A BRIEF COMPARISON OF SOME TECHNOLOGICAL AND ENVIRONMENTAL ASPECTS OF LARGE-SCALE SURFACE AND UNDERGROUND MINING OF OIL SHALE, PICEANCE CREEK BASIN, COLORADO

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ABSTRACT

Comparison of several aspects of surface and underground methods of mining for large-scale oil shale extraction in the Piceance Creek Basin suggests that surface mining techniques may have several advantages over underground methods. For a production level of one million barrels of shale oil per day, potential advantages include those related to economics, environmental effects, and the overall national interest. One million barrels of shale oil per day could be produced from 2-3 large surface mines compared to perhaps 10-20 large underground mines. Fewer surface mines would result in: (1) fewer roads and utility corridors, (2) less acres disturbed per barrel of oil produced, (3) reduced detrimental effects on ground water and surface water, (4) less wildlife disturbance, (5) a safer overall operation, (6) a greater opportunity to achieve stable long-term land and water reclamation, (7) potential economic advantages related to scale and materials handling, and (8) a three- to five-fold increase in resource recovery. Advantages to underground (including modified in situ [MIS]) mines include: (1) more flexibility of mine siting, (2) mining and handling a minimum of waste rock, and (3) simplified ore grade control for processing.

INTRODUCTION

The unique mineral resources of the Green River Formation in the Piceance Creek Basin, Colorado, require careful and comprehensive planning for best utilization. Development of the oil-shale resource appears inevitable in view of current and projected demands for petroleum and uncertain but finite sources of crude oil.

The natural resources of the Piceance Creek Basin include huge deposits of oil shale in the Green River Formation that are commingled with billions of tons of sodium- and aluminum-bearing minerals in strata that are as much as 1,800-2,000 feet (550-610 m) thick. Older strata underlying the Green River Formation include extensive, but deep, coal beds that contain potentially enormous resources of methane gas, and deposits of oil and gas. Millions of acre-feet of ground water are stored in aquifers in the basin. Basin resources also include an abundance of wildlife, particularly an internationally famous mule deer herd, a large annual production of livestock, and evidence of aboriginal man. All these resources are in a semi-wilderness western cultural setting. Because of the complexity of such a strategic multi-mineral resource, combined with the other natural resources, industry and government should cooperatively plan for the best development of these resources for present and future generations. It would be inexcusable, if for the sake of expediency, we opted for operations that left most of the oil shale resource in the ground in a condition that made future recovery difficult, or permanently damaged large parts of the livestock range, wildlife habitat, or water resources.

No oil shale industry exists there today, but limited research and development has been conducted on methods of mining oil shale, including room-and-pillar mining, modified and true in situ techniques, and surface mining. However, studies have focused on specific processess and sites, and do not relate to one another nor address the interactive complexities of basinwide development. Locations of several proposed projects and sites of experimental work are shown in figure 1.

Because of the uncertainties inherent with the start-up of a new and unproven industry, environmental assessment of potential impacts of an oil-shale industry on surface resources is necessarily speculative, as discussed in the Environmental Impact Statement for the Federal Prototype Oil Shale Program (U.S. Department of Interior, 1973) and in papers by Kilburn (1976), Baker and others (1980), and Dietz and others (1978).

Ertl (1965), Smith (1974), Lewis (1980), and Rubenson and Pei (1983), recognized many of the advantages and problems of large-scale development, and noted that a substantial portion (perhaps most) of the large oil-shale resources in the central part of the basin appear to be suitable for surface mining (fig. 3). Presumably most of the basin is amenable to underground mining. Ertl (1965) envisioned the southern part of the basin, where the oil shale resource is thinner and at shallower depths, as the logical area for an industry to start development, so as to eventually be able to efficiently mine the thick, rich deposits in the central part of the basin. Adams and others (1976) studied the techniques and costs for a large-scale surface mine in the northwest part of the basin. Lappi and others (1982) detailed several potential environmental effects on air and water of a hypothetical large surface mine in the north-central part of the basin.

This paper compares in a general way some effects of large-scale mining in the Piceance Creek Basin by a few open-pit mines on the one hand and by multiple underground mines on the other hand, and the impacts of these two methods of mining on the natural resources of the basin. This summary does not claim to be complete or definitive, but attempts to point out some important effects of each type of mining. We do not imply that the basin will be developed by "either-or" surface or underground methods. Current plans and activities indicate otherwise. The two methods as discussed, however, simplify our comparisons. Some of our comparisons are straightforward, some are qualitative, but all of them indicate that careful planning and research are prerequisite to prudent development.

