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PRELIMINARY STUDY OF THE
OIL SHALES OF THE GREEN RIVER FORMATION
IN THE
TRI-STATE AREA OF COLORADO, UTAH, AND WYOMING
TO INVESTIGATE THEIR UTILITY
FOR DISPOSAL OF RADIOACTIVE WASTE
Netherland, Sewell & Associates

May, 1975

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UNION
CARBIDE

OFFICE OF WASTE ISOLATION
OAK RIDGE, TENNESSEE

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June 6, 1975

Dr. William C. McClain, Director
Geologic Disposal Evaluations Project
Holifield (Oak Ridge) National Laboratory
Building 9104-3
Post Office Box Y
Oak Ridge, Tennessee 37830

Dear Dr. McClain:

This report sets forth the results of our preliminary study of the oil shales of the Green River formation in the tri-state area of Colorado, Utah, and Wyoming to investigate their utility for possible disposal of radioactive waste material. Our study was prepared for the Holifield (Oak Ridge) National Laboratory operated by Union Carbide Corporation, Nuclear Division, for the Energy Research and Development Administration, under Purchase Order Number 78X-70345V of Union Carbide Corporation, dated February 28, 1975.

The objective of this study was to make a preliminary investigation and to obtain a broad overview of the physical and economic factors which would have an effect on the suitability of the oil shale formations for possible disposal of radioactive waste material. These physical and economic factors are discussed in the following sections of this report.

The GENERAL DISCUSSION section sets forth in summary form the findings of our study relating to such items as (1) the areal extent, depth, thickness, and lithology of the oil shale formations; (2) the presence and/or isolation from circulating groundwater which might render the shale formations unsuitable for waste disposal; (3) the "stability" of room-and-pillar type cavities in the oil shale formations which might become available for possible waste disposal as a result of mining the oil shales for recovery of oil and gas; (4) the possible thermal effect on the strength and stability of oil shale formations as relates to the room-and-pillar type mining cavities; and (5) the economic factors relating to the use of the oil shale formations as source material for oil and gas production versus the use of the formations for possible waste disposal.

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The GEOLOGICAL DISCUSSION and GEOLOGICAL EXHIBITS sections set forth in considerable detail the findings of our investigation relating to (1) the general geology, including structure, stratigraphy, hydrology, physiography and climate, oil shale resources, etc., of the Piceance, Uinta, and Greater Green River basins of Colorado, Utah, and Wyoming; (2) the physical characteristics such as strength and associated properties, thermal and chemical properties, and logging characteristics, etc., of the oil shales; and (3) other factors affecting possible disposal in oil shale, such as stability of various mining systems, evaluation of circulating groundwater, and competing non-oil shale resources. Also shown in the report is a list of reference material used in this preliminary investigation.

In summary, the more significant findings of our investigation to date are as follows:

(1) MAGNITUDE OF THE OIL SHALES - The oil shale regions of the Piceance, Uinta, and Greater Green River basins are of great areal extent, extending over an area of approximately 25,000 square miles. Because of the vast amount of shale in these regions, the magnitude of the kerogen contained in these shales is also great - estimated at approximately 600 billion barrels for the richer shales (more than 15 feet thick with yields of more than 25 gallons of oil per ton), 80 percent of which is located in the Piceance basin, 15 percent in the Uinta basin, and 5 percent in the Greater Green River basin. The volume of in-place kerogen for the leaner shales of this area is probably in the same or higher order of magnitude as that estimated for the richer shales. We believe it significant to point out that the small area required for a possible waste disposal site, estimated to be no more than a few square miles, would be so minuscule as to be insignificant when compared with the extensive area and the enormous kerogen content of the oil shale formations and, therefore, would not be in conflict with nor impede the mining of the shales for the recovery of oil and gas.

(2) WASTE DISPOSAL NOT A CONFLICT WITH OIL MINING - The major interest of mining the oil shales for recovery of oil is concentrated in the Piceance basin whereas, for reasons discussed in other sections of this report, the Uinta and Greater Green River basins appear more suited for possible disposal of waste material. The factors of thick shale beds and the high kerogen content of the Piceance basin shales have attracted the oil mining efforts to this basin, as illustrated by Exhibit 10. These same factors, because they adversely affect the strength and stability of mined cavities in the oil shales, become unfavorable factors in con-

sidering the possible storage of waste material in the Piceance basin shale beds. Also, as discussed below, the hydrology or groundwater movement involving the oil shales of the Piceance basin is a severe problem. The combination of these factors directs more of the considerations of possible waste disposal toward the Uinta and Greater Green River basins where the thinner and leaner shales would exhibit greater strength and stability in mined cavities and the groundwater movement does not appear to involve the oil shales. With interest in oil mining directed toward the Piceance basin and interest in possible disposal of waste material directed more toward the Uinta and Greater Green River basins, it appears that there should be no conflict in considering both programs concurrently.

(3) NEW CAVITIES MAY BE REQUIRED FOR WASTE DISPOSAL -

Because of the greater thickness of the shale beds and the higher kerogen content of the shales in the Piceance basin, oil mining operations will likely be confined to this basin for many years, and it is possible that cavities resulting from these oil mining operations, if found to be completely free of water, might be suitable for the storage of at least low-level radioactive waste material. It appears, though, that cavities located in the Uinta and Greater Green River basins would be more suitable for disposal of both low-level and high-level heat-generating waste materials because of the greater strength of cavities associated with the thinner and leaner shale beds of these basins; there is also less likelihood of water problems since the oil shales of these basins do not appear to be a part of the groundwater system. However, since it appears that significant oil mining operations will not be undertaken in these basins for many years, we expect that cavities to be considered for waste disposal would have to be mined for this specific purpose. We believe that certain advantages of design and construction would result from mining of these cavities for the specific purpose of waste disposal.

(4) HYDROLOGY OR WATER FLOW A MAJOR PROBLEM - The oil shales of the Piceance basin are extensively and pervasively fractured and jointed such that the shale deposits become a part of the groundwater system in which the water flows into and through the shales themselves, as illustrated by Exhibits 5 and 8. The interconnected jointing system is the principal transmissive pathway for the downward percolating groundwater and, therefore, has a controlling effect on the hydrologic regime in this basin; this becomes a severe problem in considering the possible disposal of waste material in the shale beds of the Piceance basin. The oil shales of the Uinta and the Greater Green River basins do not appear to be part of the groundwater system; however, much less is known at this time about

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the groundwater systems of these basins so that more comprehensive analyses will be required as part of future considerations of possible waste disposal projects in these areas.

(5) FURTHER STUDIES REQUIRED - Much more comprehensive study of the groundwater systems of these basins, particularly the Uinta and Greater Green River basins, will be required as part of future considerations of possible waste disposal projects in these areas. Also, further detailed study will be required for each possible storage site, regarding the physical characteristics of the shales in the particular area as well as the characteristics of the particular waste material being considered for disposal.

The oil shale areas, in general, are fairly accessible via major highways along the southern margins of each of the three basins and a reasonably good network of state and local hard-surface roads with subsidiary gravel and graded roads throughout most of the areas. The area appears to be dormant as relates to seismic activity except possibly for certain minor fault and thrust belts along the western edges of the Uinta and Green River basins.

Basic geologic data and our engineering work sheets are maintained on file in our office. Certain geological data, such as oil and gas field location maps, etc., were obtained from private libraries and commercial map companies. Certain engineering data such as oil and gas production records, etc., were obtained from published reports of data filed with the state regulatory bodies, such as the Oil and Gas Conservation Commissions of Colorado, Utah, and Wyoming. We believe these data to be accurate; however, we do not certify as to the authenticity of all such data used.

We appreciate the opportunity of performing this investigation for you.

Very truly yours,

A handwritten signature in cursive script that reads "Clarence Netherland". The signature is written in dark ink and is positioned to the right of the typed name "Clarence Netherland".

CMN:LL

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SUMMARY OF CERTAIN FACTORS AFFECTING THE SUITABILITY OF THE OIL SHALES

for the

DISPOSAL OF RADIOACTIVE WASTE MATERIAL

TRI-STATE AREA OF COLORADO, UTAH, AND WYOMING

Data by Basins	Piceance Basin, Northwestern Colorado	Uinta Basin, Northeastern Utah	Greater Green River Basin, Southwestern Wyoming
LOCATION AND EXTENT OF THE OIL SHALES -			
1. Location	Northwestern Colorado	Northeastern Utah	Southwestern Wyoming
2. Areal Extent of Deposits	Approximately 2,500 square miles	Approximately 11,000 square miles	Approximately 11,000 square miles
3. Stratigraphic Nature of the Shales	Bulk of oil shale in Parachute Creek Member of Green River Formation. A layered system with basin margins consisting of interbedded rocks representing various depositional environments such as floodplain mudstones and sandstones; fresh water pond shales and lime-stones; swamp shales, coals and sandstones; and lake bottom shales, marlstones and tuffaceous sandstones. In all cases, the layers are composed of material with different rock properties, such as strength, plasticity, transmissivity, sonic velocity, density, conductivity, heat capacity, specific heat, etc.	Bulk of oil shale in Parachute Creek Member of Green River Formation. Parachute Creek Member consists mainly of marlstone, oil shale, siltstone, sandstone, and tuff, representing deposition in a saline or stratified saline/fresh water lake. The oil shale occurs in layers ranging from paper thin to more than one inch thick in beds varying from a few hundred to more than 1,000 feet thick. Color varies from tan to very dark grey; the richer the bed, the darker the color.	Oil shale in three members of the Green River Formation: Tipton Shale; Wilkins Peak; and Laney Members, with the Tipton containing bulk of oil shale. Tipton Member consists of tan to brown oil shales, calcareous sandstones, and subordinate siltstones, marlstones and limestones. This heterogeneous sequence varies in thickness from zero to about 400 feet and contains maximum "net" shale thickness of approximately 150 feet.
4. Depth and Thickness of the Shales	Shale at surface of valley walls on southern margin of basin to depth of 1,000 feet in the northern portion of basin; thickness of 100 feet at margin of basin to 1,000 feet at center.	Depth varies from approximately 500 feet to 3,000 feet and the thickness reaches a maximum of approximately 130 feet.	Depth varies from approximately 1,200 to 2,800 feet and the thickness reaches a maximum of approximately 150 feet.
5. Magnitude of In-Place Kerogen	Approximately 80 percent of the estimated 600 billion barrels of oil in the richer shales (more than 15 feet thick and 25 gallons of kerogen or oil per ton of shale). Probably a similar range of in-place kerogen found in the leaner shale beds of less than 25 gallons per ton and less than 15 feet thick.	Approximately 15 percent of the estimated 600 billion barrels of oil in the richer shales. Probably in excess of 250 billion barrels of kerogen or oil in the leaner shale beds; mining of these shales likely will not be considered until the richer and thicker beds of the Piceance basin have been mined, which may be many years.	Approximately 5 percent of the estimated 600 billion barrels of oil in the richer shales. Probably in excess of 200 billion barrels of kerogen or oil in the leaner shale beds; the possible mining of these leaner shales probably will follow by many years the mining of the thicker and richer beds of the Piceance basin.
AVAILABILITY OF MINED CAVITIES -			
1. Current Status of Mining Operations	See paper by Charles H. Prien, <u>Current Oil Shale Technology: A Summary</u> , Appendix A of this report, for general discussion of several mining processes under study or in various stages of research-type operations. The forward progress of most mining operations has been substantially slowed, awaiting the resolution of a number of economic, political, and environmental issues. Current interest is in central and southern portion of basin where richer and more accessible deposits are located.	Since the richest oil shale deposits are in the Piceance basin, most of the current mining operations under study or in progress are in that basin; therefore, the Uinta basin is essentially dormant except for some consideration being given to a possible modified in-situ process for the east-central portion of the basin.	Several trona (sodium carbonate) mines in operation in the Green River basin at depths of 1,200 to 2,000 feet. These are of the "longwall" and larger "room-and-pillar" type mines with access via shafts and tunnels. The Greater Green River basin is essentially dormant as far as oil shale mining is concerned.

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SUMMARY OF CERTAIN FACTORS AFFECTING THE SUITABILITY OF THE OIL SHALES (Contd)

Data by Basins	Piceance Basin, Northwestern Colorado	Uinta Basin, Northeastern Utah	Greater Green River Basin, Southwestern Wyoming
AVAILABILITY OF MINED CAVITIES (Contd)			
2. Probable Future Mining Operations	Forward progress of current and future mining operations expected to remain essentially inactive until the resolution of the important economic, political, and environmental issues.	Expect that future mining operations in the Uinta basin will follow by many years the mining operations in the more prolific Piceance basin.	Expect that consideration of oil shale mining will follow by many years the mining operations of the more prolific Piceance basin.
3. Types of Cavities Being Mined	Room-and-pillar mines with adit access in the rich oil shale zone; "in-situ" in-place retorting techniques being studied and tested.	A modified "in-situ" process being considered; expected that, when mining gets under way, the room-and-pillar method also will be used.	"Longwall" and larger room-and-pillar type mines for extraction of trona (sodium carbonate) with access via shafts and tunnels. Mines are at depths of 1,200 to 2,000 feet.
CERTAIN CHARACTERISTICS OF THE OIL SHALES -			
1. Compressive Strength and Stability			
a. With Increased Kerogen Content	Strength decreases - see Exhibit 23.	Strength decreases - see Exhibit 23.	Strength decreases - see Exhibit 23.
b. With Increased Temperatures	Strength decreases - see Exhibit 25.	Strength decreases - see Exhibit 25.	Strength decreases - see Exhibit 25.
c. With Increased Thickness of Shale	Strength decreases; important in the thicker shale beds of central Piceance basin.	Strength decreases; thinner beds of this basin less affected.	Strength decreases; thinner and laminated beds of this basin less affected.
d. With Lithologic Variations	Strength increases for thinner and more heterogeneous beds. However, strength decreases with thicker, more homogeneous beds of this basin.	Strength increases for the thinner shale beds of the Uinta basin.	Strength increases for the thinner beds and more heterogeneous lithology of this basin.
2. Kerogen or Oil Content			
a. Gallons Per Ton of Shale	25 to 30 gallons per ton common; certain shales as high as 40 to 50. See Exhibit 9.	Approximately 15 to 25 gallons per ton of shale; less attractive than Piceance basin for oil mining.	Approximately 10 to 18-20 gallons per ton of shale; less attractive than the Piceance basin for oil mining.
b. In-Place Oil for the Richer Shales	Approximately 80 percent of the estimated 600 billion barrels of oil in the richer shales (more than 15 feet thick and more than 25 gallons of kerogen or oil per ton of shale).	Approximately 15 percent of the estimated 600 billion barrels of oil in the richer shales.	Approximately 5 percent of the estimated 600 billion barrels of oil in the richer shales.
3. Thickness of Oil Shale Beds			
a. At Center of Basin	Approximately 1,000 feet thick at basin center.	Approximately 130 feet maximum thickness.	Approximately 150 feet maximum thickness.
b. At Margin of Basin	Approximately 100 feet thick at basin margin.	Very thin at the margin of the basin.	Zero to 25 feet at the margin of the basin.
HYDROLOGY OR GROUNDWATER SYSTEMS -			
1. Predominant Characteristic	Shale beds and adjoining formations are an integral part of the groundwater system, at least to overburden depths of 1,500 to 1,800 feet. Controlled by extensive jointing and fracturing.	Indications are that the shale beds are not a part of the groundwater system in the Uinta basin where the associated aquifers are coarser clastic wedges interbedded with the oil shale.	Indications are that the shale beds are not a part of the groundwater system in this basin where the associated aquifers are coarser clastic wedges interbedded with the oil shale.

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SUMMARY OF CERTAIN FACTORS AFFECTING THE SUITABILITY OF THE OIL SHALES (Contd)

Data by Basins	Piceance Basin, Northwestern Colorado	Uinta Basin, Northeastern Utah	Greater Green River Basin, Southwestern Wyoming
HYDROLOGY OR GROUNDWATER SYSTEMS (Contd)			
2. Secondary Features	Indications are that certain areas along the southern margins of the basin are not a part of the groundwater system and may present conditions for relatively dry operations.	Indications are that certain areas along the southern margins of this basin may present conditions for relatively dry mining operations. Needs further study.	Current longwall trona mining between 1,200 and 2,000 feet have some water invasion thought to be from fractures caused by the longwall mining method; also some water in the shafts.
AS SOURCE MATERIAL FOR RECOVERY OF OIL -			
1. Primary Areas of Probable Activity	This basin has attracted most of attention for attempts at oil mining because of the richer and thicker shale beds; see Exhibit 10.	Not much attention and activity have been attracted to the Uinta basin for oil mining because of the richer and thicker beds of the Piceance basin.	Not much attention has been attracted to this basin for oil mining to date; there are several trona mines operating between 1,200 and 2,000 feet.
2. Areas of Marginal Interest	Certain areas around the edges of the basin may attract marginal interest for oil mining because of thinner zones and lower kerogen content.	Certain areas around the basin edges may be of marginal interest for oil mining.	With the lower kerogen content and thinner shale beds, most of the areas of this basin probably would be considered to have marginal, if any, interest for mining to recover oil and gas.
CONSIDERATIONS RELATING TO POSSIBLE STORAGE OF RADIOACTIVE WASTE MATERIALS -			
	Groundwater movement into and through the oil shales presents severe problems. In particular areas, the Parachute Creek Member (richest oil shale zone) may not be a part of the groundwater system; would need further study.	Shale beds do not appear to be a part of the groundwater system; instead, the associated aquifers are coarser clastic wedges interbedded with the oil shale; however, more study needed.	Shale beds do not appear to be a part of the groundwater system. Associated aquifers appear to be coarser clastic wedges interbedded with the oil shale; more study needed.
	Area of primary interest for oil mining due to richer and thicker shale beds.	Very little activity at this time relating to oil mining of the shale beds. Shale beds are thinner and leaner than those in Piceance basin, thus probably be many years before interest in oil mining picks up.	Very little activity relating to oil mining of the shale beds. Shale beds are thinner and leaner than those in Piceance basin, thus probably be many years before any interest shown in oil mining.
	Richer, thicker, and more homogeneous shale beds reduce the strength and stability of mined cavities	Thinner and more heterogeneous beds should give added strength to mined cavities.	Trona mines in operation at about 2,000 feet. These mines have some water invasion thought to be from fractures caused by the "longwall" mining method being used; also some water in the mine shafts.
	Selected areas along southern margin of basin situated above water level might offer favorable potential for storage of certain waste material; however, thinness of overburden could be an unfavorable factor.	Some gilsonite veins that run perpendicular to direction of groundwater movement might offer shield from groundwater movement.	Thinner, leaner and more heterogeneous beds could add strength to mined cavities.
		Depth of shale beds, at 1,000 to 3,000 feet, could be considered favorable for disposal cavities.	Depth of shale beds, at 1,200 to 2,800 feet, could be considered favorable for disposal cavities.

