 1978.

[d] Amy, 1978.

Permeability measurements in Nevens et al. (1977), Colorado State University (1971), and Amy (1978) were made using permeameters in which dry shale was placed in a tube and compacted before water was introduced. In Petersen et al. (1978), permeability measurements were made on consolidated undrained triaxial compressive strength test specimens. Therefore none of these results actually simulates the permeability of a grout slurried with water. Since the amount of water required to produce a pumpable slurry may be much greater than the amount used in these tests, the actual permeability of a spent shale grout may be quite different from the results presented in Table 3. However, spent shale will tend to dehydrate the slurry so that the water-to-solids ratio of the grout in place may be reasonably low.

The effect of the water-to-cement ratio (WCR) on the permeability of cured cements is illustrated in Figures 4 and 5. This suggests that some compromise in grouting will have to be made between pumpability and permeability. Further implications of the water-to-solids ratio are discussed elsewhere.

Stability. A grout must be stable for very long time periods under conditions which exist underground. These conditions may include: high in-situ strains, heavy overburdens and large hydrostatic pressures, elevated temperatures, and contact with high-salinity groundwaters. Since any grout has a finite permeability, flow through a grouted retort may erode away particles, or reactions may occur between the grout and chemical species in the groundwater. For example, Piceance Creek Basin groundwaters are high in sulfate, which attacks hydraulic cements such as portland cement. These reactions may lead to grout failure caused by slow erosion or dissolution of cementing compounds. The factors involved must be investigated in laboratory studies to facilitate selection of a grout which is stable under in-situ conditions.

Viscosity. The viscosity of a grout is an important factor to consider in planning a grouting operation because it determines the rate at which grout can be injected, the distance to which it can penetrate with a given injection pressure, and the size of pores into which the grout can flow. Voids in an abandoned retort can be filled more economically if a less viscous grout is used because fewer injection points will be needed and penetration will be more complete.

Strength and Stiffness. Strength and stiffness of grouted retorts determine their ability to support overburden and prevent subsidence. Stiffness (the elastic modulus or ratio of stress to strain) measures how far retorts will subside under the stress imposed by the overburden. Strength is the maximum stress that can be carried by the retort without failure. Thus, these two properties together determine whether grouted retorts will fail structurally and how much subsidence will occur. The grouted retorts will be much weaker and less stiff than the pillars. Consequently, the overburden may settle unevenly. Such uneven settling may create tensile stresses in the overburden which could cause overburden fracturing, especially at the edges of retorted areas.

Increasing resource recovery requires substitution of grouted retorts for pillars and development of strength and stiffness in the grouted retorts. The structural requirements for retorts in current development plans (Gulf,

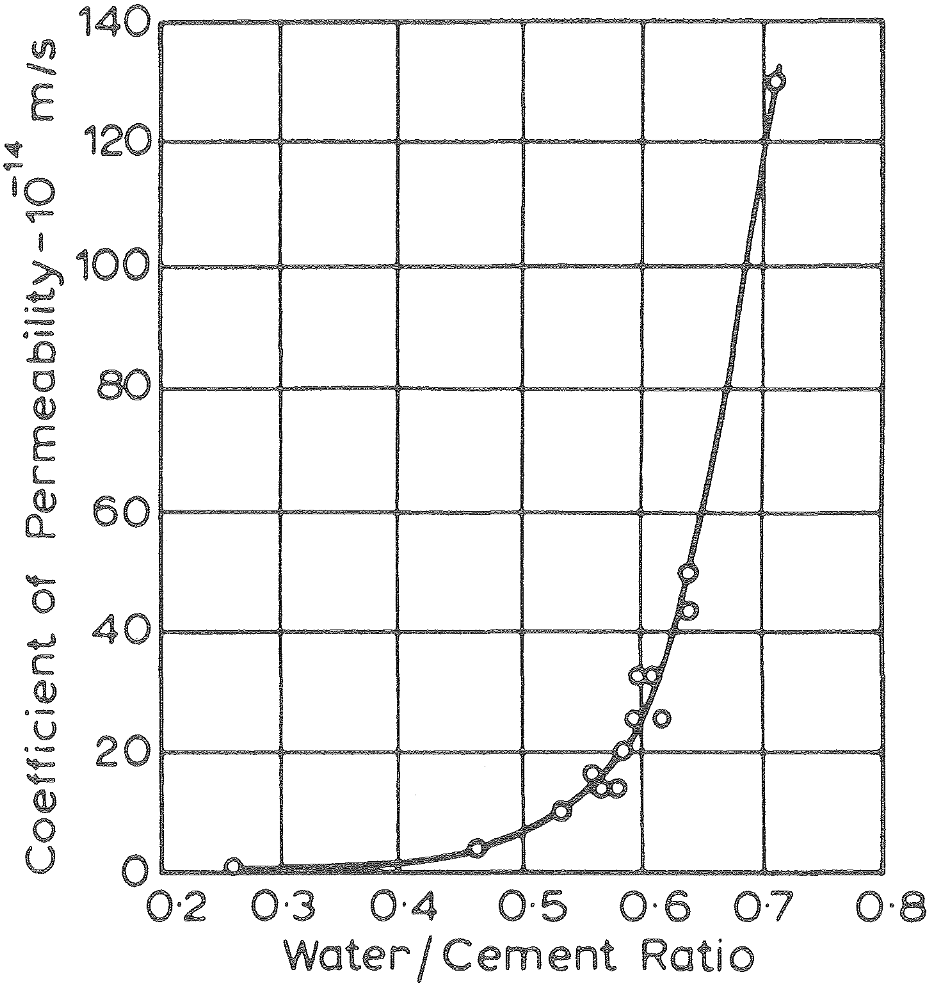

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Figure 4. Relationship between permeability and water-cement ratio for mature cement pastes (93% of cement hydrated). Source: Neville, 1973. Reproduced by permission of Pitman Publishing, Ltd., Copyright 1970.

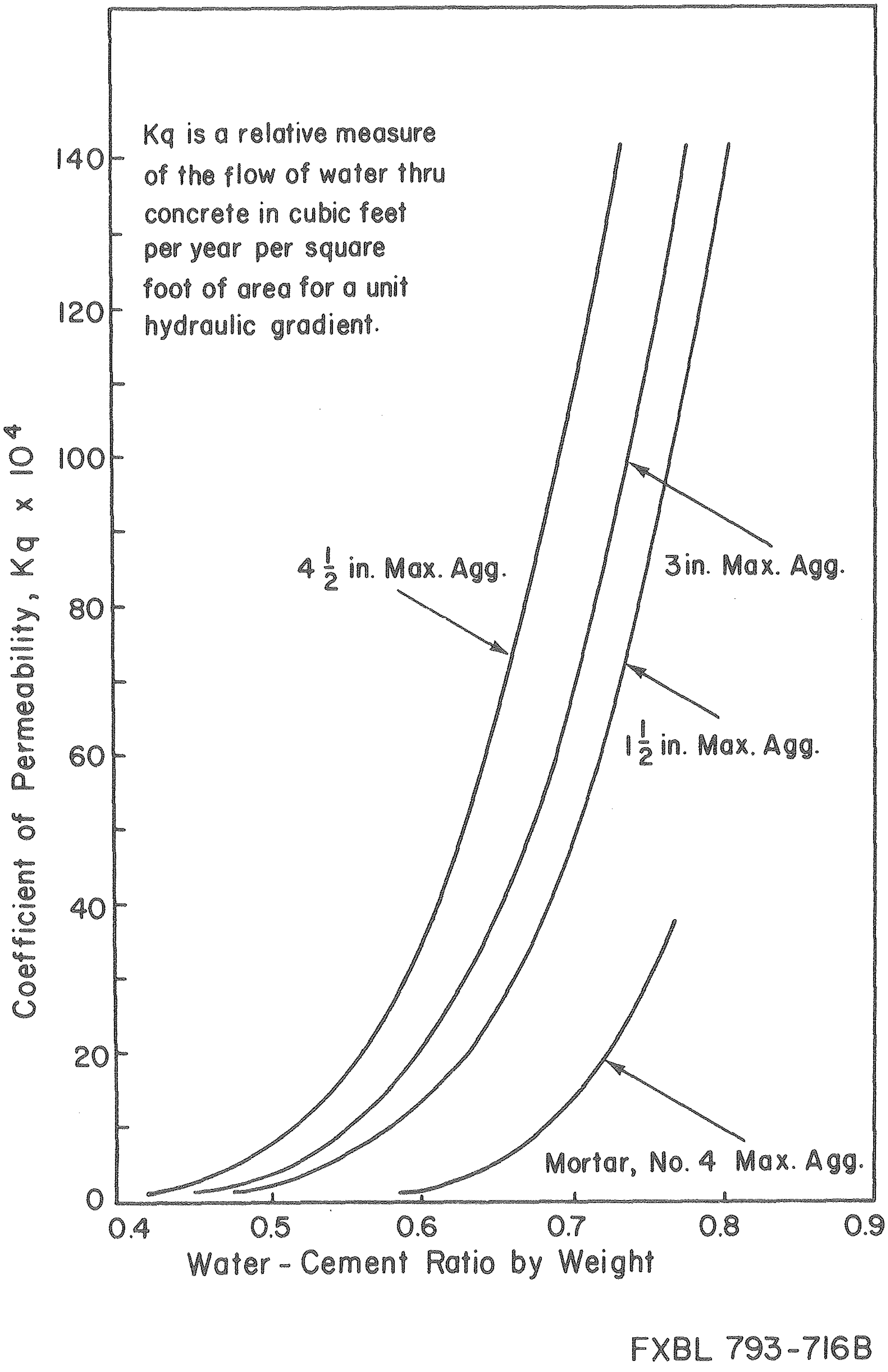


Figure 5. Relationship between permeability and water-cement ratio for mortar and concrete. Source: USID, 1963.

1977; Ashland, 1977) are low because massive raw shale pillars are used to support the overburden. However, increasing the extraction ratio would require the development of increased compressive strength and stiffness in grouted retorts. The actual requirements are site specific and also depend upon the temporal sequence of primary extraction, grouting, and secondary extraction. It may be difficult to achive adequate properties by grouting retorts because the majority, 60 to 77 percent, of the material in the retorts will be weak spent shale.

Grouting Materials

Various materials could be introduced into an abandoned retort or surrounding strata to increase structural strength or to reduce the flow of groundwater through the retort. These materials, called grouts, have been widely used in a number of fields including oil field reservoir engineering, dam construction, gas storage in underground formations, deep coal mining, soil consolidation, and various construction activities. Selection of a proper grout is based upon consideration of factors such as viscosity before setting, time of set, chemical stability under service conditions, and cost. Viscosity and time of set can often be regulated to some extent by formula control. Another important consideration is whether the grout is a true solution (as are the chemical grouts) or a suspension of particulates (such as cement grouts). This is important because the penetration of solutions into fine pores is limited only by viscosity, while the flow of particulate grouts is further limited by the relative sizes of the particles in suspension and the pore diameters.

An impressive array of commercially available grouting materials has been used in other industries. These have been extensively described in the literature (Herndon and Lenahan, 1976) and include cement and chemical grouts. Cement grouts typically have long setting times, are non-Newtonian, and have relatively high viscosities compared to chemical grouts. Chemical grouts are water solutions of various inorganic or organic compounds and are most typically based on sodium silicate, acrylamide, polyphenolic and urea-formaldehydes, lignins, and resins. Properties and cost factors for some of these grouts are compared with spent shale in Table 4. Preliminary estimates indicate that it could cost from \$16 to \$120 per barrel of oil for the grouting material alone if abandoned retorts were sealed with these conventional materials. These high costs are due to the large volume of voids that must be filled. Each barrel of oil recovered in combined in-situ and surface retorting leaves voids of 13 and 8 ft^3 for tracts C-a and C-b, respectively.

Thus, commercially available grouts are too expensive by at least an order of magnitude for sealing abandoned in-situ retorts. This suggests that inexpensive locally available waste products, such as spent shale and mine water, should be used. These materials should be considered as raw materials for on-site manufacture of grouts that would not be economically competitive if purchased from commercial sources. Some possibilities, which will be explored in subsequent sections, include on-site conversion of raw or spent shale into a pozzolan or cement and the use of carbon dioxide in retort offgas to produce insoluble carbonate deposits in the abandoned retort.

Table 4. Comparison between conventional grouting materials and spent shale.

Class	Example	Viscosity before gelling, cp (range)	Gel time min. (range)	Cost factor relative to neat cement
Cement	Portland cement slurry	a	10-300	1.0
Silicate	Water glass (sodium silicate)[b]	1.5-2	0.1-60	1.3
Polymer	AM-9 polyacrilamde[c] PWB[b]	1.2-1.6 1.5	0.1-300 ->300	7.0 9.0
Resins	Herculox[b]	13	4-60	4.5
	Epseal[b]	80-90	-	-
Foams	Polyurethane foam[e]	-	15	1.5
Spent shale	Lurgi[f]	a	28 days	0.05
Lignin base	Blox-All[c]	8-15	3-90	1.65
Unsaturated fatty acid	Polythixon FRD[c]	10-80	25-360	-
Formaldehyde base	Urea-formaldehyde[c]	3.5-13	1-60	6.0

[a] Depends on the water-cement ratio (WCR) and presence of additives. With a WCR of 45%, and no additives, the viscosity of neat cement is 200 cp. Addition of a slurry fluidizer (i.e., naphthalene polymer) may reduce this to 20 cp. By comparison, a WCR of 450% to 900% is needed to reduce the viscosity of Lurgi spent shale to 200 cp.[f].

[b] Halliburton, 1971.

[c] Herndon and Lenahan, 1976.

[d] Black, 1977.

[e] Nevens et al., 1977.

The most promising on-site waste material is spent shale from surface retorts. Oil shale, which is low-grade fossil fuel, produces about 1.4 tons of solid waste, referred to as spent shale, for each barrel of oil produced. This abundant on-site material may be suitable for manufacturing a grout if certain technical problems can be resolved. This material is typically light tan to black in color, may have little strength, and is easily crushed to a fine powder. The physical and chemical properties of spent shales from some surface processes are summarized in Table 5. The major elements in spent shales are iron, calcium, magnesium, potassium, silicon, aluminum, and sodium. The major mineral phases depend upon the retorting conditions. If temperatures are too low to decompose carbonates, the original mineral components will remain approximately intact, mainly dolomite, calcite, quartz, and feldspar. At higher temperatures, calcite and dolomite decompose to yield periclase and lime; at still higher temperatures, silicates are formed, mainly diopside and members of the akermanite-gehlenite series.

Grout Manufactured from On-Site Waste Products

It is apparent that only particulate grouts can be considered for sealing abandoned VMIS retorts and that cost is a critical factor. Low cost grouting materials such as local waste materials are required to economically grout an in-situ retort. Surface retorted spent shale has been proposed as a grouting material (Nevens et al., 1977; Gulf, 1977). Current development plans (Gulf, 1977) call for spent shale to be slurried and placed in abandoned VMIS retorts at Tract C-a.

Surface spent shale will be available at a VMIS plant. Approximately 20 to 40 percent of the in-place shale in a VMIS operation is mined to create void space and stockpiled on the surface for future retorting. The spent shale from surface retorting of the mined material may be used to manufacture a grout for sealing the abandoned in-situ retort.

Grout production from surface spent shale would alleviate part of the surface disposal problem, protect against subsidence and aquifer disruption, and provide the opportunity for enhanced resource recovery. Not all of the spent shale can be returned to the underground environment because the material expands in volume due to crushing and exfoliation during retorting and because grout production requires the addition of water and possibly aggregate. It is estimated that about 47 percent of the surface spent shale could be returned to the underground environment as a grout. If the abandoned retort chambers are filled with a solid--raw shale, spent shale, or a grout made from these materials--the reduction in voids would provide support for the overburden, reducing the likelihood of subsidence. Similarly, if adequate strength, about 1000 psi, and stiffness, about 500,000 psi, could be developed in the grouted abandoned retort, it may be possible to recover oil from the supporting pillars.

This section will review the experimental basis for considering spent shale as a grout material and subsequent sections will develop the theoretical basis. Due to the chemical and physical similarity of spent shale grouts to cement grouts, reference will be made to the literature of cement and cement grouting to anticipate properties of spent shale grouts.

Table 5. Physical and chemical properties of spent shale from surface retorts.

	TOSCO II[a]	Lurgi[b]	Paraho direct mode[c]
Mineral Phases			
Quartz	--	high	35%
Calcite	--	high	20%
Dolomite	--	low	25%
Feldspar	--	low-med	10%
Analcime	--	--	10%
Illite	--	--	5%
Elemental Abundance			
Al, %	4.8	3.8	4.50
As, ppm	--	--	35
B, ppm	--	--	123
Ca, %	12.6	15.6	13.9
Fe, %	2.3	2.1	2.50
Hg, ppb	--	--	21.2
K, %	1.2	--	1.76
Mg, %	4.7	4.5	4.31
Na, %	0.6	1.7	2.20
Pb, ppm	--	--	33
S, %	1.05	1.1	--
Se, ppm	--	--	3.1
Si, %	15.5	14.9	17
Zn, ppm	--	--	86
Physical Properties			
Particle density, g/cm^3	2.67	2.91	--
Specific surface area,[d] m^2/g			
-230 mesh	6.63	4.76	3.50
-60 +230 mesh	9.20	4.77	3.37
+60 mesh	10.19	--	--

[a] Nevens et al., 1977--raw shale came from Mahogany Ledge, Anvil Points, Colorado.

[b] Persoff et al., 1980--material was collected in electrostatic precipitator from Lurgi run No. 9, 1976.

[c] Fruchter et al., 1978--Sample collected 24 Aug. 1977, values are typical

[d] All specific surface area measurements from Fox and Jackson, 1980.

First, it is instructive to note that a process has been patented for manufacture of portland cement from raw oil shale and limestone (Sellers and Chapin, 1959). The coarse-ground raw shale and limestone in a 1.8-to-1 weight ratio are ground to a powder and fired to form clinker. The lime and silica content of the shale (with additional lime) are the raw materials. The high energy requirements, and hence cost, associated with this process make it economically unattractive for grouting of in-situ retorts. However, it does indicate that the ingredients to produce a cementitious product are present in raw shale.

Spent shale from commercial Estonian oil shale retorts has cementitious properties and has been used directly as a cement without any additions or with 20 to 30 percent portland cement addition. The 28-day compressive strength of mortar cubes (a test apparently similar to ASTM C 109) was 1490 psi for coarse oil shale fly ash (30 to 150 μm) and 2980 psi for fines (15 to 30 μm), without addition (Kikas, 1968). These properties were improved by operating retorts at high temperatures (1800° to 2000°C) and rapidly cooling it (Tager, 1968). These remarkable properties appear to be due to the composition of the mineral portion of the shale. The calcium content of Estonian shale is high (40 to 60 percent), with corresponding lower SiO_2 and MgO. Up to 32 percent free lime, 36 percent glassy phase material, and 14 percent dicalcium silicate were present in spent shale fly ash (Kikas, 1968).

Several investigators studying the stabilization of surface spent shale disposal piles have observed self-cementing properties in U.S. spent shale, either as received or after additional heat treatment. Culbertson et al. (1970) studied the stabilization of spent shale from a TOSCO retort. Shear strength and compressive strength of all samples increased gradually with time, suggesting a cementitious reaction. Compressive strengths in the range of 250 to 500 psi were obtained. Strength development was positively correlated with the amount of cohesive hydrates formed, as detected by differential scanning calorimetry. After 15 days of setting, no loss of strength was reported when samples were resaturated with water. Nevens et al. (1977) studied the backfilling of an abandoned VMIS retort with a slurry of Lurgi spent shale. Compressive strengths of slurries obtained after 28 days curing ranged from 5 to 200 psi. The temperature at which spent shale is burned to provide heat for the retorting process appeared to be important. Permeability of the Lurgi spent shale decreased from initial values of 10^{-4} cm/sec, to 10^{-5} to 10^{-6} cm/sec after 28 days. In-situ spent shale was observed to rapidly absorb water (four gallons per cubic foot), suggesting that slurries may be dehydrated when pumped into abandoned retorts. In a test to simulate grouting of an in-situ retort, a slurry with 164 percent by weight of water was poured into a hand-packed drum of in-situ spent shale and water was drained from the bottom. No cementation was observed and the compressive strength after 13 days of curing was only 16 psi.

Peterson et al. (1978) studied the geotechnical properties of a fine-grained surface-retorted spent shale from an indirect-heated process to evaluate the stability of disposal piles. Unconfined compressive strengths of compacted samples increased with time, indicating some self-cementing properties. The maximum compressive strength developed was 104 psi; this required a compaction effort of 56,000 ft-lb/ft^3.

Compaction studies on spent shales from a Paraho semiworks retort showed that compressive strengths up to 200 psi were obtained with 56,000 ft-lb/ft^3 of compactive effort. Spent shale was described as a low-grade cement (Woodward, 1976).

Farris (1979) operated a laboratory retort under varying conditions to determine retorting conditions which would maximize the strength of compacted spent shale. Direct-mode retorting for 2.0 hours at 822°C gave a strength of 270 psi. Indirect-mode retorting for 2.9 hours at 832°C gave a strength of 325 psi. The strength development was attributed to the formation of interlocking acicular crystals, thought to be hydrated calcium aluminum sulfate.

Mallon (1979) operated a laboratory retort under conditions designed to produce cementing compounds. Shale was retorted in nitrogen, then char was burned off by gradually introducing air without exceeding a temperature of 650°C. The spent shale was then heated in 100 percent steam for 70 minutes at 700°C. The resulting clinker was pulverized and slurried and poured into spent shale to simulate grouting of in-situ rubble. The grouted rubble had a 10-week compressive strength of 522 psi and a 4-week permeability of 4×10^{-7} cm/sec.

The above cited examples indicate that surface-retorted spent shales have some self-cementing properties which may make them suitable as a grout for sealing abandoned VMIS retorts. The required strength for a grout may, however, be greater than any yet reported for self-cemented spent shale. A strength of about 1000 psi would be needed to provide sufficient stability in a grouted retort to permit the pillars between retorts to be retorted for increased resource recovery.

The following sections will explore the theoretical basis for the formation of a grout from spent shale. The chemical composition of raw and spent oil shale, the mineralogical changes that occur during oil shale retorting, and the chemistry of cements suggest that spent shale may be used as is or may be modified by heat treatment and addition of chemicals, such as limestone and fluidizers, to produce a grout. Other sections will discuss the use of clay and lime-pozzolan admixtures to a grout of spent shale.

Chemistry of Cements and Pozzolans. The mineralogical and chemical composition of raw and spent oil shales are similar to those of cements and pozzolans. This, together with the experimental evidence presented previously, suggests that raw or spent shale may be used to manufacture a cementitious grout. This may be achieved by modifying the spent shale produced by existing surface retorts such as Lurgi or Paraho, or by optimizing retorting conditions to produce a spent shale with cementitious properties.

This section will discuss the theoretical basis for this proposal. The raw ingredients of cement--clay and limestone--are also present in oil shale. However, the stoichiometric ratios of Ca, Al, Si, Fe, and Mg in oil shale are different from cements and pozzolans. Therefore, oil shale retorting--in which crushed shale is heated to 500°C or higher in the presence of air, steam and/or nitrogen--may form different end products than cement or pozzolan production. Thus, it may be necessary to adjust the stoichiometric ratios in the oil shale by additions of materials and/or to modify the retort operating conditions to produce a spent shale grout with optimum properties.

The following sections will demonstrate that calcium silicate and other strength-forming compounds present in cements and pozzolans may be formed during oil shale retorting, or by post-retorting treatment of spent shale, if the appropriate set of operating conditions are employed.