EXTRACTION SCHEMES

For purposes of this paper, we assume a total production rate from Piceance Creek Basin of 1 million barrels (0.16×10^6 m^3) of shale oil per day (BPD). On the basis of numerous published plans and production estimates, we assume that 1 million BPD would require 10-20 underground mines, or as few as 2-3 surface mines. Some mix of the two methods is likely to occur. There is no precedent in mining of any deposit in terms of comparable size, character, or potential importance. Mining rates for a 1-million-BPD industry by multiple underground mines could total 1-1½ million tons (0.9-1.36×10^6 mt) per day of 30-40 gpt (125-167 l/mt) shale, and more than twice this tonnage of lower-grade shale (15-20 gpt [63-83 l/mt]) and waste overburden from surface mines.

In this paper "underground" methods include conventional mining methods as well as in situ and modified in situ (MIS) methods. Also, because shale oil and associated minerals have not yet proven to be economically extractable, we use here the term "resource" (Brobst and Pratt, 1973).

An oil-shale industry of this size and complexity will require the coordination of many technical disciplines, including environmental sciences, geology and hydrology, mining engineering, milling, and processing engineering and chemistry. Similarly, close coordination between industry and all levels of government--including local, State, and Federal--will be essential for land and resource planning and management, socioeconomic planning, and environmental concerns.

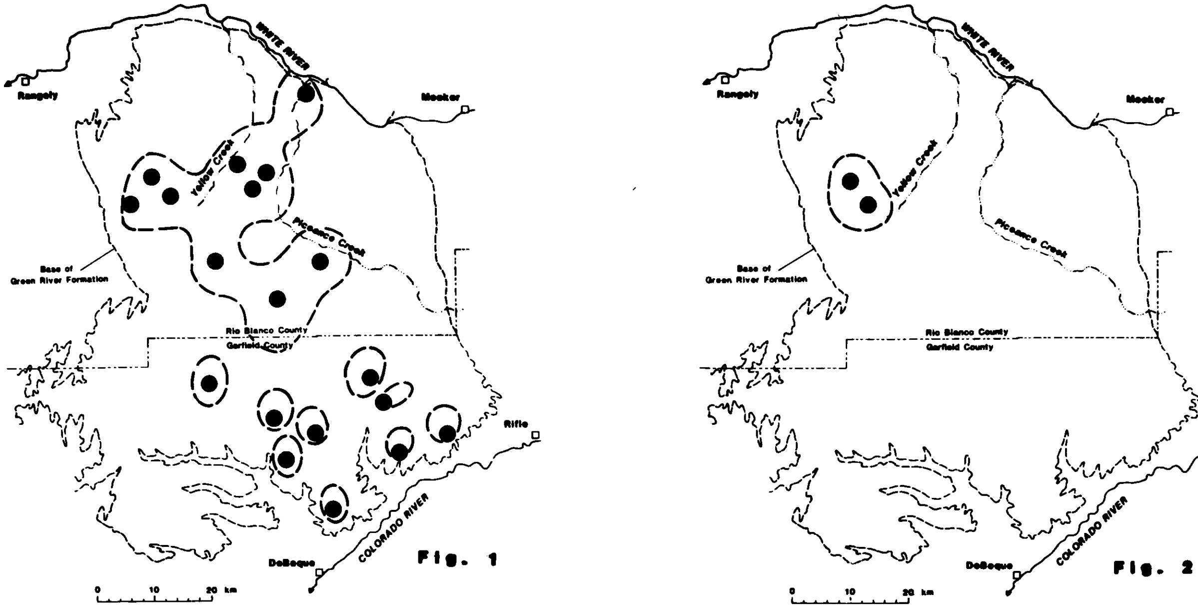

Fig. 1

Fig. 2

Figures 1 and 2.--Diagrammatic sketches of the areas of 100 ft (30 m) drawdown for multiple underground mines (fig. 1) and for two surface mines (fig. 2) in the Piceance Creek Basin. The locations shown in fig. 1 are sites of proposed and experimental mines. The areas of drawdown for the mines in the southern part of the basin are discontinuous because the mines are separated by deeply incised valleys that cut below the potentially mineable beds of oil shale.

