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Oil Shale in the Piceance Basin

An Analysis of Land Use Issues

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DISCLAIMER

PREFACE

This report integrates results from two separate Rand studies performed for the U.S. Department of Energy under Contract No. DE AC01-80PE70271 over a period of two years. (Preparation of the report was supported by The Rand Corporation from its own funds.) The common purpose of the studies was to contribute to a framework for establishing policies that would promote efficient use of the nation's oil shale resource.

Rand has developed an analytical methodology that explains the effects of federal leasing policies on the resource recovery, extraction costs, and development times associated with oil shale surface mines. The methodology was applied to the types of deposits found in Colorado's Piceance Basin, which contains the most concentrated oil shale deposits in the world. This report explores the effects of lease size, industry development patterns, waste disposal policy, and lease boundaries on the potential of the Piceance Basin oil shale resource.

The approach described here should aid in understanding the relationship between federal leasing policies and the requirements for developing Piceance Basin oil shale. The results are expected to be useful to researchers interested in policy and program issues concerning the development of the U.S. oil shale resource.

SUMMARY

THE POLICY PROBLEM

The United States, Western Europe, and Japan depend on foreign oil supplies. The price of foreign oil has fluctuated, but until recent months, the upward trend has motivated interest in alternative sources of liquid fuels. In addition to financial concerns, apprehension over the stability of the Persian Gulf oil region has raised the possibility of sudden reductions or interruptions in oil supplies. Alleviating the adverse effects of dependence on foreign oil will require contributions from many different areas. One of the most important potential sources is the oil shale located in Colorado's Piceance Basin. Oil shale is a solid organic material that can be converted to a liquid by heating. The 1200 square mile Piceance Basin contains enough oil shale to support a multi-million barrel-per-day (bpd) industry for centuries.

The Piceance Basin consists of both federal and private holdings. Private holdings are in the southernmost portion of the basin, containing thin deposits of rich shale, averaging more than 30 gallons per ton. The use of underground mining to extract these rich seams appears to be feasible. The cost of developing shale oil from this region may be among the lowest in the basin. However, the bulk of the resource is on federal land in the central and northern portions of the basin. Here moderate grades of shale, averaging between 20–25 gallons per ton, occur in contiguous deposits up to 2000 ft thick. Surface mining is the only technique that can lead to extraction of a large fraction of these thick deposits.

Because most of the oil shale resource is federally owned, the rules governing the use of federal lands are particularly important. These rules were established by the *Mineral Leasing Act of 1920*, which limits the size of any lease to 5120 acres, prevents the use of additional federal lands for disposal of shale waste, and prevents any single developer from obtaining more than one lease. In this analysis we determine the effects of these restrictions on the feasibility of establishing an oil shale industry that can produce a considerable fraction of the nation's liquid fuel supplies.

RESOURCE EXTRACTION, COSTS, AND SURGE CAPACITY

The most intensely debated aspect of federal land policies is restriction of lease size and waste disposal. Using a geometrical model of a surface mine, we show that current restrictions will constrain resource recovery to approximately 10 percent, precluding the use of oil shale as a means for replacing large quantities of foreign oil. Larger leases or off-site disposal could greatly increase the resource recovery from a lease. Because waste disposal piles may cover large quantities of shale, if these deposits are included in the assessment, the policy option of maintaining a 5120 acre size and allowing off-site disposal of waste is not as effective as increases in lease size.

A measure of mining efficiency, called the stripping ratio, is used as a surrogate for extraction costs. Current leasing policies can affect extraction costs by creating constraints on project size. The limitation of one lease per developer may exclude developers from participating on projects on leases other than their own. Coupled with anti-trust concerns and the industry tradition for decentralized development, this will discourage large joint ventures. Thus project size may be limited to the capacities typically contemplated by individual developers, about 50,000 bpd. Such a constraint would considerably increase the cost of extracting most of the shale located in very thick (2000 ft thick) deposits in the center basin. Further, projects of 250,000 bpd will be required to extract this shale efficiently. Economies of scale are also indicated for the somewhat thinner (800 ft) shale deposits located on the western edge of the basin. However, these economies were fairly small, and a 50,000 bpd constraint would not severely affect extraction costs in this case.

The same factors that constrain project size will encourage developers to begin new mines rather than expand existing ones. Mine expansion is also constrained by the presence of lease boundaries. This constraint will increase the cost of extracting shale in all portions of the basin.

The rate at which mines can be expanded represents the speed with which oil shale could contribute to alleviating the problems arising from an energy emergency. Although mining is only one part of the industry, it is probably the longest lead time item in the process. If increased production must await the development of new mines, then oil shale will not make a timely contribution to national energy supplies. The only method of rapidly increasing mine capacity is to expand existing mines at the time of the crisis. However, even if the rules limiting expansion were changed after an emergency, mines would not have large surge capacity. Encouragement of mine expan-

sion before the emergency could increase surge capacity. Thus the same constraints that will increase mining costs by discouraging mine expansion will also increase the amount of time required to expand a shale industry.