The chemistry of pozzolans and cement and of the carbonate and silicate minerals in oil shale is germane to understanding the potential role of spent shale as a grout. Cements are prepared by blending proper proportions of finely ground limestone and clay and firing the mixture in a kiln at 1450 to 1550°C. The resulting clinker, which consists of calcium silicates, calcium aluminates, and other compounds is cooled; about 5 percent gypsum is added as a set retarder; and the mixture is pulverized. When water is added to this material the clinker compounds are hydrated, forming the strength-producing compounds of cements. The process can be represented by the following set of chemical equations:

<u>Calcining</u>

$$\text{Limestone or } CaCO_3 \xrightarrow{\Delta} CaO + CO_2 \tag{1}$$

$$\text{Clay} \xrightarrow{\Delta} Al_2O_3 + SiO_2 + Fe_2O_3 \tag{2}$$

<u>Formation of Clinker Compounds</u>

$$3CaO + SiO_2 \xrightarrow{\Delta} 3CaO\cdot SiO_2 \tag{3}$$

$$2CaO + SiO_2 \xrightarrow{\Delta} 2CaO\cdot SiO_2 \tag{4}$$

$$3CaO + Al_2O_3 \xrightarrow{\Delta} 3CaO\cdot Al_2O_3 \tag{5}$$

$$4CaO + Al_2O_3 + Fe_2O_3 \xrightarrow{\Delta} 4CaO\cdot Al_2O_3\cdot Fe_2O_3 \tag{6}$$

<u>Hydration</u>

$$2(3CaO\ SiO_2) + 6H_2O \longrightarrow 3CaO\cdot 2SiO_2\cdot 3H_2O + 3Ca(OH)_2 \tag{7}$$

$$2(2CaO\ SiO_2) + 4H_2O \longrightarrow 3CaO\cdot 2SiO_2\cdot 3H_2O + Ca(OH)_2 \tag{8}$$

$$3CaO\ Al_2O_3 + 16H_2O + CaSO_4\ 2H_2O \longrightarrow 3CaO\cdot Al_2O_3\cdot CaCO_4\cdot 18H_2O \tag{9}$$

$$3CaO\ Al_2O_3 + 26H_2O + 3CaSO_4\ 2H_2O \longrightarrow 3CaO\cdot Al_2O_3\cdot 3CaSO_4\cdot 32H_2O \tag{10}$$

As will be discussed in the next section, the clinker compounds that give cement its strength may not form at all or may form only to a limited extent during oil shale retorting, depending on the operating conditions. This may be one of the reasons that spent shale grouts described in the literature (Peterson et al., 1978; Woodward, 1976; Nevens et al., 1977; Culbertson et al., 1970) have low compressive strengths, 5 to 500 psi, compared to neat cement. The low calcium oxide to silica ratio of oil shale relative to cements and pozzolans results in the formation of nonreactive silicates such as akermanite or gehlenite during retorting. This suggests that the calcium content of raw or spent shales may have to be increased by the addition of limestone to produce adequate cementitious properties. This may be achieved using a scheme such as that shown in Figure 6.

Cement production, such as that described by Equations (1) through (10) is an energy-intensive process. About 7.4 x 10^6 Btu are required per ton of cement produced (Mehta, 1978). Thus, it may not be economically feasible to manufacture cement on site because of the high energy requirements. However, a hydraulic lime-pozzolan could be produced at temperatures much below clinkering temperatures.

Pozzolans are siliceous and aluminous materials that react with lime in finely divided form and in the presence of moisture to form cohesive hydrates. These hydrates are the main strength-giving compounds of hydrated cement see Equations (7) through (10) . Typical pozzolanic reactions are:

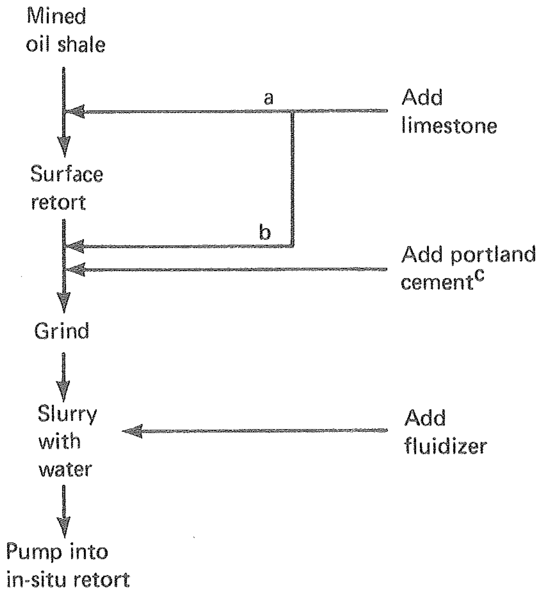
$$2SiO_2 + 3Ca(OH)_2 \longrightarrow 3CaO \cdot 2SiO_2 \cdot 3H_2O \qquad (11)$$

$$Al_2O_3 + 4Ca(OH)_2 + 10H_2O \longrightarrow 3CaO \cdot Al_2O_3 \cdot Ca(OH)_2 \cdot 18H_2O \quad . \qquad (12)$$

These equations show that if active silica and alumina react with lime, calcium silicate and calcium aluminate hydrates are formed. These compounds are similar to those that give strength to portland cement. The ability of a siliceous or aluminous material to react at normal temperature as shown is called "pozzolanic activity" and is measured by ASTM Method No. C 311-77 (ASTM, 1978). A sufficient degree of pozzolanic activity may be present in spent shale or it may be increased by heat treatment, by modifying retorting conditions, or by lime addition.

If pozzolanic activity could be induced in surface spent shale by modifying retort operating conditions, it might be possible to manufacture a hydraulic lime-pozzolan on site. This may be more attractive than manufacturing a cement since activation of silica and alumina takes place at lower temperatures (900°-1000°C) than the formation of clinker compounds. For maximum development of cementitious properties, additional lime may be required. This could be added either before or after retorting. Fine grinding of the spent shale also would be required. Because the clinker compounds of portland cement, formed in Equations (3) through (6), would not be present, the grout would set more slowly and have a lower final strength.

Table 6 compares the composition of spent shale to pozzolans. Pozzolanic activity depends not only on the oxide abundances, but also on the silica and alumina being in active form; that is, capable of dissolving and reacting to form cohesive hydrates as shown in Equations (11) and (12). Pozzolanic



a. Add limestone before retorting if retorting temperature is high enough to calcine limestone.

b. Add calcined limestone after retorting if retorting temperature is not high enough to calcine limestone.

c. Portland cement addition only if strength development without it is inadequate.

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Figure 6. Proposed strategy for abandonment of VMIS retorts. Source: Fox et al., 1978.

Table 6. Comparison of the chemical composition of pozzolans and spent shale.

	Weight percent[a]			
Compound[a]	Typical natural Pozzolan[b]	Typical lignite fly ash[c]	Lurgi spent shale	ASTM C-618-78 Class C fly ash[d]
SiO_2	55.0	28.7	32.0	$\geqslant$ 50.0
Al_2O_3	17.7	12.0	7.2	
Fe_2O_3	3.5	6.8	2.7	
CaO	3.2	40.5	21.8	-
MgO	1.0	7.4	7.5	$\geqslant$ 0.5
SO_3	-	2.5	-	$\geqslant$ 5.0
FeO	0.9	-	-	-
K_2O	6.4	-	1.7	-
Na_2O	3.4	0.6	2.3	$\geqslant$ 0.5
Loss on ignition	6.3	0.4	20.7	6.0
	97.4	98.9	95.9	

[a] The expression of chemical composition as oxides does not necessarily mean that the oxides are actually or entirely present.

[b] Turrizziani, 1964.

[c] Manz, 1966.

[d] ASTM, 1978.

activity seems to be dependent upon the silica or alumina being in a glassy (non-crystalline) state, or upon a high specific surface area (Lea, 1971).

The effect of heat on pozzolanic properties is variable. Some natural pozzolans gain in pozzolanic activity when heated at 300-700°C for a few hours, but lose it upon longer heating at higher temperatures (above 600°C). In other cases, pozzolanic properties are induced in clays or shales by burning where it appears that the effect of heating is to calcine impurities, changing them from deleterious constituents to inert or pozzolanic ones (Lea, 1971).

Pozzolanic activity of spent shale may be enhanced by modifying surface retorting conditions or by treating the shale following retorting. Since spent shale has a substantial calcium content, true cementitious properties may result from the reaction between active silica or alumina and calcined limes, as shown in Equations (11) and (12). Such a mixture of pozzolanically active silica or alumina and lime is known as a hydraulic lime-pozzolan. The strength of such a mixture is lower and the setting time longer than in portland cements, but these properties should cause no problem in grouting in-situ retorts. If addition of lime is found to enhance cementing properties, it may be available on site at low cost. A summary of the proposed technique is shown in Figure 6. Strengths of lime-pozzolan mortars have been reported by Lea (1971) and are summarized in Table 7. The strengths are higher than those reported for spent shale, which is to be expected, since the materials used were of higher quality.

The above cited data indicate that there is some theoretical basis to explain the observed cementing properties of spent shale. Development of a surface-retorted spent shale with cementitious properties depends upon the presence of one of two conditions. The first is the formation, either during retorting or during subsequent heat treatment, of significant amounts of the portland cement clinker compounds in Equations (3) through (6). This is considered unlikely because temperatures of 1450-1550°C and a raw material mix with a lime-silica ratio much greater than that found in raw or spent shale are required. The second is the formation of both pozzolanically active silica and/or alumina and free lime (CaO) in ratios that permit pozzolanic reactions producing cohesive hydrates, such as shown in Equations (11) and (12).

Table 7. Strength of lime-pozzolan mortars

Pozzolan	Mix proportions (weight)			Tensile strength (lb/in^2)			
	Hydrated lime	Pozzolan	Standard sand	7 days	28 days	90 days	1 year
Burnt shale	1	1	6	107	207	341	521
	1	2	9	133	322	459	560
	1	4	15	203	371	514	533
Trass	1	1	6	213	361	447	477
	1	2	9	225	390	425	495
	1	4	15	234	363	412	433

Source: Lea, 1971. Reproduced by permission of Chemical Publishing Co., Inc. Copyright 1971.

It is proposed that the mechanism of strength development in retorted shales is similar to that in lime-soil stabilization, namely, pozzolanic reaction between free lime and active silica to form cohesive hydrates. Compressive strength was positively correlated with compaction effort by Peterson et al. (1978) and Woodward-Clyde Consultants (1976), and compaction is needed for strength development in lime-soil stabilization. Also, the rate of strength development observed by Woodward-Clyde Consultants (1976) is similar to that for lime-soil stabilization.

Mineralogical Reactions During Retorting. The feasibility and methods of forming cements or pozzolans during oil shale retorting depend on the chemical reactions that occur during retorting. Production of cementitious properties depends principally on the availability of free lime to react as indicated in Equations (3) through (6), (11), and (12) and the absence of char. Thus, an understanding of char formation and calcium chemistry during retorting is essential to determine the potential for spent shale grout production and to design a method to produce this grout.

Green River oil shale is a marlstone whose principal minerals are dolomite, calcite, quartz, and illite. The organic phase, kerogen (about 20 percent by weight), is converted to oil by thermal distillation at about 500°C (pyrolysis). This process produces shale oil, a low BTU gas, and char. The goal of surface retorting is to pyrolyze the kerogen without decomposing the carbonate minerals because carbonate decomposition is endothermic, and the decomposition of these minerals adversely affects the energy balance of the retorting process. Pyrolysis is achieved in existing processes by direct or indirect heating. In the indirect processes, heat is transferred to the shale by a medium such as hot inert gas or ceramic spheres. In the direct processes, pyrolysis heat is derived from the combustion of char left on retorted shale. During both of these processes, the pyrolysis heat results in mineralogical changes in the shale.

The production of cementitious properties and oil generation require different operating conditions. As noted, the goal of oil production is to pyrolyze the kerogen without decomposing the carbonates. Cement and pozzolan production, on the other hand, require the decomposition of the carbonates to form free lime and the absence of char. Because of the differences in chemical and physical processing requirements, a system that is optimized for oil yield may not produce spent shale with adequate cementing properties, while a process designed to optimize cement production may not be an efficient energy producing system.

The chemistry necessary to produce free lime and to inhibit char formation is presented below. This information is then used to determine how cementitious properties can be produced in spent shales.

Campbell (1978) and Campbell and Taylor (1978) studied the fate of calcium during simulated in-situ retorting. About two-thirds of the calcium in raw oil shale is present as dolomite, $CaCO_3 \cdot MgCO_3$ (actually a fraction, less than 30 percent, of the magnesium is replaced by iron), and the remainder as calcite, $CaCO_3$. During retorting, dolomite decomposes to form periclase (MgO) and calcite, with the loss of CO_2. Calcite (either originally present or formed by decomposition of dolomite) can then undergo one of two competing reactions. In the presence of silica and periclase, it can either form akermanite or other nonreactive silicates and CO_2, or it can simply decompose to form free lime and CO_2. These two reactions are designated reactions (A) and (B) in Figure 7. Akermanite is of no value in cementing. Production of cementitious properties requires the formation of lime [reaction (B)]. Calcium silicates, including the cementitious products alite (Ca_3SiO_5) and larnite (Ca_2SiO_4), may also be formed during retorting if temperatures at which MgO reacts are not reached.

Reaction (A) occurs fairly rapidly at temperatures above 500°C. This solid-state reaction is only possible because it is favored by the small grain size of calcite and silica in oil shale. Reaction (B) does not occur until a temperature is reached at which k_{eq} for reaction (B) (units are atmospheres) is greater than the partial pressure of CO_2; then it proceeds very rapidly. For one atmosphere CO_2, this temperature is about 900°C. Thus, increasing the partial pressure of CO_2 in the retorting atmosphere delays formation of free lime until higher temperatures are reached. If temperature is raised slowly to the threshold temperature for free lime formation, much or all of the calcite present will undergo reaction (A) before the threshold is reached. Therefore, to encourage reaction (B) (formation of free lime), retorting temperatures must be raised as rapidly as possible, with CO_2 continuously flushed from the retort as it is formed.

Thermal gravimetric analysis plots (weight loss during heating) are presented by Campbell (1978) for various partial pressures of CO_2 and various heating rates. Since all three reactions involve loss of CO_2, they can be followed by this means. The experimental results show that reaction (B) is maximized when CO_2 pressure is least and when heating rates are maximum. Figure 8 shows schematically the path of these reactions.

This agrees with the results of Parker et al. (1978) who identified the major mineral constituents of oil shale as dolomite, analcime, and quartz. Pure samples of these species and oil shale were separately heated to retorting temperatures of 700-1000°C. Pure dolomite yielded only lime (CaO) and periclase (MgO). However, when oil shale was treated the same way, lime was observed at 700 and 800°C, but not at higher temperatures when silicate minerals such as gehlenite were observed.

Heistand et al. (1978) heated 100-mesh oil shale in an open crucible in a muffle furnace. Retorting was done isothermally for 8 hours at 1200, 1300, and 1400°F. No free lime was present in the raw shale. Free lime increased continuously to 7.7 percent by weight by 8 hours at 1200°F. At higher temperatures, free lime was formed early, but later decreased in quantity. These results were also confirmed by x-ray diffraction. Some of the results of this work are presented in Table 8.

Char formation is also important to the production of cementitious properties in spent shales. Because presence of carbon inhibits the hydration of calcium silicates, residual char must be removed from the spent shale by methods such as burning. Char is formed during the pyrolysis of kerogen. This char, which is a finely divided graphitic carbon giving the shale a black color, represents unconverted energy which may be combusted to generate process heat according to the equation:

$$C + O_2 \rightarrow CO_2 \qquad (13)$$

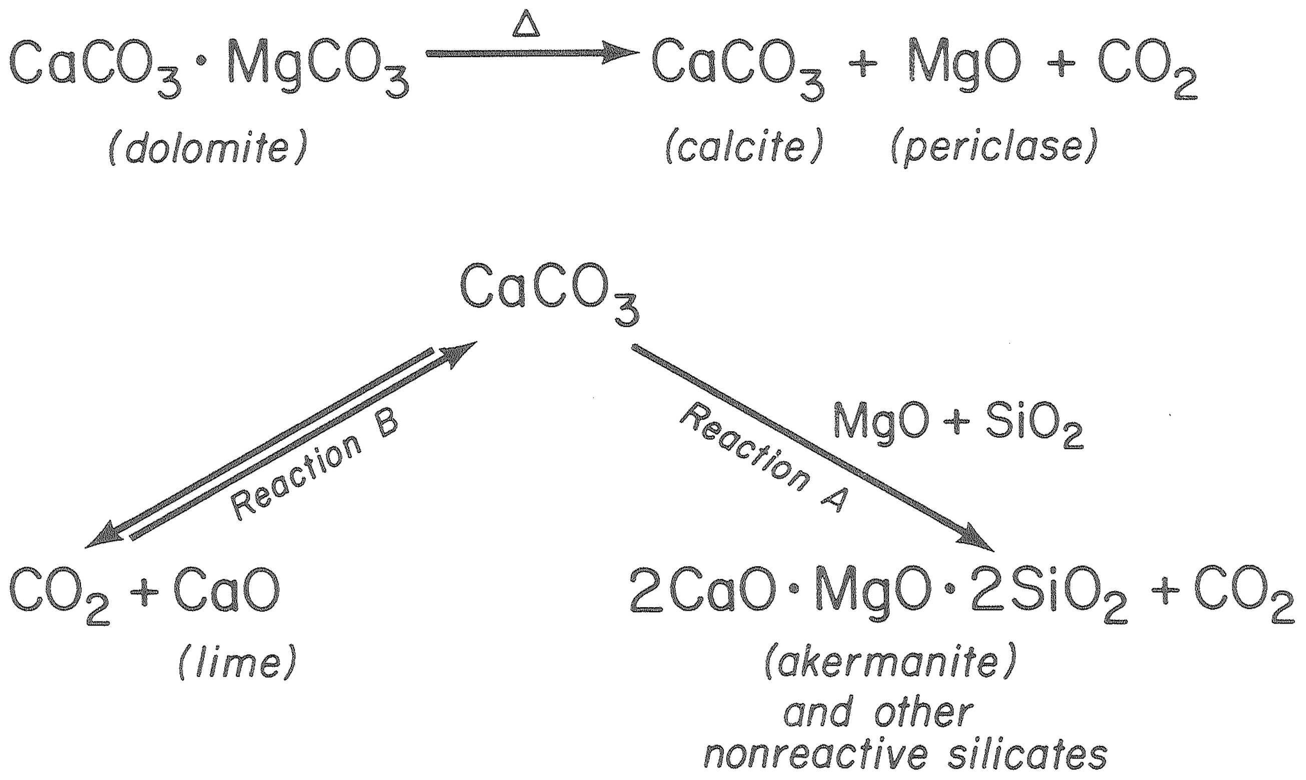

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Figure 7. Decomposition of dolomite and competing reactions of calcite.

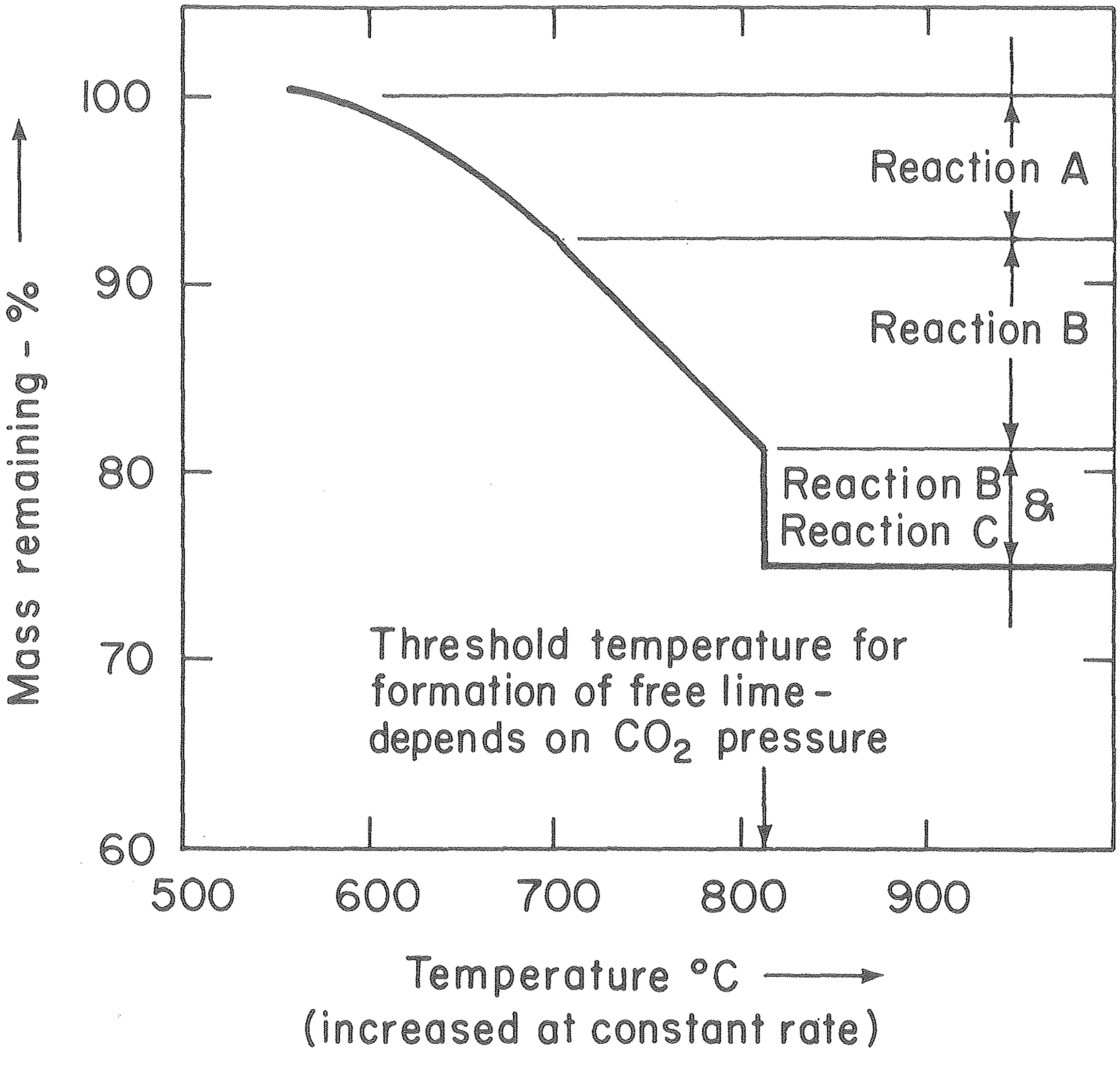

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Figure 8. Thermal gravimetric analysis of oil shale during retorting. Adapted from Campbell, 1978.

Table 8. Free lime (CaO) in oil shale retorted in air, wt %.

Time hrs	Temperature, °F 1200	1300	1400
1/2	-	0.1	4.6
1	0.1	1.7	4.8
2	0.3	4.7	2.9
3	1.8	6.6	1.7
4	3.3	6.2	1.0
5	2.0	6.0	1.0
6	2.6	3.8	1.0
7	3.1	4.0	1.0
8	7.7	-	-

Source: Heistand et al., 1978. Reproduced by permission of Crane, Russak, and Co., Inc. Copyright 1978.