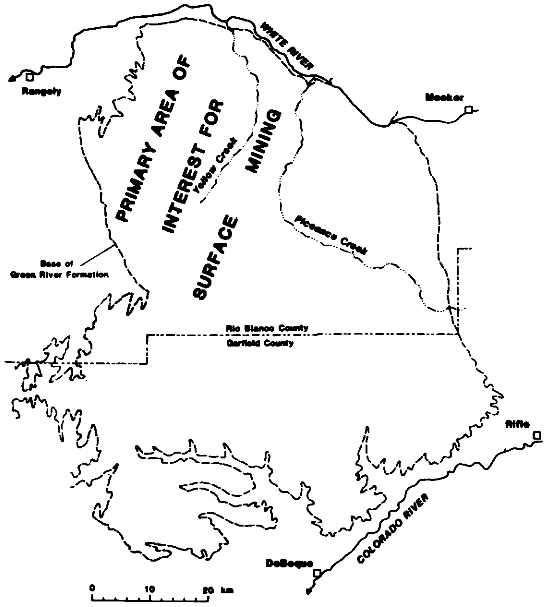

Figure 3.--Primary area most amenable for open-pit mining of oil shale in the Piceance Creek Basin.

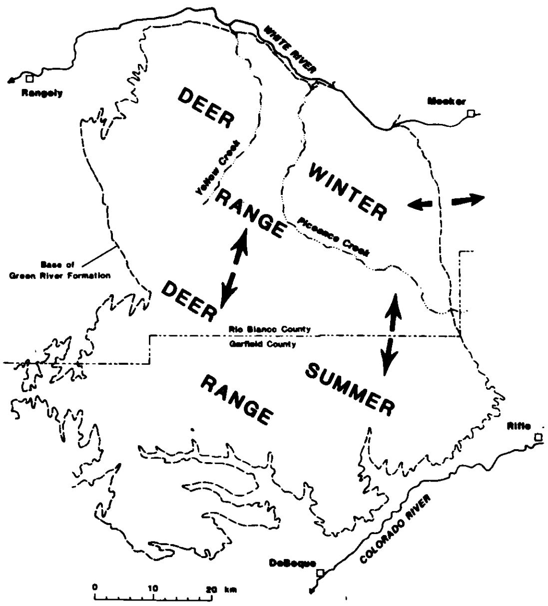

Figure 4.--Area of summer and winter range of the mule deer herd in the Piceance Creek Basin. The winter range is mostly below an altitude of about 7,000 ft (2100 m) whereas the summer range lies generally above 8,000 ft (2400 m). The arrows indicate spring and fall migration routes.

GEOLOGY AND RESOURCES

The oil-shale-rich part of the Piceance Creek Basin covers about 1,800 square miles (4700 km^2). The oil shale, most of which is a kerogen-rich dolomitic rock, originated in a large lake that persisted from about 55- to 45-million years ago. During part of the lake's existence, large amounts of sodium minerals, including nahcolite, dawsonite, and halite, were deposited. Kerogen-rich sediments were deposited in the basin throughout most of the lake's long life. As much as 2,000 feet (600 m) of oil shale, with commingled deposits of nahcolite and dawsonite, accumulated in the depositional center of the lake in the northern part of the Piceance Creek Basin.

Subsequent sedimentation covered the thickest and richest part of the oil-shale deposits in the northern part of the basin with as much as 1,000 feet (300 m) or more of sandstone, siltstone, and marly rocks, all nearly devoid of oil shale. Subsequent erosion removed some of these overlying rocks. Although the thickness of overburden increases toward the basin depocenter, so does the thickness and grade of oil shale. Because of this relationship, the stripping ratio (unit thickness of overburden/unit thickness of ore) in the basin center where the overburden is thick, is locally as low as 0.5 to 0.8 and is 1 or less over large areas. Thus, even in the deep part of the basin the stripping ratio does not preclude open-pit mining.

The enormous resources of oil shale and potential coproducts, nahcolite and dawsonitic alumina, are of vital long-range interest to the United States. Exploitation of these resources to maximize their recovery in ways that will have minimum impact on the environment will require careful planning.