OIL SHALES OF THE GREEN RIVER FORMATION

GENERAL DISCUSSION

The objective of this study was to make a preliminary investigation and to obtain a broad overview at this time of the physical and economic factors which would have an effect on the suitability of oil shale formations for possible storage or disposal of radioactive waste material. Some of the more pertinent factors included in our investigation were (1) the areal extent, depth, thickness and lithology of the oil shale formations as they are found in the Piceance, Uinta, and the Greater Green River basins of the Tri-State area of Colorado, Utah, and Wyoming; (2) the availability of cavities such as those created by the "room-and-pillar" or the "in-situ" in-place retort mining operations for possible use in waste disposal; (3) physical characteristics of the oil shales, both at normal and elevated temperatures; (4) thermal effect on the "stability" of the oil shales as relates to the roofs, walls, pillars, etc., of possible storage cavities; (5) the hydrology or groundwater movement in the oil shale formations and/or of the adjoining formations as relates to tightness of seal and dryness of possible storage cavities; (6) economics of using the oil shale formations as source material for production of oil and gas; and (7) consideration of the other non-oil shale resources of the area. Summary discussion of the results of our investigation of these items and their relationship to the Piceance, Uinta, and the Greater Green River basins of Colorado, Utah, and Wyoming is included in the following section of this report. Also, each of these items is discussed in more detail in the GEOLOGICAL DISCUSSION section of this report.

In general, it appears that certain waste material might be stored in cavities, such as the "room-and-pillar" type, in certain selected areas of each of the three basins, provided thorough study of the hydrology or groundwater systems of the basin and of each area considered verifies conclusively that cavities being considered are now and will remain completely free of any water invasion. Such room-and-pillar type cavities may become available at some future date as a result of mining the oil shales for the recovery of oil and gas, and we believe that favorable consideration may be given to the storage of low-level, non-heat generating waste material in some of these mined cavities but that further detailed study will be required for each possible storage site and of the particular

waste material to be considered for disposal. However, we believe it much more likely that cavities which would be suitable for the storage of high-level, heat generating radioactive waste, based on such factors as the compressive strength and stability of the shale beds and the subsurface movement of groundwater, will have to be created for that specific purpose. In considering the possible waste storage in underground cavities of these three basins, we believe there are favorable factors for considering cavities in selected areas of each of the basins; but, as discussed below, there are also a number of unfavorable factors which would affect the selection of location and the conditions under which such waste material might be stored.

Our investigation also indicates that consideration might be given to the disposal of waste material in the Mancos shales found in these basins; however, we did not pursue the investigation of the Mancos shales to an appreciable extent and point out that much more study would be required before even preliminary opinions could be formulated concerning their possible use for disposal of waste material.

LOCATION AND EXTENT OF THE OIL SHALES

As shown on Exhibit 1, broad areas in Colorado, Utah, and Wyoming contain significant oil shale deposits in the Green River Formation. It is estimated that these oil shale deposits underlie approximately 25,000 square miles of land in this tri-state area. Of the thicker and higher oil content shales, containing an estimated 600 billion barrels of in-place kerogen, approximately 80 percent is found in the Piceance basin of Colorado, 15 percent in the Uinta basin of Utah, and 5 percent in the Greater Green River basin of Wyoming. In the Piceance basin, the oil shale is found at depths varying from zero where it outcrops along the valley walls on the southern margin of the basin, to 200-400 feet along the ridgetops, and to approximately 1,000 feet in the northern portion of the basin. In the Uinta basin, the oil shale is found at depths of approximately 500 to 3,000 feet. In the Greater Green River basin, it is buried under an overburden of approximately 1,200 to 2,800 feet. The thickness of the oil shale varies from 100 feet along the outer edge of the deposits in the Piceance basin to as much as 1,000 feet in the center of the basin; thickness of the shale in the Uinta basin approaches 130 feet, whereas the thickness in the Greater Green River basin varies from 25 feet to a maximum of approximately 150 feet. The richest oil shales are found in the Piceance basin where shales

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containing 25 to 30 gallons per ton are common; the oil content of the shales in the Uinta basin is approximately 15 to 25 gallons per ton; and in the Greater Green River basin the content ranges from approximately 10 gallons per ton to 18-20 gallons per ton.

The above factors of depth, thickness, and oil content have attracted most of the interest in developing mining processes for recovering oil from the shales to the Piceance basin as illustrated by recent bonus bids of \$210 million and \$117 million for Colorado Tracts C-a and C-b, shown on Exhibit 10, whereas no bids were received for two Wyoming tracts during the recent offering. As a result of this, it is likely that underground cavities which may become available as a result of mining operations to extract oil from the oil shales will be located in the Piceance basin. On the other hand, it appears that cavities to be considered for the possible storage of waste material in the Greater Green River and the Uinta basins will have to be created for this specific purpose, except possibly for the trona mining cavities found at depths of approximately 1,200 to 2,000 feet in the Green River basin.

AVAILABILITY OF MINED CAVITIES FOR USE IN POSSIBLE WASTE DISPOSAL

As indicated above, it appears that underground cavities in the Piceance basin will result at some future date from the room-and-pillar method of mining and perhaps from the "in-situ" in-place retorting techniques of recovering oil from the oil shales, although we believe it will be several years before such oil mining operations reach significant levels. As pointed out in the GEOLOGICAL DISCUSSION section of this report, the richer and thicker oil shale beds are located in the Piceance basin and these are the factors attracting the oil mining operations to this basin. However, these particular characteristics become unfavorable factors on the compressive strength of the shale and, therefore, the stability of the roofs, walls, pillars, etc., of the cavities created by the room-and-pillar method of mining the oil shales. If the "in-situ" in-place retorting technique of oil recovery is used, the compressive strength of the shale and the stability of the cavities are decreased further as a result of higher temperatures, as shown on Exhibit 25.

Of particular significance, oil shale deposits in the Piceance basin are considered to be an integral part of the groundwater system, at least to overburden depths of 1,500 to 1,800 feet, as a result of the exten-

sive jointing structure system in which the interconnected jointing system is the principal pathway for the downward percolating groundwater in the basinal recharge area; the jointing also affects the strength of the rock in mine pillars and roofs. The Mahogany zone, constituting the principal oil shale zone of the Piceance basin, is thought to be not a part of the groundwater system and, therefore, mined cavities in the Mahogany zone may be free from water invasion; however, local fault zones and poorly cemented wells drilled through the Mahogany zone could result in water invasion in those particular areas. Therefore, even though certain areas may be found where water-free cavities could be mined in the Mahogany zone, more detailed and careful studies would have to be conducted to definitely confirm that this could be done. In general, it appears that the groundwater is a negative factor for waste storage in the Piceance basin except possibly at the very southern margins of the basin where local conditions could result in relatively dry operations. In the southern margins of the basin, the oil shale zones occur at the surface of some of the valley walls; but, as the shale zones become further removed from the valley walls, they are under overburdens of several hundred to a thousand feet. The possibility of long-term erosion of the overburden at or near the valley wall surfaces could become a problem when considering the long time-interval involved in the disposal of waste material.

Currently, the existing mined cavities in the Greater Green River basin are the trona (sodium carbonate) mines located in the southern portion of the basin as shown on Exhibit 20, where longwall cavity-type mines are in operation at depths of approximately 2,000 feet. It is doubtful that the oil shales will be mined for recovery of oil for many years in view of the abundance of the much richer and thicker oil shale beds found in the Piceance basin. Therefore, it appears that any cavities available for possible storage of waste material will have to be mined for that specific purpose. Such cavities mined in the Greater Green River basin would have characteristics of greater strength and stability inasmuch as the thinner and leaner oil shale is stronger than the rich thicker shale of the Piceance basin and is less susceptible to changes in physical properties with increased temperatures. The increased depth of such mined cavities, in the depth range of 1,500 to 2,800 feet, would be a favorable consideration.

The Greater Green River basin oil shales do not appear to be part of the groundwater system. In this basin, the associated aquifer is coarser clastic wedges interbedded with the oil shale and probably would not be a problem in the consideration of waste disposal. However, opera-

tions in the present trona mines have encountered some water problems that seem to be associated with their longwall mining technique which probably would not be encountered in smaller room-and-pillar operations. But the very presence of any water in these mines emphasizes the necessity of further detailed study of the groundwater system of the basin when considering the possibility of using mined cavities in the shale or trona beds for the storage of waste materials. At the present time, the absence of useful data for studying the groundwater system of the Greater Green River basin would present a problem in conducting such a study; comprehensive studies may have to await the availability of further pertinent data and this is considered a negative factor at this time in considering when mined cavities may become available for possible waste disposal.

In the Uinta basin, no mined cavities are currently available for consideration as storage sites for waste materials. It is doubtful that the oil shales will be mined for recovery of oil for many years in view of the greater interest shown for the richer and thicker oil shale beds of the Piceance basin. Therefore, it appears that any cavities available for possible storage of waste will have to be mined for that specific purpose. This could be an advantage since the cavity size, the room-and-pillar dimensions, and other design and construction features could be incorporated to provide maximum strength and stability of such cavities. As in the Greater Green River basin, any cavities mined in the Uinta basin should have characteristics of greater strength and stability inasmuch as the thinner and leaner oil shale is stronger than the rich, thicker shale of the Piceance basin. Also, the greater depth, in the range of 2,000 to 3,000 feet, would be a favorable consideration for the possible storage of waste material.

The Uinta basin oil shales do not appear to be part of the groundwater system; however, much less is known about the groundwater system of the Uinta basin than that of the Piceance basin and more detailed studies would be required as part of a waste storage program study.

PHYSICAL CHARACTERISTICS OF THE OIL SHALES

The physical characteristics of the oil shales at both normal and elevated temperatures are discussed in the geological section of this report and illustrated on certain of the accompanying exhibits. Some of

these characteristics and the manner in which they may be affected by the possible storage of radioactive waste in the shales are summarized below:

1. Compressive Strength and Stability of the Oil Shales -

- a. Increased kerogen or oil content decreases the compressive strength of the shale, as shown on Exhibit 23.
- b. Increased temperatures decrease the strength of the shale; the reduction in strength is greater the higher the kerogen content, as shown on Exhibit 25.
- c. Thicker shale beds exhibit decreased strength and stability whereas the thinner beds are stronger and more stable. The thinner beds are less susceptible to changes in physical properties by increased temperatures.

2. Range of Kerogen or Oil Content of the Oil Shales -

- a. Piceance basin of Northwestern Colorado - 25 to 30 gallons per ton is common, with some shales having as much as 40 to 50 gallons per ton.
- b. Uinta basin of Northeastern Utah - approximately 15 to 25 gallons per ton.
- c. Greater Green River basin of Southwestern Wyoming - 10 to 20 gallons per ton.

3. Thickness of the Fair to Richer Oil Shales -

- a. Piceance basin of Northwestern Colorado - 100 feet at the edge of the basin to approximately 1,000 feet at the center.
- b. Uinta basin of Northeastern Utah - approximately 130 feet maximum.
- c. Greater Green River basin of Southwestern Wyoming - approximately 150 feet maximum.

4. Stratigraphic Nature of the Shale Beds -

- a. Piceance basin - The bulk of the oil shale occurs in the Parachute Creek Member of the Green River Formation. The overall stratigraphic nature of the Parachute Creek Member is one of a layered system, with the basin margins consisting of interbedded rocks representing the various depositional environments such as flood-plain mudstones and sandstones; fresh water pond shales and limestones; swamp shales, coals and sandstones; and lake bottom shales, marlstones, and tuffaceous sandstones. In the center of the basin, the layered system consists of interbedded shales, marlstones, tuffaceous sandstones, and salines. In all cases, the layers are composed of material with different rock properties, i.e., strength, plasticity, transmissivity, sonic velocity, density, conductivity, heat capacity, etc. The thickness of the "net" oil shale varies from approximately 100 feet at the edge of the basin to 1,000 feet at the center. The richer and thicker beds of the Piceance basin affects the strength and associated properties of the oil shales as indicated above and as discussed in more detail in the Geologic Section of the report.
- b. Uinta basin - the Parachute Creek Member is the principal oil shale unit, consisting mainly of marlstone, oil shale, siltstone, sandstone, and tuff. Most of the oil shale members represent deposition in a saline or stratified saline/fresh water lake. The oil shale occurs in layers ranging from paper thin to more than one inch thick and varies in color from tan to very dark grey; the richer the beds, the darker the color. The Parachute Creek Member varies from a few hundred to more than 1,000 feet thick and contains maximum "net" oil shale thickness of approximately 130 feet.
- c. Greater Green River basin - The oil shale is found in three members of the Green River Formation: the Tipton shale; Wilkins Peak; and Laney Members, listed from bottom to top. The Tipton Member contains the bulk of the oil shale in this basin. The Tipton Member consists of tan to brown oil shales, calcareous sandstones, and subordinate siltstones, marlstones and limestones. This heterogeneous sequence varies in thickness from zero to about 400 feet and contains a maximum "net" oil shale thickness of approximately 150 feet.

The thermal properties of the oil shales such as (1) specific heat, (2) heat content of raw and spent oil shale, and (3) thermal conductivity and diffusivity of raw oil shale are described in considerable detail in the Geological Section of the report. The reaction time for 90 percent decomposition of kerogen in Colorado oil shale is shown on Exhibit 27. As shown, the reaction time for 90 percent decomposition of the kerogen decreases as the temperature increases. Thus, retorting of the shale with its change in rock characteristics can take place at temperatures lower than the conventional retorting temperatures used to define commercial oil shale processing. As illustrated, retorting can take place in about 6,000 minutes for temperatures as low as 650° F. and this could become an important factor in considering the storage of heat producing radioactive wastes in the oil shales of the Piceance basin and to a lesser degree in the Uinta and Greater Green River basins where the thinner and leaner oil shales are less affected by increased temperatures; and, of course, the thermal properties of the shales would not be affected by the storage of low-level waste material which produces little, if any, heat.

HYDROLOGY OR GROUNDWATER SYSTEMS OF THE OIL SHALE FORMATIONS

The Geological Discussion section of this report contains detailed discussion of the hydrology or groundwater systems for each of the three basins under study, i.e., the Piceance basin, the Uinta basin, and the Greater Green River basin. Also, there is a lengthy discussion of the subsurface jointing system of the rocks in the Piceance basin and the important effect that the joint structures or systems has on the hydrologic regime of the basin.

In the Piceance basin, the oil shale deposits are part of the groundwater system, at least to overburden depths of 1,500 to 1,800 feet. The oil shale in this basin is more pervasively fractured and comprises the principal groundwater aquifer in the basin. In addition, the fracture and jointing system of the rocks adjoining the oil shales permit the movement of groundwater through these rocks into and through the oil shales themselves. Thus, it would appear that the groundwater movement in most of the Piceance basin presents some problems in the consideration of waste storage in the oil shales.

The Uinta and Greater Green River basin oil shales do not appear to be part of the groundwater system. In these basins, the associated

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aquifers are coarser clastic wedges interbedded with the oil shale and probably would be less of a problem in the consideration of waste disposal in the oil shales of these basins. Operations in the present trona mines of the Greater Green River basin have encountered some water problems that seem to be associated with their longwall mining technique which probably would not be encountered in smaller room-and-pillar operations. The closing of the mined-out area following the final draw has apparently opened fractures between the underlying aquifers and the workings, permitting flows into the mines of several hundred gallons per minute. In addition, low volume water leaks from the overlying Bridger Formation of 10 to 30 gallons per minute have occurred around working and ventilation shafts. Even though the water encountered in the trona mines of the Green River basin is thought to be controllable by using smaller room-and-pillar type cavities, the very presence of any water in these mines emphasizes the necessity of further detailed study of the groundwater system of the basin when considering the possibility of using mined cavities in this basin for the storage of waste materials, and this becomes an unfavorable factor in the consideration of such waste storage.