These theoretical discussions indicate that free lime can be formed and char removed during oil shale retorting. Lime formation requires a rapid retorting rate, the continuous removal of produced CO_2, and temperatures of 700 to 800°C. The destruction of char, on the other hand, requires retorting in an oxygen atmosphere. This set of conditions does not coincide with the operating conditions of any of the proposed surface retorting systems such as Paraho, Lurgi, or TOSCO. This suggests that cement or pozzolan production from spent shale will require the redesign of one of these existing processes, the design of a new surface process, or the additional processing of spent shale discharged from one of the existing retorts. It is recommended that all three approaches be pursued to develop a spent shale grout.

Lime-Pozzolan Cement Grouts. In conventional construction practice, a portion of portland cement can be replaced by pozzolans to reduce costs. This strategy may be feasible in spent shale grouting if an adequate pozzolan or hydraulic cement can be produced from spent shale. Pozzolans such as fly ash could be mixed with a spent shale hydraulic cement or, conversely, portland cement could be mixed with a spent shale pozzolan or cement. Therefore, it is appropriate to review the literature from this related field.

While use of lime-pozzolan mixtures in construction is rare because of the strengths required and the need for rapid setting, substitution of pozzolan for a portion of portland cement is often used as an economy measure with little or no sacrifice in strength. As shown in Equations (7) and (8), the hydration of portland cement clinker compounds yields $Ca(OH)_2$ as a by-product. This adds little strength to the mass; but, if pozzolan is present, it can react with the $Ca(OH)_2$ and yield additional cohesive hydrates, as shown in Equations (11) and (12). Since the objective of using spent shale as a grout is to reduce the cost of grout material, the portion of portland cement replaced by pozzolan (i.e., spent shale) must be as large as possible, preferably over 90 percent. The effect of pozzolan substitutions up to 60 percent is presented in Figure 9. The strengths of pozzolan-portland cement mixtures ranging from 83 to 95 percent pozzolan (pulverized fuel ash) are given by Bowen (1975) and summarized in Table 9. These strengths are in the range of those reported for surface retorted spent shales. Bowen also suggested that materials using only pulverized fuel ash are an effective low cost means of filling large cavities in the ground. Use of a 3-to-1 fly ash-portland cement grout has also been successfully and economically used for blanket grouting under an earth-fill dam (McGavock and Depman, 1968) and pozzolan-cement ratios up to 3-to-1 are also reported for oil well cementing (Parker, 1977). Thus there is considerable precedent for the use of grouts with high proportions of pozzolan with 25 percent or less cement. The pozzolans used in these examples, however, may be better quality than can be obtained from spent shale.

Clay-Cement Grouts. Clay minerals, particularly bentonite, have been successfully used in pond sealing and other waterproofing applications. The sealing ability of the clay is attributed to its tendency to absorb water which causes the particles to swell, forming a gel which blocks soil pores. Clay grouts do not set and are held in place only by the pressure of soil particles around the clay particles. Since grouting an abandoned VMIS retort involves filling large voids, clays are not considered suitable for this sealing application.

Table 9. Compressive strength of pozzolan-portland cement mixtures.

Pulverized fuel ash-to-portland cement ratio	5:1	10:1	20:1
Water-to-total solids ratio	0.5	0.57	0.54
Compressive strength, psi			
3 day	193	72	57
7 day	334	170	110
1 month	616	297	119

Adapted from Bowen, 1975.

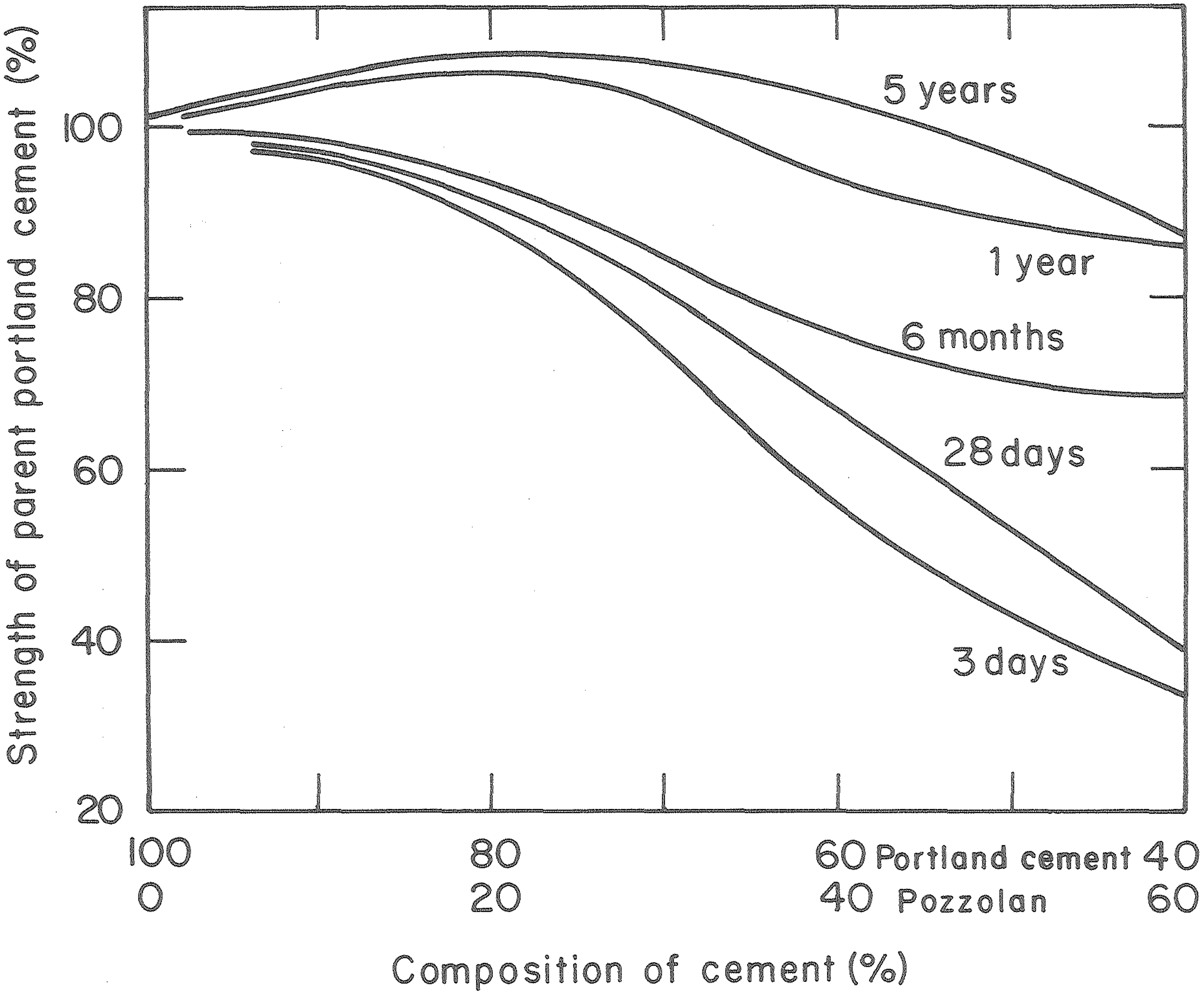

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Figure 9. Effect of substituting pozzolan (burnt shale) for portland cement on strength of concrete stored in water at 18°C. Source: Lea, 1971. Reproduced by permission of Chemical Publishing Co., Inc. Copyright 1971.

Bentonite has also been used as an admixture in cement grouts. A grout with a 2.7 clay-cement ratio was used by the TVA to successfully fill solution cavities in dolomitic limestone (Leonard and Grant, 1958). Since clay is locally available and relatively cheap (less than $30 per ton) there is a economic motivation for its use. Jones (1963) lists the following effects of bentonite admixture in cement grouts:

1. Addition of bentonite increases the Bingham yield value (see p. 43). Therefore addition of too much bentonite will make the slurry unpumpable.
2. Decreases compressive strength.
3. Decreases specific gravity of the grout.
4. Permits the use of a higher water-cement ratio without bleeding.

The above factors suggest that bentonite may be useful as an admixture in a spent shale grout. Figure 10 shows the regions of stability for water-cement-bentonite grouts. Thus, given a clay-to-cement ratio, the acceptable range of water-to-solids ratio may be determined. Similar effects may be expected for spent shale-bentonite-water grouts.

Grout Distribution in Abandoned Retorts

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. Since 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.

The flow of grout through an abandoned retort depends on many factors including the porosity and permeability of the abandoned retort and the viscosity of the grout used. These variables are related by the following equation for Bingham fluids:

$$R_L - a = \rho \frac{hd}{2S} \tag{14}$$

where R_L is the limiting radius of penetration, ft or m
a is the diameter of the injection pipe, ft or m
ρ is the specific gravity of water, lb/ft^3 or N/m^3
h is the injection head, ft of water or m of water
d is the effective pore diameter, ft or m
S is the Bingham yield stress, lb/ft^2 or N/m^2

For neat cement grouts, some calculated values of limiting penetration radius are presented in Table 10.

This equation shows that the radius of penetration of grout in an abandoned retort is directly proportional to the grout density, grout injection head, and the effective pore diameter; and inversely related to the

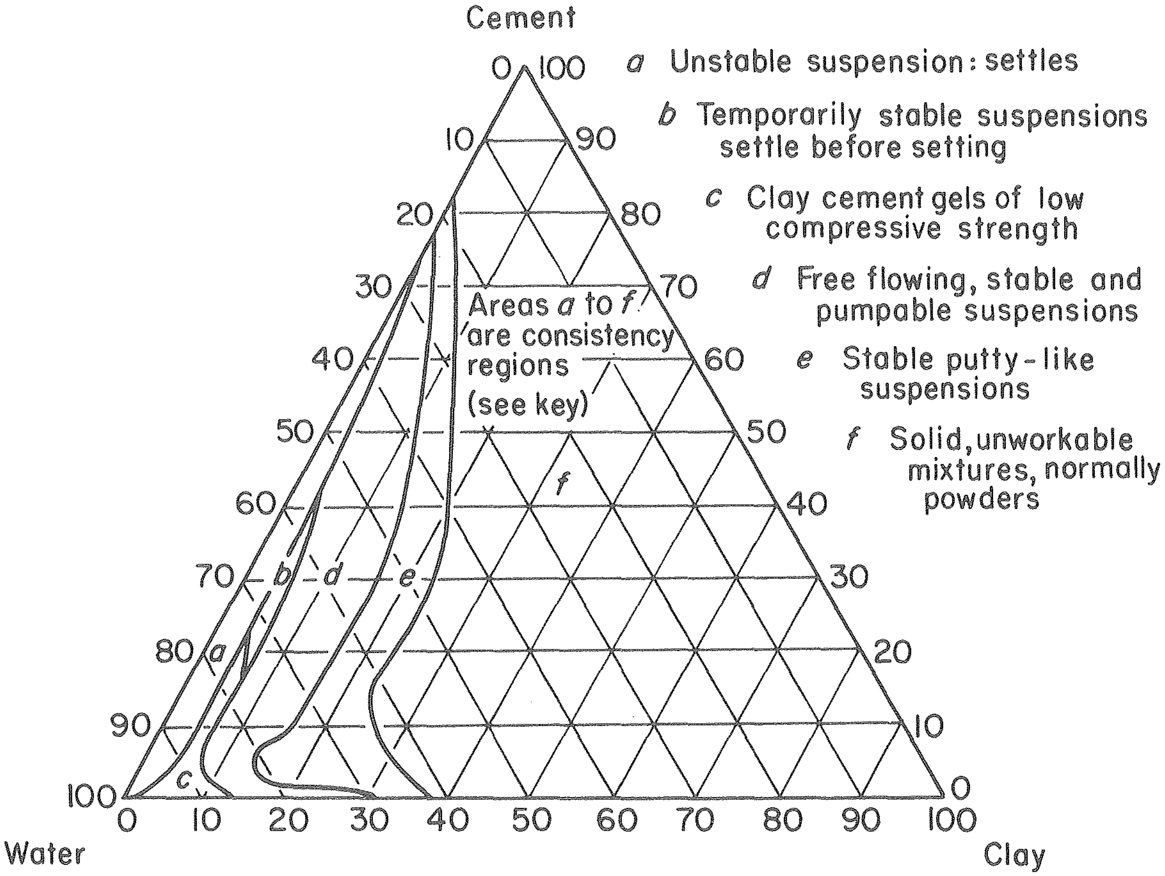

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Figure 10. Consistency of water-cement-clay (Fulbent 570) mixtures. Source: Jones, 1963. Reproduced by permission of Laporte Industries, Ltd. Copyright 1963.

Table 10. Limiting radius of penetration for Bingham fluids.

		Limiting penetration, ft		
		Pore radius, cm (equivalent permeability, cm/sec)		
Shear strength (dyne/cm^2)	Corresponding water-cement ratio for neat cement grout	0.019 (1)	0.0059 (0.1)	0.0019 (0.01)
67.6	0.4	14.1	4.68	1.7
25.6	0.5	--	11.73	3.9
6.6	0.66	--	--	14.3

100 feet of injection head.

Soil porosity = 0.3.

Source: Raffle and Greenwood, 1961. Reproduced by permission of Editeur Dunod, S. A. copyright 1961.

Bingham yield stress (the minimum shear stress required before a particulate grout will flow).

In this section, factors affecting the flow of grout through an abandoned retort will be considered, including characteristics of an abandoned retort and rheological properties of particulate grouts.

This section will conclude that presently there is inadequate data to answer the critical question of grout distribution in a rubble-filled abandoned in-situ retort--the spacing of grout injection holes to achieve uniform grout penetration. The answer to this question requires very specific information on the porosity and permeability of the spent rubble bed and the viscosity of the spent shale grout.

Porosity and Particle Size Distribution in an Abandoned Retort. Porosity and particle size distribution of a VMIS retort are important because they determine the distribution of sizes of pores through which grout must penetrate. The nature of porosity and particle size distribution of abandoned retorts is different from those encountered in conventional grouting operations. It is therefore important to understand these variables and the effects they may have on grout distribution.

Porosity in soils consists of spaces between more or less closely packed grains, such as shown in Figure 11. Porosity in an abandoned VMIS retort is more varied. It consists of (1) large voids, up to one inch and larger, where flow may be turbulent rather than laminar as usually found in flow through porous media; (2) small voids between small pieces of rubble;

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Figure 11. Cast of pore space in sandstone. Source: Collins, 1978. Reproduced by permission of Petroleum Publishing Co. Copyright 1978.

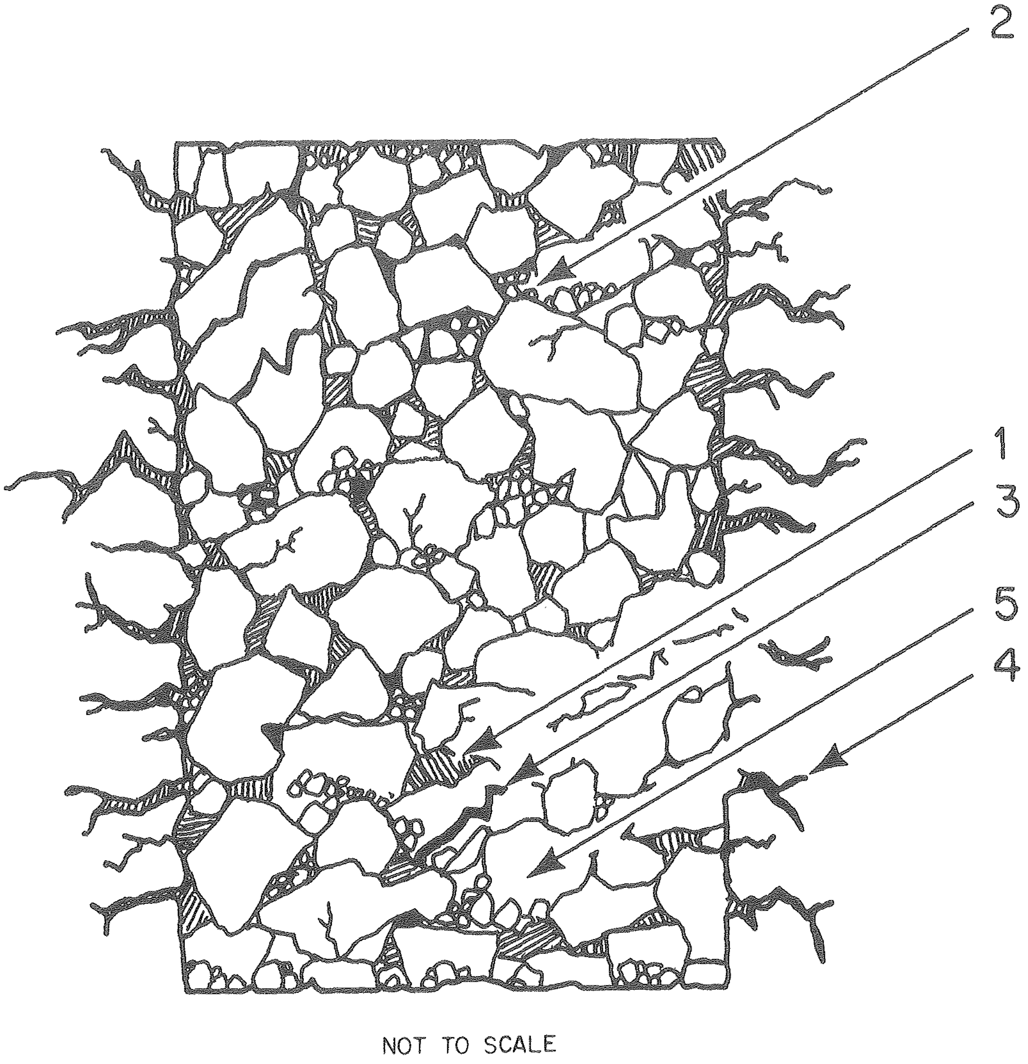
(3) small voids between fragments of rubble that remain in close contact (such as when a block is broken into two pieces but the pieces are wedged together and cannot move apart); (4) cracks and fissures in retort walls; and (5) pores within rubble fragments remaining after pyrolysis of kerogen. These classes are listed in order of decreasing diameter, and are illustrated schematically in Figure 12.

Void ratios used in VMIS retorting will probably be between 20 and 40 percent; this will further increase during retorting due to removal of kerogen from the oil shale matrix. The particle size distribution of VMIS retorted shale is unknown and can only be observed by coring an abandoned retort. However, particle sizes of fractured raw shale have been measured. The so-called Matzick size distribution (Figure 13) was observed for explosively fractured oil shale from the Anvil Points mine (Braun, 1978). However, this is for blasting to a free face and very different distributions may occur when blasting in-situ retorts. In the absence of better information, it is assumed that the Matzick distribution applies to retorted VMIS shale, although shale expands when retorted and some fracturing may be expected due to strength loss in retorting and bed settling. No void-size distributions have been reported.

Permeability of an Abandoned Retort. Permeability of a porous medium depends upon several factors including porosity (volume percent voids), interconnectedness of pores, pore sizes, and specific surface area. Porosity is necessary but not sufficient for permeability, and the two are not proportional. The permeability of an abandoned retort is a critical factor determining the flow of grout through it. No values have been reported for VMIS retorts. In computer modeling of VMIS retorts at Lawrence Livermore Laboratory, the Ergun equation has been used to predict the permeability of a retort. With 20 percent voids and particle sizes taken as the Matzick size distribution (see Figure 13), a permeability of 40 cm/sec was calculated. Pressure drops observed during runs of simulated in-situ retorts tend to corroborate this figure (Carley, 1978). This is similar to a loose packed gravel which would be favorable for grout penetration.

In experimental true in-situ retorts (no mining; permeability is introduced by hydraulic fracturing or other methods), permeabilities observed have been on the order of 5×10^{-5} cm/sec which is inadequate to permit retorting, much less grouting.

Dehydrating Capability of Spent Shale. The tendency of VMIS-retorted spent shale to absorb water will affect the flow of slurry through the shale. This is important because it will increase the water requirement of the grouting operation and may also complicate grout distribution. Nevens et al. (1977) submerged cubes cut from spent shale from the LETC 150-ton simulated in-situ retort and found that the cubes absorbed between 2.5 and 4 gallons of water per cubic foot of shale (except one sample, not well burned). Most of this absorption took place within five minutes. This suggests that the water-to-solids ratio of a spent shale grout would change while being pumped into a retort. This property could be exploited to advantage if a less viscous, more easily-pumped slurry could be dehydrated after placement because dehydration would yield a stronger grout. However, this dehydration capability might make pumping grout more difficult if the dehydration took place before the slurry reached its destination. The dehydration process could be



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1. Large voids between rubble blocks.
2. Small voids between small pieces of rubble.
3. Small voids where a block has broken but pieces cannot move apart.
4. Cracks and fissues in retort walls.
5. Micropores created by pyrolysis of kerogen.

Figure 12. Porosity in an abandoned MIS retort (schematic).

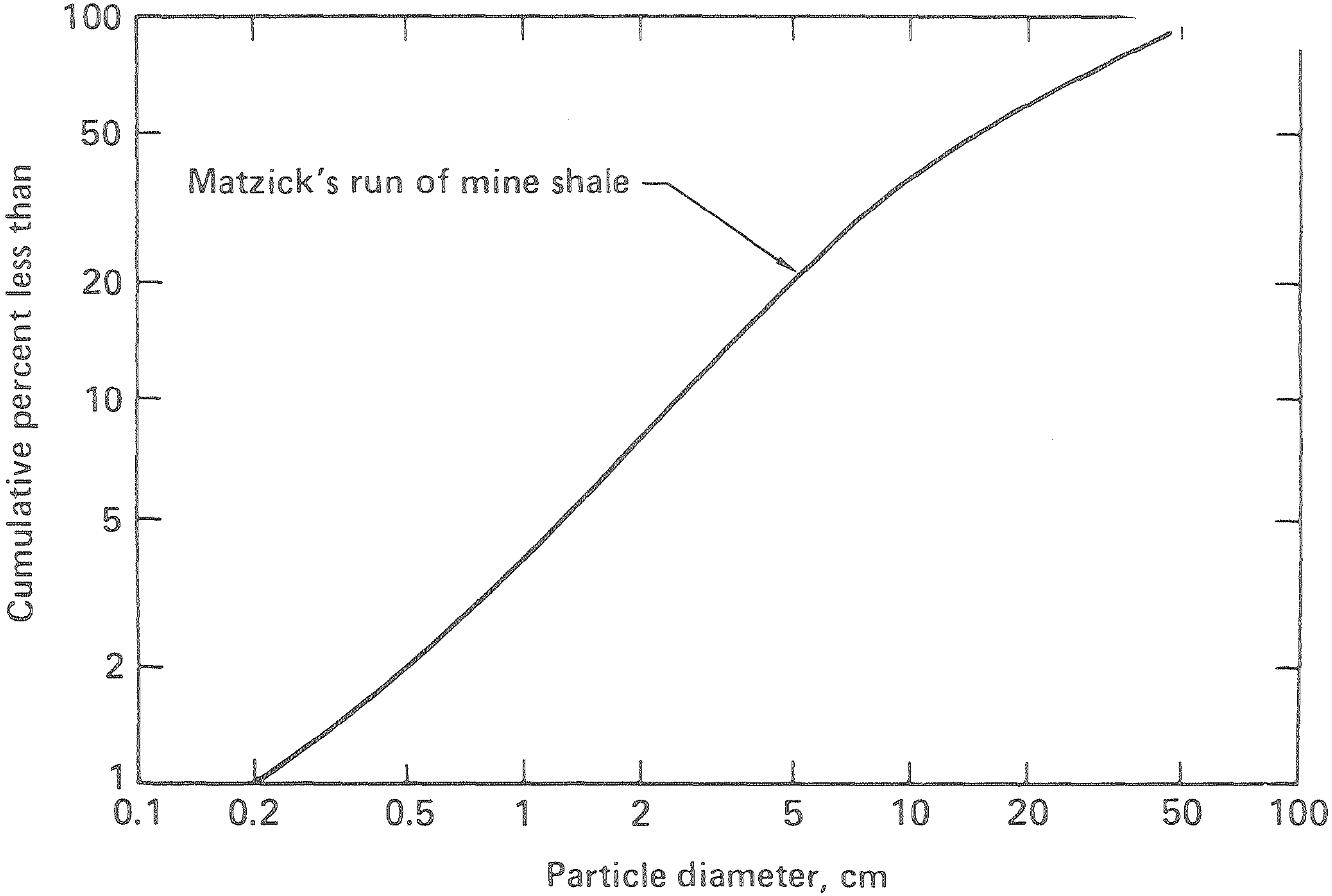

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Figure 13. Particle size distribution of explosively fractured oil shale from Anvil Points Mine. Source: Braun, 1978.

controlled by pre-wetting the spent shale in the retort. If the retort was grouted while still hot, there would be greater and faster dehydration because some water would be removed as steam.