Oil:--The total resource of oil shale in the Piceance Creek Basin is estimated to be about 1.2 trillion equivalent barrels (191 X 10^9 m^3) of oil of which 50 percent is in beds that will yield 25 gallons or more per ton (104 l/mt) (Donnell, 1980). This resource is approximately 10 times as great as the total quantity of oil (about 130 billion barrels [21 X 10^9 m^3]) that the United States consumed through the mid-1970s. The size and grade of this deposit makes it the most important potential fossil-energy resource in the country, if not the world.

Nahcolite ($NaHCO_3$):--About 32 billion tons of nahcolite (29 X 10^9 mt) occur in the lower half of the oil-shale deposits in the northern part of the basin. About 60 percent of the nahcolite is commingled with oil shale in aggregates and crystals, therefore, it will need to be mined as a byproduct of an oil-shale industry. Some beds of nahcolite, however, may be amenable to mining separately (Dyni, 1974; Beard and others, 1974).

If large-scale production of nahcolite as a oil-shale byproduct is achieved, it could become competitive with Wyoming trona which now dominates the domestic soda-ash market. The mineral may find other important uses such as for flue gas desulfurization and as an additive to animal feed (Kostick and Foster, 1979; Dyni, 1981).

Alumina and other byproducts:--Dawsonite [$NaAl(OH)_2CO_3$], a potential source of alumina, occurs as finely disseminated crystals in the lower part of the oil-shale sequence in the deeper part of the Piceance Creek Basin (De Voto and others, 1970). Beard and others (1974) estimated the alumina content of the dawsonite resource to be 6.5 billion tons (5.9 X 10^9 mt). Although the in-place resource of dawsonitic alumina is large, production levels will probably be entirely dependent on the rate of production of oil shale. More than 400 mi^2 (1000 km^2) of the northern part of the basin is underlain by dawsonitic oil shale, and locally the dawsonitic strata are 800-1,000 feet (240-300 m) thick (Beard and others, 1974). The nearest access from the surface to dawsonitic oil shale is at the north end of the basin along Piceance Creek. A small rate of production of byproduct alumina from dawsonite could conceivably be attained in a few years in this area; but large-scale production (+500,000 tons [+0.45 X 10^6 mt]) of alumina/year) is probably scores of years in the future. At a production rate of 1 million tons (0.9 X 10^6 mt) of oil shale per day containing 8 percent dawsonite, the annual rate of production of equivalent aluminum metal would amount to about 5 1/2 million tons (5.0 X 10^6 mt). This is nearly equal to current United States annual use (U.S. Bureau of Mines, 1980). Total in-place resource as equivalent aluminum metal is about 3 1/2 billion tons (3.2 X 10^6 mt), or about 20 times that in the known bauxite resources of the United States. Research is needed to further delineate the occurrence of dawsonite in oil shale. Extraction methods for alumina from dawsonitic oil shale have been developed on a laboratory scale, but further research is needed.

When large-scale production of oil shale is attained, other byproducts may be recovered such as sulfur and ammonia. Assuming an average sulfur content of 0.76 weight percent for Colorado oil shale (Dyni, 1983, p. 144), about 2.5 tons (2.3 mt) of sulfur could be produced per 1000 bbl (159 m^3) of oil. Limited data (Gulf Oil Corp. and Standard Oil Co., 1976) suggest that about 3 to 4 tons (2.7-3.6 mt) of ammonia could be produced per 1000 bbl (159 m^3) of oil. Thus, a 1 million BPD (0.16 X 10^6 m^3/day) industry could produce more than 1 million TPY (0.9 X 10^6 mt) of each byproduct. Even trace amounts of metals and other products may become economically feasible to recover, because mining and milling costs would be largely offset by production of shale oil. Further, the spent shale after retorting may be more amenable to recovering trace metals because it would be in small-sized particles amenable to easy leaching, and be free of binding kerogen.

In addition to these mineral resources, the surface of the basin supports important wildlife and domestic animal resources of mule deer, sheep, and cattle as discussed in the following section.