OIL SHALES AS SOURCE MATERIAL FOR PRODUCTION OF OIL AND GAS

The oil shales of Colorado, Utah, and Wyoming are considered an important potential source material for the recovery of oil and gas. It is estimated that the richer portions of the shales (more than 15 feet thick and yielding more than 25 gallons of kerogen or oil per ton of shale) contain as much as 600 billion barrels of in-place oil, of which approximately 80 percent is located in the Piceance basin of northwestern Colorado, 15 percent in the Uinta basin of northeastern Utah, and 5 percent in the Greater Green River basin of southwestern Wyoming. Considerable numbers of research and pilot type operations have been undertaken during the past several years in an attempt to determine the most practical method of recovering oil and gas from the oil shales and to determine the economics of such mining operations. Most of the programs and processes currently under study and in various stages of operation are outlined in the accompanying paper by Charles H. Prien titled Current Oil Shale Technology: A Summary, included as an Appendix to this report. References to indicated capital costs and annual operating costs are expressed in 1970 dollars; these costs at the present time probably would be about double those indicated in the article. Our investigation indicates to us that a stable oil price in the range of \$12 to \$16 per barrel will be required to provide the economic

incentive necessary to justify the initiation of the full-scale mining programs to recover substantial amounts of oil from the oil shales under present economic conditions and current state of technological development.

The forward progress of most mining operations has been substantially slowed during the recent past, awaiting the resolution of a number of economic, political, and environmental issues; we believe the future mining operations of the oil shales will remain essentially inactive until most of these important issues have been resolved, which we believe will require at least three to five years. Thus, we believe it will be several years before mined-out cavities resulting from these operations will become available for consideration as possible storage or disposal sites for radioactive waste material. However, we believe it more likely that such cavities as would be suitable for waste storage will have to be mined for that specific purpose and that certain advantages of design and construction would result from the mining of cavities for that specific purpose.

Our investigation further indicates that cavities more favorably suited for waste storage will likely be located in areas least attractive for oil mining operations. It is also noted that the small area required for a possible waste storage site would be so minuscule as to be insignificant when compared to the approximate 25,000 square mile area of the oil shale formations. Therefore, we believe that the use of the oil shales as source material for production of oil and gas does not preclude the storage of waste material in certain areas of each of the three basins included in our study. The factors affecting the selection of locations of such possible storage sites including the effect that these factors have on the suitability of underground cavities located in the various areas of these basins were the subject of our investigation, the results of which are covered in the different sections of this report.

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SUMMARY OF GEOLOGICAL DISCUSSION

Information on the oil shale and associated groundwater is available in good detail for the Piceance basin and in fair to poor detail for the Uinta and Greater Green River basins. The oil shale is a very heterogeneous deposit. The thickest sections of fair to rich oil shale occur in the Piceance basin. The oil shale in the Greater Green River basin generally consists of beds of poor to fair oil shale a few tens of feet thick separated by beds of different lithology. The Uinta basin oil shale geometry is intermediate between the Piceance and Green River basin situation. The oil resources in the richer oil shale in the three basins are distributed about 80 percent in the Piceance basin, 15 percent in the Uinta basin, and 5 percent in the Greater Green River basin. At the present time, the processing of the oil shale to obtain oil involves open pit and "room-and-pillar" type mining and different above-ground retorting methods together with experimental "in-situ" in-place retorting recovery techniques. To date, the type of exploitation technology to be used in developing the oil shale has not been determined for any of the basins.

Oil shale mining has been initiated along the southern margin of the Piceance basin. The mines are associated with research projects, are rather small, and use adit access to the room-and-pillar operations in the rich oil shale zone. Some shaft access, room-and-pillar, or longwall mining operations are being carried out in the Green River basin in the trona associated with the oil shale.

The oil shale in the Piceance basin is more pervasively fractured and comprises the principal groundwater aquifer in the basin. The oil shale in general is not the aquifer material in the Uinta or Green River basins. In these basins the associated aquifers are coarser clastic wedges interbedded with the oil shale. The groundwater systems in both the Uinta and Green River basins are not well known. The groundwater systems could complicate radioactive waste storage projects in all three basins.

The physical characteristics of the oil shale tend to be quite heterogeneous as a result of (1) the variation in the kerogen content of the individual thin layers or varves that comprise the oil shale and (2) the variation in properties measured parallel, perpendicular, and oblique to the bedding. The oil shale sequence can be generally characterized by a comprehensive suite of logs. The compressive strength of the shale decreases as the kerogen content increases. Also, the strength of the oil

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shale is markedly reduced if it has been subjected to high temperatures; the reduction in strength is proportional to the kerogen content. The strength of large structures such as pillars or roofs is also reduced by fractures, joints, and clay seams. Rooms with 60 x 60 x 60-foot dimensions have been constructed in the thin overburden Mahogany Zone mines in the Piceance basin. Some roof falls and pillar instability have been encountered in these operations.

All three basins are considered regions of considerable non-oil shale resource value. They contain significant oil and gas, saline mineral and coal as well as uranium, copper, phosphate, gold, etc. Thus, the development of these mineral resources should be factored into any waste storage planning.

Active and vocal groups with anti-nuclear biases are present in and near the Piceance basin in Colorado and the Green River basin in Wyoming.

The recent oil shale leasing program produced a voluminous environmental impact statement⁽¹⁾ that provides a good compilation of data on the regional flora and fauna, esthetic and socioeconomic resources, land ownership, etc., as well as a summary of the hydrology, oil shale, and other resources of the area.

Respectfully submitted,

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GENERAL GEOLOGY OF OIL SHALE AREAS

Introduction

In discussing the general geology of oil shale, it is interesting to point out that oil shale does not contain oil, nor is it a shale. The rock is classified as a marlstone, a rock containing approximately equal parts of carbonate and clay size silicate material. The hydrocarbon in the rock is in the form of kerogen, a solid mineraloid that is relatively insoluble in organic solvent such as benzene and must be pyrolyzed to yield oil.

Broad areas in the tri-state area of Colorado, Utah, and Wyoming contain significant oil shale deposits in the Green River Formation, Exhibit 1⁽¹⁾*. The Green River Formation was deposited in a large inland Eocene Lake complex that probably had a maximum cumulative extent of over 50,000 square miles. Currently known oil shale deposits underlie approximately 25,000 square miles of land in this tri-state area.

This discussion of the geology of the oil shale areas will be divided into three parts: (1) the Piceance basin in Colorado; (2) the Uinta basin in Utah; and (3) the Greater Green River basin in Wyoming and Colorado.

Piceance Basin

Introduction

The Piceance basin contains the bulk of the fair-to-rich oil shale of the tri-state or western oil shale area (80 percent of the estimated 600 billion barrels of oil in place) that is more than 15 feet thick and yields more than 25 gallons of oil per ton. The geology of the oil shale beds, the associated groundwater systems, and other parameters associated with oil shale development have been studied in greater detail in the Piceance basin than in the other basins because of its greater apparent economic value. For instance, the successful bonus bids on Colorado Tract C-a and C-b were \$210 million and \$117 million, indicating the magnitude of current interest in the oil shale of Colorado.

* Numeric footnotes refer to the references at the end of the report. Reference (1) is the 1973 Oil Shale Environmental Statement. The oil shale underlies land largely owned by the Federal Government. Some of this land was recently leased and the comprehensive Environmental Statement was prepared prior to the leasing. The authors of the Environmental Statement attempted to collect and evaluate all the factors that would impact on oil shale development.

The U.S. Bureau of Mines has had oil shale mining and processing research operations in the Piceance basin since the late 1940's, and several other organizations or groups of organizations have been active in the area in the last ten to fifteen years. Thus, there is some background experience and, more important, facilities that can be inspected.

One additional factor that should be considered in a possible nuclear waste storage project is the attitude of the people in the area and the local, regional, and statewide biases on "nuclear" operations. Colorado has a number of outspoken anti-nuclear groups. In addition, there are local (Grand Junction, Colorado) hard feelings about alleged "Federal Government's lack of responsibility" in taking care of tailings and other residue from Government-associated uranium milling and mining operations in the past. There are also State Laws resulting from a recent referendum that require an affirmative majority vote from a statewide ballot prior to commencing a nuclear operation in the state. This law might be unconstitutional, hence not applicable to nuclear waste disposal, but it reflects the general feelings of a majority of the voters in the state.

Other factors that will be discussed in some detail in this section of the report are (1) the oil shale beds themselves constituting the principal groundwater aquifer in the basin and (2) the lack of definition about the type of oil shale operations that will be undertaken.

Physiography and Climate

The principal oil shale resources in the Piceance basin lie in the area between the Colorado and White Rivers. This is a saucer-shaped plateau bounded by oil shale capped scarps and is deeply dissected on its southern margin, Exhibit 2. Drainage in the southern portion of the basin flows into the Colorado River via Parachute, Evacuation, and Roan Creeks. Drainage in the northern portion of the basin flows into the White River via Piceance and Yellow Creeks.

The elevation on the plateau varies from about 5,000 feet at the mouths of Piceance and Yellow Creek to about 9,000 feet on the divides along the south basin margin. The relief varies from several thousand feet in the creek valleys along the southern basin margin to 400 to 600 feet in the rolling parallel valley ridge region in the basin's center. The higher elevations are forested with pinon pine, juniper, and aspen; the lower elevations are typified by a sagebrush-rabbit brush vegetation.

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Precipitation varies from 24 inches per year in the higher portions of the plateau to less than 12 inches in the center of the basin. About half of the precipitation occurs as snowfall in the period December through April. About 1,000,000 acre-feet of precipitation falls on the basin each year. About 65,000 acre-feet is carried into the Colorado and White Rivers as runoff. The rest is carried back into the atmosphere as evapotranspiration or seeps into the basin's groundwater system. Temperatures in the Piceance basin vary from more than 100° F. in the basin center during the summer to minus 40° F. in the higher elevations during the winter.

A comprehensive discussion of the fauna, soils, vegetation, esthetic and socioeconomic resources, ownership, etc., for the Piceance basin is found in Reference 1.

Stratigraphy

The Piceance basin contains a sequence of sedimentary rocks more than 20,000 feet thick. Exhibit 3 is a generalized east-west cross-section across the basin center showing the relative thickness and the inter-relationships of the various formations. The stratigraphy of the oil shale-bearing Green River Formation and the underlying Wasatch and overlying Uinta Formations will be summarized below. Information about the other formations can be found in the literature⁽⁴⁾.

The Wasatch Formation of Eocene age consists predominately of interbedded shales and sandstones of fluvial origin, Exhibit 4. The shales, the dominate Wasatch lithology, are generally brightly colored (yellow, tans, reds) and are relatively easily eroded when exposed to weathering processes. The sandstones are predominately of fluvial channel and point bar origin, with subordinate lacustrine deltaic and mountain front pediment sands. In general, they do not have very great horizontal continuity. This lack of continuity is probably a critical factor limiting the occurrence of a pervasive groundwater system in the Wasatch rocks of the Piceance basin. Other subordinate lithologic types found in the Wasatch Formations are fresh-water limestones, marlstones, and siltstones.

The Green River Formation is commonly divided into three units: the Douglas Creek; the Garden Gulch; and the Parachute Creek Members, in ascending order. The bulk of the oil shale occurs in the Parachute Creek Member.

The Douglas Creek Member is the basal unit of the Green River Formation over most of the basin and varies in thickness from zero to 470 feet. Predominate lithology is shale and sandstone, with minor amounts of algal and oolitic limestone. The sandstone continuity is not sufficient under most of the basin to provide aquifer capacity. Gas and oil occur in some of the isolated sandstone lenses located in the center of the basin.

Also in the Green River Formation, the Garden Gulch Member overlies the Douglas Creek. Thickness of the Garden Gulch Member varies from 290 to 1,000 feet, and predominate lithologies are clay shales and lean-to-fair grade oil shales. The Garden Gulch Member is impermeable except for minor fracturing near the outcrop areas.

The Parachute Creek Member overlies the Garden Gulch. The Parachute Creek varies in thickness from 200 to 2,000 feet. Predominate lithology is lean-to-high grade oil shale with thin analcitized tuff and sandstone beds. Bedded and disseminated saline minerals such as halite, nahcolite, and dawsonite occur in the central part of the basin. The Parachute Creek sequence is the most important oil shale bearing unit and will be discussed in greater detail than the other units.

A brief review of the Eocene depositional environment is helpful in presenting the Parachute Creek stratigraphy in perspective. The mountain building that marked the transition from Cretaceous to Tertiary also produced the broad intermountain basins in which were formed Lake Uinta (in which the oil shales of the Piceance and Uinta basins were deposited) and Lake Gosiute (in which the oil shales of the Green River, Washakie, and Sand Wash basins were deposited). The mountain front environment produced the coarse clastic conglomerates and pediments. These commonly red-colored and generally highly transmissive sediments are present along the eastern margin of the Piceance basin as a clastic wedge in the Wasatch Formation. The coarse clastic rocks that were the time equivalent of the Green River Formation, formerly called the Anvil Point Member, now are generally considered a tongue of the Wasatch Formation.

Flood plain deposition by distributary streams produced interbedded lenticular sandstones and mudstones. Where the soils were well-drained and oxidized, the resulting sandstones are red or grey in color and the mudstones or shales are variegated in red, maroon, purple, brown, grey, and green. Where the soils were moist and saturated, the

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resulting colors are greys and greens. This later environment typically occurred between the red beds and the beds deposited along the margins of the fresh water lakes. These lake margin fluviatile rocks are generally less highly transmissive than those of the red bed environment. Tongues of both red bed and non-red bed fluviatile sediments occur in the Parachute Creek Member along the basin margins. The sandstones have some transmissivity, hence can act as aquifers; but a more important aspect is that these layers have rock properties that contrast markedly with some of the vertically adjacent pond, swamp, and lake deposits that make up the bulk of the Parachute Creek Member.

The lacustrine environments found in the Piceance basin are of two types, fresh and saline. The fresh water lake deposits are generally finely laminated, light to medium brown, papery, kerogenaceous shales. Their carbonate content is generally less than 25 percent, and they generally assay less than 15 gallons per ton. The saline lake deposits are finely laminated, dark brown to black, tan weathering, dolomitic, kerogenaceous shales. Their carbonate content is generally greater than 50 percent and generally they assay more than 15 gallons per ton⁽⁵⁾. These saline lake deposits have an associated evaporite sequence in the lower and middle Parachute Creek Member in the north-central part of the basin⁽⁶⁾, Exhibit 5. The principal minerals are halite (NaCl), nahcolite (NaHCO_3), and dawsonite ($\text{NaAl}(\text{OH})_2\text{CO}_3$). The halite occurs as bedded deposits; the nahcolite and the dawsonite generally occur as admixtures with the oil shale. The saline mineral area corresponds to the maximum thickness of the oil shale and to the maximum thickness of the Parachute Creek Member⁽⁶⁾.

Thus, the overall picture of the Parachute Creek Member is one of a layered system. On the basin margins, the layering consists of interbedded rocks representing the various depositional environments: floodplain mudstones and sandstones; fresh water pond shales and limestones; swamp shales, coals and sandstones; and lake bottom shales, marlstones, and tuffaceous sandstones. In the center of the basin, the layered system consists of interbedded shales, marlstones, tuffaceous sandstones, and salines. In all cases, the layers are composed of material with different rock properties, i.e., strength, plasticity, transmissivity, sonic velocity, density, conductivity, heat capacity, etc.

Overlying the Parachute Creek Member, currently considered the uppermost unit in the Green River Formation, is the Uinta For-

mation. Until recently, the Uinta Formation in the Piceance Basin was called the Evacuation Creek Member of the Green River Formation. A revision was made by Cashion and Donnell⁽⁷⁾ that seems to be accepted. The Uinta Formation consists of interbedded fresh water lacustrine tuffaceous sandstones, siltstones, shales, and marlstones. These rocks constitute a sequence comprising differing characteristics. Some of the sandstones have enough continuity and transmissivity to conduct water.

Structure

The Piceance basin is one of the major structural features of northwestern Colorado⁽⁸⁾, Exhibit 6. The deepest part of the basin is near the depocenter of the oil shale bearing Parachute Creek Member. The relatively simple structure displayed in Exhibit 6 is probably due to a lack of information about the deeply buried basement rocks. In the areas where detailed seismic and well surveys are available, the structure is more complicated than Exhibit 6 would suggest, but becomes simpler and less faulted as the surface is approached⁽³⁾. The simpler geology of the Mahogany Marker in the Parachute Creek Member of the Green River Formation⁽³⁾ can be compared with the relatively complex faulting found in the Mesaverde Formation⁽³⁾. Although the fault density decreases in the younger rocks, fracturing or jointing is a ubiquitous feature of the near surface strata.

The Piceance basin can be considered a feature marginal to the Colorado Plateau. This plateau and surrounding areas are pervasively jointed^(9,10). The primary regional joint system in the Piceance basin is west-northwest and north-northeast⁽¹¹⁾. Where the regional surface dip is roughly parallel to a primary joint set, the drainage and topography tend to pick up this alignment. Although the primary joint orientation may be relatively uniform over broad areas, the areal distribution of the joint density is usually non-uniform⁽¹²⁾. (Density refers to the spacing of joints, i.e., number of joints per unit area). In addition, local features can induce or modify the joint set direction and density^(13,14).

The jointing density is also characteristic of the rock. In general, the thinner and more brittle the rock unit, the denser the jointing. This general concept is expressed quantitatively by equation⁽³⁾:

$$D \cong (DnF)/h$$

where

D = joint density, number of joint traces per square yard

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and

D_n = normalized joint density, number of joint traces per square yard (Normalized joint density is the density at a specific locale of jointing in a hard sandstone one foot thick.)

h = thickness of bed, feet

F = formation lithology factor (ranges from 0.25 for plastic shales to more than 2 for brittle limestone layers).

The rock units in the Piceance basin may range from an inch to many tens of feet in thickness. The critical feature in identifying a rock unit is that the physical characteristics of adjacent element within the unit must be similar enough so that the unit bends and breaks as an entity.