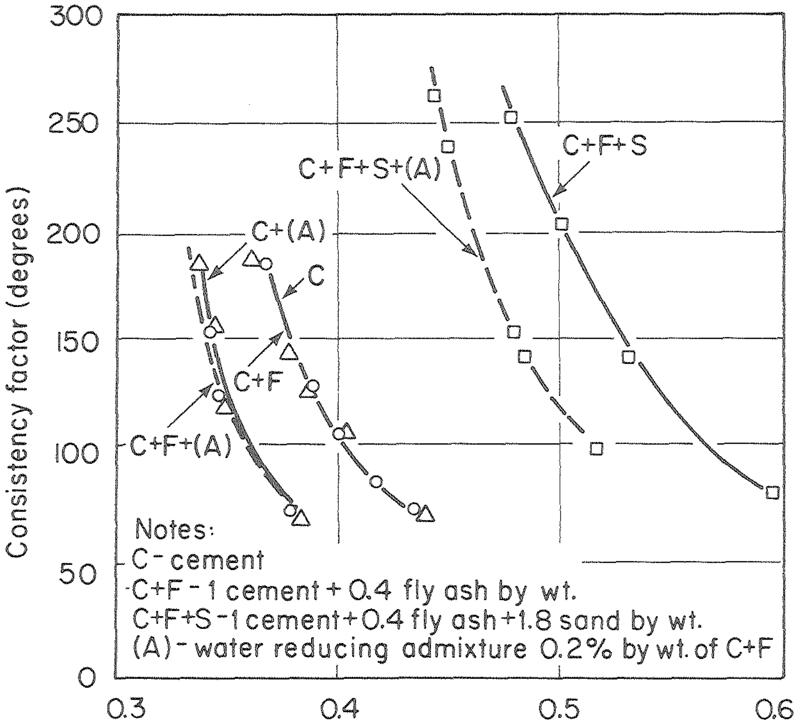
Viscosity of Particulate Grouts. Spent shale grouts, such as those proposed for sealing abandoned retorts, are particulate grouts which consist of a suspension of fine particles and are non-Newtonian fluids. The viscosity of these grouts generally obeys the Bingham or Casson models in which fluid flow does not occur until the shear stress is greater than some minimum value, S, called the yield stress. When the shear stress is less than the yield stress, the fluid acts as a plastic solid, deforming but not flowing.

In this section, the factors controlling the viscosity of a particulate grout will be considered. As very little has been published on the viscosity of spent shale slurries, reference will be made to the literature of cement grouts to show the effects of particle size, water-to-cement ratio, and use of fluidizers.

It is desirable to use as low a viscosity grout as possible to promote complete void penetration and to lower grouting costs by minimizing the number of grout injection holes required. However, low grout viscosities may result in a number of technical problems. These include increased permeability and reduced strength of the in-place grout. There are a number of tradeoffs between grout viscosity, permeability, strength, and other factors that need to be considered in designing a spent shale grout for retort abandonment purposes.

The viscosity of a particulate grout depends in part upon the size of particles in suspension. The particle size distribution of surface-retorted spent shale will depend upon the retorting method used. Retorting by contact with recirculating hot solids, planned for Tract C-a (as in the Lurgi and TOSCO II processes), results in a silt-like particle size distribution, because the shale is subjected to much handling after retorting, when it is friable. Nevens et al. (1977) found that for Lurgi spent shales from several runs, d_{85} was usually about 200 mesh, or 0.074 mm. The Matzick size distribution (Figure 13) was observed for explosively fractured oil shale, and is presumed to represent in-situ retorts in absence of better data; it indicates a d_{15} of 3.5 cm. The groutability ratio $d_{15}(\text{soil})/d_{85}(\text{grout})$ for this combination is 470, which is very much higher than the minimum recommended, and suggests that abandoned retorts can be grouted successfully with spent shale.

For grouts with a constant water-to-solids ratio, the smaller the particle size of grout material, the higher the viscosity (Clark, 1955-56). The viscosity can also be reduced by increasing the water-to-solids ratio. This effect for cement grouts is shown in Figures 14 and 15. However, increasing the water-cement ratio also increases the voids in the cured cement and the permeability of the final product, as shown in Figures 4 and 5. Strength is also reduced by increasing the water-to-cement ratio. A potentially more important problem associated with an increasing water-to-cement ratio is the increased tendency of grouts to segregate or bleed, simply the settling of suspended particles, leaving voids that increase permeability. The effect of increasing water-to-cement ratio upon the bleeding of neat cement grouts (i.e., a mixture of cement and water only) is illustrated by Table 11. Percentage bleeding refers to the volume of supernatant, expressed as a percent



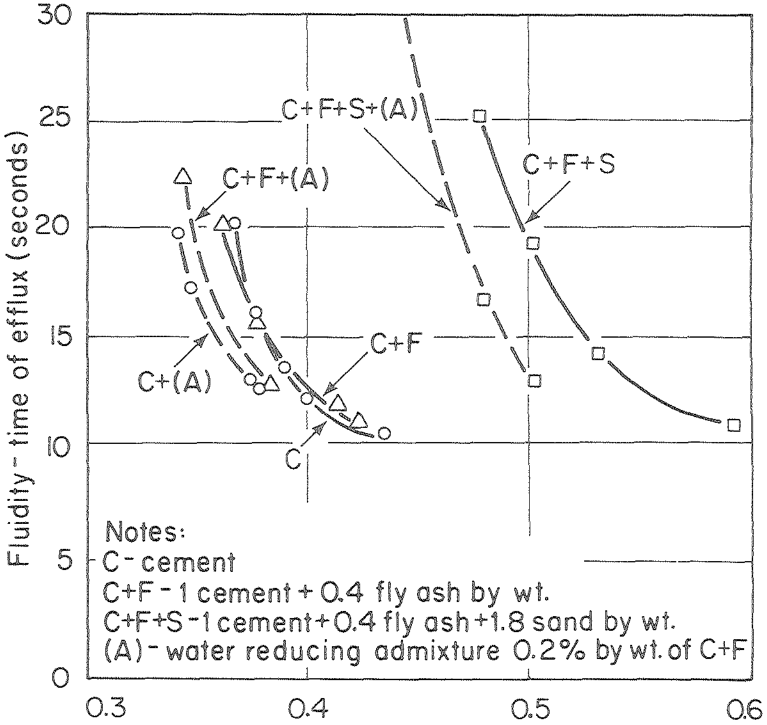


Figure 14. Effect of water-cement ratio and fluidizer addition on consistency of grouts.

Figure 15. Effect of water-cement ratio and fluidizer addition on time of efflux from flow cone.

Source: Klein, 1958. Reproduced by permission of ASCE. Copyright 1958.

Table 11. Bleeding of neat-cement grouts.

Water-cement ratio by weight	(4 hr test) Percentage bleeding	Penetration ratio
0.40	0	0.4
0.55	2	1.0
0.65	10	4.0
0.75	12.5	5.8
0.90	20	9.0
1.00	25	11.5
1.15	30	16.0
1.50	40	30.0
1.85	50	65.0
2.25	60	90.0
2.70	70	160.0
3.12	80	270.0
3.60	90	480.0
(4.0) Extrapolated	(99)	(720.0)

Source: King and Bush, 1961. Reproduced by permission of ASCE. Copyright 1961.

of the original volume. The penetration ratio is the ratio of actual solid that can be injected. For example, four times as much cement solid can be injected at the same pressure using a water-to-cement ratio (WCR) of 0.65 as at a WCR of 0.55. Assuming that a similar relationship holds for spent shale grout, this implies that a high water-to-solids ratio will enable a greater mass of shale to be injected into the formation, but that once in place, water could bleed, causing voids in the grout and possibly preventing it from setting. This may be compensated for by the tendency of the in-situ spent shale to absorb water. Successful grouting of an abandoned VMIS retort with a spent shale grout will therefore require careful attention to the water-to-solids ratio, so that a slurry can be pumped into the retort without more water bleeding from the grout than can be absorbed by the in-situ spent shale.

Fluidizers, also called water reducers, are admixtures which can be added to cement grouts to reduce viscosity without requiring too high a WCR. Some common fluidizers are listed in Table 12. The costs shown indicate that addition of fluidizers may represent a significant cost increase, but if effective at low levels, they may enable a spent shale grout to be economically pumped into a retort. The effect of fluidizers on the viscosity of cement grouts is shown in Figures 14 and 15.

Water-to-Cement Ratios Used in Particulate Grouts. As shown in the above discussion, the water-to-cement ratio is an important factor in determining the flow of particulate grouts and also the properties of cured grouts. Water-to-cement ratios used in cement grouting are reported in Table 13. Grouting jobs are often started with a high water-to-cement ratio, which is then reduced to give the desired pumping pressure. Use of an initially thin mixture lubricates the pores and allows them to accept a more viscous grout than they would without use of the mixture. These figures indicate the range of water-to-solids ratios which may be considered for use in spent shale grouts, considering the fact that the lower the water-solids ratio, the stronger the grout will be.

Table 12. Common cement-slurry fluidizers.

Supplier	Product	Type	Maximum recommended proportion by weight of cement	Cost $/lb
American Admixtures	Melment F-10	melamine formaldehyde	2	1.12
Dow	Dowfax 3B-2 2A-1 XD-8390	alkyl-aryl sulfonates	1	1.20
	Methocel	carboxymethyl cellulose		
Halliburton	CFR-1 CFR-2	naphtalene polymer	0.3 1	-
Diamond Shamrock	Lomar-D	sodium napthalene sulfonate	-	0.65
Crown Zellerbach	Product 503	lignin sulfonate	0.3	0.15

Table 13. Typical water-cement ratios used in cement grouts.

Water-cement ratio	Comment
3-4[a]	Maximum permitted by U. S. Army Engineers specifications
1 or less[a]	Usually used by U. S. Army Engineers
0.89[b]	If greater than this, cement can settle out of slurry
0.44-0.55[b]	Usually used in water-well cementing
0.65[c]	Typical water well grout
0.5-5[d]	Range used in grouting soils
Start at 4 reduced to 1[e]	Aberfeldie Dam, B. C., Canada

[a] Burwell, 1958.

[b] Campbell and Lehr, 1975.

[c] Moehrl, 1964.

[d] Parrag, 1955.

[e] Mitchell, 1970.

The water-to-solids ratio that will be needed for a spent shale grout must be determined experimentally. Nevens et al. (1977) reported values of viscosity of water slurries of Lurgi surface-retorted spent shale. High water-to-solids ratios were needed to get adequate fluidity, and problems with bleeding were encountered. For example, water-to-solids ratios of 1.2 to 2.0 were needed to reduce viscosity to 100 cp. When shale was calcined after retorting, water-to-solids ratios of 5.0-9.0 were needed. Bleeding was also observed at these water-to-solids ratios, and the grout did not set up until the excess water was drained off.

Link et al. (1978) studied the transport of slurries of raw and spent shale. For a slurry of fine spent shale (maximum particle size 13 mm) with a water-to-solids ratio of 1.5, flowing with an average velocity of 2.4 m/sec through a pipeline of inside diameter 880 mm, a head loss of 372 kN/m^2 was calculated for a theoretical 4.8 km long pipeline. This corresponds to a hydraulic gradient of about 8 feet per 1000 feet, and suggests that slurries of this concentration are readily pumpable. No conclusions can be drawn from this work regarding flow of a slurry through rubble.

Experience in Flow of Grout Through Rubble. Grouting experience data which have been presented thus far have been gathered from the literature of grouting in soils, which comprises the great majority of grouting experience. The flow of grout through an abandoned VMIS retort, as pointed out above, is a different problem because of the different nature of the porosity of the medium. The nearest approximations in civil engineering experience are cases where grout has been made to flow through rubble.

In the construction of preplaced aggregate concrete (also called prepacked concrete), coarse aggregate (about 30-35 percent voids) is packed into forms; and mortar is grouted into the mass through slotted pipes, starting from the bottom. Typical size distributions of aggregate for preplaced-aggregate concrete are shown in Table 14; this may approximate the voids of class (1) and (2) of Figure 12. Grout pipes are placed at a spacing of not more than five feet (USDI, 1963). Thus, the grout is not required to penetrate through great distances, as it would be in an abandoned VMIS retort.

Another application of grouting through aggregate is the construction of grouted aggregate bulkheads to seal abandoned coal mines. Figure 16 shows a double bulkhead seal. In this case, the goal of grouting is to stabilize the rubble bulkheads; hydraulic sealing is accomplished later by injecting grout into the space between the bulkheads. This technique is described by Skelly (1973). A single grouted aggregate seal for a coal mine was tested by the Halliburton Co. (Skelly, 1973). In this case, the bulkhead itself was used to seal the drift hydraulically. Figure 17 shows such a seal. Layers of aggregate smaller than 3/8 inch were used to keep the grout inside the rubble bulkhead. Grout leaked through these barriers until flake cellophane was added to the grout.

Experience to date does not provide sufficient information to predict the answer to the critical question of grout flow through a rubble-filled abandoned retort. If it were economically possible to drill closely spaced injection holes, nearly total void penetration could be assured. In the absence of such information, however, experimental work or computer modeling will be needed to determine the distance a spent shale grout may penetrate through an abandoned VMIS retort.

Table 14. Typical gradings of coarse aggregate for preplaced aggregate concrete.

Sieve Size	mm	150	75	38	19	13
	in.	6	3	1-1/2	3/4	1/2
Cumulative Percentage Passing		100	67	40	6	1
		-	100	62	4	1
		-	100	97	9	1

Source: Neville, 1973. Reproduced by permission of Pitman Publishing, Ltd. Copyright 1973.

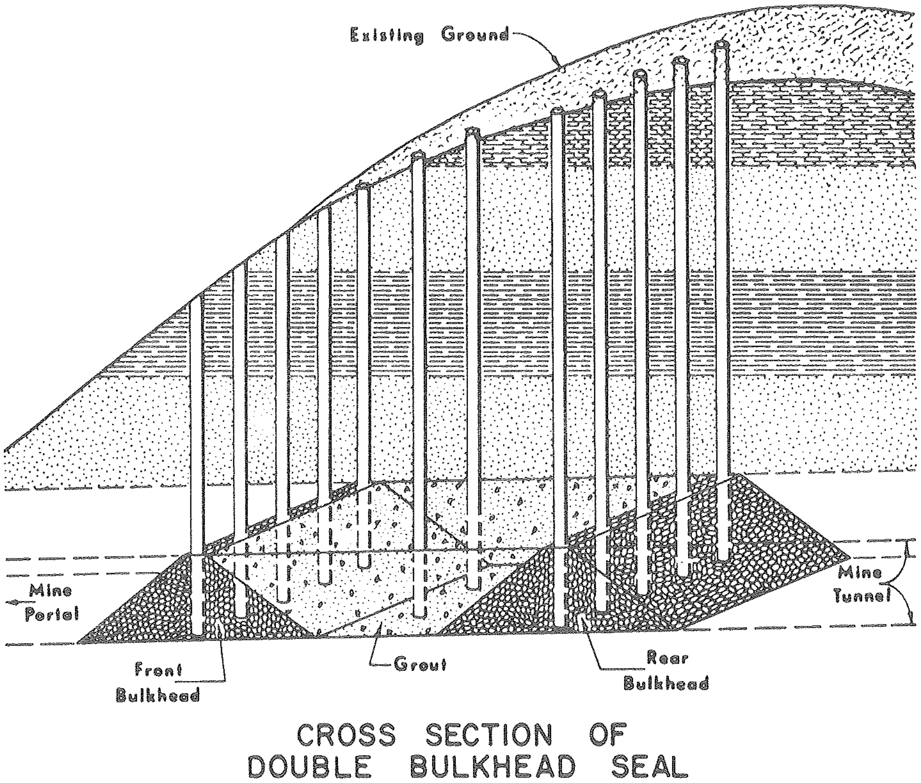


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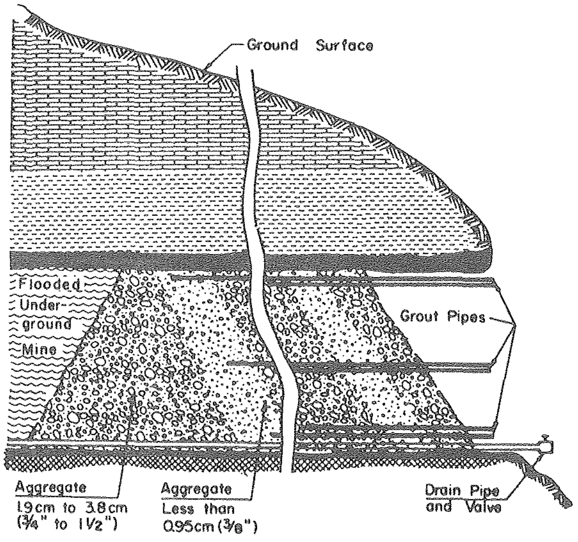
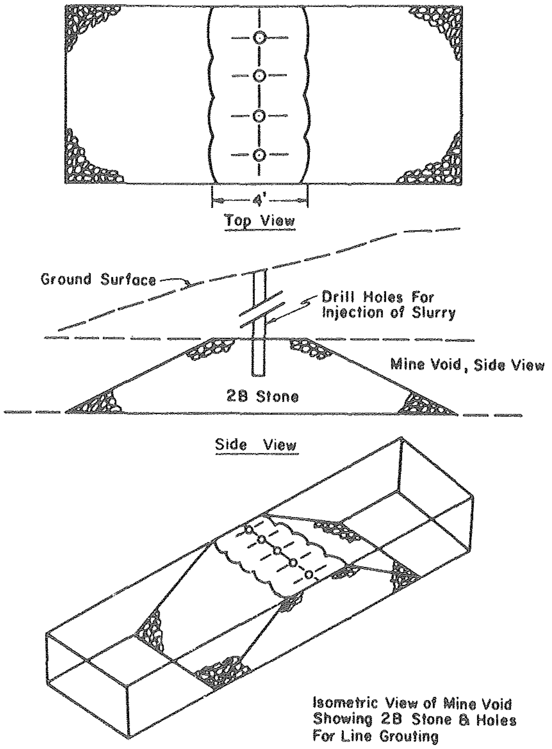
Figure 16. Double bulkhead mine seal. Source: Skelly, 1973.



CROSS SECTION OF
ACCESSIBLE ENTRY SINGLE BULKHEAD SEAL



INACCESSIBLE ENTRY SINGLE BULKHEAD SEAL

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Figure 17. Grouted single bulkhead mine seal. Source: Skelly, 1973.

HYDRAULIC ISOLATION BY IN-SITU PRECIPITATION

In-place formation of precipitates may also be used to seal pores in an abandoned retort, using the principle that gases or solutions can penetrate into fine pores and there react, sealing the pores. Permeability of the aquifers in the Piceance Creek Basin is due, not to original (primary) porosity of the rock, but to subsequent fracturing. This primary porosity has been reduced by precipitation of $CaCO_3$. The management of this natural phenomenon will be considered as a control strategy here.

Precipitation of Calcite

The reaction of CO_2 gas with hydrated lime, $Ca(OH)_2$, has been exploited to stabilize coal mining refuse (La Rosa et al., 1971). The reaction [Equation (15)] proceeds slowly in air, but rapidly in CO_2-rich atmospheres.

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3(s) + H_2O \qquad (15)$$

In a demonstration of the carbonate bonding of coal refuse, La Rosa et al. (1971) mixed -10 mesh coal waste with three percent finely divided dolomitic limestone 2/3 $Ca(OH)_2$ and 1/3 $Mg(OH)_2$ and 12 percent water for compaction. Strengths of over 500 psi were developed after four hours under an atmosphere of 20 percent CO_2. The permeability of test briquettes was found to be similar to that of a sand-cement mortar. Strength is attributed to the development of a continuous calcite crystal structure.

In-place precipitation of $CaCO_3$ has also been used by some irrigation and water districts in California to seal leaking concrete pipes. The technique used is described by Tanji et al. (1978). Basically the method consists of raising the Ca and HCO_3 concentrations in the water to 2.5 meq/l each, and then adding ammonia to raise the pH. Above pH 9, the HCO_3 is converted to CO_3 and the solubility product of $CaCO_3$ is exceeded. The seals appear to be permanent even though the water carried in the pipes is normally undersaturated with $CaCO_3$.

In lime stabilization of clay soils, Diamond and Kinter (1966) postulated that the mechanism of strength development is adsorption of lime on the faces of clay particles, followed by pozzolanic reaction with silica or alumina at the edges of platelets. If silica in spent shale is not entirely consumed by formation of silicates, it may have pozzolanic properties and this reaction may occur in situ. The cohesive hydrates formed would not be subject to solution.

In spent shale adsorption studies, Fox and Jackson (1980) found that calcite may precipitate in packed beds of some spent shale when carbonate-bearing waters are trickled through them. In a series of batch experiments, 50 gm of several spent shales were contacted with 50 ml of various retort waters for 120 hours. The pH of the final water was raised from initial levels of 8 to 9 to final levels of 10 to 11; and 90 to 99 percent of the inorganic carbon was removed from the waters. Fox and Jackson proposed that these results were due to chemical reactions between the carbonate species in the retort water and hydroxides formed from the hydration of CaO and other metal oxides as follows:

$$Ca(OH)_2 + HCO_3^- \rightarrow CaCO_3 + H_2O + OH^- \qquad (16)$$

These results are consistent with work reported by Parker (1978), who noted that calcite was formed when spent shale was leached with carbonate groundwaters. Calcite was identified by x-ray diffraction.

These reactions are analogous to those used by La Rosa et al. (1971) to stabilize coal wastes and by Tanji et al. (1978) to seal leaking concrete pipes. The lime required for the reaction is produced by decomposing carbonates during surface retorting. These results suggest that surface spent shale can be pumped into an abandoned in-situ retort and reacted with CO_2 in the offgas or carbonate-laden groundwaters to precipitate calcite in place.

If precipitates formed by reactions in water are to seal porosity of abandoned retorts, the pores themselves must be no larger than some specified maximum size. An indication of this size is given by experiments in which the clogging of rubble by precipitates formed in situ was demonstrated (Penrose and Holubec, 1973). The purpose of this experiment was to demonstrate the use of self-sealing limestone plugs for coal mines discharging acid mine drainage. Acid mine drainage was neutralized as it flowed through the plugs, and iron hydroxide precipitate was formed. Various limestones and additives were tested in various size distributions. Addition of bentonite or flyash was found to enhance the sealing. The final permeability of test plugs is shown in Table 15. Effective sealing occurred only when the plug contained material finer than 50 mesh. This fine material created a network of fine pores which could be clogged by precipitates. Pores in an abandoned retort are likely to be much larger than these, which indicates that formation of precipitates in situ will not be effective in sealing abandoned retorts unless some fine aggregate is placed in the retort to catch and hold flocs of precipitate.