BIOLOGICAL RESOURCES

Because of the importance of the migratory mule deer herd (fig. 4) to the economy and ecology of the Piceance Creek Basin, they will be used as the representative fauna and their habitat will be the representative flora for our discussion of the effect of various mining methods and strategies on the surface biology. Deer hunting and livestock production are, and have been historically, the major surface resource use of the region. From a hunting standpoint, the Piceance Creek Basin deer herd is one of the largest and most famous in North America. Populations have fluctuated in recent times from a high of about 35,000 in 1978 to a low of about 15,000 in 1979. The present deer population is estimated at about 27,500, but reports suggest that in the mid-1950's the herd numbered more than 50,000 (John Ellenberger, personal commun.,1984). Livestock (cattle and sheep) are estimated to number about 100,000 animals within the basin (U.S. Bureau of Land Management, 1983).

An understanding of the ecology of the mule deer in this relatively wild area must precede large-scale oil-shale development if we are to minimize its impacts on the deer. Much still remains to be learned about the value of both summer and winter range to deer as well as about other factors such as migration, predation, disease, poaching, livestock competition, and weather-related stress. Despite the dearth of pertinent scientific data, general predictions can be made concerning the impact of oil-shale development on wildlife and its habitat.

Some ecologic factors related to survival of the mule deer are: (1) a herd nucleus that will survive the harsh winter and early spring period, (2) ability of winter-stressed does to migrate to fawning areas on summer range (fig. 4), (3) sustenance of does through successful fawning and the early summer period, (4) provision of adequate nutrition for does and fawns, (5) a safe habitat free of harassment in which to gain strength and maintain good general body condition for the approaching winter, (6) assurance that enough does, bucks, and fawns survive the fall hunting season to achieve the proper sex and age ratios for productive herd dynamics, and (7) ability of the herd to migrate to the winter range in the best possible body condition.

COMPARISON OF SOME FACTORS RELATED TO SURFACE AND UNDERGROUND MINING

(1) National Interests:--Perhaps the most important factors of an oil shale industry in the basin in terms of national interest are the percentage of recovery of the total multi-mineral resource, resource production rates, and environmental concerns.

A high percentage of in-place resource recovery appears to be critical. Each 10 percent increase in recovery of the oil-shale resource is about equal to the total United States production of crude oil from Drake's discovery in the mid-19th century through the early 1970's. Secondary recovery attempts following underground mining of oil shale may be marginally successful because of the great thickness of the deposit.

Current plans for underground mining in thick sections of oil shale may achieve <20 to about 30 percent of the total resource, whereas surface mining might obtain nearly 100 percent recovery. Undoubtedly, surface mining could recover more of the resource at higher rates of production and may cause less damage to the environment. The potential for large resource recovery is inherent in surface mining, where cutoff grades can be utilized. In underground mining of thick deposits, mine design dictates that much ore be left in place to support mine workings. Specialized methods such as multi-level block caving and similar techniques (J. W. Miley, written commun., 1984; Reeder and Senocak, 1982) may significantly increase the percentage of mineral recovery by underground mining, but the feasibility of such techniques remains to be demonstrated.

(2) Economics:--Economics warrants mention in this paper because it is inseparable from the technical and environmental factors. Production costs, including profit, for shale oil from Piceance Creek Basin are currently estimated to be 1.4 to 2 times the cost of conventional crude oil, based on limited public information from negotiations and existing contracts between companies and the Synthetic Fuels Corporation. A necessary assumption here is that this spread will disappear as crude oil becomes scarce and demand for oil continues to rise. To date, small-scale field experiments have been carried out in Piceance Creek Basin for underground mining, surface retorting, MIS, *in situ*, and in the refining and utilization of produced shale oil. Few data are available on cost estimates from these limited mining experiments, and comparative mining costs are still highly uncertain. Surface mining involves moving all material (overburden, interburden, ore), which is collectively of low unit value, at a low cost per ton, whereas underground methods move much less material of collectively high unit value, at a higher cost per ton. Comparisons of processing costs, which account for much of the total costs, are largely unknown. Large-scale processing provide an opportunity for scale-related advantages in costs. Much additional research and development are needed to develop cost data, especially for large-scale mining and retorting.

(3) Safety:--The overall rate in the United States for serious accidents at all surface mines is less than half that at all underground mines. A more rational comparison, large surface mines with large underground mines, suggests that the accident rate at large oil-shale surface mines would be about two-thirds that at large underground mines (Mary Monroe, written commun., 1984). In addition, underground mines may place more than twice the workforce at risk than at surface mines. Mine safety is a critical part of any operation, and research will be needed to keep abreast of effects on safety of newly evolving mining methods.