The picture of near surface jointing in the Piceance basin that was developed during field studies by a number of workers^(3,11) is one of a great number of relatively thin rock units that are cut by a hierarchy of joints. The basic joints are confined to the basic rock units. A series of rock units can deform as a major unit and be cut by a major joint set. Major units can deform together as master units and be cut by master joints. The height of the joints varies from inches to a few tens of feet for basic sets, from a few feet to a hundred feet for major sets, and from a few tens of feet to several hundred feet for the master joints. The basic joints may be many orders of magnitude more numerous than the major joints, and the major joints are probably several orders of magnitude more numerous than the master joints. The joints terminate vertically at the boundaries of the unit, and horizontally they may just die out within the unit or terminate in a cross-cutting joint. The horizontal extent of a single joint is usually much larger than the vertical extent.

Lateral variation in joint density within a rock unit may vary by a factor of two to three while the variation in joint density between vertically adjacent rock units may vary by a hundred-fold. A periodicity is noted in the lateral variation in joint density. The characteristic "wave length" in the thicker Green River oil shales is in the order of a few hundreds of feet. Hence, it would be uncommon for even one cycle of joints to occur within a mined room, although several cycles could occur in an access tunnel.

The joints tend to close at a critical depth, which depends upon the rock plasticity, the pressure of the fluids in the joints,

and the bulk density of the rocks comprising the overburden⁽¹⁵⁾. Layers in the Mahogany zone appear to close at depths of burial approaching 1,000 feet in the Piceance basin⁽¹⁶⁾. The joint structures in the rock have a controlling effect on the hydrologic regime in the basin.

Waters moving along the joints have leached halite layers in the central portion of the basin. The subsurface removal of as much as 100 feet of material may be the cause of some of the shallow faulting found in the northern part of the basin. The major shallow structural features found in the southern and eastern part of the basin are folds and flexures. The area is part of the seismically rather stable Rocky Mountain province⁽¹⁷⁾. The current lack of anomalous stresses has been verified by several programs^(11,18). However, water injection activities in the nearby Rangely oil field, Exhibit 7, have resulted in a flurry of seismic events in that area⁽¹⁸⁾.

The interconnected near surface jointing system is the principal pathway for the downward percolating groundwater in the basinal recharge area. Also, this jointing system provides the bulk of the transmissivity in the non-leached confined groundwater system. The jointing also affects the strength of the rock in mine pillars and roofs, and is generally a critical factor in the selection of the directions for underground workings.

Hydrology

Surface water runoff from the Piceance basin is small. The 1,500 square mile drainage area within the basin yields an average stream flow into the Colorado and White Rivers of about 65,000 acre-feet per year⁽¹⁹⁾. Data relating to the stream flow into the Colorado and White Rivers are summarized on Table 1. The flow is highly variable from year to year and also during the year⁽²⁾.

The general chemical quality of the water is degraded as the water flows from the streams. The concentration of dissolved salts in the streams is higher when water flow rates are at lower levels⁽²⁾. This relationship is especially marked in the streams located in valleys subject to irrigation during the times of maximum water withdrawal for such irrigation. An appreciable amount of the water used for irrigation is returned to the atmosphere as evapotranspiration. However, a sizable portion percolates into the alluvium of the valley floor and is subsequently discharged

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SUMMARY OF STREAMFLOW RECORDS (Ref. 19)

Streamflow Station	Period of Record	Drainage Area (Sq. Mi.)	Average Discharge (cfs)	Extremes of Discharge (cfs)	
				Maximum	Minimum Daily
West Fork Parachute Creek near Grand Valley	Oct. 1957 Sept. 1962	48.1	4.37	147	0
Parachute Creek near Grand Valley	Oct. 1948 Sept. 1954 Oct. 1964 Sept. 1967	144	17.7	738	0
Parachute Creek near Grand Valley	Apr. 1921 Sept. 1927 Oct. 1948 Sept. 1954	200	30.3	912	0
Roan Creek at Simmons Ranch	June 1935 Sept. 1935 Apr. 1936 Oct. 1936 Mar. 1937 Sept. 1937	79		142	0
Carr Creek at Altenhern Ranch	June 1935 Nov. 1936 Mar. 1937 Sept. 1937	17	2.85	143	0
Roan Creek above Clear Creek	Oct. 1962 Sept. 1967	151	14.8	800	1.0
Clear Creek near DeBeque	July 1966 Sept. 1967	111		1,540	0
Roan Creek near DeBeque	Apr. 1921 Sept. 1926 Oct. 1962 Sept. 1967	321	40.0	1,220	3.2
Piceance Creek at Rio Blanco	Oct. 1952 Sept. 1957	9	1.40	23	.1
Piceance Creek near Rio Blanco	Oct. 1940 Sept. 1943	153	20.3	430	.1
Piceance Creek below Ryan Gulch	Oct. 1964 Sept. 1967	485	12.5	400	.80
Piceance Creek at White River	Oct. 1964 Sept. 1966	629	17.0	550	.90
Yellow Creek near White River	Oct. 1964 Sept. 1966	258	1.37	1,060	0

into the stream as a "bank storage" contribution. The water going through this part of the cycle increases in dissolved solids content and helps to increase stream salinity. Another source of dissolved solids is the contribution from springs and from underflow resulting from groundwater discharge into the alluvium.

General groundwater circulation in the northern part of the basin is schematically portrayed in Exhibit 8. The groundwater system is quite complex and can be broken into three subsystems: the alluvium in the stream valleys; the "A" zone between the Uinta Formation and the Mahogany zone; and the "B" zone between the Mahogany zone and the Garden Gulch or high resistivity zone.

Groundwater flow in the alluvium is predominantly through gravel layers. The bedrock valley floor is usually covered by a basal gravel. This may be overlain with a sandy or clay-like layer and then additional layers of gravels, sands, and clays. The upper layer of the alluvium is generally a rather deep soil. Stretches of the alluviated valleys have piezometric surfaces above stream levels. This occurs when the gravel is overlain by a relatively impermeable clay-like layer and the free water table in the gravel is above the local stream elevation either laterally in the valley⁽²⁾ or upstream or the gravel is being charged by flow from one of the deeper confined groundwater zones. In general, the dissolved solids content of the alluvial groundwater and the stream water are similar, but the alluvial water at any location has a higher salinity. Thickness of the alluvium varies from zero to 140 feet. Transmissivities vary from 1,500 to 100,000 gallons per day per foot, and the storage coefficient averages 0.2⁽²⁾.

Circulation in the upper, moderately transmissive "A" aquifer subsystem is quite complex. The vertical joint or fracture network is the high permeability component of the subsystem. As previously discussed, the fracture pattern varies in density and orientation. Individual rock units have a characteristic fracture density and transmissivity, thus the aquifer behaves like a layered sequence with layers of different permeability. These layers are subject to cross flow as a result of the major and master joints and the wells and faults that cut across them. The cross-section presented as Exhibit 5 will be used to illustrate the flow regime.

The higher elevations receive the bulk of the basin's precipitation and are the recharge region for the Green River groundwater sys-

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tem. The water moves downward through the interconnected fracture system (marked "R" on Exhibit 5). In this region, the water forms one continuous regime and flows toward the north in the groundwater system and toward the south to a lesser degree where it is discharged as springs.

Water moving north in the subsurface is separated by the Mahogany zone. The "A" zone water is confined on the top by the mudstones, shales and siltstones of the Uinta Formation. The water flows through the fractured oil shales and is discharged along fault zones in the center of the basin and from the outcropping, or subcropping, "A" zone rocks along the north-central margin of the basin. The dissolved solids content of the "A" zone water varies from 250 milligrams per liter near the southern periphery of the basin to several thousand milligrams per liter near the north-central portion of the basin^(19,20). Wells producing water from the "A" zone vary in deliverability from 1,000 to 20,000 gallons per day per foot, and the storage coefficient averages 0.002^(2,16).

In at least one location, tests were made to evaluate the communication between the "A" and "B" aquifers through the Mahogany zone⁽¹⁶⁾. At this location in the central part of the basin, no communication was apparent. However, the large number of uncemented wells drilled through the Mahogany zone as well as communication through fault zones means that, for the northern part of the basin, the Mahogany zone is more of an aquitard than an aquiclude.

The "B" zone, which includes the leached zone in the zone in the central part of the basin, is probably the most important element in the Green River aquifer system. The fractured or jointed oil shale is the high permeability component in the system in the intermediate area between the recharge zone and the central portion of the basin. The transmissivity of the "B" zone is not as great as that found in the "A" zone in this region because the overburden is greater and the joints are more likely to be smaller or closed under these circumstances. Equity Oil Company ran a pilot in-situ oil shale experiment in this intermediate area of the "B" zone and found no measurable loss to the overlying Mahogany or underlying Garden Gulch Member⁽²¹⁾.

In the central portion of the basin, water flowing through the "B" zone fractures has removed a large amount of soluble material. This has produced some rubblization in the aquifer and generally resulted in a more transmissive region. The transmissivities for the "B" zone vary

from less than 100 gallons per day per foot in the intermediate area of the basin to more than 20,000 gallons per day per foot in the leached area near the basin center. Salinity also increases near the center of the basin. The variation is from about 1,800 milligrams per liter in the intermediate area to more than 65,000 milligrams per liter in the center of the basin.

Flow directions in the "B" zone are similar to the "A" zone since the piezometric maps are similar. However, locally pressure differences are apparent; since interzone water movement was reported for the majority of wells open in both zones^(22,23).

The finger-like ridges that constitute the southern basin margin are similar to the recharge region previously mentioned and have variable jointing with water working down through the joint. However, free surfaces are present along the valley wells, and little head buildup or water mounding on very coarsely jointed layers occur because it is relatively easy for the water to move to the valley well. The existing mines have encountered some weeping along master joints, but the flows have been trivial. However, the mines are also quite near the free surfaces and little flow would be expected until the workings move further into the mountain.

Oil Shale Resources, Piceance Basin

The Parachute Creek Member of the Green River Formation has been divided into a number of zones on the basis of higher oil shale yields such as R-2 through R-6 below the Mahogany zone, the Mahogany zone itself, and units 1 through 4 above the Mahogany zone^(24,25), Exhibit 9. The Mahogany zone is the richest extensive unit and the richest part of the zone, in barrels of oil in place per acre, occurs in the center of the basin⁽²⁶⁾. The maximum shale oil resources of the R-2 through R-6 zones also occurs in the central portion of the basin. The maximum shale oil resources of units 1 through 4, overlying the Mahogany zone, occur more toward the southern and eastern parts of the basin⁽²⁴⁾. A recent estimate of the oil in place in the various units is: R-1 through R-6, 200-plus billion barrels; Mahogany zone, 130-plus billion barrels; Units 1 through 4, 130-plus billion barrels, for a total of approximately 500 billion barrels⁽²⁸⁾. These figures represent oil shale in beds more than ten feet thick and assaying more than 25 gallons per ton.

Exhibit 10 is an oil shale resource map for the Piceance Basin. The various oil shale units outcrop along the valley walls on the

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southern basin margin and are buried under from 200 to 400 feet of overburden along the ridge tops. The depth of burial becomes greater in the northern portion of the basin⁽²⁷⁾, Exhibit 11.

Non-Oil Shale Resources, Piceance Basin

Coal occurs throughout the Piceance Basin which is part of the Uinta region of the Rocky Mountain Coal Province⁽²⁹⁾, and known economic deposits are around the periphery of the basin. Estimates of the coal resources for the region are as high as 60 billion tons⁽³⁰⁾, for the coal occurring within 6,000 feet at the surface. Eleven percent of Colorado coal production has been from mines in the Piceance Basin area.

Although Piceance Basin coal is well located for supplying electrical power requirements for the western slopes, the existence of high quality strippable coal in adjacent fields probably will preclude large-scale coal production in the area, at least in the immediate future⁽³⁰⁾.

Drilling for oil or gas in the Piceance Basin area has been going on since 1890. Production from the Rangely field was started in 1902. There was little activity during the period 1902 to 1924. However, the middle and late 1920's were pretty much of a boom period. Major discoveries were made in the 1930's and 1940's, and gas development became an increasingly important factor with the advent of the first interstate gas pipeline in the 1950's. About 50 oil or gas fields have been discovered in the area, and current cumulative production is more than 1 trillion cubic feet of gas and about one-half billion barrels of oil⁽³¹⁾. In addition to the producing fields in the area, Exhibit 7, a recent Federal Power Commission Report indicated there may be as much as 210 trillion feet of gas in place (not to be construed as recoverable gas which currently is estimated to be only a small fraction of the gas in place) in the Tertiary and Cretaceous rocks of the Piceance Basin⁽³²⁾.

Uinta Basin

Introduction

The Uinta basin is the second most prolific oil shale area, following the Piceance basin, and represents deposition in the same ancestral Lake Uinta. Because of the less favorable oil shale resource, a less aggressive oil shale information retrieval program has been followed. Thus, background information on the Uinta basin is not as extensive as

that found on the Piceance basin. The richest oil shale deposits are found in Uintah County, so that will be the area of major consideration. There is current interest in oil shale development in the Uinta basin. The Utah U-a and U-b tracts received bonus bids of \$75 million and \$45 million. In addition, a multi-company group is investigating the feasibility of in-situ mining on a Utah state oil shale lease along the east-central basin margin.

Physiography and Climate

The Uinta basin is a broad trough, bounded on the north by the Uintah Mountains, on the west by the Wasatch Range, on the south by the Roan Cliffs, and on the east by the Douglas Creek Arch. The central portion of the basin is an undulating surface cut by the major drainage features. The eastern and southern margins are sharply dissected into a canyonland terrane by deep gulleys and stream valleys. Oil shale crops out along this cliff area. The elevation varies from 4,000 to 8,000 feet and the Green, White, Duchesne, and Uinta Rivers form the principal drainage in the region. The area is semi-arid. Summer temperatures vary from 50° F. to above 90° F., and winter temperatures from below zero to the 30's. The mean annual temperature is 45° F.

Precipitation varies from seven inches in the basin's center to about fifteen inches in the higher elevations among the southern basin margin. Most of the precipitation is in the form of rain, the bulk of which occurs as thunderstorms, resulting in rapid runoff and erosion. Snowfall averages about 30 inches per year. Snow melt in the spring is slow, allowing much of the water to percolate into the ground. Evapotranspiration is the major moisture loss from the basin. Vegetation ranges from sagebrush-rabbit brush and cactus in the plains area to pinon pine and juniper forests capping the high ridges along the southern and eastern margins of the basin.

Stratigraphy

Sedimentary rocks, with a total thickness of more than 15,000 feet, fill the Uinta basin. The rocks range in age from Precambrian to Holocene. Only the Tertiary rocks will be considered in this report. Descriptions of the old rocks can be found in the literature⁽³³⁾.

The Wasatch Formation is a sequence of variegated sandstones, shales, mudstones, and conglomerates underlying the Green River

Formation. The formation is characterized by a basal conglomeratic pediment deposit and marginal red beds of fluvial origin. In the central part of the basin, the red rocks grade into the reducing series as lake conditions are approached. The upper Wasatch intertongues with the basal Green River as several lacustrine transgressions and regressions occurred prior to the widespread development of Lake Uinta⁽³⁴⁾. The Wasatch Formation varies in thickness from about 700 feet in the northeastern part of the basin to more than 4,000 feet in the west-central portion of the basin. Most of the sandstones are of channel and point bar origin and lack great lateral continuity. The variation in lithology results in a number of units that have quite different rock properties and responses.

The Green River Formation is divided into four members. The eastern portion of the basin uses a nomenclature similar to that of the Piceance basin: Douglas Creek; Garden Gulch; and Parachute Creek, Exhibit 12. Workers in the western part of the basin use a slightly different nomenclature: Willow Creek; Douglas Creek; and Parachute Creek. Deltaic or shoal conditions appeared in the central part of the basin during much of Green River time, and a somewhat different sequence appeared in the two subprovinces.

The Willow Creek Member represented an early fresh water lake and lake margin environment. It consists of mudstones, sandstones, thin fresh water limestones, and lean oil shale. It has an aggregate thickness of 1,500 feet in the western portion of the basin and intertongues with the underlying Wasatch Formation and overlying Douglas Creek Member.

The oil shale content has not been well defined because of lack of core drilling or widespread cutting analysis for wells drilled in the thicker oil shale sections. It is an interbedded unit with beds of variable rock properties. Based upon a limited amount of information, the oil shale appears to be quite lean.

The Douglas Creek Member consists of littoral sandstones, siltstones, fresh water limestones, and some lean oil shales. The sandstones and siltstones are grey or brown in color; the limestones and shales are commonly grey, tan, or green. The sandstones have enough continuity to form limited aquifers along the southeastern basin margin and are frequently oil or gas bearing in the central part of the basin. The Douglas Creek intertongues into the Garden Gulch Member in the eastern part of the basin and into the Parachute Creek Member in the central and western parts of the basin.

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The Garden Gulch Member consists chiefly of shale, siltstone, and oil shale. It varies in thickness from zero to about 300 feet. It is only present in the eastern part of the basin and intertongues vertically into the Parachute Creek Member. The Garden Gulch is a thin, thinly interbedded heterogeneous sequence with limited areal extent and oil shale content.