Limestone and dolomite are locally available. Efforts are presently under way to develop a limestone quarry near Glenwood Springs, about 40 miles from Rio Blanco. If approval is granted for quarrying, it is likely that usable sources will be available in the Piceance Creek Basin itself. While some cost would no doubt be incurred in calcining these sources, the cost of hydrated lime on site should be substantially less than the market price of \$30 per ton. Even at this low price, however, precipitation of calcite is too expensive to fill an entire retort. Cost calculations (page 89) show that precipitation of calcite must be limited to filling about ten percent of the original voids in an abandoned retort if limestone is used, and therefore this sealing technique can be considered only an adjunct to some other control technology.

These experimental results from other fields suggest that the in-situ precipitation of calcite may be feasible, using waste materials and locally available resources. Local groundwaters, which are pumped to the surface during dewatering operations, contain high concentrations of carbonates. Geometric means of HCO_3 and CO_3 concentrations in the upper aquifer on Tract C-a are 482 and 0.88 mg/l, respectively. In the lower aquifer, the

Table 15. Final permeability of limestone plugs (cm/sec) after 50 days of percolation of synthetic mine drainage water at unit hydraulic gradient.

Maximum Particle Size of Graded Limestone				Minimum Particle Size of Graded Limestone
1 in.	1/2 in.	1/2 in	1/8 in	
3.3×10^{-1}	2.0×10^{-1}	NT	NT	50 mesh
2.8×10^{-1}	1.9×10^{-3}	4.3×10^{-4}	4.3×10^{-4}	dust

NT = Not tested.

Adapted from Penrose and Holubec, 1973.

concentrations are 842 and 68.8 mg/l (Gulf, May 1977). Quarryable limestone is locally available. Additionally, both surface and in-situ spent shales may contain calcium oxides. Although most in-situ spent shale will be retorted at temperatures high enough to convert most carbonate minerals into nonreactive silicates (see "Mineralogical Reactions During Retorting," p. 36), these retorts are never completely burned, and a plug of partially retorted spent shale will be present in the bottom of VMIS retorts (20 to 40 feet). This plug, because it is exposed to lower temperatures, may contain hydratable calcium oxides which may be used in calcite precipitation reactions.

Several configurations may be used for in-situ precipitation of calcite. The injection of lime and its reaction with CO_2 may lead to the in-situ formation of calcite to seal the pores in an abandoned retort. If lime is injected into the retort as a solution or slurry, the dehydrating effect of spent shale and the heat of the retort may leave a deposit of hydrated lime. Retort gas, which is rich in CO_2 [30-40 percent from the Lawrence Livermore Laboratory 125-kg experimental retort with air-steam retorting, 15-30 percent from other retorts (Fox, 1980)] could then be reacted with the hydrated lime. Diffusion of CO_2 into the limed retort through vertical slotted pipes may be difficult as precipitation near the pipes would impede the further diffusion of CO_2. Closely spaced pipes may be required, which would be costly.

The lime content of surface and in-situ spent shales may also be used to enhance in-situ precipitation of calcite. If surface spent shale can be produced with an adequate calcium oxide content (this will have to be determined experimentally), it may be possible to pump a slurry of this material into the retort. Carbonate-rich groundwaters would be used as the slurry medium, or they could be allowed to naturally invade the area, precipitating out calcite. This method is favored because it provides the fine aggregate (Penrose and Holubec, 1973) necessary to catch and hold flocs of precipitates, and because it disposes of part of the surface spent shale.

A variation on this proposal would be the use of calcium oxide in the bottom plug of the retort to supply the necessary calcium and pH elevation to precipitate calcite. This plug could be packed with a slurry of surface spent shale to provide precipitation sites and groundwater could be allowed to naturally invade the area.

A potential difficulty with the use of $CaCO_3$ precipitates to seal retorts is the possibility of their being dissolved. Average values of Ca, HCO_3, and CO_3 for upper and lower aquifers reported by Gulf (May 1977) indicate that the aquifers are, on the average, supersaturated with $CaCO_3$ and that there is a tendency to precipitate, rather than dissolve, calcite. However, this does not guarantee that dissolution will not occur. At present, it appears that calcite precipitation may be taking place in both the upper and lower aquifers (Gulf, May 1977). The fate of a precipitate will depend upon kinetics of solution and precipitation and the thermodynamics of supersaturated solutions. It might be possible to place crushed limestone at the product recovery level of retorts to assure that groundwater invading the retorts would be saturated, if flow were upward.

Another difficulty with in-situ precipitation is the method of introducing the reacting medium, i.e., CO_2 gas or carbonate-rich groundwaters. Any effort to inject a gas or liquid that will react to form solids in situ may be limited by the kinetics of the solid-forming reaction. If solids are formed very rapidly, the amount of material that may be injected through any single injection hole will be limited. This may necessitate a large number of injection holes, leading to a higher cost for this control technology. Ideally, no solids would be formed until the desired amount to seal or fill the entire retort has been injected.

HYDROGEOLOGIC MODIFICATION USING A GROUT CURTAIN

When grouting is used to stop water movement rather than to strengthen the soil, it is generally placed as a curtain. In this operation, columns of closely spaced grout are injected to cut off a specified depth of rock or soil (schematically represented in Figure 18). Often two or more rows of injection holes are used. The spacing of injection holes is based upon the distance penetrated by the grout. In the often-used split-spacing technique, holes are first drilled and grouted at some wide spacing. Subsequent series of holes are then drilled between the earlier holes until no more grout can be injected, indicating that penetration is complete.

The proposed use of a grout curtain to prevent leaching of abandoned retorts is illustrated schematically in Figure 19. Retort development plans call for many retorts to be closely spaced in large retort blocks, as shown in Figure 20. If a large area is enclosed by a grout curtain, the ratio of area to perimeter becomes large and the cost per retort of placing a grout curtain around a large number of retorts, say 150, becomes small.

Most of the reported permeabilities in Table 2 were determined for grout curtains. Some cost experiences for grout curtains have been summarized (Bussey, 1963) and are presented here in Table 16. Based upon these examples, the costs for surrounding retort blocks have been projected in a later section, "Cost Projections."

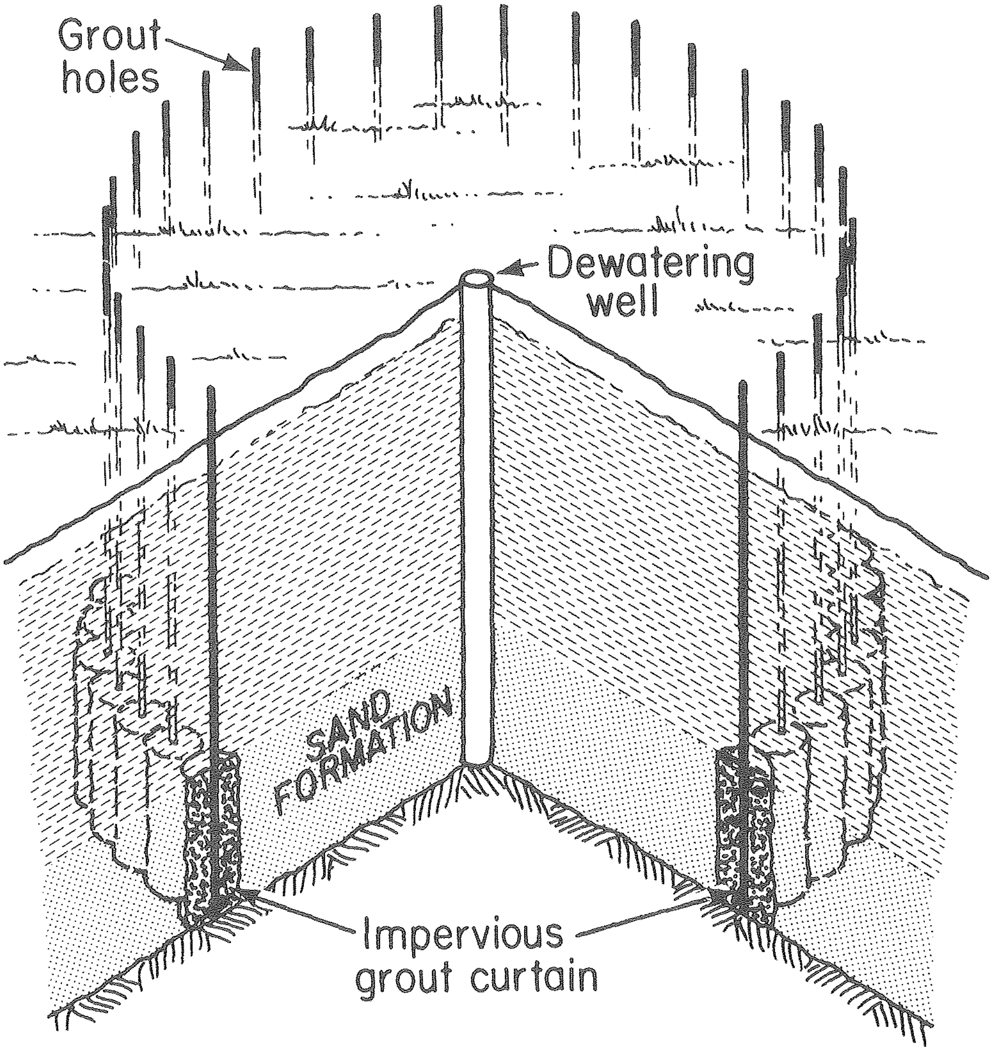

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Figure 18. Grout curtain. Adapted from Halliburton, 1970.

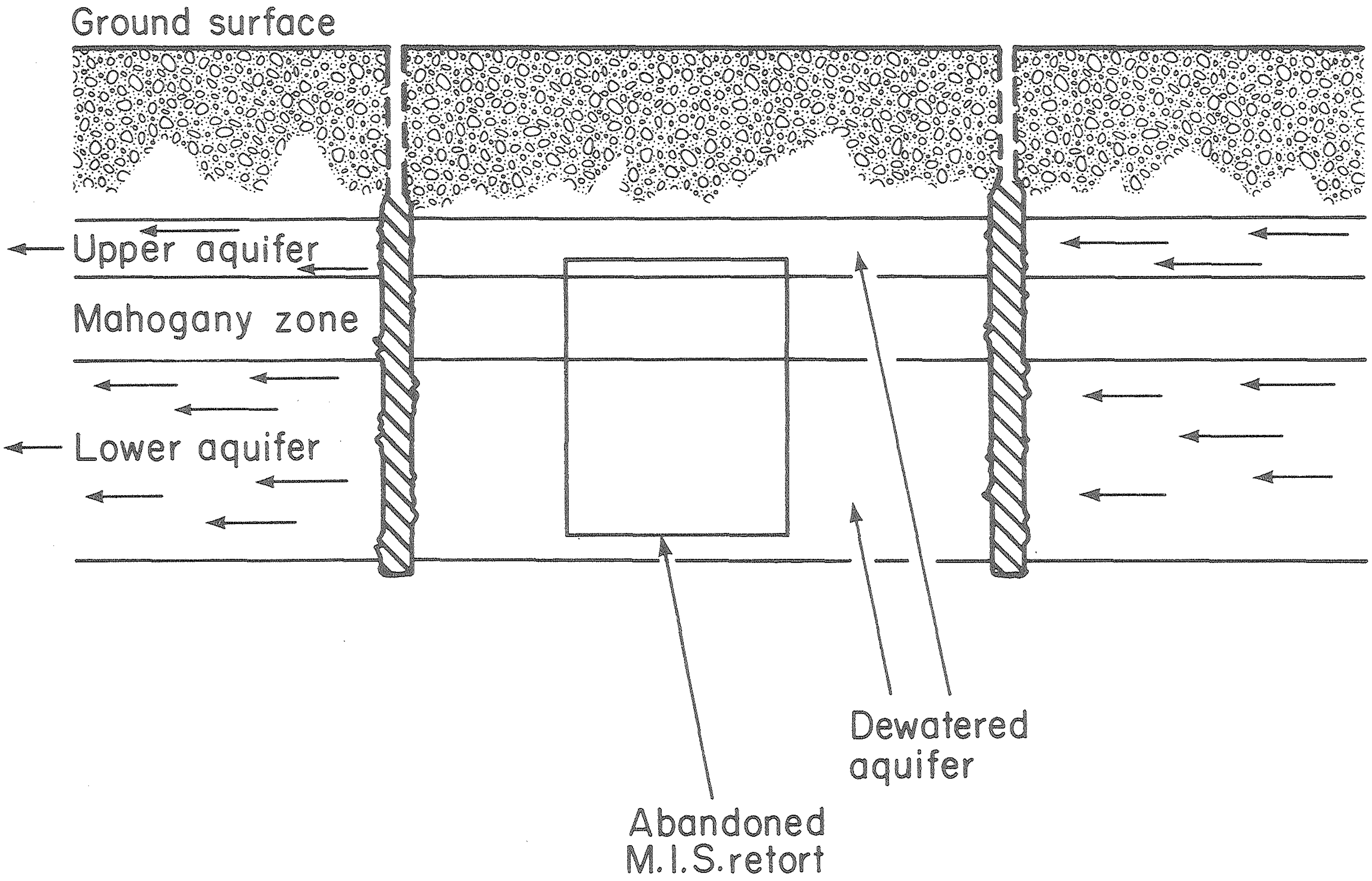

Figure 19. Grout curtain to protect groundwater quality in Piceance Creek Basin.

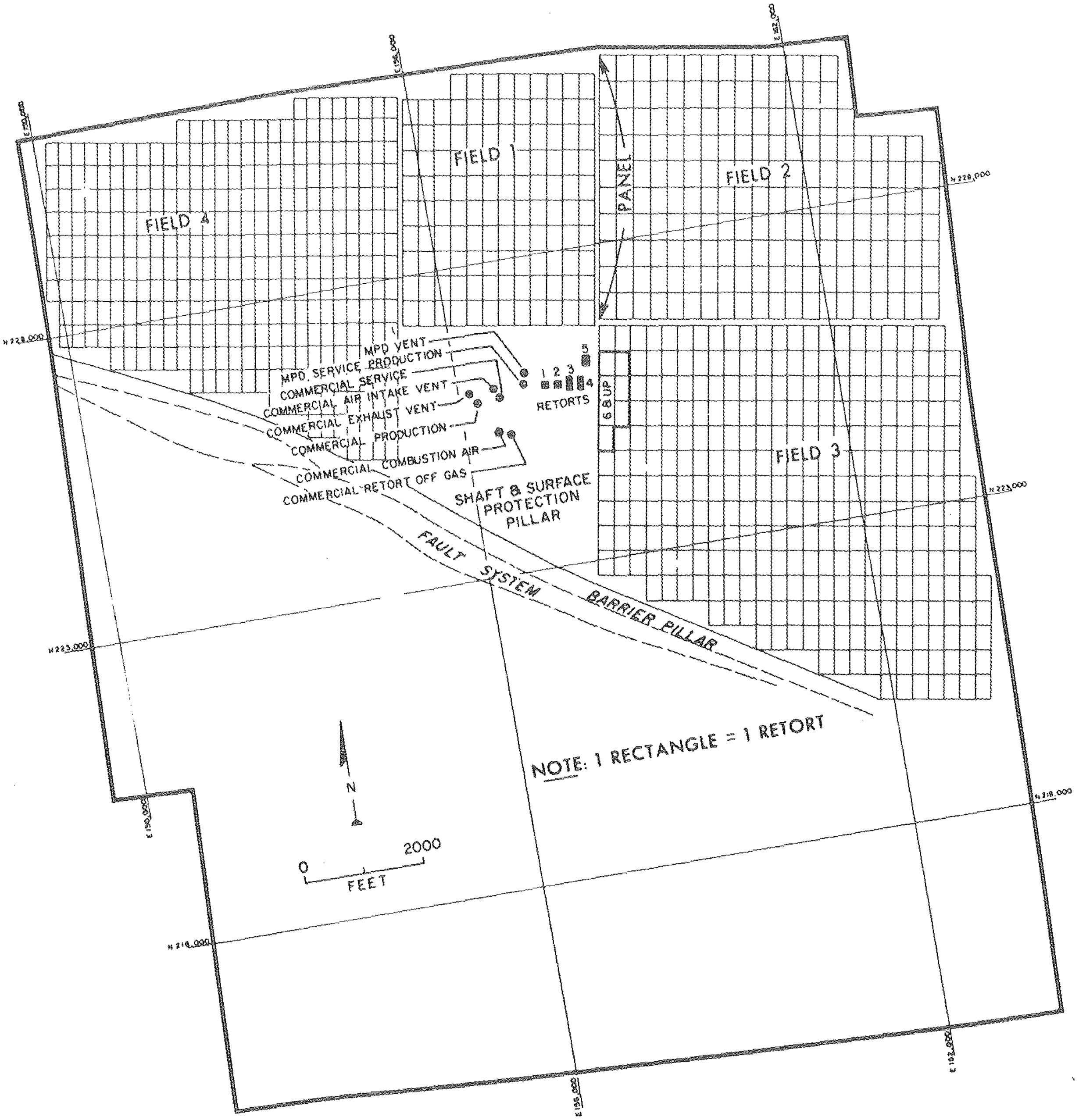

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Figure 20. Closely spaced retorts in blocks, as planned for lease tract C-a. Source: Gulf, May 1977. Reproduced by permission of the Rio Blanco Oil Shale Company.

Table 16. Cost of grout curtains (1963).

	Fellows Lake	Priest Rapids	Karadj	Puente Viejo
Average depth, ft	70	57	131	112
Area, ft^2	64,000	275,000	180,780	368,000
Drilling, lin. ft	--	54,840	82,800	69,500
Material, ft^3	53,030	99,247	672,221	2,569,400
Drilling cost, $	30,761	233,360	672,221	367,050
Mixing and placing, $	--	244,250	127,910	621,950
Materials, $	81,699	222,162	39,730	238,400
Total, $	152,200	599,772	839,861	1,227,400
Rock type	Cavernous linestone	Basalt flow with porous interbeds	Massive diorite	Scoriaceous lava flows
Cost per ft^2, $	2.38	2.18	4.65	3.34
Cost per ft^3 of dry solid, $	2.85	6.40	16.74*	0.48
Type of grout	Cement and rock flour	Neat cement	Neat cement	Silt, sand, and cement

*Adjusted to include direct and indirect costs; bid price of this job covers only direct costs.

Source: Bussey, 1963. Produced by permission of Harza Engineers, Inc. Copyright 1963.

Since the curtain will not be perfectly impermeable, water will eventually reinvade the retort area, although at a much slower rate. The rate of leachate transport through a grout curtain should be estimated using a computer model of the basin. This rate of flow may be much less than with no control technology, and the resulting transport of leachate into aquifers and surface waters may be small enough not to constitute serious degradation of the resource. The effect of a grout curtain on the piezometry of the aquifers and on stream flows should also be checked using a computer model to determine if existing water rights will be satisfied when equilibrium is eventually re-established.

Recent experience at Tract C-a has shown that dewatering flows were greater than anticipated. Construction of a grout curtain before retorting would reduce the expense of dewatering, but would necessitate a large investment prior to realization of any return.

A problem in forming a grout curtain will be the low permeability of the aquifers, compared to the kinds of soil that are usually grouted. Local aquifers are fractured and have a permeability of only 26 to 60 millidarcy on Tract C-b (Occidental, Feb. 1977). As already stated, it is easier to grout a more permeable soil. The relative costs of grouting soils of various permeabilities are presented in Table 17. In the case of a grout curtain around a block of retorts, fractured rock, rather than soil, is being grouted. It is likely that costs will be higher than for grouting porous media. The depth of this proposed grout curtain is much greater than ordinarily encountered, and this may create difficulties. Field experience is required to adequately assess the feasibility of this project.

Any seismic activity or subsidence that occurs in the region could damage a grout curtain. However, if damage is confined to a limited area, it could be repaired at reasonable cost. Slow groundwater velocities should limit the escape of pollutants to an acceptable level while the damage is being repaired.

Table 17. Increase in cost associated with grouting soils of lesser permeability.

Permeability before grouting, cm/sec	Relative cost
1×10^{-3}	1
3×10^{-4}	1.25
1×10^{-4}	2.2
3×10^{-5}	3.6

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HYDROGEOLOGIC MODIFICATION USING A HYDRAULIC BYPASS

The greatest potential for groundwater degradation exists when abandoned retorts connect two aquifers which are at different pressures. This head differential will cause flow between the two aquifers through the abandoned retort, transporting leachate into the aquifer at lower pressure. One way to minimize leaching flow through retorts would be to design retorts or retort blocks so that groundwater would flow through parallel flow paths of greater permeability instead of through the abandoned retorts. Such a hydraulic bypass or shunt could be constructed or installed at the time of retort construction, probably at low cost. One example of a hydraulic bypass would be a palisade or curtain of wells or drill holes, as shown in Figure 21. Because vertical permeability of the aquifers is much less than horizontal permeability, they should extend through the entire height of both aquifers.

Since some flow would still pass through the retort, the value of this control technology must be based upon the dilution obtained by mixing the flow through the retort with the bypass flow. If, for example, a 10:1 dilution is desired, the geometries and permeabilities of the retort and the bypass must be such that nine times as much flow goes through the bypass as through the retort. Given the large cross-sectional area of the retort and its high permeability, probably about 40 cm/sec, some degree of sealing would probably be necessary, although not to the extent needed to render the retort impermeable. A hydraulic bypass would minimize vertical, but not horizontal flow through retorts. Thus a grout curtain or some other means of deterring horizontal flow may be required, depending on retort-aquifer geometry. The potential benefits of this control technology could be quantified by computer modeling of the groundwater system. As with a grout curtain, cost-effectiveness is predicated upon a large number of retorts being surrounded by a relatively small amount of control works.

HYDROGEOLOGIC ISOLATION USING A CAP ROCK

In the Piceance Creek Basin, oil shale is located beneath the water table. The rich Mahogany Zone lies between two confined aquifers, and any retorts that intersect either aquifer will be flooded on abandonment. However, because the Mahogany Zone itself has very low permeability, a retort constructed entirely in this zone, or protected above and/or below by a cap rock of undisturbed oil shale material, may also be flooded by groundwater; but the rate of flow through the retort would be low.

There are two reasons why this would be a difficult technology to apply. First, the retort would have to be completely isolated from the aquifers; no fractures could be present in the cap rock either before or after retorting. If the cap rock were to collapse during retorting, some remedial technology must be available. Good hydrologic data, probably involving extensive testing, would be needed to guarantee the integrity of the cap rock. Even more discouraging is the limit that such a control technology would place on resource recovery and the adverse economical impact. VMIS retorts must be at least 200 feet high to be economical (Fennix and Scisson, 1976). Confining retorts to the interior of the Mahogany Zone, or some other zone, would leave much rich shale unrecovered and could increase the unit cost of recovery.