(4) Surface disturbance:--Disturbed areas include mine, plant, and waste disposal sites. Available data and estimates vary widely, but 10-20 underground mines may disturb about the same total acres as 2-3 surface mines. The necessary additional access corridors would increase the disturbed acreage at underground mines. At a production rate of 1 million BPD (0.16×10^6 m^3/day), the required miles of roads, pipelines, and power lines would be less for 2-3 surface mines than for 10-20 underground mines. Environmental effects of corridors include increased road kills of deer and livestock, increased vehicle and people density, and lessened scenic values. A general idea of the corridor requirements can be envisioned from figure 1. Some mines might share portions of some corridors. On the basis of acres disturbed per barrel of oil produced, when considered over the mining life of the entire basin, surface mining would disturb one-third or less number of acres than underground mining because of the much higher percentage of resource recovery.

(5) Air quality:--Geographically dispersed shale oil production at 10-20 underground mines producing at rates of 50,000-100,000 BPD (8,000-16,000 m^3/day) each *may* produce less degradation in air quality than the same total production at 2-3 surface mines. Published estimates vary widely, and emission sources are based in large part on similar activities in other industries. However, production localized at a few sites *may* result in advantages of scale in emission control technology that could offset this more concentrated source. The necessary blasting and crushing at surface mines would produce airborne particulates. Air quality effects related to surface disposal of

spent shale may be similar for both technologies. Current air-quality laws, combined with current technology for emission controls, may limit shale oil production from Piceance Creek Basin to about 0.4-1.5 million BPD (64-238 X 10^3 m^3/day). Oxides of sulfur and nitrogen, reduced visibility, carbon dioxide, and acid rain are some atmospheric concerns requiring research. In addition to the need for improved emission control technology, research is needed to better measure biological and health effects of air pollutants.

(6) Water requirements:--A wide degree of uncertainty exists in the estimated water requirements for oil shale development. The range for many estimates is 1-4 barrels of water consumed per barrel of shale oil produced. Within this range, local sources of surface water are potentially adequate for shale oil production of about 0.4 to 1.6 million BPD (64-239 X 10^3 m^3/day), with minor amounts needed from the Colorado River system (Miller, 1982). Economies of scale may allow more efficient water use at a few large surface mines than at multiple underground mines. Shallow ground waters in the basin, which will be partly pumped during mine dewatering, could theoretically supply a one-million-BPD (0.16 X 10^6 m^3/day) oil-shale industry for 50-200 years (Miller, 1982). Large additional supplies of ground water may be present in deeper still untested aquifers (Teller and Welder, 1983). Careful planning and research are essential to minimize water use by an oil shale industry, because although large quantities of water are present in the area, water laws and regulations may be an important long-term deterrent to large-scale development.

(7) Surface water:--Mine dewatering is expected to cause widespread impacts on streams (Weeks and others, 1974) with multiple underground mine development, whereas very localized impacts are expected from a few surface mines. Stream depletion probably will be widespread as a result of dewatering at 10-20 underground mines (figs. 1 and 2), unless carefully controlled augmentation, such as artificial recharge, is practiced. The added flexibility in methods of land reclamation after surface mining should provide a wide range of options to achieve desired runoff characteristics. Depletion of Colorado River system flows can be minimized by combined use of ground-water and surface waters (Alley, 1982). Research, including modeling studies, is needed to learn how to manage surface water supplies in order to minimize adverse effects on streamflows and on water quality.

(8) Ground water:--The area of large water level decline within the cone of depression accompanying mine dewatering would be localized at few closely spaced surface mines. At a given site, the dewatering rate and accompanying drawdown may be about the same for an underground mine as for a surface mine. Thus at 10-20 mines, widespread, overlapping cones of depression would occur, leading to probably significant basinwide effects, including diminished flow in many streams. Figures 1 and 2 diagrammatically illustrate different drawdown patterns for each type of mining. The patterns are extrapolated from early modeling by Weeks and others (1974) and from more recent observed drawdown data from mines in the basin (Rutledge, 1982). However, because of the many scattered pumping centers, 10-20 underground mines might extract stored ground water more efficiently than a few surface mines. Research, field testing, and modeling are needed to quantify future site-specific effects on ground water. Aquifer disruption, dewatering effects, post-mining hydrologic regimes, and the effect of surface-retorted and MIS processed shale management on water quality and quantity are among the critical topics in need of research.