The Parachute Creek Member is the principal oil shale unit in the Uinta basin, consisting mainly of marlstone, oil shale, siltstone, sandstone, and tuff. Most of the oil shale members represent deposition in a saline or stratified saline/fresh water lake. The oil shale occurs in layers ranging from paper thin to more than one inch thick and varies in color from tan to very dark grey; the richer the beds, the darker the color. The other rock types are usually tan or grey to green in color. Widespread tuff beds are common in the eastern portion of the basin. These beds are usually oil streaked in the outcrop and, especially where they have a sandy aspect, appear to have a low but finite permeability. Some tuffaceous sandstones occur in the upper portion of the Parachute Creek Member and intertongue with the overlying Uinta Formation. Sandstones of this sequence have sufficient transmissibility to constitute aquifers along the southern basin margin. The Parachute Creek Member varies from a few hundred to more than 1,000 feet thick.

The Uinta Formation intertongues with the Parachute Creek Member and represents deposition in the waning phases of Lake Uinta and in the fluviatile environment that followed. The rocks range in color from greys and greens of the lacustrine stage to the browns and reds of the red bed fluviatile stage. Thickness varies from 700 feet to well over 2,000 feet in the western part of the basin. The Uinta grades conformably into the Bridger Formation in the central part of the basin and is overlapped by the Bridger on the northern margin of the basin.

Structure

The Uinta structural basin is a broad asymmetrical syncline. Along the southern margin of the basin, the beds dip northward at only one to two degrees. The dip angles increase along the eastern and western basin margins, and steep dips and major faulting occur along the northern margin adjacent to the Uinta Mountains, Exhibit 13. The axis of the basin is near the northern edge and has a sinuous axial trace.

Faulting is common throughout the basin. The larger displacement faults are restricted to the northern part of the basin. Small displacement, northwest trending, faults offset the oil shale along the eastern and southern basin margins⁽³⁵⁾.

A well-developed fracture system is present in the Uinta basin. The major set is northwest-northeast. Gilsonite, a solid bitumen has been injected into some of the master joints and have opened the joint as wide as 17 feet. As indicated in Exhibit 12, the veins seem to start in the Mahogany zone and generally go up, although a few go down. The veins have a maximum vertical extent of about 1,000 feet and a length of up to 10 miles⁽³⁵⁾.

The gilsonite veins are perpendicular to the general direction of groundwater movement in the southern part of the basin. In some places, they appear to have isolated areas from the active shallow groundwater system⁽³⁶⁾.

The gilsonite veins also indicate a very low minimum principal stress in at least the eastern part of the basin. Since some small veins have been found running in a northeast direction, indications are that the intermediate principal stress is also rather low. Hence, the basin was under some apparent tension at the time of the vein formation. The eastern portion of the basin is in an area of low earthquake activity. Thus, the probability of a damaging earthquake is low.

Hydrology

The groundwater resources of the Uinta basin are not well defined. Few water wells have been drilled in the basin, thus most of the data comes as a by-product of oil and gas exploration. The western part of the basin is the least well understood. Some of the pre-Tertiary Formations appear to contain fresh water at least near the basin margin, and the Wasatch, Green River, and Uinta Formations are all reported to contain fresh water near the outcrops⁽³⁷⁾.

At least one Wasatch Formation spring is found along the southern margin of the basin, and several gas or oil wells are known to produce slightly saline water from the Wasatch in the same general area of the basin⁽³⁷⁾. The Wasatch aquifers generally appear to be fluviatile sandstones.

The Green River Formation is the source of several fresh water springs in the southern part of the basin, and fresh to slightly saline water has been reported from a number of oil and gas wells in the basin. In the subsurface, water is found in some of the tuffaceous zones which are interbedded with the oil shales⁽³⁸⁾. Some of the sandy units that inter-tongue with the oil shales in the center and along the basin margins also are water productive.

The basal Horse Bench sandstone of the Uinta Formation is probably the most widespread and prolific Tertiary aquifer in the basin. The water is under enough pressure on the east-central portion of the basin to yield flowing wells. Shell Oil Company encountered flows from the Horse Bench sandstone in excess of 200 gallons per minute during the evaluation of one of the richest oil shale sections in the basin.

Thus, water under artesian head would be expected above and interbedded with most of the richer and thicker oil shale beds in the eastern portion of the basin. However, some local areas are present where gilsonite veins have deflected the flow in the upper aquifers and only low flow rates are encountered in the tuffaceous beds in the lower part of the Parachute Creek and the Douglas Creek Members⁽³⁶⁾.

The groundwater system is very poorly known in the western part of the basin. The aquifers in the Green River Formation in the eastern part of the Uinta basin are elements that are interbedded with the richer oil shale beds and are not part of the oil shale as is the case in the Piceance basin.

Oil Shale Resources

Maximum oil content appears to occur in the Parachute Creek Member in the east-central portion of the basin⁽³⁹⁾, Exhibit 14, with a possible secondary but poorly defined center in the western part of the basin. In both areas where the thicker deposits occur, they are under an appreciable overburden⁽³⁹⁾, Exhibit 15. Oil content in shales with a thickness of greater than 10 feet and a yield of 15 gallons per ton, or greater, probably falls between 30 and 300 billion barrels.

The oil shale along the eastern and southern outcrop area is rather thin and not too rich. This area probably will not be mined in the foreseeable future, even though part of it has been designated a Naval Oil Shale Reserve.

Most of the current interest is in the east-central portion of the basin. The technique being considered is a modified in-situ process in which a room is mined at the base of the oil shale section of interest. The room floor is fitted with sumps, and piping is fitted into a collection system in an adjacent tunnel. A chimney is formed by shooting conventional high explosives in holes drilled through the oil shale pay. The intent is to form a high permeability fracture system in the chimney, which can subsequently be batch retorted in place.

Other techniques being considered in the central area are straight in-situ, using explosives to generate permeability, and conventional room and pillar mining.

Non-Oil Shale Resources

The oil shale overlies an oil and gas producing region, Exhibit 7. In addition to the known reserves, a recent Federal Power Commission Report indicated there may be as much as 150 trillion cubic feet of gas in place (not to be construed as recoverable gas which currently is estimated to be only a small fraction of the gas in place) in the Uinta basin⁽³²⁾.

Also, tar sands are known to occur along the northeastern, eastern, and southern basin margins. At least one deposit is situated adjacent to one of the richest oil shale beds in the area. The tar sands contain approximately seven billion barrels of oil⁽¹⁾. No estimate has been made of the portion, if any, of this tar sand oil which may ultimately be recovered. Gilsonite veins are abundant in the basin and are associated with the richer oil shale deposits. The bulk of the veins are generally located above the oil shale and are partially mined out.

Nahcolite (NaHCO_3) occurs as thin lenses, beds, and pods in the central part of the basin in an interval extending from 300 to 600 feet above the Mahogany zone. The quality is so poor that it probably is not commercial.

There are minor occurrences of uranium, copper, and other metallics in the Green River and Uinta Formations in the eastern part of the basin. They are not being developed at this time and their value is unknown.

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There are major coal deposits currently being mined along the southern margin of the basin. This coal also underlies the oil shale in the Uinta basin and outcrops around the basin margin. Some additional marginal deposits could be mined in the near future, and some of the deeply buried deposits might be exploited in the future by in-situ techniques.

Current estimates place about one-sixth of the world's high volatile bituminous coal in the close proximity of the tri-state oil shale area⁽⁴⁰⁾.

Green River Basin in Wyoming

Introduction

The Greater Green River basin of Wyoming contains the leanest oil shale deposits within the group of basins discussed in this report. An indication of the general lack of current interest in oil shale development in the Green River and Washakie basins was the lack of a bid on either of the two Wyoming tracts during the recent offering.

The Wyoming shales contain about five percent of the oil shale resource in the tri-state area. However, the Green River Formation contains appreciable trona deposits ($\text{Na}_2\text{CO}_3 \cdot \text{NaHCO}_3 \cdot 2\text{H}_2\text{O}$) in the Wyoming area. Trona is the only oil shale or associated mineral in the Wyoming area that is currently being mined. Thus, the subsurface information from the trona mines should provide some insight into subsurface oil shale mining and possible waste storage problems.

Some idea on the feelings of people in the Green River basin about nuclear projects can be derived from the resounding rejection of the Wagon Wheel Project in the northern part of the basin^(41,42).

Physiography and Climate

Wyoming oil shale deposits occur in the Greater Green River basin complex in the southwestern part of the state. The basin is divided into three smaller basins - Green River, Washakie, and Sand Wash - by the Rock Springs Uplift and the Cherokee Ridge. Each of the three areas are structural and topographic basins with elevations ranging from 6,000

to 8,000 feet. They are semi-arid, and basin floors are typified by low relief ridges and valleys. The valleys are generally occupied by intermittent streams. The drainage is into the Colorado River system via the Green River in the Green River basin and by tributary streams to the Yampa or Green Rivers in the Washakie and Sand Wash basins.

The Green River basin has an area of about 7,000 square miles. Average precipitation at the town of Green River in the basin center is about eight inches per year. Temperature extremes are between minus 40° F. and 104° F. with an average temperature of 44° F. (43).

The Washakie basin has an area of about 2,600 square miles. Average precipitation at the town of Wamsutter near the northern basin margin is about six inches per year. Temperature extremes are between minus 37° F. and 104° F. with an average temperature of 42° F. (44).

The Sand Wash basin has about one-half the area of the Washakie basin and similar precipitation and temperatures.

Stratigraphy

The Green River, Washakie, and Sand Wash basins have sedimentary sections ranging in thickness from 12,000 to 30,000 feet and in age from PreCambrian to Holocene. This discussion will be limited to the Green River and adjacent formations. A comprehensive discussion of the other rock units can be found in the literature (45).

The Wasatch Formation underlies and intertongues with the Green River Formation in all three basins. The main body of the Wasatch consists of brightly colored claystones, siltstones, calcareous sandstones, carbonaceous shales, oil shales, and coal. Some of the sandstones become conglomeratic locally at the basin periphery.

The Green River Formation is generally divided into three members in the Greater Green River basin. From bottom to top, these are the Tipton Shale, Wilkins Peak, and Laney Members. Exhibit 16 is a generalized cross-section for the Greater Green River basin. There are localized mappable tongues of the Green River that contain oil shale. There are also numerous clastic tongues of Wasatch that wedge into the Green River Formation from the basin margins.

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The Tipton Member consists of tan to brown oil shales, calcareous sandstones, and subordinate siltstones, marlstones and limestones. This heterogeneous sequence varies in thickness from zero to about 400 feet.

The Wilkins Peak Member consists of marlstone, claystone, oil shale, siltstone, tuff, sandstone, limestone, and salines. Oil shales in this area are generally thin and separated by thicker beds of other lithologies. Salines are also present as numerous thin beds separated by other lithologic types, with the important concentrations of salines confined to the south-central portion of the Green River basin.

The Wilkins Peak Member varies in thickness from zero to about 1,200 feet, and is interbedded with some coarse clastic wedges of Wasatch Formation along the basin margins.

The Laney Member consists of marlstones, oil shale, tuff, siltstones, limestones, and sandstones. These rocks are characteristically brown and buff colored. The Laney Member varies in thickness from zero to almost 3,000 feet and intertongues laterally with the Wasatch and vertically into the Bridger Formation.

The Bridger Formation consists of varicolored claystones, fine grained sandstones, and minor shales, limestones, and dolomite. The sandstones are locally conglomeratic along the portions of the basins flanking the Uinta Mountains. The Bridger Formation varies from about 500 to about 2,500 feet in thickness. The exact thickness is difficult to determine because of the interfingering and gradational contact with the Laney Member of the Green River Formation.

Structure

The structure of the Greater Green River Basin is very complex and can best be treated by considering the individual basinal elements. The greatest thickness of sediments in the Green River basin is in the syncline that trends through Township 30 North, Range 108 West and parallels the Wind River Mountains. A trough trends southward from this axis toward the southwestern margin of the basin, Exhibit 17. The northern and western margins of the basin are near large thrust faults associated with the Wind River Mountains and the Wyoming Thrust Belt. Normal faulting, associated with the Uinta Mountains, is present along

the southern basin margin. Fractures and joints are a common feature of the rock outcrops in the basin. The fractures and jointing are also noted in the subsurface. Solution along joints has removed trona locally and resulted in sags in the overlying rock⁽⁴⁶⁾.

The Washakie basin is a bowl-shaped structural feature east of the Green River basin. The sinuous synclinal axial trace meanders from the southwestern to the northern edge of the basin, Exhibit 17. Faulting is common along the southern basin margin and the predominate trend is northwest.

Fractures and joints are common in the rock outcrops, and the joint systems appear to provide the connection between the artesian aquifers on the west side of the basin and the springs in that part of the basin.

The Sand Wash Basin is an east-west trending feature located south of the Washakie basin. The symmetry of the basin is truncated by faults along the southwestern margin. The northwest trending faults present in the southern part of the Washakie basin continue into the northern-most part of the Sand Wash basin, Exhibit 17.

Hydrology

The hydrology of the Greater Green River basin is not well defined; however, a number of water wells have been drilled in the basin, so some information is available^(47,48)

In general, water enters the aquifers, which are usually clastic wedges, along the basin margins. The saturated wedge tips dip down into the basin and contain water under artesian pressure. The aquifers have been tapped by wells exceeding 1,000 feet in depth and the water levels are less than 200 feet subsurface.

The higher transmissivity units in the Green River basin are located within the Green River Formation and in the underlying Wasatch Formation. Wells topping these aquifers have potentials from 10 to 800 gallons per minute.

In the Green River basin, the Wasatch aquifers have water with a dissolved solids content of from 200 to 3,700 milligrams per liter.

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The members of the Green River Formation have water with a dissolved solids content of 650 to 4,200 milligrams per liter⁽⁴⁷⁾.

The high transmissivity units in the Washakie basin are in the main body of the Wasatch and Laney Members of the Green River. The Wasatch aquifers are best developed in the western portion of the basin. Yields of from 5 to 500 gallons per minute are possible and the dissolved solids content of the water varies from 500 to 2,800 milligrams per liter.

Oil shale intervals in the Tipton and Wilkins Peak Members are interbedded with low transmissivity layers containing mineralized water. Similar units occur in the Laney Members, but in addition there is a clastic wedge in the western portion of the basin that has yielded up to 200 gallons per minute of low salinity water, containing 500 to 900 milligrams per liter of dissolved solids⁽⁴⁸⁾.

The Sand Wash basin probably has groundwater yields and salinities similar to the Washakie basin, but has not been studied in any detail.

Oil Shale Resources

Oil shales in the Greater Green River basin range from lean (less than 10 gallons per ton) to fair (more than 18 gallons per ton). Exhibit 17 shows the distribution of the various grades in the Green River and Washakie basins.

The Tipton Member contains the bulk of the oil shale in the Green River basin. The oil shale has its maximum thickness in the south-central part of the basin⁽⁴⁹⁾, Exhibit 18. The overburden in this area varies from 1,200 feet in the northern part to more than 2,800 feet in the southern part, Exhibit 19. The shale lies under the principal trona deposits and is in a series of rather widely spaced beds interbedded with lean oil shale or other lithologic types.

The Laney Member contains the bulk of the oil shale in the Washakie and Sand Wash basins. The resource is too poorly defined to isopach in these two basins. The area's maximum resource concentration is in the western portions of the basins. The Silver Bench averages more than 20 gallons per ton and has a thickness ranging from 100 to 120 feet

in the area of the W-a and W-b lease tracts. The Silver Bench dips downward toward the basin center. Exhibit 19 is an isopach map of the overburden showing the increased depth of burial toward the east.

Non-Oil Shale Resources

Important trona resources occur within the Green River Formation in the Green River basin. Exhibit 20 shows the location of the estimated 100 billion tons of bedded trona and associated halite deposits⁽⁵⁰⁾. The bulk of the deposits occur in the Wilkins Peak Member and overlie the richest oil shale beds. Trona development programs have been in operation for more than thirty years, and the two present mines each have capacities in excess of one million tons per year. In addition, two new mines are starting production.

Operations in the present mines have encountered water problems that seem to be associated with their longwall mining technique. The closing of the mined-out area following the final draw has apparently opened fractures between the underlying aquifers and the workings. Flows into the mines of several hundred gallons per minute have been encountered. In addition, low volume water leaks from the overlying Bridger Formation of from 10 to 30 gallons per minute have occurred around working and ventilation shafts.

The Greater Green River basin is an important oil and gas producing area. In addition to the current fields, Exhibit 7, a recent Federal Power Commission Report indicated there may be as much as 240 trillion cubic feet of gas in place (not to be construed as recoverable gas which currently is estimated to be a rather small fraction of the gas in place) in the tight upper Cretaceous and lower Tertiary sands underlying the oil shale⁽³²⁾.

The Greater Green River basin also contains significant coal resources. These coal beds are below and within the Green River Formation, and active mining areas surround the basins⁽⁵¹⁾.

Bituminous sandstone deposits also occur below the oil shale along the western flanks of the Washakie and Sand Wash basins.

Uranium deposits have been mined in several places along the basin margins and a number of deposits have been identified closely

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associated with the oil shale^(51,52). In addition, uraniferous phosphate deposits occur in the area.

Placer gold deposits have been mined in several locations in the basins. Principal deposits are in the Wasatch Formation below the oil shale and within the Green River Formation itself⁽⁵¹⁾.

Other minerals also occur within the area such as Zeolites, Monazite, Rutile, and Columbite⁽⁵¹⁾.

PHYSICAL CHARACTERISTICS OF OIL SHALE

Introduction

The key concept in looking at the physical characteristics of oil shale is heterogeneity. Not only are the properties different from bed to bed, but some of the properties vary within an individual bed. The concept of vertical characteristics, horizontal characteristics, or intermediate characteristics thus becomes important.