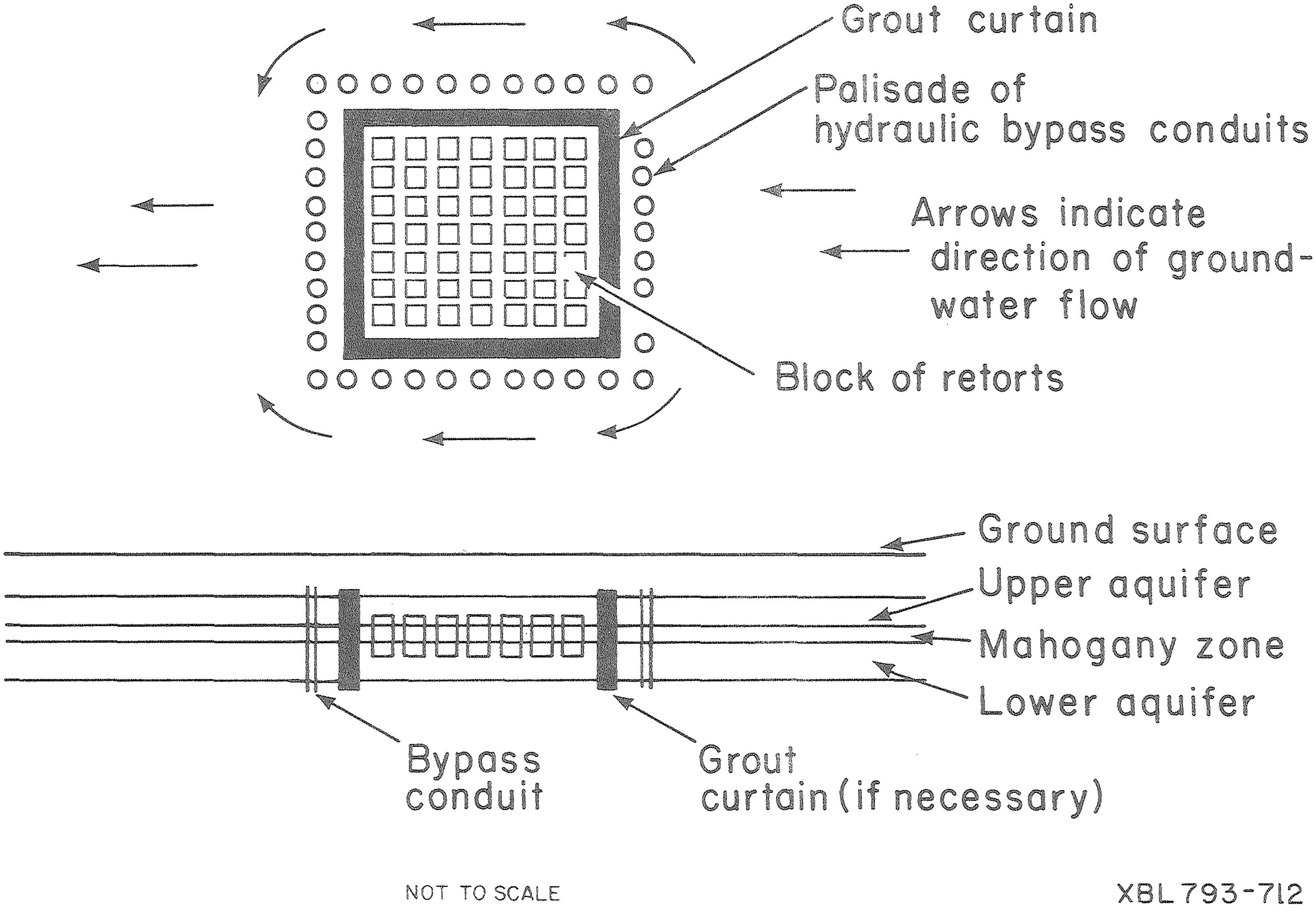

Figure 21. Hydraulic bypass around block of retorts.

RECOVERY AND TREATMENT OF LEACHATE

The objective of any control strategy is to prevent leached material from entering aquifers. Hydraulic isolation control strategies focus on accomplishing this by preventing groundwater from contacting and leaching spent shale. Another method would be to leach abandoned retorts, recover the leachate by pumping it to the surface, and then treat it to remove leached material. The treated leachate would be suitable for on-site use or could be injected into an aquifer. An attractive feature of this control strategy, as compared to hydraulic isolation, is the actual disposal of leachable material instead of keeping it in place. Another advantage is that it uses existing technology.

Recovery and treatment of leachate could be accomplished in various ways. One would be to allow groundwater to reinvade abandoned retorts. However, since it may take from decades to centuries for groundwater to reinvade the retort area (Fox, 1979), there is no guarantee that the operator would be present to collect and treat the leachate. Another means of recovering leachate is to deliberately inject water into retorts, pumping the same water to the surface, and treating it. Water could be treated and reused for several cycles of this process. This has the advantage that there would be no need to wait for groundwater to reinvade the retorts, and control measures could be implemented on a "pay-as-you-go" basis.

Whichever method is used to recover leachate, the volumes to be treated would be large. Estimates of dewatering flows are presented in Table 18. These indicate that at least 3.8 MGD of leachate would have to be recovered and treated. On the other hand, if water is injected into retorts and then recovered, 10 to 14 MGD of leachate would have to be formed and collected per day in order to keep pace with a 50,000 barrel-per-day industry (page 97). Treatment of these flows would not necessarily be a problem, but if the treatment process selected produces a significant waste stream (as brine or sludge), say 10 percent of the treated flow, the land requirements for evaporation ponds could become excessive. Recovery of waste heat for evaporation could reduce these land requirements.

Composition of Leachate

The composition of in-situ leachate must be known to select treatment methods. Leachate contains high concentrations of both inorganic and organic constituents. The composition of leachate depends on shale source, retort operating conditions (temperature and atmosphere), and composition of leach water. Table 19 summarizes the range of concentrations expected for several constituents in leachate from the vicinity of lease tracts C-a and C-b.

The economics of recovering and treating leachate are strongly dependent upon the assumption that all the leachable matter will be contained within a limited volume of leachate. Laboratory studies have shown that, as leaching

Table 18. Estimates of dewatering flows.

Flow Rate, MGD	At end of	Tract
5.8-14.4[a]	8-60 yr	C-b
3.8[b]	3 yr	C-b
7.6[b]	10 yr	C-a
43[c]	30 yr	C-a
128[c]	30 yr	C-b
13.0[d]	30 yr	C-a
14.4[d]	30 yr	C-b

[a] Tipton and Kalmbach, 1977.

[b] Banks, 1978.

[c] Open pit mines. Weeks et al., 1974.

[d] MIS, no subsidence, 100,000 bbl/day. Brown et al., 1977.

flow passes through spent shale, the concentration of both organic and inorganic compounds declines rapidly, and that essentially all the leachable material is contained within the first few pore volumes that pass through the retort. For example, Hall et al (1978) found that, after six pore volumes of water had passed through a bench-scale leaching column, the level of organic carbon in the leachate was not significantly higher than the background level present in the influent (see Figure 22), with the majority of the organic carbon contained in the first two pore volumes. Similar results have been found for inorganic species, as shown in Figure 23 (CSU, 1971).

These results are encouraging, for they indicate that only a limited amount of leachate need be treated for this to be an effective control strategy. However, it is important to note that laboratory studies have used

Table 19. Estimated composition of leachate from an in-situ retort located on lease tracts C-a and C-b.

Constituent	Leachate Composition, mg/l	
	Tract[a] C-a	Tract[b] C-b
Al	0.49 - 31	0.89 - 53
B	0.33 - 1.9	36 - 39
Ca	35 - 2350[c]	14 - 3950[c]
Cl	32 - 73	1234 - 1300
CO_3	110 - 2400	408 - 4250
Cr	0.02 - 20	0.01 - 34
F	4.8 - 47	29 - 100
Fe	5.0 - 5.5	0.8 - 1.6
HCO_3	560 - 920	4140 - 4750
K	2.5 - 200	21 - 360
Li	0.20 - 4.8	10 - 18
Mg	52 - 140[c]	11 - 160[c]
Na	212 - 2800	2500 - 6900
NO_3	1.7 - 30	1.7 - 49
Pb	0.22 - 0.36	0.12 - 0.35
Si	100 - 980	170 - 1660
SO_4	326 - 1800	65 - 2500
Zn	0.26 - 0.54	0.2 - 0.7
TDS	905 - 31,700	6190 - 58,700
TOC	12 - 430	16 - 720
Phenols	0.04 - 0.44	0.06 - 0.8

[a] Assumes the retort is leached with upper aquifer water, that the mass of spent shale in the retort is 1.1×10^9 kg, and that the volume of water contained by the retort is 5.0×10^8 liters.

[b] Assumes the retort is leached with lower aquifer water, that the mass of spent shale in the retort is 7.5×10^8 kg, and that the volume of water contained by the retort is 2.0×10^8 liters.

[c] These constituents may be reduced on passage through the groundwater aquifer.

Source: Fox, 1979.

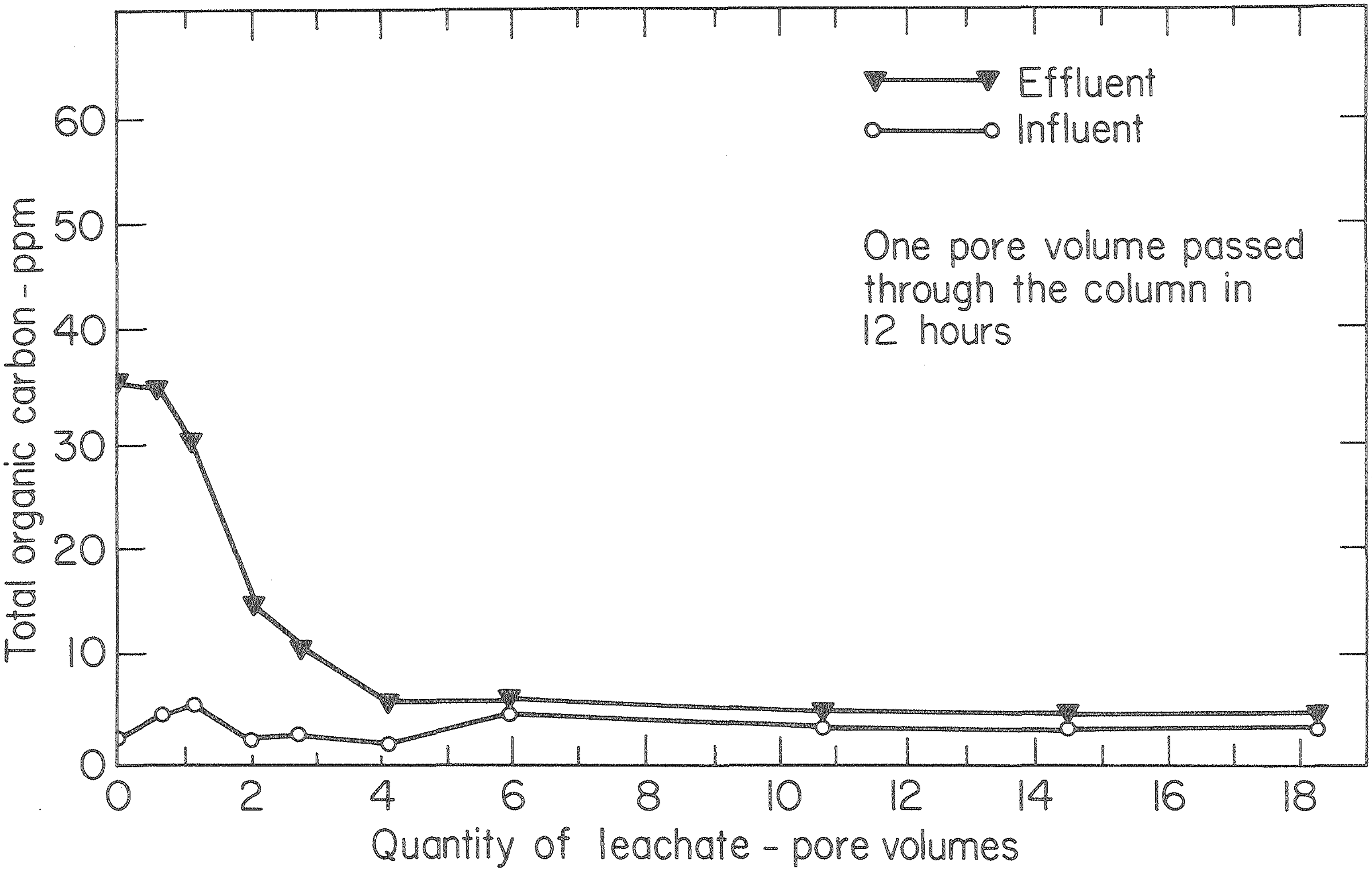

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Figure 22. The effect of increasing pore volumes on organic carbon concentration of leachate from spent shale from the LETC 10-ton retort. Source: Hall et al., 1978.

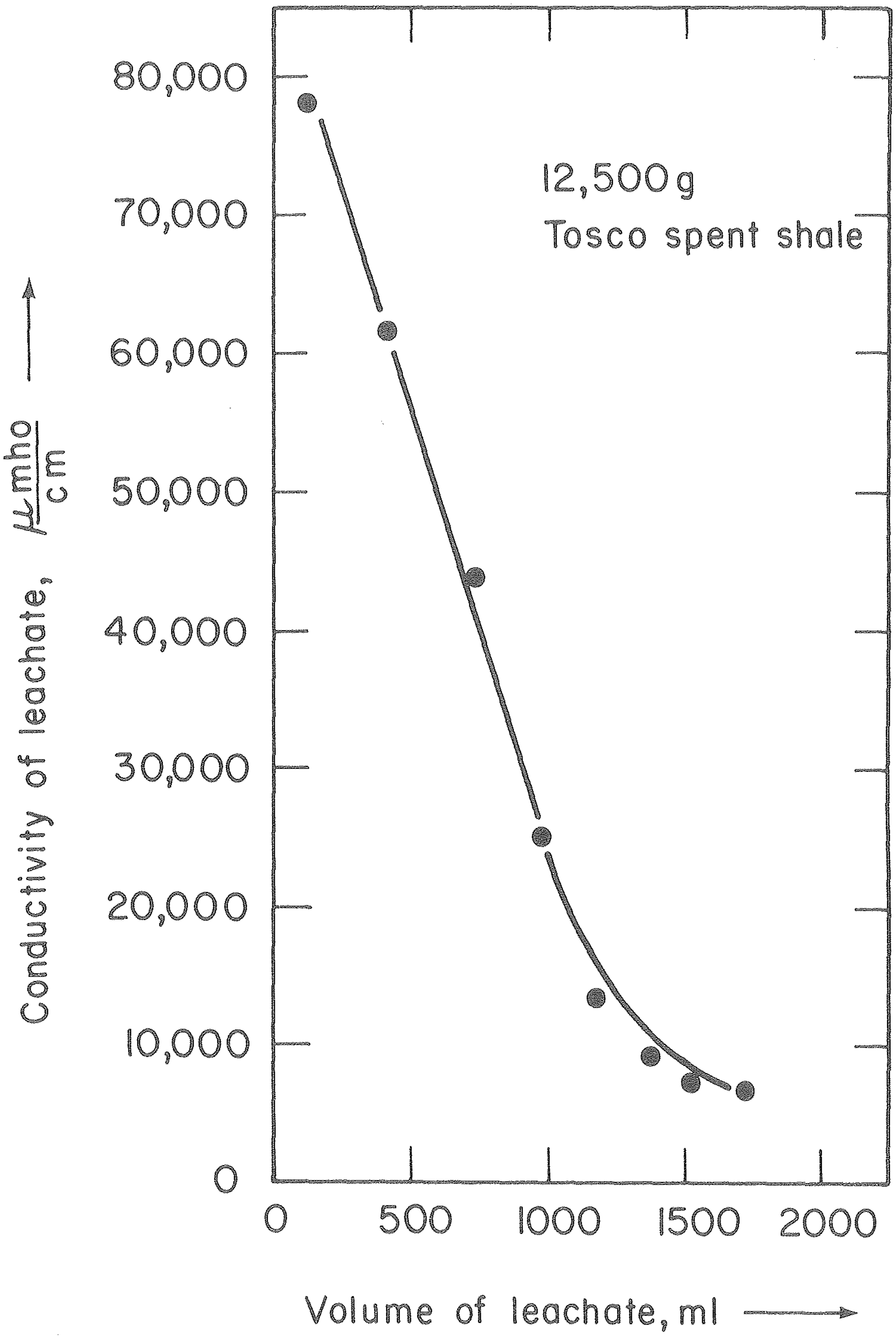

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Figure 23. The effect of increasing leaching volume on electrical conductivity of leachate from TOSCO spent shale. Adapted from CSU, 1971.

only small spent shale particle sizes. Since spent shale contains a network of fine internal pores left by pyrolysis of kerogen, it is possible that the majority of the surface of the spent shale and a majority of the leachable matter lie within internal pores. Leaching requires three consecutive steps: desorption of the species into the water phase, diffusive transport through the internal pore network to the outer surface of the spent shale, and transport by film diffusion into the bulk liquid. The slowest of these steps will be rate-limiting. In the case of large particles, pore diffusion through the long distance to the outer surface of the particle may be the limiting step. Internal pore diffusion did appear to be rate-limiting in leaching combustion-retorted shale in work by Amy (1978). The temperature of the leaching water may also affect the leaching rate. If pore diffusion is indeed limiting with the large particles of spent shale expected in field conditions (see Figure 13), the effect illustrated in Figures 22 and 23 will be less pronounced, and a larger volume of leachate will require treatment. Although unlikely, it is also conceivable, that, with large particles, leachate may be produced so slowly that no treatment will be necessary. It will be necessary to establish an acceptable leachate concentration, based upon water quality standards and expected dilution, to be transported into the aquifers. Another caveat that must accompany laboratory leaching studies is that spent shale from laboratory retorts may or may not be representative of spent shale from in-situ retorts.

Methods of Treating Leachate

The goals of leachate treatment depend upon the proposed re-use or disposal of the water. Some water uses, such as boiler feed, require high quality, low TDS water; others uses, such as moistening spent shale disposal piles, can accept water of lesser quality. If high quality water is available from other sources, there is little incentive to treat leachate to a standard higher than that required for disposal. This will probably be the case for VMIS retorting since excess mine water may be produced during dewatering which cannot be used in the process (Nevens et al., 1979). Recovered leachate would be a poorer quality water than mine water, and therefore would not be used until the mine water had been exhausted. Treatment processes will be considered to upgrade leachate for disposal.

Recovered leachate can be disposed of in three ways: it can be treated for discharge into a local stream or for reinjection into a local aquifer or it can be evaporated. Evaporation is considered unlikely because of the large volumes of leachate and the attendant large land areas required. The tradeoffs between reinjection and stream discharge must be evaluated on a case-by-case basis. Selection of a final method will depend on the quality of the receiving waters, the characterization of the recovered leachate, and the governing water-quality standards. Groundwater reinjection will be regulated by individual state standards and the Federal Safe Drinking Water Act of 1974. The specific application of the proposed reinjection regulations to in-situ oil shale is presently uncertain. In the worst case, if surrounding aquifers are declared to be drinking water aquifers (any aquifer with a TDS of less than 10,000 mg/l may be a drinking water aquifer), reinjected leachate would have to be treated to meet drinking water standards.

On the other hand, if leachate is treated for discharge into local streams, state (Colorado, Utah, and Wyoming) or federal water quality standards will apply. Both Colorado and Utah have nondegradation policies which apply to both surface and ground waters and require the maintenance of existing quality unless it can be demonstrated that a change is justified. This policy may result in more severe limitations than the Federal Safe Drinking Water Act.

A comparison of the leachate quality summarized in Table 19 with applicable standards in the oil shale region indicate that, as a minimum, total dissolved solids (TDS), total organic carbon (TOC), phenol, fluoride, boron, and certain toxic or carcinogenic organics will have to be removed from recovered leachate. This may require an advanced wastewater treatment step such as reverse osmosis (RO), electrodialysis (ED), or ion exchange (IX). These processes would require pretreatment which would likely include flow equalization, sedimentation, pH adjustment, and carbon adsorption. Costs of treatment by electrodialysis or ion exchange increase proportionately with the TDS of the influent, and these processes are not generally economic if TDS exceeds 1000 mg/l (Linsley and Franzini, 1972). As shown in Table 19, TDS of leachate is likely to be much higher. Because electrodialysis is also much more sensitive to dissolved organics than reverse osmosis (Belfort, 1977), attention will be directed toward reverse osmosis to dimineralize leachate, with a pre-treatment step of activated carbon adsorption.

In reverse osmosis (RO), product water passes through a semipermeable membrane under applied pressure greater than direct osmotic pressure, leaving a concentrated brine. Depending upon the turbidity of the influent, preliminary filtration may be needed to prevent fouling of the membranes. Dissolved organics are also removed by RO. Pilot studies of RO treatment of municipal wastewaters and industrial effluents found that TDS removals averaged 93 percent, and TOC removals averaged 92 percent (Culp et al., 1978). Preliminary removal of organics by activated carbon adsorption decreases the rate of fouling of membranes. Phenol was also present in RO product water in significant quantities (Culp et al., 1978). Since leachate contains a significant amount of phenol, which is readily removed by adsorption on activated carbon, a preliminary step of activated carbon adsorption may be necessary. Because RO membranes are damaged by exposure to high pH (Culp et al., 1978), pH adjustment may also be required. Besselievre and Schwartz (1976) recommend that RO influent have TDS between two and five percent, pH between four and eight, and manganese and iron less than 0.3 mg/l. Consequently, removal of iron and manganese may also be necessary.

An important problem associated with the use of RO is the disposal of the brine waste stream. Pollutants are not destroyed, but are concentrated in a brine that must be eliminated. The fraction of influent flow that appears in the product stream is usually about 75 percent. This fraction can be increased by increasing the pressure applied to the RO unit. However, with higher pressures, operating problems increase, and it does not appear that more than 90 percent of the water can be recovered. This requires disposal of a concentrated brine stream containing at least ten percent of the treated leachate flow. As indicated earlier, this could amount to 1 to 1.4 MGD, or 365 to 511 million gallons per year. Since net evaporation in the Piceance Creek Basin is about four feet per year, or one million gallons per acre-year, this would require at least 292 acres of lined evaporation ponds (as developed in Table 30), plus winter storage. Thus, the disposal of brine from RO could be a serious problem. Possibly heat from abandoned retorts or low Btu offgas might be used to minimize evaporation pond requirements. Similar considerations apply to electrodialysis.

IN-SITU LEACHATE TREATMENT BY ADSORPTION AND ION EXCHANGE

Collecting and treating leachate on the surface involves costs for pumping and re-injecting and is sensitive to the kinetics of leaching and the rate of re-invasion of retorts by groundwater. These would not be problems if treatment were accomplished in-situ by adsorption and ion exchange. In principle, an adsorbent could be placed in a retort to remove organics from leachate and mixed ion-exchange resins used to remove dissolved cations and anions. The amount of these materials needed would depend on the amount of organics and inorganics to be removed from solution, and the capacity of these materials to remove pollutants. The data presented in Figure 22 and Table 19 suggest that over 100 equivalents of anions and cations and 30 mg/l TOC would have to be removed for two pore volumes of leaching per barrel of oil recovered. While the TOC could probably be economically controlled using an adsorbent resin, the cost of ion exchange resin to remove this large quantity of TDS would be prohibitive. Therefore, this strategy would not provide adequate salinity control. The pertinent costs are developed on page 99.