(9) Wildlife:--A large open-pit mine would disturb much more wildlife range than a single large underground mine. For multiple underground mine development, each mine will have similar requirements for surface facilities, including plants, roads, utility corridors, etc. Thus, the comparison between multiple underground mines and a few surface mines is essentially that of the influence of one large concentrated area of disturbance on wildlife versus many smaller disturbed areas, each with a network of roads, utility corridors, workers camps, plant and waste sites, and other facilities.

Major potential impacts to wildlife and their habitat from oil shale development are described by U.S. Geological Survey (1979), National Academy of Sciences (1979), Dietz and others (1978), Dietz and Tucker (1983), and Baker and others (1980).

Impacts on deer and their habitat are assumed to be representative of impacts on fauna and flora in general. A few large surface mines will impact deer and their habitat differently than multiple underground mines.

Multiple underground mine development will result in much more stress on deer and their habitat than 2-3 surface mines. Collisions with deer will occur more frequently along the massive road and utility network for multiple underground mines. Many more barriers to migration will result from the many miles of roads, utility corridors, and plant sites. Human activity around the mine sites and on roads to and from the mines will cause stress to deer during critical periods such as during late winter when their resistance to stress is low. Streams, springs, and seeps may diminish in flow or dry up, making large areas of habitat less attractive to deer. On the other hand, development may create new springs and seeps, making available new areas for deer. The possibility of contamination of water sources from underground seepage, spills, and surface discharges present an unquantified threat.

Research is needed to clarify the many uncertainties in our knowledge of wildlife ecology, and to allow accurate prediction of impacts on wildlife and their habitat.

(10) Land and water reclamation:--Long-term success of reclamation appears more certain following surface mining than after underground mining. Surface mines provide a variety of materials for reclaiming the mined area and waste piles to minimize long-term adverse effects. Surface mine activities typically cause fewer subsidence problems than underground mines, and provide a greater opportunity to sculpture the reclaimed landscape as desired. Reclamation of surface mines provides an opportunity to reconstruct a functional aquifer system.

Underground mines provide little choice of materials for reclamation, which may result in a less stable area, and cause a variety of adverse effects on aquifers. Some plans for reclamation of processed shale at underground mines would potentially diminish both surface flows and ground-water recharge, because little runoff is expected and very little downward seepage presumably occurs through the processed shale. The effects of surface and subsurface subsidence, old mine workings, and abandoned MIS retorts filled with spent shale on ground-water flow and quality are potentially serious problems. Backfilling of underground mines would reduce subsidence and might lessen effects of waste disposal. Research and modeling are needed to develop and evaluate reclamation techniques, including the future hydrologic regimes of a variety of simulated mined-out and reclaimed areas, for both open pit and underground mines.

PLANNING FOR BASINWIDE DEVELOPMENT

The primary considerations in large-scale development of the Piceance Creek Basin are the geology, topography, wildlife, and scenery, and how best to adapt the most suitable methods of extraction to these conditions. We assume that current Federal, State, and local rules and regulations will be easier to change than the physical conditions of the basin, in order to achieve the best balance between resource development and preservation of the environment. Sir Francis Bacon's admonition (1620, cited in Robinson & Spieker, 1978), made at a time when man's understanding and awe of the physical world must have been different from ours, seems pertinent: "Nature, to be commanded, must be obeyed."

We have briefly outlined two fundamentally different methods of mining that should be considered in planning for large-scale development of the oil-shale deposits in the Piceance Creek Basin. A detailed evaluation of these differences is beyond scope of this paper, but we fully agree with an earlier proponent of prudent resource development, Dr. Tell Ertl, who sounded a clear warning in 1965: "...increased demand cannot give serious consideration to any method of production of shale oil from the center of the basin that does not result in substantially complete recovery. Our civilization has passed the stage in which it can kill the whole buffalo merely to consume the tongue and liver as was done in the area less than a century ago."

SUMMARY

There will be actions in the near future to develop this unique and critically important national resource. In view of diminishing world oil reserves, oil-shale development appears to be a logical step to production of synthetic fossil liquid fuels. The most efficient way of developing the oil-shale resource should be based on physical characteristics of the area and the deposit, in order to achieve its maximum utilization with minimum adverse effect on the environment.

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