Most of the information on rock properties has been determined on samples from the Piceance basin. However, based on a limited cross-section of samples, it appears that the organic content is the most important single factor and that measurements based on Piceance basin material can be used as a first-order approximation for the tri-state oil shale behavior.

Another factor that should be kept in mind is that the samples used in most of the analyses are the most homogeneous available. Hence, standard "fudge factors" must be used to compensate for the joint systems that are ubiquitously present and other heterogeneities that will cause the material to behave, in the aggregate, differently than the small relatively homogeneous samples used for measurements.

Characteristics of Oil Shale

Strength and Associated Properties

The laminated structure of the oil shale and the variation in kerogen and mineral content in the individual layers have a marked effect on the physical properties of the oil shale. The change in properties in a small sample when moving from perpendicular to parallel to the layering is illustrated in Exhibit 21. The properties measured in this example are compressional and shear velocities. These properties correlate with the compressive strength and other rock moduli, hence are valid examples of the direction variation in rock properties⁽⁵³⁾.

The effect of the variation in the kerogen content of the shale on the strength of the rock is illustrated by Exhibit 22. In this example, a poor oil shale sample (18 gallons per ton) behaves in a granite-like manner with respect to brittle/ductile stress-strain response while a fair oil shale sample (26 gallons per ton) behaves more like salt⁽³⁾.

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The average physical properties for two oil shale cores from the Mahogany zone in the Bureau of Mines Anvil Points Mine are displayed in Table II⁽⁵⁴⁾. The samples were classified as poor (18 gallons per ton) and fair (24 gallons per ton) oil shale, and again illustrate the variation in rock properties between samples having different orientations and kerogen contents.

The variation in compressive strength, Young's Modulus and Poisson's Ratio, as a function of oil shale grade, are illustrated in Exhibits 23 and 24. The strength decreases and the plasticity increases with increased kerogen content⁽⁵⁵⁾.

The strength of the richer shales decreases markedly after they have been heated to retorting temperatures. Exhibit 25 illustrates the change in compressive strength for a sequence of samples with oil yields varying from 2 to 58 gallons per ton when heated to pyrolysis temperature. There is little loss in strength upon heating for the very lean oil shales. However, the strength of the poor-to-rich shales declines markedly, and the rich oil shales have essentially no strength after pyrolysis⁽⁵⁶⁾.

The strength behavior suggests that storage of wastes which could generate temperatures above 500° F. should be carefully evaluated.

"Logging" Characteristics

The Green River Formation has been logged and cored more extensively than any of the other rock units in the various basins. The logs allow a general lithologic evaluation of the intervals encountered in the well bore, as well as yielding semi-quantitative information about the oil yield from the oil shale^(57,58,59). Exhibit 26 displays the oil shale yields versus density log and sonic log responses⁽⁶⁰⁾.

The variation in response for several other logs is presented in Table III. The use of logs to evaluate oil shale may be important in a reconnaissance for waste disposal sites, since many more logs than cores are available from the subsurface of all the basins.

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AVERAGE PHYSICAL PROPERTIES

TWO OIL SHALE CORES FROM THE MAHOGANY ZONE

ANVIL POINTS, COLORADO

	<u>Horizontal Core</u>	<u>Vertical Core</u>
Assay Value (Estimated), Gal./Ton	18	24
Specific Gravity	2.36	2.25
Compressive Strength, Lb./Sq.In.	25,000	15,100
Scleroscope Hardness No.	61	55
Elastic Constants (Dynamic Method):		
Young's Modulus, Lb./Sq.In.	5.95×10^6	3.66×10^6
Modulus of Rigidity, Lb./Sq.In.	2.22×10^6	1.59×10^6
Specific Damping Capacity	0.07	0.10
Apparent Poisson's Ratio	0.33	9/12
Bar Velocity:		
Longitudinal, Ft./Sec.	13,700	10,600
Torsional, Ft./Sec.	8,400	7,000

Table II.

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RANGE OF GREEN RIVER FORMATION LOGGING RESPONSE

<u>Log</u>	<u>Readings</u>		<u>Units</u>
	<u>Maximum</u>	<u>Minimum</u>	
Natural Gamma	240	24	API
Neutron	1,450	550	API
Sonic	145	67	Microsec/Ft.
Density	2.57	2.0	G/CC
16" Normal	400	4	Ohm-m
Induction	Saturation	2	Ohm-m
Lateralog	∞	4	Ohm-m

Thermal Properties of Oil Shale

Thermal properties of oil shale have been measured by a number of workers and comprehensively summarized in at least one publication⁽⁶⁰⁾.

The specific heat of oil shale is given by the equation⁽⁶¹⁾:

$$S_{OS} = 0.172 + (0.067 + 0.00162G)10^{-3} (460 + T)$$

where

S_{OS} = Specific heat of raw shale above 77° F., BTU/Lb.-°F.

G = Fischer assay of shale, gpt.

T = Temperature, °F.

The heat content of the spent and raw oil shale is given by the following equation⁽⁶²⁾.

$$H_s = -52.17 + 0.5559T - 1.16 \times 10^{-3}T^2 + 1.68 \times 10^{-6}T^3 - 8.153 \times 10^{-10}T^4 + 4.113 \times 10^{-6}T^2G$$

where

H_s = Heat content of oil shale above 77° F., BTU/Lb.

The thermal conductivity of the raw oil shale is given by the equations⁽⁶³⁾:

$$k_{hH} = 1.23 \left[1 - 1.093 \times 10^{-4}(T-75) - 4.195 \times 10^{-7}(T-75)^2 \right] (-0.0184G)$$

$$k_{hG} = 1.128 \left[1 - 1.149 \times 10^{-4}(T-75) - 3.667 \times 10^{-7}(T-75)^2 \right] (-3.667G)$$

$$k_{hV} = 1.034 \left[1 - 1.19 \times 10^{-4}(T-75) - 3.127 \times 10^{-7}(T-75)^2 \right] (-0.01846G)$$

where

k_H = Thermal conductivity, BTU/Ft-Hr-°F.

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and subscripts

H = Horizontal

V = Vertical

G = Geometric mean

The thermal diffusivity is given by the equation⁽⁶³⁾:

$$\alpha = k_h / \rho S_{os}$$

where

α = Thermal diffusivity, Ft.²/D

ρ = Density, gm/cc.

Reaction time for 90 percent decomposition of the kerogen decreases as the temperature increases. Thus, the retorting of the shale with its change in rock characteristics can take place at temperatures lower than the conventional retorting temperatures used to define commercial oil shale processing. Exhibit 27 is a plot of reaction time versus temperature. For example, retorting can take place in about 6,000 minutes for temperatures as low as 650° F. Thus, the storage of heat producing wastes in oil shale must be carefully evaluated. Another thermal factor which has recently attracted attention is the exothermic reactions that take place in the center of large blocks of oil shale that are heated with a surface exposed to air^(64,65). These reactions can produce internal temperatures that are higher than the surface or driving temperatures.

The pyrolysis reaction typically produces the following reaction products: 66 percent by weight oil; 9 percent gas; 5 percent water; and 20 percent residual carbon⁽⁶⁶⁾. Thus, the heating of the oil shale in place causes flammable and volatile decomposition products as well as high internal fluid pressures and usually causes a decomposition of the rock.

Chemical Properties of Oil Shale

Oil products derived from the oil shale are usually reported in gallons per ton (gpt) from the modified Fischer assay. The assay has

limitations in that it does not measure all the organic material in the rock nor does it adequately characterize the gaseous products. However, the method is simple, reproducible, reliable, and economical; hence, it is used for most oil shale property evaluations.

In addition to the organic constituents in the oil shale, there are a number of compounds, including trace elements. These compounds can be rendered water-soluble by the pyrolysis reaction, thus must be evaluated in any proposal that may produce pyrolyzation of the oil shale. Tables IV and V present some typical inorganics as well as sulphur and nitrogen distributions⁽⁶⁷⁾.

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CHEMICAL COMPOSITION OF THE INORGANIC PORTION OF VARIOUS GRADES OF SHALE AND OF THE SPENT SHALE PRODUCTS

<u>Chemical Constituent</u>	<u>Very Low- Grade Shale (10.5 Gal/Ton)</u>	<u>Medium- Grade Shale (26.7 Gal/Ton)</u>	<u>High-Grade Shale (36.3 Gal/Ton)</u>	<u>Very High- Grade Shale (61.8 Gal/Ton)</u>
Raw Shale:				
SiO ₂ , percent	40.9	26.1	25.5	26.4
Fe ₂ O ₃	4.3	2.6	2.9	3.1
Al ₂ O ₃	9.4	6.5	6.3	7.0
CaO	11.0	17.5	14.2	8.3
MgO	5.4	5.3	5.6	4.5
SO ₃	0.1	0.6	1.2	1.4
Na ₂ O	1.8	2.6	2.7	1.9
K ₂ O	3.4	1.0	1.9	1.0
Spent Shale:				
SiO ₂	53.27	41.90	42.36	49.19
Fe ₂ O ₃	5.64	4.10	4.74	5.87
Al ₂ O ₃	12.28	10.53	10.46	13.13
CaO	14.82	28.11	23.54	15.40
MgO	7.00	8.53	9.30	8.35

Maximum Percentage of Minor Elements Reported in Colorado Oil Shale (Data Source: USBM RI #4825)

As,	0.005	Ba,	0.03	B,	0.003
Cu,	.008	Cr,	.007	Au,	.001
Pb,	.09	Li,	.05	Mo,	.001
Mn,	.08	P,	.4	Se,	.001
Ag,	.001	Sr,	.08	Tl,	.7
Ti,	.06	V,	.06	Zn,	.1

Table IV

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AVERAGE DISTRIBUTION OF SULPHUR AND NITROGEN IN THE MINEABLE-BED OIL SHALES AND THEIR ASSAY PRODUCTS

	Percent	Remarks
Type of Sulfur Compound in Raw Shale		
Sulfide Sulfur	67	As pyrite and marcasite, FeS_2
Organic Sulfur	33	
Sulfate Sulfur	<u>Trace</u>	As CaSO_4 , FeSO_4 , and MgSO_4
Total	100	
Distribution of Raw Shale Sulfur in Assay Products		
Spent Shale	66	As FeS_2 , FeS , CaS , and MgS with minor amounts of organic and sulfate sulfur
Oil	11	As H_2S and possibly some SO_2 or SO_3
Gas Plus Water by Difference	<u>23</u>	
Total	100	
Organic Nitrogen in Raw Shale	100	No inorganic nitrogen was found
Distribution of Raw Shale Nitrogen in Assay Products		
Spent Shale	38	
Oil	50	
Gas Plus Water by Difference	<u>12</u>	As N_2 , NH_3 , and ammonium salts
Total	100	

DISTRIBUTION OF SULPHUR IN COLORADO OIL SHALE

	Average						
Oil Yield of Shale, Gal/Ton	10.5	26.7	36.3	57.1	61.8	75.0	
Total Sulfur in Raw Shale, Percent	.62	.56	.73	1.96	1.99	1.86	
Distribution of Total Sulfur into Types, Percent							
Organic Sulfur	27	27	37	19	21	24	26
Pyritic Sulfur	71	73	63	79	77	72	72
Sulfate Sulfur	<u>2</u>	<u>Trace</u>	<u>Trace</u>	<u>2</u>	<u>2</u>	<u>4</u>	<u>2</u>
Total	100	100	100	100	100	100	100
Distribution of Total Sulfur into Assay Products, Percent							
Oil	5	11	8	7	9	11	8
Gas	2	10	19	18	23	6	13
Spent Shale	<u>93</u>	<u>79</u>	<u>73</u>	<u>75</u>	<u>68</u>	<u>83</u>	<u>79</u>
Total	100	100	100	100	100	100	100

Table V

FACTORS AFFECTING POSSIBLE WASTE STORAGE IN OIL SHALE

Introduction

The oil shale region selected for consideration as a possible waste storage site is of great areal extent. The Piceance basin has been studied in reasonable detail with respect to the configuration of the oil shale resources, the composition of adjacent beds, and the basinal groundwater system. The Uinta basin has not been studied in as great detail; hence, many factors are poorly defined. The Greater Green River basin must be classified as very poorly defined. Thus, this discussion of factors affecting waste storage must be considered tentative in nature.

Mines are present in the oil shale of the Piceance basin and in the trona deposits of the Green River basin. Hence, some fragmentary information is available on the response of the systems to mining operations. Because of the current energy shortage and the interest in oil shale development, a number of studies are currently in progress and information is being developed at this time. Thus the evaluation of the possible storage of waste in the oil shale area should become more valid as more information is developed. Also, additional specific data should be secured from studies of key areas to upgrade future evaluation efforts.

Stability of Various Mining Systems

The different oil shale processes for handling the rock are (1) room and pillar mining, (2) long wall mining, (3) open pit or strip mining, (4) in-situ processing in a fractured or tight environment, and (5) modified in-situ processing. A brief description of the various techniques currently being considered is presented in the accompanying paper by Charles H. Prien entitled Current Oil Shale Technology: A Summary, included as Appendix A.

If waste storage with access is desired, then the room and pillar mining process and the modified in-situ recovery process are the only processes that would lend themselves to this storage option.

The room and pillar mining process generally leaves approximately 25 to 45 percent of the mined interval in place as pillars for support. In the USBM mine at Anvil Point, Colorado, the rooms and pillars were 60 feet square with a room height of 73 feet, mined in two levels of 39 and

34 feet. The pillar and room dimensions are variables for each location and depend on overburden thickness, competency of the rock, and thickness of the deposit being mined. Several roof falls have occurred in the Anvil Points facility, so their pillar-room size and/or roof bolting techniques are marginal.

It will probably be inefficient to use room and pillar techniques where the deposit thickness is much greater than 100 feet and where appreciable interbedding of barren rock or lean shale occurs. Thus, room and pillar mining will probably be restricted to the margins of the basins, with the southern margin of the Piceance basin and the southeastern margin of the Uinta basin being the most probably areas for room and pillar operations.

The disposal of spent shale will be a problem for full scale commercial mining operations. Thus, there will be some incentive to backfill the rooms. An estimated 60 percent of the spent shale can be stored in this manner. Thus, if extensive mined out areas are required for waste storage, room backfilling will be compromised.

Spent shale is usually piled and compacted as a slurry or wet aggregate. Water from this source could combine with the normal groundwater flow to increase water problems in the waste storage area if backfilling operations proceeded immediately adjacent to waste storage areas.

In the Piceance basin, the oil shale mine at Anvil Points has been in existence since the late 1940's, hence visual observation and testing is possible to determine pillar stability and weathering characteristics for a period of approximately 30 years. The Anvil Point Mine has a minimum overburden and minimum water problems.

The trona mines in the Green River basin have been in existence for about 20 years. They could provide information on pillar stability and weathering under conditions of greater overburden and shaft mining conditions.

If areas vertically adjacent to the fair-to-rich oil shale section were chosen for a possible waste storage site, poor or lean oil shale would be available. The leaner oil shale is more brittle, hence could be more heavily jointed than the rich oil shale. The jointing would make the strata more likely to be influenced by water flow. However, the leaner oil

shale is stronger than the rich shale and is less susceptible to changes in physical properties if heating should occur.

Any room and pillar or modified in-situ operation will probably be subjected to repeated stress loading from the explosive shooting operations. Thus, areas should be selected for possible storage consideration that have been completely mined up and would not be subjected to additional shooting or a second mining pass at a different level.

The stresses and strains associated with drawing pillars can be quite large. This operation in the trona mines has caused floor buckling and fracturing and the influx of water from an underlying aquifer.

The modified in-situ process results in much lower ceiling rooms and tunnels and a minimum of mined area for the section being re-torted, as detailed in Appendix A. This type of operation is envisioned for areas with a poor-to-rich mix of oil shale layers having an average yield of 15 or more gallons per ton and a thickness of 300 feet or more. Thus, this type of operation could proceed from the margin of the basins, well into the interior portions of the basin.

Most of the development probably could be through the utilization of shafts; and, if the fracturing was achieved in one pass through holes drilled up from the basal rooms, then there would be a minimum effect from the overburden and mining could proceed well out into the basins.

This in-situ type of mining would result in a minimum amount of useful abandoned workings. In addition, the high permeability chimneys formed in the operation would be ideal conduits for groundwater, possibly resulting in a very wet tunnel environment that would be unsuitable for long-term access type waste disposal.

No commercial size modified in-situ chimneys have been utilized to this point in time. Occidental Petroleum Company is planning this type of operation for the summer-fall of 1975. Hence, this operation should be closely monitored for pertinent information.

The Federal Tract C-b operations in the Piceance basin have encountered a very wet environment. This area was envisioned as a room and pillar operation from surface shafts. This type of process may not be applicable unless the water can be handled. Even if this is possible, it

may be very expensive to keep a mined waste disposal area dry. Hence, there are considerable problems associated with the use of basin center disposal sites for access type storage.

Evaluation of Circulating Groundwater

The Piceance basin oil shale deposits are part of the groundwater system, at least to overburden depths of 1,500 to 1,800 feet. The basin's groundwater system is understood in a general way. However, the oil shale development program could greatly modify or completely change the system. Hence, waste storage plans likely can proceed no faster than the final plans for oil shale exploitation. In general, it would seem that the groundwater is a negative factor for waste storage except at the very southern margins of the basin, where local conditions result in relatively dry operations.

The Uinta and Green River basin oil shales do not appear to be part of the groundwater system. The aquifers appear to be interbedded with the oil shale. However, much less is known about the groundwater systems in the Uinta and Greater Green River basins, so some comprehensive analyses would be required as part of a waste storage project study.