MODIFY RETORT OPERATING CONDITIONS

Several studies have shown that leachability of organics and inorganics from spent shale depends upon retorting conditions. Amy (1978) found that more organic carbon was leached from spent shales retorted in externally heated inert gas runs than from spent shales retorted in combustion runs and that recycle gas in combustion runs contributed strongly to leachable organic carbon. Parker (1978) reported that shale retorted at 1000°C or 430°C contained less soluble minerals than shale retorted at 780°C. Low solubility at low temperatures is due to mineral phases remaining largely unchanged in the spent shale. Campbell (1978) found that the major elements in oil shale are largely converted at high temperatures to silicates (e.g., diopside, gehlenite, akermanite), which are relatively insoluble. Kuo et al. (1979) found that this conversion to silicates took over 200 hours to reach equilibrium for shale retorted at 760°C in a nitrogen atmosphere containing one percent oxygen. Burnham et al. (1978) found that 10 percent or more steam in the retorting atmosphere catalyzes the conversion to silicates and that retorting in an atmosphere of 100 percent CO_2 delayed formation of silicates.

From the above reported results, several retort operating conditions can be listed which would minimize the leachability of organics and inorganics from spent shale:

- Combustion-retorting to burn off as much char as possible.
- Use of a sweep gas to remove CO_2.
- High operating temperature, about 1000°C.
- Steam retorting.
- Slow retorting rate, i.e., long residence time at high temperature.

These conditions approximately coincide with those presently proposed for use by the developers of lease tracts C-a and C-b. Combustion retorting in the presence of steam at slow retorting rates, about one foot per day, are proposed by the C-b operators, while similar conditions at higher rates, about 10 feet per day, are proposed by the C-a operators. Combustion retorting in the presence of steam is known to enhance oil and net energy recovery from the VMIS process. Char is burned to produce process heat; and, because oil shale is a poor heat conductor, high temperatures can be attained in an in-situ retort. Steam can be generated to moderate the temperature within the retort and to improve the Btu content of the offgas by the char-steam reaction. However, the issue of fast versus slow retorting rates has not been resolved and is presently a controversy among oil shale process developers. Low retorting rates, however, favor the formation of a sparingly soluble spent shale, and this factor should be considered in the final analysis of slow versus fast retorting.

For spent shale to be as nonleachable as possible, all the shale in a retort must meet the conditions listed above. Channeling, resulting in bypassing some parts of the retort, and uneven temperature distribution could leave zones of highly leachable shale. It will be difficult to achieve uniform formation of silicates in field retorts. Improved rubblization and retort operating techniques will be required, compared to those presently available.

REVERSE WETTABILITY OF SPENT SHALE

Immediately following retorting, the voids of an abandoned retort will be entirely occupied by air and retort gases. For leaching to occur, the spent shale must be wetted by groundwater. Spent shale is wettable, that is, water will tend to displace gases from the surface. If the shale were rendered non- wettable, leaching could not occur. The possibility of rendering spent shale non-wettable by applying a water-repellent coating will be considered in this section.

Fink and Meyers (1968) reported laboratory and field experiments in which various water-repellent coatings such as waxes and silicones were applied to soils. The silicones appeared to reduce wetting substantially at only monolayer coverage (2×10^{-5} g/m^2). These treatments were found not to be permanent; it was suspected that hydrolysis of the silicones occurred. All organic coatings, furthermore, may be susceptible to microbial degradation. The high cost of these materials ($4 per pound or more for silicones, $0.20 per pound for waxes), puts them out of consideration for this application. Also, introduction of a coating into an abandoned retort to provide efficient monolayer coverage may be technically complex.

SELF-TREATMENT IN AQUIFER MEDIA

As a general rule, all natural waters have some capacity for self-purification. Mechanisms of self-treatment in Piceance Creek Basin aquifers might include precipitation, natural decomposition of complex organic molecules, microbial degradation, and adsorption and ion exchange on aquifer media. Since it is anticipated that it will take many years for discharged leachate to reach any downstream users or surface waters, even a slow rate of self-treatment may be sufficient to preserve groundwater quality. This self-treatment capacity of the aquifers has never been measured, but controlled laboratory or field studies could quantify that capacity. This rate of self-treatment could then be used in computer models of an aquifer-retort system.

COST PROJECTIONS

The touchstone of any control strategy is cost, here expressed in 1979 dollars per barrel of oil extracted. Although it is impossible to make accurate cost estimates without first developing and demonstrating a control strategy, there is little incentive to develop such a technology without some assurance that it would be cost-effective if proven technically feasible. Therefore, we project costs for several of the most promising control technologies. These costs are speculative and highly dependent upon several assumptions which are stated explicitly in the following sections. These costs also may be strongly influenced by logistics, retort operations, and presently unknown factors. For example, the economics of treating recovered leachate depend strongly upon the number of pore volumes which must be treated. This in turn depends upon spent shale characteristics that are poorly defined at present. The composition of the leachate depends upon field retorting conditions which are uncertain. Additionally, some cost items, such as slurrying and injecting spent shale, are without precedent and can only be estimated. Costs of water quality monitoring, which would be a necessary adjunct to any control technology but presumably the same for all of them, are not considered here. Since most of these candidate control strategies would not be applied until some time--possibly decades to centuries--after the recovery of oil, there is an economic advantage to be obtained by waiting to spend the money for control technology. This has not been considered here and would not necessarily be equal for all control strategies.

Nevertheless, we believe that cost projections are useful and necessary to properly focus development work. The word "projection" is used rather than the usual "estimate" to denote an added degree of uncertainty. In conventional architectural and engineering construction projects, large discrepancies between cost estimates and bids are distressingly common. It has also been observed that, when faced with an unfamiliar project such as high-risk technology, contractors bid high as insurance against unforeseen difficulties. Novel techniques such as most of those proposed here are indeed high-risk technologies. Because design parameters have not been established, no design work has been completed, and no field experience exists, any cost figures at this stage must necessarily be rough estimates. As experimental work and computer modeling reveal some of the design parameters and as retorting technology progresses, cost projections can be refined. The technologies for which cost projections are presented in this section are those which have not been eliminated from consideration because of any major foreseeable technical problem. Further study may reveal unforeseen problems which may eliminate additional candidates from this list.

All costs have been normalized as 1979 dollars per barrel of oil extracted using combined surface and in-situ retorting; they are developed for the proposed oparations on lease tracts C-a and C-b. The development conditions assumed in these calculations are summarized in Table 20 and the resulting costs in Table 21. Cost differences between the two lease tracts reflect the deeper overburden on Tract C-b as well as the larger retort size and greater void volume on Tract C-a.

Table 21 presents the assumptions, which have been divided into three categories, on which these cost projections were based. Cost assumptions are the basis upon which the control technology cost has been projected. Technical assumptions are conditions which must be met for a technology to succeed, but which are external to the technology itself, such as the availability of water. Unresolved technical questions are factors directly related to the technology which are presently poorly understood, such as the ability of grout to penetrate the voids in an in-situ retort. Generally, these unresolved issues must be studied in laboratory and field investigations.

Several other benefits can be achieved by control technologies, besides the primary goal of preventing pollution of aquifers. These include preventing communication between the upper and lower aquifers, eventual removal of pollutants (as opposed to locking them in place), and strengthening abandoned retorts to prevent subsidence and to permit retorting of the pillars between retorts. Table 21 also shows which benefits can result from each candidate control technology.

An important point to bear in mind when comparing control technologies is that the environmental impact of development, with no control technology or with any of the control technologies proposed here, is highly dependent upon the magnitude of the development project(s) and site-specific conditions. A control technology which is environmentally acceptable for a given site at one phase of development may be unacceptable when applied to a larger development project or at a different site. Treating two pore volumes of leachate may result in a permissible amount of leachate transport into aquifers when applied to a 30 year, 50,000 barrel-per-day project, but may result in an unacceptable amount of leachate when applied to a 100 year, 100,000 barrel-per-day project. Similarly, differences in geologic and hydrologic conditions may make grouting technically and economically favorable at one site and unfavorable at another. In general, it appears that larger development projects will require more stringent control measures. At the same time, if development of oil shale is profitable for 30 years at 50,000 barrels per day, there is no reason why it should not be continued for a longer period of time. Development planning will thus require that control technologies be used which are suitable for the ultimate scale of development.

Table 20. Key assumptions for the Rio Blanco and Occidental vertical modified in-situ processes.

	Tract C-a Rio Blanco Process	Tract C-b Occidental Process
Commerical production (bbl/day)	50,000	50,000[a]
Retort size, length x width x height (ft)	300 x 150 x 750[b]	310 x 155 x 390[a]
Retort spacing (ft)		
between ends	95[b,c]	50[a]
between sides	95[b,c]	150[a]
Retort porosity (percent)	40	23[a]
Distance from ground surface to top of retort (ft)	450[c]	1400[c]
Retort efficiency		
In-situ	65	65
Surface	90	90
Burn rate (ft/day)	14[b]	1[d]
Time to burn one retort (days)	54	390
Oil shale density (lb/ft^3)	137	137[a]
Shale grade (gal/ton)	24	24
Surface retort	Lurgi	Lurgi
Days of operation per year	350	350[a]

[a] Occidental Oil Shale, 1979

[b] Gulf Oil Co. and Standard Oil Co. (Indiana), 1977

[c] Varies over tracts; reported values are typical

[d] McCarthy, 1976

Table 21. Candidate control strategies for VMIS retorts.

Control Strategy	Benefits[1]			Projected cost[2] $/bbl		Cost based on assumptions (*critical)	Technical assumptions (*critical)	Unresolved technical questions (*critical)
	Achieved	Partial	Possible	C-a	C-b			
Site selection	a		b	Not applicable				
Grout abandoned retorts with spent shale	a,b,d	f	c,e	\$0.49[4]	\$0.35[4]	Grout injection from air level of retorts	Can use air level as grounting gallary; adequate water available	*Penetration of grout through rubble
				(\$0.65)[5]	(\$1.30)[5]	Grout injection from ground surface		Permanence of non-cementitious grout
						\$2/ton to prepare and inject slurry		Ultimate permeability of retort
						No addition of portland cement or fluidizers		
In place precipitation of calcite to seal pores[3]		a,b		\$1.88	\$1.15	Filling 10 percent of voids with $Ca(OH)_2$	Ability to place $Ca(OH)_2$ in fine pores where grout cannot penetrate	Eventual solution of precipitates
Grout curtain around block of retorts	a,b			\$0.74	\$2.85	144 retorts enclosed, \$20/foot to drill, \$3/foot^3 for grout in place, single row of grout holes	*Geotechnical feasibility--can drill deep holes parallel	Effectiveness should be estimated by modeling; fracture size in aquifers determines grout to be used.
Design retorts with hydraulic bypass[3]		b		\$0.46	\$1.76	144 retorts enclosed, \$20/foot to drill	Groundwater flows between aquifers through path of least resistance	Effectiveness should be estimated by modeling

Table 21. Candidate control strategies for VMIS retorts - (continued).

Control Strategy	Benefits[1]			Projected cost[2] $/bbl		Cost based on assumptions (*critical)	Technical assumptions (*critical)	Unresolved technical questions (*critical)
	Achieved	Partial	Possible	C-a	C-b			
Cap rock in place	a,b			Not applicable		Not feasible on tract C-a or C-b		
Recover and treat leachate	b,g			$0.67	$0.59	*Adequate to treat 2 pore volumes	*Treatability by reverse osmosis--fouling problems solved	*Economics of treatment process; brine disposal
Treat leachate in situ by adsorption and ion exchange	b,g			Too costly		$125/ft^3 for cation exchange resin		
Modify retort operating conditions	b			0	0	Modifications improve resource recovery	Can control retorting conditions accurately	*Non-leachability of shales retorted under specified conditions
Reverse wettability of spent shale	b			Too costly		$0.20 to $4.00/lb for water-repellant coatings		Method to "coat" spent shale in-situ. Permanence, non-biodegradability
Self treatment (no action)	g			0	0		Self-treatment capacity of aquifers adequate	Mechanisms and kinetics of process

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[1] Benefits:
a. Prevent flow from one aquifer to another.
b. Prevent leachate from entering groundwater.
c. Disposes of retort water.
d. Prevent subsidence,
e. Permit additional resource recovery.
f. Dispose of surface-retorted shale.
g. Eventually remove pollutants.

[2] Cost per barrel based on combined surface and in-situ retorting, 40 percent voids on Tract C-a and 23 percent voids on Tract C-b.

[3] Possible application in conjunction with another technology; not adequate by itself.

[4] Air-level drilling.

[5] Ground-level drilling.

Cost projections presented here are based upon the developments proposed in the detailed development plans for lease tracts C-a and C-b and summarized in Table 20. Costs are presented only for those strategies which appear economically and technically feasible. Unless otherwise stated, all costs are in 1979 dollars. Altering the scale of development will probably change the unit costs. In development planning, the selection of a control technology must consider the cost per barrel of oil at the ultimate level of development. However, the technology selected should also be cost-effective at lower levels of development.

HYDRAULIC ISOLATION BY SITE SELECTION

The purpose of using site selection as a control strategy is to locate VMIS retorts in groundwater-free zones by placing them above the water table or by separating them from aquifers by other means. This would minimize or eliminate in-situ leachate formation and transport and represents the most desirable conditions for protecting groundwater from degradation. This strategy is not feasible for lease tracts C-a and C-b, the subject of this report, because of their geohydrology. However, it may be viable for other resources in the Green River Formation.

The cost of site selection in other cases would include the cost of site evaluation (a hydrogeologic survey) and the costs associated with resources that may not be developed. This strategy would be most effective in guiding future leasing policies of the U. S. government. There is probably little incentive for industry today to use site selection on a large scale due to land ownership considerations (industry will develop only the lands on which it has mineral rights) Additionally, the costs associated with undeveloped resources are much higher than the cost of development with another control technology, for example, grouting. However, the government could effectively use site selection in choosing future lands for leasing. Dry sites or sites with thick continuous zones of dry shale could be selected for early leasing. Leasing of wet sites could be deferred until adequate control strategies have been demonstrated.

HYDRAULIC ISOLATION BY GROUTING ABANDONED RETORTS

Summary

The cost calculations for grouting abandoned in-situ retorts with a grout produced from surface spent shale assume that the mined-out shale is retorted by an existing surface retorting technology, such as Lurgi, Paraho, or TOSCO II. Some of the spent shale produced by the surface retort would be slurried with mine water and injected into the retort through a pattern of injection holes drilled to the bottom of the retort. The slurry would be pumped to the bottom of the retort through injection pipes which would be withdrawn upward as injection proceeds, until the retort is completely filled. Based upon cost projections which follow, it appears that the control technology used for proposed operations at lease tracts C-a and C-b may cost \$0.49 and \$0.35 per barrel, respectively, if drilling and grouting can be done from the air level above retorts, and \$0.65 and \$1.30 if drilling and grouting is done from the surface. These figures do not include the cost of any additives to improve the grout quality or the cost of modifying surface retorting processes to produce a spent shale suitable for grouting. For example, \$2 per ton was used as the cost of grout preparation and injection. Addition of ten percent portland cement by weight would increase this cost by \$6, making the cost per barrel \$3.00 and \$1.85 at tracts C-a and C-b, respectively, for drilling and grouting from the air level.

Cost Projection

The cost for this process can be divided into several components: (1) costs associated with modifying the surface retorting process; (2) cost of additives to improve the strength or flow properties of the grout; (3) cost of supplying slurry water; (4) capital cost and operating costs of material handling, slurry preparation, and injection facilities; and (5) cost of drilling injection holes. For this estimate, no costs are applied for items (1) and (2). The process considered uses a spent shale without modification, and cost of any modification found to be necessary would have to be added to these estimates.

About 150 gallons of water (item 3 above) are needed for the grouting operation per barrel of oil produced, as shown in Table 22. This water is required to prewet the in-situ spent shale and to slurry the grout. No cost has been included for water since it is assumed to be available as excess mine water which would otherwise have to be disposed of either by injection into aquifers or by discharge into surface streams.

Table 22. Water requirements to grout one in-situ retort.

	Tract C-a	Tract C-b
Volume of in-situ spent shale,[a] ft^3	2.03×10^7	1.44×10^7
Volume of water needed to completely wet spent shale,[b], gal	8.12×10^7	5.76×10^7
Volume of grout,[a] ft^3	1.35×10^7	4.31×10^6
Volume of water contained in grout,[c] gal	6.83×10^7	2.18×10^7
Total volume of water needed for grouting, gal	1.50×10^8	7.94×10^7
Oil produced,[a] gal.	1.01×10^6	5.30×10^5
Water needed for grouting, gal/bbl	1.49×10^2	1.50×10^2

[a] Assume equal in volume to raw shale retorted in-situ, as derived in Table 24.

[b] 4 gal/ft^3, based on Nevens et al., 1977. Because large blocks of spent shale may not be completely wet, this item may be over-estimated.

[c] Grout density = 95 lb/ft^3, 44 percent water = 5.1 gal/ft^3.

Item (4) above, the capital and operating cost of material handling, slurry preparation, and injection, was determined by adapting cost estimates published for this process (DOE, 1979), for the slurry transport of spent shale into deep mines (Earnest et al., 1977), and for the hydraulic backfilling of coal mines (NAS, 1975). These cost estimates ranged from $0.75 to $2.48 per ton of material placed, considering only the cost of material handling, slurry preparation, and injection; but not including any cost for drilling of injection holes, as shown in Table 23. Based on these figures, a cost of $2 per ton for slurry preparation and injection is used for this projection.

The required spacing of drill holes depends upon the injection pressure and ease of penetration of the grout through the in-situ retort. Because injection pressure is limited by the need to prevent uplift of the material in the retort, penetration must be determined in field or laboratory tests. For this estimate, it is assumed that grout can penetrate 35 feet from the point of injection. If holes are drilled in a square pattern, this 35-foot penetration requires that a spacing of 50 feet be used. Spacing of five to ten feet is generally used in soil grouting, but greater penetration should be possible in an abandoned retort. Placing injection holes in retorts as described in Table 24 requires that 18 holes be drilled in each retort. The cost of drilling injection holes depends strongly upon whether the air injection level can be used as a grouting gallery and upon the number of air injection holes in the top of each retort. If the air injection level can be used as a grouting gallery, holes need be drilled only from that level through rubble to the bottom of the retort. On the other hand, if the air injection level is too cramped or unsafe, grout injection holes must be drilled from the ground surface, through the air injection level, and then through the rubble to the bottom of the retort. This additional drilling represents a significant cost factor. However, working from the air level could necessitate development of new drilling equipment.

In calculating control technology costs, it is appropriate to take as a credit the cost of surface disposal of an equal amount of spent shale. Estimates for this cost, including revegetation, ranged from $0.30 to $1.28 per ton of material placed, as shown in Table 23. A cost of $1 per ton is used for this cost projection.

Salient features of present industrial development plans for lease tracts C-a and C-b are presented in Table 24, and are used as a basis for estimating drilling and grouting costs in Table 25.

HYDRAULIC ISOLATION BY IN-SITU PRECIPITATION OF CALCITE

Summary

In-situ precipitation of carbonates may be an effective way to seal pores of an in-situ retort. Cost considerations make it impossible to seal all the voids in a retort. If limestone precipitation is used, the cost of sealing 10 percent of the voids created by mining would be from $1.15 to $1.88 per barrel of oil.

Table 23. Cost estimates for hydraulic backfilling and surface disposal (adjusted to 1979 dollars).

	Type of operation	Material placed, ton/day	Total cost $/ton
Hydraulic backfilling	Coal waste into deep coal mine[b]	3,000	2.48[a]
	Spent shale into deep mine[c]	68,000	1.48
	Spent shale into retort[d]	33,600	0.75
Surface disposal	Spent shale[d]	54,000	0.32
	Spent shale[c]	68,000	0.30
	Coal mine waste[b]	3,000	1.28

[a] Costs due to underground equipment and lost mine productivity are not included.
[b] NAS, 1975.
[c] Earnest et al., 1977.
[d] Derived from data in DOE, 1979.

Cost Projection

In the limestone precipitation method described briefly here, hydrated lime is transported as a slurry into the retort where it reacts with the CO_2 to precipitate $CaCO_3$. Costs shown in Table 26 are for sufficient lime to fill 10 percent of the voids in an abandoned retort. For a higher percentage filling, the cost can be increased proportionately. However, it appears that calcite precipitation will not be economically feasible as a control technology.

Limestone ($CaCO_3$) is converted to CaO by calcining; this CaO hydrates to $Ca(OH)_2$ when slurried. The $Ca(OH)_2$ then reacts with CO_3 in the slurrying water, invading groundwater, or CO_2 in the offgas. Aqueous CO_3 or gaseous CO_2 is needed to react with the $Ca(OH)_2$ in place. The amount of CO_3 needed is more than can be dissolved in a flooded retort. However, adequate CO_2 is available from decomposition of carbonates in an adjacent retort, as shown in Table 27.

In addition to placing limestone in retorts, some free lime may be present in surface and in-situ spent shale. Heistand et al. (1978) found up to 7.7 percent free lime in surface retorted shale. If free lime is present in spent shales, it will react like emplaced lime to precipitate calcite. Thus, surface or in-situ spent shale could be substituted for some of the lime. This needs to be investigated experimentally.

Table 24. Projected industrial development plans for lease tracts C-a and C-b related to retort grouting.

	Tract C-a	Tract C-b
Retort dimensions, ft		
Length	300	310
Width	150	155
Depth	750	390
Pillar Dimensions, ft		
Between length	300x95	310x150
Between width	150x95	155x50
Drilling		
Number of holes per retort, in square grid on 50 foot centers	18	18
Distance from ground to top of retort,[a] ft	450	1400
Distance of drilling through rock, ft	8100	25,200
Distance of drilling through rubble, ft	13,500	7020
Quantity of grout		
Volume of retort, ft^3	3.38×10^7	1.87×10^7
Void percentage	40	23
Volume of voids, ft^3	1.35×10^7	4.31×10^6
Grout material placed,[b] ton	3.58×10^5	1.14×10^5
Oil produced per retort		
In-situ		
Volume of oil shale, ft^3	2.03×10^7	1.44×10^7
Weight of oil shale,[c] ton	1.42×10^6	1.01×10^6
Oil recovered,[d] bbl	5.27×10^5	3.75×10^5
Surface		
Volume of oil shale, ft^3	1.35×10^7	4.31×10^6
Weight of oil shale, ton	9.45×10^5	3.02×10^5
Oil recovered,[e] bbl	4.86×10^5	1.55×10^5
Total oil recovery, bbl/retort	1.01×10^6	5.30×10^5

[a] Varies over tract, reported values are typical.

[b] Assumed 95 lb/ft^3 in place, 56 percent solids = 53 lb/ft^3.

[c] 140 lb/ft^3 for 24 gal/ton oil shale.

[d] 24 gal/ton, 65 percent recovery.

[e] 24 gal/ton, 90 percent recovery.

Table 25. Projected cost of grouting one retort.

	Tract C-a	Tract C-b
Drilling		
Drilling through rubble from air level to bottom of retort, assume \$10/ft	\$135,000	\$70,200
Drilling through rock from ground to top of retort, assume \$20/ft[a]	\$162,000	\$504,000
Grouting		
Grout material placed,[b] ton	$3.58\mathrm{x}10^5$	$1.14\mathrm{x}10^5$
Cost of grout preparation and and injection, \$2/ton	\$716,000	\$228,000
Credit taken for cost of surface disposal of equal amount of surface spent shale, \$1/ton	-\$358,000	-\$114,000
Net cost of grout preparation and injection	\$358,000	\$114,000
Total cost		
Grouting from air level	\$493,000	\$184,200
Grouting from ground	\$655,000	\$688,200
Oil recovered,[b] bbl/retort	$1.01\mathrm{x}10^6$	$5.30\mathrm{x}10^5$
Cost per barrel		
Grouting from air level	\$0.49	\$0.35
Grouting from ground	\$0.65	\$1.30

[a] Include this cost if air level cannot be used as a grouting gallery.

[b] From Table 24.