IMPLICATIONS

Both the specific restrictions associated with current leasing practices and the general practice of leasing will reduce the potential of the resource. Larger leases are necessary for increased resource recovery, but by themselves they are not sufficient to promote the centralized mining operations needed for efficient extraction of the resource. The unique features of the Piceance Basin resource call for unique land use strategies, including: the careful siting of shale waste piles and process facilities to avoid covering large quantities of shale, mines allowed to migrate without concern for lease boundaries, and concentration of industry's mining capability to allow development of the super-large mining operations needed for efficient development of the central basin.

There are many socioeconomic and environmental concerns about the effects of development warranting a phased development of oil shale so that additional information can be obtained. The need for phased development is also consistent with industry's current lack of incentive or capability to develop the large projects required for efficient development of the central basin. Finally, the need for centralized mining is a direct result of the close connection between mining and the physical distribution of the resource. Other parts of the shale industry, such as processing and upgrading, are probably more sensitive to financial and managerial considerations than to resource distribution. Developers have typically viewed mining, processing, and upgrading as steps in a single operation, so centralized mining may result in unnecessary centralization of all aspects of the industry. The policy challenge is to develop a strategy that satisfies the requirements for maximum resource potential but remains sensitive to environmental, socioeconomic, and industry concerns.

A policy that satisfies these two objectives is outlined in the final section. An important aspect of this strategy is to designate the central basin as a reserve until industry is ready to take on the super-large projects needed for efficient development. Initial development should be concentrated on the private lands, where underground mining can lead to efficient development of the small 10,000 bpd projects needed to minimize financial risks in a new industry. Development of

federal lands should at first be confined to the western edge of the basin where efficient development can occur at production levels of 50,000 bpd. To insure that centralized mining does not predetermine the design of other parts of the industry, the mining and processing operations can be separated, permitting the process facilities to be decentralized and competitive while still addressing the need for centralized mining operations.

The proposed strategy for maximum resource use has the counterintuitive feature of calling for a go-slow policy on the release of federal lands. This is a result of the industry fragmentation that would occur if the basin were suddenly divided into many separate leases. Instead of preparing the release of more federal lands, federal activities should concentrate on stimulating development of private lands and on the institutional and engineering considerations needed to establish the required strategy. The former activity could involve participating in land exchanges and giving the private sector assurance that more federal land will become available when needed.

ACKNOWLEDGMENTS

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I. INTRODUCTION

THE IMPORTANCE OF OIL SHALE

There has been price instability for almost all forms of energy, but fluctuations in the price of foreign oil and dependence of the United States and its allies on imported oil have made liquid fuels a source of particular concern. The political and military instability of the Persian Gulf oil region has raised the possibility of sudden reductions in oil supplies. Even a short term cutoff, as in 1973 and 1979, had a severe effect. The limited size of U.S. and allies' oil reserves has created an incentive to develop alternative sources of liquid fuel.

The current rate of consumption of liquid fuels is so large that any single solution to this dependence is impractical. Over the last few years the United States has consumed between 12 and 16 million barrels per day (bpd) of liquid fuels, and our allies have consumed a comparable amount. As of spring 1983, a world wide recession has reduced OPEC (Organization of Petroleum Exporting Countries) production to a still enormous figure between 14 and 17 million bpd. However, OPEC production has been as high as 32 million bpd.[1] Replacing even a fraction of this output will require many different resources. Conservation and increased efficiency have already contributed greatly, but new sources of liquid fuels will be required even with increased conservation. Heavy crudes and Canadian tar sands are two alternatives that are already contributing to energy supplies, and the immense Venezuelan heavy crude resource may also be important. This source would not reduce dependence on foreign supplies, but it would provide a considerable degree of supplier diversification.

One of the most important potential sources of synthetic crude is Green River Formation oil shale. This resource, which is located in northwestern Colorado, northeastern Utah, and southern Wyoming, represents an immense potential source of liquid fuel. It has been suggested that an oil shale industry as large as eight million bpd might be established.[2] Efficient utilization of this resource could greatly reduce the adverse effects of dependence on imported oil.