Competing Non-Oil Shale Mineral Resources

All three basins are areas of current and past oil and gas development. In addition to the currently developed oil and gas fields shown on Exhibit 7, a recent report by the Natural Gas Technology Task Force of the Federal Power Commission which had been assigned the objective "to assess the current status and future potential of new or advancing technologies which might be used to economically produce a marketable natural gas from gas deposits which are currently considered non-commercial and which are not presently (1972) included in the nation's potential gas supply resources" indicated that there may be as much as 600 trillion cubic feet of gas in place in these three basins; however, it should be cautioned that this gas in place should not be construed as recoverable gas reserves inasmuch as only a small fraction, if any, of this gas in place can be recovered under present economic conditions utilizing current operational procedures and the present state of technology. However, in light of the critical national shortage of natural gas and the great need of natural gas for fuel and as chemical feedstock, the protection of this potential source of gas supply should be considered carefully in all regional planning of exploration, exploitation, and development operations.

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The tri-state region is also an area of important coal resources. These deposits are adjacent to and underlie the oil shale. The mining of this coal should also be considered in connection with a possible waste storage program. Saline minerals, uranium, uraniferous phosphates, metallics, and zeolites also occur adjacent to, within, above, and below the oil shale. The general area chosen for this study as a possible waste storage site is one of diverse mineral wealth and any plans for a possible waste storage project in this area likely will be coordinated with and be compatible with plans for the future development of these other resources also.

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Exhibit 1

Basins containing Green River Oil Shales
in the Tri-State Area of
Colorado, Utah, and Wyoming

Physiographic Sketch of Piceance Basin

Northwestern Colorado

Douglas Pass
Secs. 24 and 25,
T. 5 S., R. 102 W. and
Sec. 7, T. 5 S., R. 101 W.

East Douglas Creek
Sec. 34, T. 4 S., R. 101 W.

Willow Creek
Sec. 33, T. 3 S., R. 100 W.

Tommys Draw
Secs. 3, 4, 10 and 11,
T. 3 S., R. 100 W.

British-Am. Oil Prod. Co.
Corral Gulch H-1
Sec. 8, T. 2 S., R. 99 W.

U.S.B.M.-AEC
Duck Creek Corehole 2
Sec. 14, T. 1 S., R. 99 W.

U.S.B.M.-AEC
Yellow Creek Corehole 1
Sec. 13, T. 1 N., R. 98 W.

Mouth
Piceance Creek
Secs. 1, 11, 12 and 14
T. 1 N., R. 97 W.

East Douglas Creek
Sec. 7, T. 4 S., R. 100 W.

Cathedral Creek
Secs. 29 and 32,
T. 3 S., R. 99 W.

Pipeline section
Sec. 34, T. 2 S., R. 100 W.

Type section of Douglas
Creek Member (Bradley, 1931)

Southwest-Northeast Cross-Section
of Eocene Rocks

Piceance Basin, Northwestern Colorado

OIL & GAS FIELDS
IN THE TRI-STATE AREA OF
COLORADO, UTAH, & WYOMING

EXHIBIT 7

Diagrammatic Section Across
Piceance Basin, Northwestern Colorado

Southwest-Northeast Oil-Yield Histogram Cross-Section,
Federal Tract C-a,
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OIL SHALE MINERAL RIGHT OWNERSHIP PICEANCE CREEK BASIN, COLORADO

Oil Shale Resource Map
Piceance Basin, Northwestern Colorado

Cross-Section of Green River Formation in Uinta Basin,
 Northeastern Utah

Cross-Section of the Green River Formation
in the Green River Basin, Southwestern Wyoming

Map Showing Location of Saline Mineral Deposits
Green River Basin, Southwestern Wyoming

Exhibit 21 Calculated compressional-wave, V_p and shear-wave velocity $V_{sh,sv}$, as a function of confining pressure and direction of propagation for dry Green River shale

Exhibit 22 Comparison of brittle ductile failure behavior of lean and intermediate grade oil shale with granite and salt.

Exhibit 23. Compressive strength versus Fischer assay of Colorado oil shale, Anvil Points Mine, (55)

Exhibit 24. Typical elastic properties of Green River oil shale. (55)

Exhibit 25. Compressive strength of oil shales. (56)

Exhibit 26. Relationships between density, velocity, and oil assay established by various investigators. (3)

Exhibit 27. Reaction time for 90-percent decomposition of kerogen in Colorado oil shale. (9)

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CURRENT OIL SHALE TECHNOLOGY: A SUMMARY

by

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ABSTRACT

Shale oil syncrude production from oil shale requires enormous care to ensure (1) cheap, large-scale methods of handling materials at all stages of mining, retorting and disposing of spent shale; (2) maximum heat recovery in retorting and upgrading; and (3) minimum use of water and power. Most mining is expected to be by the underground room-and-pillar method, using rooms and pillars approximately 60 ft. square, 60 to 75 ft. in height, at depths of as much as 1500 ft., with a recovery of 50-70 percent of the mined strata. Surface mining may be applicable to 15-20 percent of the mineable shale reserves, predominantly by open-pit techniques in areas where the ratio of overburden plus interbedded waste to ore is between 0.5 to 1 and 2.5 to 1.

Between 80-85 percent of all mined shale normally must be discarded as spent shale residue, of which at least 40 percent must be permanently stored above ground, compacted and revegetated. With open pit mining, overburden and residue initially must be stored off-mine-site, until pit disposal is feasible.

Above-ground retorting of shale is of three general types involving the use of (1) recycled hot solids, (2) retorts with internal combustion zones, and (3) retorts with external furnaces. Included in these three classes are the Tosco II, Lurgi-Ruhrgas, Union, Gas Combustion, Paraho, and Petrosix retorting processes, each with its own peculiar advantages and drawbacks.

In-situ processing of shale involves a combination of suitable fracturing (or rubblization) and in-place retorting and recovery techniques. The "state-of-the-art" is at least 5 years less advanced than mining with surface retorting. However, because of its potential for less environmental impact, active research on in-situ processing must be continued.

A direct comparison of costs for various shale oil recovery processes is not possible because of the lack of published data. The recent National Petroleum Council study for a 100,000 bbl/day plant and mine indicated a capital cost of \$602 million, and an annual operating cost of \$74 million, in 1970 dollars.

INTRODUCTION

At the present time, the processing of oil shale to obtain oil involves a sequence of mining and above-ground retorting. In later years, improved technology may also permit the use of *in situ* retorting, thus reducing the handling of materials. This paper describes the current status of oil shale technology and discusses briefly the economics involved.

As now contemplated, an oil shale industry will be the world's largest industry processing low-grade minerals; solids will be mined and handled at a magnitude not heretofore accomplished on an industrial scale. The following example, using 30 gal/ton shale, illustrates the point:

For every 2000 lbs. of shale mined and then retorted, there is obtained approximately only 230 lbs. (11.5 percent of original weight) of shale oil

product, plus 40 lbs. of undiluted retort gases, 30 lbs. of water, and 80 lbs. of residual organic carbonaceous coating (a potential fuel) on the spent shale. The total weight of "useful" organic material is, therefore, about 350 lbs. or only about 17.5 percent of the original weight of the mined shale. Thus, 82 percent of the shale mined (86 percent if the carbonaceous coating is not used as fuel) must be discarded as waste material.

A 50,000 bbl/day plant will mine about 73,000 tons of shale per day (24 million tons/yr), and discard approximately 59,000 tons/day (19.5 million tons/yr) of waste spent shale. A projected one million bbls per day industry will require the mining of 480 million tons of shale annually, which is the approximate current annual level of U.S. coal production (520 million tons per year). There will be produced annually 390 million tons of waste shale.

All of this processing must be done in a region in which water for processing and domestic use is very limited. Finally, the shale oil produced must be transported 700-1000 mi to substantial markets.

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The ultimate result of the above constraints is that enormous care must be taken to ensure (1) economical large-scale methods of handling materials at all stages of shale processing (mining, retorting, spent-shale disposal); (2) maximum heat recovery in retorting and upgrading; and (3) minimum use of water and power. Only in this way can the resulting shale oil be produced at a price competitive with conventional petroleum.

In the sections that follow, the mining and retorting technologies currently available for shale-oil production are examined in brief detail. Two types of mining (underground and surface) and 3 basic heating methods of retorting (recycled hot solids, internal combustion, and externally-heated hot gases) have been developed. A processing sequence for shale oil may be constructed by selecting any combination of mining method and retorting method from among these available possibilities, depending upon the nature of the shale deposit and the richness of shale to be used.

MINING, SHALE RESIDUE DISPOSAL, AND CRUSHING

Either underground mining or surface mining may be employed for oil shale. Because of the stratigraphic position and depth of burial of the richer deposits, it is probable that the majority of shale will be recovered by underground mining, with perhaps only 15-20 percent mined by surface methods. This prediction is reasonable because the usual advantages of lower-cost surface mining are considerably offset by the reduced costs made possible by large-scale underground operations.

Underground Mining

Underground mining likely will use the room-and-pillar method (Fig. 1). It will initially be confined mainly to shales of the Mahogany zone that are 1500 ft. or less below the surface, and that average 30 gal/ton or more in beds 30 to 90 ft. thick. These limitations are imposed by costs currently encountered in underground mining technology, and could be expected to be relaxed as improved "second-generation" technology becomes available in later years.

Commercial-scale room-and-pillar mining of oil shale has been demonstrated by the U.S. Bureau of Mines at Anvil Points, Colorado; and by Colony Development Operations and Union Oil Company at their Parachute Creek sites. In all cases, mine access to the producing interval was by adit from an escarpment. Since the number of locations is limited where adit entry is possible, it is more likely that entry by vertical shaft or incline will be used more often.

In room-and-pillar mining, a series of rooms is created underground, with 25-45 percent of the deposit left standing as pillars for support. In the USBM mine, for example, room openings and pillars each were 60 ft.

square; the total mineable section (room height) was 73 ft., in 2 levels of 39 ft. and 34 ft., respectively. Pillar size, room dimensions, and percent recovery of ore for a given site are functions of the thickness of overburden present.

An underground mine will require at least 2 outlets to the surface for production, men and materials, and ventilation. If vertical shafts are used, each shaft complex (or single large shaft) could serve a maximum area with a diameter of 5 mi (12,500 ac). Beyond this, a new shaft installation would be required. A 50,000 bbls/day plant mining 73,000 tons of 30 gal/ton raw shale per day in a USBM-type underground mine, as previously described, would utilize an underground area of about 170-200 ac per year, including pillars.

At the contemplated scale of underground mining, large mechanized equipment can be used, including multiple rotary drill jumbos, 20-cu-yd front-end loaders, and 100-ton or larger trucks or large capacity conveyors. Explosives will be of the ammonium nitrate-fuel oil type.

In the latter stages of mine development, some 60 percent of the spent shale residue could be returned to the mine by conveyor or perhaps as a slurry. This will be discussed further below.

Little or no surface subsidence is expected from room-and-pillar mining of the type described, because of the competency of the oil shale beds. Underground waters might pose a problem in a few mining locations, although more data still are needed to evaluate the prospects.

Fig. 1. Room and pillar in U.S. Bureau of Mines underground mine, Anvil Points, Colo.

Surface Mining

Surface mining could involve either open-pit or strip techniques. The shale strata should average at least 25 gal/ton, in thicknesses of 50 ft. or more. The ratio of "overburden plus interbedded waste" to ore should range from 0.5:1 to 2.5:1, depending upon the richness of the ore and the amount of hauling of overburden that would be required. More than 100,000 tons/day should be mined for greatest efficiency.

It generally will be necessary to dispose of overburden away from the minesite for the first 10 yrs of operation, prior to the time that it can be continuously replaced in mined-out pit areas as further mining proceeds. Over a 10-year period, for example, a site with a 1:1 overburden-waste to ore ratio, a thickness of 500 ft. of 30 gal/ton shale, and a production rate of 144,000 tons of raw shale per day would require 1000 ac off-mine-site for overburden storage, at 250 ft. average pile depth. Such an off-site storage area would be permanent and would be revegetated. Spent shale also would be stored above ground during the initial years of open pit development, but could thereafter be returned to the pit (see discussion below).

In some areas of the oil shale region (e.g., Piceance Creek basin), saline waters at depth could present a serious disposal problem in open-pit mining if the water was not all utilized in subsequent processing. The extent of this problem is unknown at the present time. Distribution of mined, interbedded lean shale layers to separate dump areas could pose a substantial economic burden on open-pit mining, in terms of excessive hauling costs.

Open-pit mining will require large rotary drills for drilling and blasting; and the use of large shovels, trucks and conveyors to move material. Large draglines at times also could be used. In the rare case where strip mining might be feasible, such large draglines would be employed to move blasted overburden into previously mined areas.

A recent proposal would create a *very large* unitized open pit operation in the Piceance Creek basin, with a pit as much as 2000 ft. deep. Such a pit would permit economic recovery of both lower grade shales (perhaps 20 gal/ton) and any associated saline minerals. The entire area involved would be made part of the "unitized system," which eventually could include a combination of both open-pit mining and underground mining. Subsequently, the pit would be filled and revegetated, and the entire disturbed area restored. This proposal certainly requires further serious study.

Disposal of Spent-Shale Residue

The disposal of the solid spent-shale residue from retorting, about 80-85 percent of the weight of the shale mined, is best considered as part of the overall system

of mining and handling materials. The residue may contain 2-5 percent of a carbonaceous coating (spent shale), or may be completely denuded of carbonaceous matter (shale ash), depending upon the retorting process used.

For surface disposal, this residue will be transported by truck or belt conveyor, preferably to adjacent canyons, gullies or similar topographic depressions, wetted with about 15 percent by weight of water, and compacted to 80-100 lbs./cu ft. To prevent downstream pollution by leaching of soluble components, the disposal sites will be guarded by adequate culverts, dams, and diversion ditches. Slurry disposal systems might be used, but only if adequate water supplies exist, or if low-grade saline aquifer waters could be used.

Upon completion, a residue-disposal site will be contoured, topsoil added (or the top several ft. leached to create a salt-free upper layer), fertilizer applied, and the area revegetated. Several years of continuous care, including watering and re-fertilizing, probably will be necessary until the new vegetation is self-sustaining; but requirements will not impose an excessive added economic burden on industry costs.

If all the shale residue from a 50,000 bbl/day plant mining 30 gal/ton shale were stored above ground in 250-ft.-deep spoil piles, as much as 75 ac/yr of storage area would be required, or 1500 ac over 20 yrs of operation. But it may be possible to return as much as 60 percent of the shale residue to the mine as a slurry, if water availability and drainage would permit, or by conveyor. Because of the void space and hence greater volume of shale residues resulting from crushing, all of the residue will not "fit" back in the mined-out rooms. For the remaining 40 percent to be stored above ground, 30 ac/yr will be required, or 600 ac over 20 yrs of plant operation. Compaction both above and below ground would be to approximately 80-100 lbs/cu ft.

In the case of open-pit mining, the shale residue, like the overburden, will initially be stored off-site for at least the first 5 yrs or longer of operation, and then could be returned to the mine by truck or by belt conveyor. The mined-out area required for disposal depends upon the depth of the pit, but would approximate 75 ac/yr for each 250 ft of depth.

Crushing and Screening

Although oil shale can be readily drilled and blasted, it tends to be unusually resilient to crushing, probably because of its kerogen content; and abrasive, as a result of silica present. Also, the shale tends to slab. Any crushing system must allow for these characteristics, as well as provide effective means for dust control.

The size of the crushed shale required depends upon the retorting process employed. Some retorts use a minus

2-in. or minus 3-in. feed devoid of fines below $\frac{1}{8}$ -in., thus requiring open-circuit primary and secondary crushing; others need a minus $\frac{1}{2}$ -in. feed stock, which requires additional closed-circuit secondary crushing, but the retort will accept the fines produced.

The crushing systems employed to date have included jaw crushers, gyratory crushers, roller crushers, and/or impact mills. However, it has not yet been precisely shown which systems are the most efficient, although this will be determined as pilot plant work continues.

RETORTING PROCESSES

It is possible in the laboratory to recover the solid organic matter (kerogen) in oil shale by solution in a solvent at elevated temperatures; but such a process does not appear to be economically feasible on an industrial scale. The only commercially acceptable process for producing shale oil at present is to heat the rock to 900°F or higher, at which temperatures the kerogen decomposes (pyrolyzes) to yield oily vapors, which condense to a viscous liquid shale oil, gases, and a carbonaceous residue on the remaining rock. This process is called retorting.

Oil shale retorting is certainly a worthy challenge to chemical engineering. Large quantities of crushed rock must be heated to 900° to 1000°F, approximately 15 percent of useful oil vapors, gas, and water separated therefrom, and the remaining 85 percent of rock and its carbonaceous coating cooled once more to as nearly an ambient temperature as possible, before being discharged. Efficient heat recovery, therefore, is required. The entire process must consume as little water as possible, because of the limited water supplies available. Because the raw shale contains both $MgCO_3$ and $CaCO_3$, which begin to decompose somewhat above 1100°F, retort temperature control must be adequate to avoid these unwanted heat-consuming reaction. In certain temperature ranges, coking, and hence agglomeration of rich shales may occur in the retort. Prolonged contact of the oil vapors with hot surfaces must be minimized, in order to avoid gas losses due to cracking. If the volume of fixed gases is high in the vapor phase, formation of shale-oil aerosols may occur, making condensation difficult. Gases from retorting contain salable light hydrocarbons, and are useful fuel gases if not excessively diluted in the retort.