Table 26. Projected cost of lime to fill 10 percent voids in abandoned retorts.

	Tract C-a	Tract C-b
Voids created by mining,[a] ft^3/retort	$1.35x10^7$	$4.31x10^6$
Weight of calcite to fill 10 percent of voids, tons ($\rho = 2.71$)	$1.14x10^5$	$3.64x10^4$
Cost of delivered limestone, \$5/ton	\$$5.70x10^5$	\$$1.82x10^5$
Cost of calcining limestone thermochemical,[b] \$8.45/ton sensible heat,[c] \$1.24/ton	\$$1.10x10^6$	\$$3.53x10^5$
Total cost of lime	\$$1.67x10^6$	\$$5.35x10^5$
Cost of preparing and injecting slurry, \$2/ton	\$$2.28x10^5$	\$$7.28x10^4$
Total cost	\$$1.90x10^6$	\$$6.08x10^5$
Barrels of oil produced,[a] per retort	$1.01x10^6$	\$$5.30x10^5$
Cost per barrel	\$1.88	\$1.15

[a] From Table 24.
[b] 40 kcal/mole, 9080 moles/ton, \$0.0000233 per kcal.
[c] 908,000 g/ton, 2/3 of sensible heat recovered, heated to 800°C, specific heat = 0.22.

Table 27. Availability of CO_2 to precipitate carbonates.

	Tract C-a	Tract C-b
Weight of calcite placed in retorts by slurry transport,[a] ton	$1.14x10^5$	$3.64x10^4$
Weight of CO_2 needed to react with $Ca(OH)_2$	$5.02x10^4$	$1.60x10^4$
Weight of raw shale retorted in-situ, per retort,[b] ton	$1.42x10^6$	$1.01x10^6$
Weight of CO_2 released by decomposition of carbonates, ton	$2.84x10^5$	$2.02x10^5$

[a] From Table 26

[b] From Table 24

HYDROGEOLIC MODIFICATION USING A GROUT CURTAIN

Summary

The economic attractiveness of this technique is based upon the fact that for a block of retorts the perimeter-to-area ratio is much less than for a single isolated retort. It can therefore be considered only for use when large blocks of retorts are planned. Costs of grout curtains placed under dam foundations and reported in Table 16 range from \$2.18 to \$4.65 per square foot of curtain (1963 prices). Adjusting these prices by a factor of 3.24 (increase in Engineering News-Record Construction Cost Index 1963-1979), grout curtains may cost between \$6.30 and \$13.50 per square foot. The costs calculated in Table 28, \$8 per square foot, are within this range. As shown in Table 28, grout curtain costs appear to be from \$0.74 to \$2.85 per barrel of oil recovered.

Cost Projection

Costs for surrounding blocks of retorts with a grout curtain shown in Figure 24 depend upon the number of retorts enclosed by the curtain. As a minimum, an entire lease tract could be enclosed with a single curtain, but horizontal groundwater flow through a developed area would be less if the area were crossed by several curtains. The maximum size of a block of retorts to be surrounded should be determined by groundwater-flow modeling of each individual case. In the absence of such information, the size of blocks to be enclosed has been taken as approximately 4000 x 4000 feet. This is approximately the size of retort blocks shown in the Detailed Development Plans (Gulf, May 1977; Ashland, 1977).

The costs for the grout curtains described in Table 28 were estimated by assuming that a single row of holes would be drilled at five-foot centers along the perimeter of the curtain. Cement grout was assumed to penetrate to a width of ten feet; the porosity of the formation was taken as ten percent (Collins, 1978). The "take" of grout material is $(5)(10)(0.10) = 5\ ft^3$ per linear foot of hole grouted. Drilling costs used were \$20 per linear foot. With these assumptions, the costs per barrel for grout curtain construction amount to \$0.74 on Tract C-a and \$2.85 on Tract C-b. This difference is due to the fact that the lower aquifer on Tract C-b is deeper than on Tract C-a. There is evidence that the lower aquifer on Tract C-b is actually divided into two isolated aquifers (designated Lpc 3 and Lpc 4) (Occidental, Feb. 1979). Only the upper of these two lower aquifers intersects the retorts. It might therefore be possible to achieve the same effect with a grout curtain extending only as deep as the bottom of the Lpc 3 zone. This would reduce the costs for Tract C-b.

Table 28. Cost projection: surrounding retort block with a grout curtain.

	Tract C-a	Tract C-b
Grout curtain perimeter,[a] ft	15,740	15,850
Number of retorts enclosed by grout curtain[b]	16x10	11x13
Grouted depth of curtain,[c] ft	950	1750
Vertical area of grout curtain, ft^2	1.50×10^7	2.77×10^7
Additional height drilled but not grouted, ft	235	350
Number of holes, 5 ft centers	3148	3170
Total grouted length of holes, ft	2.99×10^6	5.55×10^6
Material injected, ft^3	1.50×10^7	2.77×10^7
Material cost, $\$3/ft^3$	$\$4.49 \times 10^7$	$\$8.32 \times 10^7$
Total drilled distance, ft	3.73×10^6	6.66×10^6
Drilling cost, $20/ft	$\$7.46 \times 10^7$	$\$1.33 \times 10^8$
Total cost, $	$\$1.20 \times 10^8$	$\$2.16 \times 10^8$
Oil produced per retort,[d] bbl	1.01×10^6	5.30×10^5
Total oil produced, bbl	1.62×10^8	7.58×10^7
Total cost, $/bbl	$0.74	$2.85

[a] Approximately 4000 ft x 4000 ft area enclosed within grout curtain.

[b] Using retort and pillar dimensions as shown in Table 24.

[c] From definition sketch, Figure 23.

[d] From Table 24.

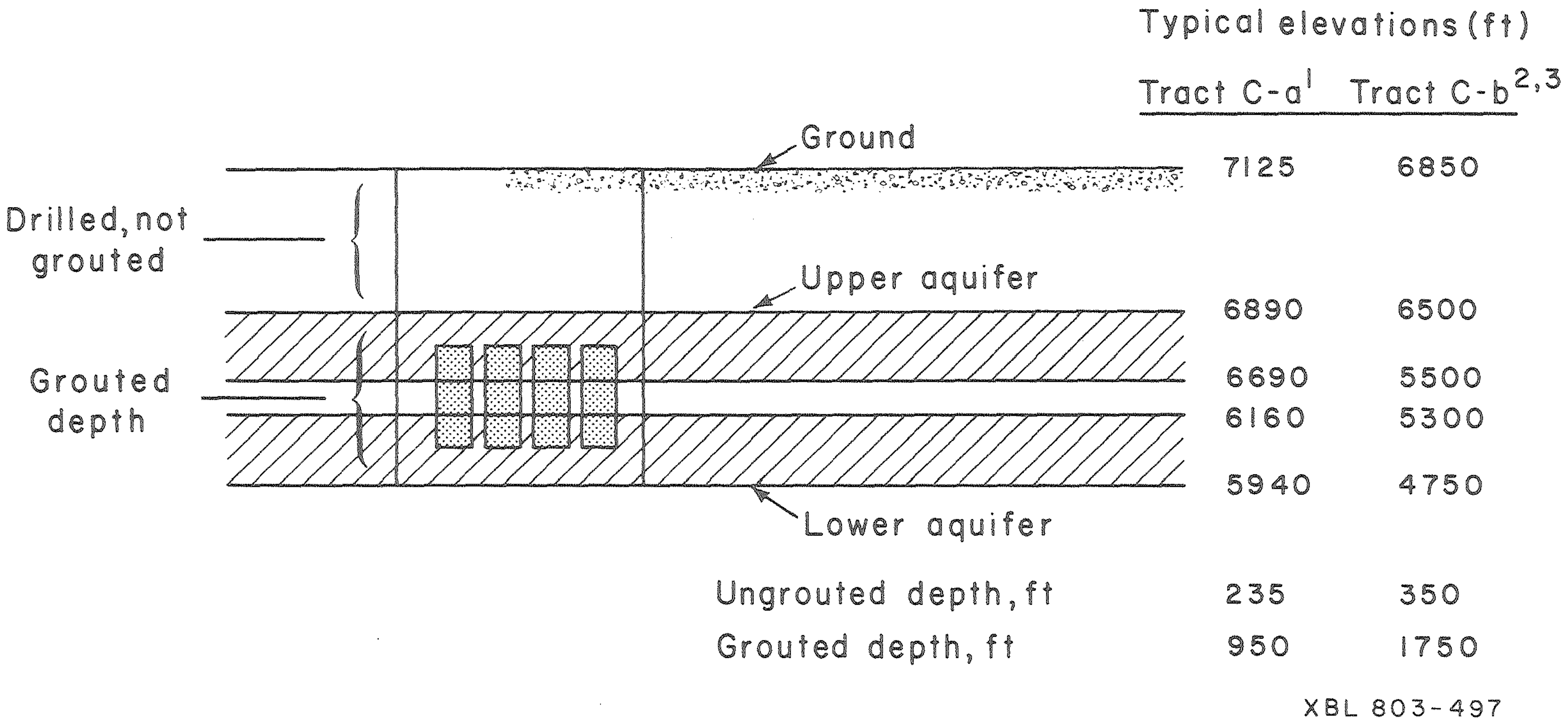

Figure 24. Definition sketch for grout curtain calculations. Source of elevation data: [1]Gulf, May 1977; [2]Occidental, Feb. 1977; [3]Tipton, 1977.

The curtains are assumed to extend vertically from the top of the upper aquifer to the bottom of the lower aquifer. An additional distance between the top of the upper aquifer and the ground surface is drilled but not grouted. Grouts used in jobs cited in Table 16 were neat cement, silt, sand, and rock flour. For each site, an inspection will be necessary to determine the actual grout to be used. If a grout based on spent shale can be used, grouting costs will be somewhat lower. However, a grout curtain would only dispose of a small fraction of surface retorted spent shale.

Site inspection is necessary to predict costs of grouting accurately. The size of water-carrying factures is important because, if they are smaller than 0.025 inch (approximately), cement grout might not be useable and a more expensive chemical grout would be needed. It is recommended that a geologist or a grouting contractor be consulted for a better determination of the feasibility of this approach.

HYDROGEOLOGIC MODIFICATION USING A HYDRAULIC BYPASS

Summary

A palisade of hydraulic bypass conduits may be constructed as shown in Figure 21. Assuming that conduits are placed around the perimeter of a retort block at five-foot centers and that the cost of drilling is $20 per linear foot, the total cost of providing a hydraulic bypass is $0.46 to $1.76 per barrel of oil (Table 29). As with a grout curtain, this cost depends heavily on the feasibility of surrounding a large block of retorts, and this should be verified by field inspection.

Cost Projection

Costs for forming a hydraulic bypass around a block of retorts are shown in Table 29. Where the two aquifers are at different piezometric heads, groundwater would tend to flow through the abandoned retorts which connect the aquifers. A hydraulic bypass is simply a series of holes drilled around the perimeter of a retort block. These holes are not grouted but are left open to permit water to pass from one aquifer to the other without leaching abandoned retorts. Costs for this technology are similar to costs for a grout curtain, less the cost of slurrying and injecting grout. As in the grout curtain cost projection, it was assumed that an area approximately 4000 ft x 4000 ft was to be surrounded. Groundwater modeling should be done to test these assumptions and determine the effectiveness of a hydraulic bypass.

HYDROGEOLOGIC MODIFICATION USING A CAP ROCK

Hydrologically isolating retorts from aquifers by leaving a cap rock of intact oil shale material above and/or below retorts appears uneconomical and unreliable for tracts C-a and C-b. An in-place cap rock requires the entire retort to be contained within a dry zone, which may be only 100 to 200 feet thick. To be profitable, VMIS retorts must be tall. For example, Fennix and Scisson (1976) used 200 feet as the minimum retort height in their economic analysis of retorting methods; other proposed retorts are twice to four times this height. Applying a cap rock control strategy to the Mahogany Zone would require the use of retorts shorter than the minimum recommended by Fenix and Scisson. Even without projecting exact dollar costs, this strategy is not applicable to tracts C-a and C-b.

Table 29. Cost projection for hydraulic bypass.

	Tract C-a	Tract C-b
Bypass perimeters, ft	15,740	15,850
Total depth of drilling to bottom of lower aquifer, ft	1185	2100
Number of holes, at 5 ft centers	3148	3170
Total distance of drilling, ft	$3.73\text{x}10^6$	$6.66\text{x}10^6$
Drilling cost, \$20/ft	$\$7.46\text{x}10^7$	$\$1.33\text{x}10^3$
Number of retorts enclosed	160	143
Oil produced per retort, bbl	$1.01\text{x}10^6$	$5.30\text{x}10^5$
Total oil produced, bbl	$1.62\text{x}10^8$	$7.58\text{x}10^7$
Cost per barrel	\$0.46	\$1.76

RECOVERY AND TREATMENT OF LEACHATE

Summary

The cost of recovering and treating leachate depends upon the volume of leachate to be treated and the cost of treatment, which can be assessed only after treatability studies have been conducted to determine the best process to use. For tertiary treatment, it is reasonable to assume a cost of \$1.40 per 1000 gallons. Assuming that two pore volumes are all that need to be treated, a total cost of about \$0.59-\$0.67 per barrel is derived, including costs for pumping and reinjection, as shown in Table 30.

Cost Projection

Calculating costs for recovering and treating in-situ leachate assumes that in-situ retorts are leached on abandonment with excess mine water from site dewatering. Natural leaching following site abandonment is not considered practical due to the long lead times required, problems related to maintenance of on-site pumping facilities, and long-term liability of the operator. New pumping equipment and piping would have to be installed for this option. Mine dewatering effluents that would otherwise be directly reinjected (Tract C-a) or discharged into surface streams (Tract C-b) would be introduced at the bottom of the retort and pumped up through the retort to a surface treatment plant. A surface treatment facility would remove total dissolved solids and total organic carbon; treatment processes would

Table 30. Projected costs for intentional leaching.

	Tract C-a	Tract C-b
Drilling one injection well per retort		
Ground to top of retort--distance, ft	450	1400
Drilling cost, at $20/ft	$9,000	$28,000
Height of retort--distance, ft	750	390
Drilling cost, at $10/ft	$7,500	$3,900
Drilling cost per retort	$16,500	$31,900
Barrels of oil recovered per retort	1.01×10^6	5.30×10^5
Drilling cost, per barrel	$0.02	$0.06
Drilling costs, per year	$285,900	$1,053,300
Leaching		
Flow rate, gal/min[a]	9310	7360
Pumping requirements		
a. Two pore volumes circulate through retort against 100 ft friction head power requirement (80 percent efficient)	294 HP	232 HP
100 HP pumps, 1.15 service factor, number required	3	2
Capital costs		
Pumps at $9,000 each	$27,000	$18,000
Installation and controls	$27,000	$18,000

Table 30. Projected costs for intentional leaching (continued).

	Tract C-a	Tract C-b
b. One pore volume lifted to surface, average lift, ft	825	1595
Power requirement	1210 HP	1850 HP
600 HP pumps, multistage 1.15 service factor, number required	2	3
Capital costs		
Deep-well turbine pumps column, at $100,000	$200,000	$300,000
Installation and controls	$100,000	$150,000
Piping--10,000 ft of PVC pipe at $25/ft	$250,000	$250,000
Total connected HP	1504	2082
Total capital cost	$604,000	$736,000
Amortized capital cost per year[b]	$120,800	$147,200
Pumping energy per year[c]	$196,600	$272,700
Total cost per year	$317,400	$419,900
Treatment		
Sedimentation		
Basin surface area,[d] ft^2	22,300	17,700
Capital cost[e]	$386,000	$315,900
Amortized capital cost per year[b]	$ 77,200	$ 63,200
Operating cost per year[e]	$334,600	$265,400
Total cost per year	$411,800	$328,600
Activated carbon		
Capital cost[e]	$5,164,000	$4,235,900
Amortized capital cost per year[b]	$1,033,800	$847,200
Operating cost per year[e]	$699,100	$530,800
Total cost per year	$1,702,900	$1,378,000

Table 30. Projected costs for intentional leaching (continued).

	Tract C-a	Tract C-b
Reverse osmosis		
Amortized capital and operating cost, including pretreatment for scale control[f]	\$4,690,000	\$3,710,000
Total treatment costs per year	\$6,804,700	\$5,416,600
Disposal		
Pond area needed to evaporate 10 percent brine stream + 1/4 percent sludge stream,[g] acre	369	292
Lined evaporation ponds		
Capital costs[h]	\$21,402,000	\$16,923,000
Amortized capital cost per year[c]	\$ 4,280,400	\$ 3,384,600
Total annual costs		
Drilling	\$ 285,900	\$ 1,053,300
Leaching	\$ 317,400	\$ 419,900
Treatment	\$ 6,807,400	\$ 5,416,600
Disposal	\$ 4,280,400	\$ 3,384,600
TOTAL	\$11,691,100	\$10,274,488
Total cost, \$/bbl	\$ 0.67	\$ 0.59

[a] Two pore volumes, 50,000 bbl/day.

[b] Capital recovery factor = 0.20.

[c] 2¢/kwh = \$131.00/HP-yr.

[d] Sized for 600 gpd/ft^2.

[e] After Eckenfelder, 1970--costs adjusted to 1979.

[f] After Argo and Moutes, 1979, \$1000/MG.

[g] 4 ft/yr net evaporation.

[h] After Sinor, 1977--\$58,000/acre.

involve scale control by chemical addition, sedimentation, carbon adsorption, and reverse osmosis. Salts in the leachate would be concentrated in a brine stream, assumed to be 10 percent of the leachate flow, which would be disposed of by evaporation in ponds along with sludges. Treated water would be re-used for leaching or disposed of by reinjection or by discharge into surface water, depending upon the availability of mine water for leaching.

Treatment costs are strongly dependent upon the volume of leachate to be treated. Leaching studies of in-situ spent shales have shown that the majority of the leachable materials may be removed in the passage of two to six pore volumes (Fox, 1979). The lower value will be used for this cost projection because it has recently been confirmed for actual in-situ retorted shales (Kuo et al., 1979). Pore volume in a retort is the void space originally present plus the additional void space resulting from pyrolysis of kerogen. Voids caused by decomposition of carbonates are not included in the total pore volume because these voids, once wet, are considered too small to be drained. Values of original voids are taken from Table 24 (1.35×10^7 ft^3 per retort for Tract C-a and 4.31×10^6 ft^3 per retort for Tract C-b). Voids due to in-situ pyrolysis of kerogen are assumed to be 3.21 ft^3 or 24 gallons per ton of oil shale. Although recovery is less than 100 percent, unrecovered kerogen is burned off as char. This gives a void space due to pyrolysis of kerogen of 4.56×10^6 ft^3 per retort for Tract C-a and 3.24×10^6 ft^3 per retort for Tract C-b. One pore volume for a retort for Tract C-a is therefore 1.81×10^7 ft^3 and 7.55×10^6 ft^3 per retort for Tract C-b. Dividing these volumes by the total amount of oil recovered per retort, considering both in-situ and surface recovered oil as developed in Table 24, the pore volume per barrel is 17.9 ft^3 for Tract C-a and 14.2 ft^3 for Tract C-b. Thus, two pore volumes of leachate are 268 and 212 ballons per barrel for tracts C-a and C-b, respectively.

For this cost projection, it is assumed that leaching of retorts will keep pace with retorting. To leach retorts from a 50,000 barrel-per-day industry would require 13.4 gallons per day (MGD) of leachate on Tract C-a and 10.6 MGD on Tract C-b. If this is greater than the rate of production of excess mine water, the treated leachate must be used for leaching; if not, it can be processed for disposal. The costs of this process are divided into leaching, treatment, and disposal costs.

Leaching Costs. Excess mine dewatering effluents, or treated leachate will be injected into spent retorts for intentional leaching. Total expenses for this operation include: the capital costs of injection and recovery wells in each retort; costs of a pumping station and piping to transport water from dewatering wells to retorts and to treatment and disposal equipment; and operating costs for the pump station. Two different pumps are required: one distributes flow to retorts and circulates flow through full retorts against a low head (100 feet) while the other removes the last pore volume and empties the retorts against a high static lift, from water level in the retort to the ground surface. The high static lift pump would have to be relocated after each retort, or group of hydraulically connected retorts, is leached. The capital and operating costs for leaching are developed in Table 30.

Treatment Costs. Treatment costs are amortized capital and operating expenses for sedimentation, activated carbon adsorption, and reverse osmosis with chemical addition for scale control. As shown in Table 30, costs for sedimentation and activated carbon adsorption are based upon the flow rate to be treated (Eckenfelder, 1970). The cost for reverse osmosis was estimated by allowing a suitable margin over costs observed for a 5 MGD wastewater reclamation system (Argo and Moutes, 1979).

Disposal Costs. The reject stream from the reverse osmosis process is a brine containing most of the salts concentrated into a small fraction of the water, assumed to be 10 percent for this cost projection. This stream, plus sludges from the treatment process, would be evaporated from lined ponds. Net evaporation from ponds is about four feet per year in western Colorado, and the cost for lined ponds is about \$58,000 per acre (Sinor, 1977). The resulting disposal cost per barrel of oil is shown in Table 30.

IN-SITU LEACHATE TREATMENT BY ADSORPTION AND ION EXCHANGE

The cost of this method depends upon the amount of organics and inorganics to be removed and the costs of the required amounts of adsorbent or ion-exchange resin. Based upon an expected leachate composition for treating two pore volumes of leachate, as shown in Table 19, using ion-exchange resins for TDS removal by this method is too costly to be considered. For example, Duolite GPA-9316, a typical cation-exchange resin in hydroxide form, has an exchange capacity of 0.9 eq/l (25.5 eq/ft^3) and costs \$126/ft^3 or \$5 per equivalent. Two pore volumes on Tract C-b, about 780 liters per barrel (more on Tract C-a), would contain about 200 meq/l (see Table 19). The large amount of material to be removed makes it obvious that in-situ ion exchange is too costly for consideration.

MODIFIED RETORT OPERATING CONDITIONS

Operating conditions that minimize leachability of in-situ spent shale include using steam, burning char on spent shale, and maintaining shale at high temperatures for long periods (1000°C for several days). None of these conditions adds to the cost of retorting since they all contribute to oil recovery. Uniform rubblizing and burning of the retort will be necessary to ensure that all the shale meets the conditions needed to minimize leachability. These requirements, however, may be more stringent from an environmental viewpoint than from processing economics and may be impossible to meet.

As field experiments progress toward establishing commercial-scale techniques, examination of recovered cores will show how effective these conditions are in minimizing leachability of spent shale. The most likely prognosis is that commercial practice will result in formation of spent shale that is less leachable than simulated in-situ spent shale but that some additional control technology may still be needed.

REVERSE WETTABILITY OF SPENT SHALE

It is impossible to assign a cost to this strategy as no technology to apply a water-repellent coating to in-situ spent shale has been identified. Furthermore, the cost of materials (waxes at \$0.20/lb and silicones at \$4/lb) makes it unlikely that any such strategy could be economical.

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The following abbreviations are used as text citations for the following references:

Ashland: Ashland Oil, Inc., and Occidental Oil Shale, Inc.

API: American Petroleum Institute

ASTM: American Society for Testing and Materials

CSU: Colorado State University

DOE: U. S. Department of Energy

Gulf: Gulf Oil Corp. and Standard Oil Co. (Indiana)

Halliburton: Halliburton Services, Inc.

NAS: National Academy of Sciences

Occidental: Occidental Oil Shale, Inc.

Skelly: Skelly and Loy, Engineers

USDI: U. S. Department of the Interior

Woodward: Woodward-Clyde Consultants

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