In order to minimize heat requirements for the retorting process, the carbonaceous residue on the spent shale (20-25 percent of the total organic matter) might be burned as a source of heat for the pyrolysis of the kerogen itself. Thus, the ideal retorting process could provide the following: (a) a preheat zone for the raw shale feed, (b) a pyrolysis zone for shale oil production, (c) a combustion zone for heat production, and (d) a cooling zone for heat recovery from the spent shale. A supplemental source of heat in the combustion zone can be a portion of the retort gases previously mentioned. A small percentage of the shale oil also can be used for heat.

Among the more than 3000 oil shale patents in the literature, numerous retort designs have been proposed to accomplish the above objectives. In these

designs, heat is transferred externally through the retort wall; internally by contact with hot gases, liquids, or solids; or by radiant means. Vertical and horizontal retorts, as well as tunnel kilns, fluidized beds, and entrained-solid designs, have been employed. Crushed shale has been moved downward by gravity, upward by mechanical means, or suspended in hot gases or liquids, and horizontally on moving belts. In the internally-heated designs, hot gases have been moved upward, downward, or across the flow of crushed shale. Almost every conceivable means of heating a solid seems to have been tried at one time or another.

At the present time, in the United States only 3 basic methods for retorting above-ground have reached the stage of industrial interest. The classification is based upon the way heat is supplied to the retorting process. These methods include the use of (1) recycled hot solids; (2) a combustion zone within the retort; and (3) retorts with an external, fuel-fired furnace. The various retort designs which employ these methods are discussed below.

Processes Using Recycled Hot Solids

Two processes currently use recycled hot solids as heat carriers. These are the TOSCO II process, which uses heated ceramic spheres; and the Lurgi-Ruhrgas process, which uses hot sand or other finely-divided solids.

TOSCO II Process

This is the process of The Oil Shale Corporation. Initial development work was done by Denver Research Institute from 1955 to 1966. In 1964, the Corporation formed Colony Development Operation (Sohio, Cleveland Cliffs, Atlantic Richfield, Tosco, and later, Ashland Oil and Shell Oil), which has constructed and operated a 1000 ton/day semi-works plant for a number of years near Grand Valley, Colorado. This operation includes a room-and-pillar mine which has produced over 1 million tons of raw shale. It is believed that this process is closest to immediate industrial scale-up, and that final plans to construct the first commercial (50,000 bbl/day) plant will be announced shortly.

In the Tosco process, minus $\frac{1}{2}$ -in. crushed shale is fed to a horizontal retorting retort, where it is heated by mixing with small ($\frac{1}{2}$ -in.) hot ceramic balls. Shale-oil vapors are distilled, removed, and condensed. The cooled balls and spent shale are discharged from the retort and screened to separate the spent shale from the balls, which are then sent to an external heater, reheated, and recycled to the retort. The spent shale is cooled, discharged, and sent to waste piles for moistening and compaction. When discarded, the spent-shale particles normally contain about 4 percent of carbonaceous "semi-coke" coating.

The ball heater can use a small part of the shale-oil product, the retort off-gases, and/or even the carbonaceous "semi-coke" on the spent shale as sources of fuel. The combustion gases from the ball heater are used to pre-heat the raw shale before it is fed to the retort.

This is the only potentially commercial process employing solid-solid heat transfer in a horizontal kiln, which is advantageous in securing high throughput rates. In addition, because external heating is employed, the retort off-gases are not diluted with air and combustion products, and hence have a high heating value (800 Btu's/SFC, as produced). Oil yields are 100 percent or more of Fischer assay.

Lurgi-Ruhrgas (LR) Process

This process was developed jointly by Lurgi-Gesellschaft and Ruhrgas A.G. in the 1950's for low-temperature coal carbonization and for cracking hydrocarbons to olefins. Two lignite carbonization units with a combined plant capacity of 1700 tons/day began operation in Yugoslavia in 1963. A small 16-25 ton/day plant in West Germany has been used to retort Colorado oil shale, at a yield of 100 percent of Fischer assay. Lurgi indicates that a retorting unit of 5000 tons/day is technically feasible.

In the L-R process, minus 1/2-inch shale is heated by contact with hot, finely-divided solids in a horizontal, cylindrical vessel with a screw conveyor. The finely-divided heat carrier may be sand or coarse shale ash. The products are withdrawn from the top of the mixer, dedusted, and condensed. The spent shale and heat carrier pass into a lift line, together with dust from dedusting; air is added, and the carbon is burned off the spent shale-heat carrier mixture, thus reheating the carrier, after dust removal, for recirculation.

Because of direct contact among solids and heat carrier, heat transfer is rapid, leading to high-capacity retorts. Care must be taken to avoid readsorption of shale-oil vapors on the solids in order to prevent loss of yield. Patents cover related processes developed by a number of U.S. companies that are examining this potentially attractive retorting method further.

Internal Combustion Zone Retorts

Three U.S. retorting processes utilize a combustion zone within the retort to furnish heat for decomposition of the kerogen to shale oil. These are the (1) Union Oil Company Rock-pump Retort, (2) U.S. Bureau of Mines Gas Combustion Retort, and (3) Development Engineering, Inc. (DEI) Kiln. All three of these retorts have a shale preheat zone, combustion zone, pyrolysis zone, and a final spent-shale cooling zone.

Union Oil Rock-pump Retort (Type A)

This retort was developed during the late 1940's. A demonstration plant was constructed near Grand Valley, Colorado in 1956 (Fig. 2) and operated through August 1958, during which time it attained throughput rates of 1200 tons/day for continuous periods up to 6 weeks. The unusual feature of this retort is a reciprocating

piston ("rock pump") which forces raw shale feed (minus 5-in., plus 1/8-in.) upward through the vertical retort, countercurrent to hot gases which are pulled downward through the shale bed by suction blowers.

The hot gases are produced in the combustion zone at the top of the retort, where the residual carbon on the spent shale is burned by injecting air. The resulting 2000°F flue gases are drawn downward to the retorting zone, where shale oil vapors and gases are evolved. These vapors continue downward into the bottom of the retort, where the oil condenses on the cool incoming shale, thus preheating the shale, and is withdrawn. The remaining flue gas has a low heating value of about 100 Btu/SCF. The spent shale is discharged as clinker from the top of the retort.

Gas Combustion Retort (USBM)

The Gas Combustion Retort was initially developed by the U.S. Bureau of Mines at Anvil Points, Colorado in 1951, and reached a 150 ton/day pilot plant-capacity at the conclusion of the Synthetic Liquid Fuels Program in 1955. Between 1964 and 1966, a consortium of 6 petroleum companies (Mobil, Humble, Pan American, Sinclair, Continental, and Phillips) improved the process, attaining a capacity of about 350 tons/day.

The vertical retort is fed from the top with minus 3-in., plus 1/4-in. raw shale, which moves downward by gravity through a top preheat zone, thence into a retorting zone, next into a combustion zone, and finally into a spent shale cooling zone. Oil vapors from the retorting zone pass upward through the preheat zone, where they are condensed to a stable aerosol mist that passes out with the retort gases and is recovered in mist collectors.

Part of the gases released by retorting (80-100 Btu/SCF) are recycled near the bottom of the retort, where they are heated and passed upward into the combustion zone. Here, new retort gas is injected and the gases burned, together with a portion of the residual carbon on the retorted shale to furnish the heat for the process.

The studies by the 6-company consortium indicated that the gas combustion process experienced some difficulties with small shale sizes, high rates of gas and shale throughput, and bridging due to rich shales. It is expected that these difficulties can be mitigated with further development. Yields in excess of 85 percent of Fischer assay were obtained.

Development Engineering, Inc. Kiln (DEI)

The DEI vertical kiln has been initially engineered for line-burning, by which it has attained a capacity of 600 tons/day in a 10-ft. inside-diameter design. It has not yet been used on oil shale. However, a consortium of 17 petroleum, energy, and investment companies, known as Paraho Development Corp., has been formed to commercialize this process for oil shale, under a 5-year lease

Fig. 2. Union Oil Co. demonstration plant (1956), Parachute Creek, north of Grand Valley, Colorado.

of the Anvil Points, Colorado-Federal oil shale facilities. A 400 ton/day or larger oil shale retort ($8\frac{1}{2}$ -ft in diameter) is expected to be in operation in the latter part of 1974.

The Paraho retort (Fig. 3) is essentially a gas combustion type, but incorporates changes in design of raw feed distribution, and spent shale discharge grates so as to improve continuous downward vertical flow of the shale being processed. In addition, a multiple-level gas/air (or hot gases) injection system for heating has been incorporated.

External Furnace Retorting Processes

All of these processes employ vertical retorts and

are essentially modifications of gas-combustion processes with gravity flow described in the previous section. The objective in all cases is to separate the internal combustion zone from the retort in an external furnace, where hot gases are produced and continuously recirculated to the retort. In this way, the usual dilution of retort off-gases in gas-combustion-type retorting is avoided, thus producing high-Btu gases (700-800 Btu/SCF). The external furnaces can be heated by these high-Btu gases, or by other available fuel, such as natural gases.

The three processes of potential industrial interest are the (1) Petrosix Process, (2) Union Oil (Type B) Process, and (3) Paraho (Type II) Process.

Figure 3. Paraho retort (reproduced with permission of Paraho Oil Shale Demonstration, Inc., Grand Junction, Colo.)

Petrosix Process

This retorting process was initially developed for use on Brazilian oil shales by Cameron and Jones (now Cameron Engineers, of Denver) in cooperation with the Brazilian energy company, Petrobras. A 2200 tons/day retort recently has been placed in operation by Petrobras on Irati shales in the State of Paraná, in south-central Brazil. A portion of recycle retort gas is heated to 1300°F and injected into a middle section of the retort. Cool recycle gas also is added in the lower part of the retort, where it is preheated by hot spent shale. The retort design includes a unique feeding mechanism and a discharge grate that is moved laterally with hydraulic pistons in order to insure uniform shale flow. Oil is withdrawn as a mist, as in conventional gas-combustion retorts.

Union Oil (Type B) Process

The Union Oil Company Type B retort is covered by 1960, 1964 patents. Hot recirculating gases from an external heater are used as a source of heat. The heater may be fired with natural gas, or with low-Btu gases derived from retorting in a conventional Union retort. The Type B process has been investigated at a pre-pilot level, but has not yet been scaled-up to the 1200 ton/day capacity of the original Union retort design previously described. A new steam gas recirculation process has just been announced.

Paraho (Type II) Process

This retort is similar to the original Paraho (DEI) kiln previously described; but as in the case of the Union and Petrosix processes, an external heater is used to furnish hot gases for retorting. The process has not yet been tried, but a large-scale kiln is to be built by Paraho at Anvil Points in 1975.

Brief Comparison of Retorting Methods

The Tosco II and Lurgi retorts both employ solid-to-solid heat transfer, which results in high heat transfer rates and leads to high throughput capacities. The rotating-kiln Tosco retort will accept a wide range of raw shale feeds without the necessity of removing fines. The retort off gases are not diluted with combustion products, and hence are a high-Btu fuel. While capital costs per unit throughput tend to be lower than with vertical retorts, operating costs may be somewhat higher. The solid wastes from the Tosco or Lurgi processes are more finely-divided, and hence require greater care for dust removal and for disposal.

Vertical retorts generally accept larger-sized raw shale feed stock, and hence have lower crushing costs. Most of these retorts, however, require the screening out of fines, which partially offsets the lower cost of crushing. Vertical retorts tend to "bridge" at hang-up when richer portions of shale occur in the feed. This problem is avoided by more elaborate solids feed and discharge

mechanisms; or, in the case of the Union retort, by using a reciprocating piston upflow feeder. These feed and discharge mechanisms also are included to minimize the channeling which is always a problem as vertical retorts (Union, Gas Combustion, Paraho, Petrosix) are scaled-up in size.

The combination of the combustion zone, the retorting zone, and both the preheat and cooling zones in the single vessel of a vertical retort improves heat economy, but does result in emission of diluted, lower-Btu gases from retorting. The latter disadvantage is overcome when an external furnace and recycle gases are used. The feed and spent shale residues in vertical retorts are of larger particle size, which tends to decrease dusting problems and aids in creating stable dump sites through the use of traditional soil-compaction techniques.

It is important to note that a variety of retort designs, each with its own peculiar advantages and disadvantages, will be used as the oil shale industry grows.

IN-SITU PROCESSING

Retorting the oil shale in place (Fig. 4) always has been an attractive alternative to mining and to above-ground retorting, because it eliminates both handling steps and the necessity to dispose of the spent shale. The usual approach to *in-situ* processing has been to drill a pattern of wells, consisting of a central well surrounded by 4 or 5 off-take wells, into the shale deposits. The shale is fractured between wells by using hydraulic pressure, chemical explosives, or, as proposed, by using nuclear explosives. Compressed air is injected into the central well, the shale ignited, and the hot combustion gases forced through the shale, to convert the organic matter to oil, which is pumped from the peripheral off-take wells. In the place of underground ignition, the heat required might be furnished by hot gases, such as methane, or by liquids.

In-situ retorting has not been economically or technically successful to date, although field tests have been conducted during the past 15 yrs by Sinclair Oil & Gas, Mobil Oil, Equity Oil, Shell Oil, and U.S. Bureau of Mines, among others. In 1972, Occidental Petroleum began the most recent *in-situ* field tests, using a process involving a combination of some mining (15-20 percent) and in-place retorting. Because of its potential for reducing the impact on the surface environment of the shale lands, and assuming no adverse underground impacts, *in-situ* processing should be an active subject of continuing research in the decade ahead.

UPGRADING, BY-PRODUCTS, SALINE MINERALS

The high-pour-point, viscous shale oil obtained from retorting above ground must be subjected at least to either coking or vis-breaking in order to produce a crude

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WATER AND POWER REQUIREMENTS

The water requirements for mining and above-ground retorting of oil shale and for upgrading the shale oil vary with the processes involved. For a typical 50,000 bbl/day plant the water consumed would be 20 ac-ft/day (7,300 ac-ft/yr), which is approximately 3 bbls of water per bbl of shale oil produced. About 45 percent of this water is used for wetting and compaction of the discarded spent shale; 25 percent for upgrading shale oil by hydrotreating; and 30 percent for mining, crushing, and retorting. All water diverted for use eventually is consumed somewhere in the process. Degradation of the water quality of existing streams would not likely occur.

A 1 million bbl/day shale oil plant would require approximately 145,000 ac-ft/yr of process water, 15,000 ac-ft/yr for domestic use, and 15,000 ac-ft/yr additional for power generation, or a total of 175,000 ac-ft/yr. The Bureau of Reclamation has estimated that as much as 340,000 ac-ft/yr of surface waters might be available for oil shale and other uses in the Upper Colorado River Basin at present. Thus, a 1 million bbl/day oil shale industry using surface water sources seems possible, although additional storage reservoirs may be necessary beyond the 500,000 bbl/day stage. I believe, however, that by the time a 1 million bbl/day level is reached, other processing in the region, such as mineral processing, coal gasification, and power generation, will have claimed the remaining surface water. Thus, growth of an oil-shale industry beyond 1 million bbl/day capacity will require further technological reduction of its present water requirements or access to other sources of water.

One such alternate water source is the possible existence of a saline water aquifer approximately 1000 ft beneath the surface of the Piceance Creek basin. According to U.S. Geological Survey estimates, the aquifer may contain 25 million ac-ft of water. Salinity is estimated to vary from 2,000 to 63,000 ppm. While the high salinity may restrict the application of this ground water in oil shale processing, it likely could be used at least for wetting and compacting spent shale, which consumes 45 percent of direct process water requirements.

Surface retorting plus underground mining requires a consumptive power capacity of approximately 1 KW for each 1 bbl/day of shale oil production. A 50,000 bbl/day plant will, therefore, have a consumptive power requirement of 50,000 KW; and a one million bbl/day industry will need a capacity of approximately 1000 megawatts. (Installed capacity would be as much as 50 percent higher). The domestic power requirements of the associated communities would increase these figures by an additional 10 percent.

ECONOMICS OF SHALE OIL PRODUCTION

It would be desirable to compare the cost of shale

oil production by the various processes previously described. Unfortunately, meaningful comparison is impossible at present because detailed published economic data on each process are unavailable. The most recent (1972) cost estimates of the National Petroleum Council (NPC), however, serves as a basis of "order of magnitude" data representative of current oil shale economics.

The NPC figures are based on an estimated value of the dollar in the mid-1970's. The major assumptions include a 100,000 bbl/calendar day syncrude (upgraded shale oil) plant using 30 gal/ton shale obtained by underground room-and-pillar shaft mining. The Tosco II retorting process was used for the estimates, with the resulting shale oil upgraded by hydrotreating to a low-sulfur and low-nitrogen, 50°F pour point, 46° API high-gravity synthetic crude. The following rounded NPC figures were obtained:

Capital Costs: Mining, crushing, residue disposal, \$170 million; retorting, \$207 million; upgrading, \$193 million; miscellaneous, including working capital, \$32 million. Thus, total investment, exclusive of land, is \$602 million. (At 1974 costs and dollars, some \$720 million probably would be required.)

Annual Operating Costs (exclusive of depreciation): Mining, crushing, residue disposal, \$36 million; retorting, upgrading, miscellaneous, \$38 million. Total average operating costs thus are \$74 million/yr. (At 1974 costs and dollars, this now is probably about \$90 million/yr.)

Price of Shale Oil Syncrude: The NPC data indicated that the required selling price of shale oil syncrude, in mid-1970 dollars, was approximately \$5.10/bbl, in order to achieve a discounted cash flow rate of return of 15 percent.

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