Oil shale is a solid material that contains an organic substance called kerogen. The kerogen in oil shale can be converted to a liquid

[1] *The Economist*, Vol. 286, No. 7274, January 29, 1983, p. 11.
[2] See Exxon Company, 1980.

by heating. The process of extracting oil from shale is one of the oldest known methods of producing liquid fuels. Before the availability of low cost petroleum, several countries, including the United States, had shale industries. The U.S. shale industry lasted until the development of the oil well in the mid-nineteenth century, and those in other countries survived until the middle of the twentieth century when low cost imported oil made shale oil uneconomical. Only the Soviet Union and the People's Republic of China still maintain shale oil production. Since the mid-1960s, political and economic concerns over liquid fuel supplies have renewed interest in oil shale. However, uncertain cost estimates for shale plants and uncertainties in the price of imported oil have precluded many attempts to renew production. Only one project is currently under construction.[3]

Oil shale could reduce or eliminate many of the problems arising from dependence on imported oil. The domestic shale resource is so immense that production could exceed current U.S. import levels for decades, if not centuries. The size of this resource implies that once an industry is initiated, and production techniques and costs are verified, shale may become an important constraint on the price of foreign oil even if only a small fraction of the resource is developed, as long as the potential for increased production existed. Shale may also help the nation respond to energy emergencies. Shale is a secure domestic resource that can be developed with available technology. Although shale probably cannot contribute to meeting short term energy shortages, it could help the nation recover from a permanent loss of imported oil. Furthermore, shale oil is particularly well suited for production of jet fuel and could provide secure military supplies during a national energy emergency.

Many institutional, environmental, and technical issues will affect development of the U.S. oil shale resource. This report addresses the issue of federal land use policies and their effect on (1) the amount of shale that can be recovered, (2) the recovery costs, and (3) the lead times required for industry expansion. Total recovery and recovery costs are important if oil shale is to be used as a replacement for imported oil or as a constraint on its price. The extent to which oil shale can help the nation respond to extended reductions in foreign oil supplies depends on the time required to expand the industry.

The remainder of this section provides a description of the oil shale resource and the techniques that can be used to extract it. Section II discusses federal land utilization policies and states the research questions in specific terms. Section III presents our analysis, the as-

[3]Union Oil Company's Parachute Creek Shale Oil Program has a production target of 10,000 bpd. For a description of this project, see Randle and McGunegle, 1982.

sumptions underlying it, and quantitative results. These are then discussed in Sec. IV, as are alternative land use policies and their relationship to other development factors.

PROCESSING OIL SHALE

The factors inhibiting development of a commercial oil shale industry are mainly economic rather than technological. The conversion of the kerogen in oil shale to a liquid fuel is a fairly simple pyrolytic process. Retorting, heating the shale to about 900°F, has been used in earlier small oil shale industries for the last two centuries. The large retorting vessels that would be used in a modern industry will require substantial testing and refinement, but there are no fundamental obstacles preventing the conversion of kerogen to a liquid. There are, however, several operational and financial uncertainties associated with processing oil shale at the production levels required for today's needs.

A conventional oil shale processing facility consists of several process steps in addition to retorting. These steps are illustrated in Fig. 1. Before retorting, the oil shale must be mined, hauled, and crushed. Any overburden that is mined must be hauled to a disposal site. Oil shale is mostly inorganic material, and this material is not converted to liquid form. Enormous quantities of inorganic waste are generated, and this waste must also be hauled to a disposal site. Oil shale retorting also produces gases, which must be cleaned and upgraded. Shale

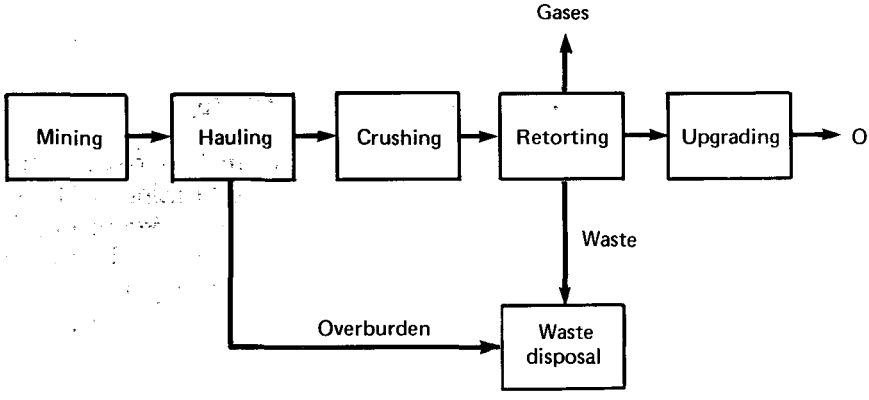

Fig. 1—Oil shale process flow

oil emerging from the retort must be upgraded before it can be used as a substitute for crude oil.

The major factor inhibiting the development of oil shale is the cost of implementing the process steps. Oil shale plants with capacities of 50,000 bpd have been estimated to cost several billion dollars.[4] At these high costs shale oil is not competitive with the current price of foreign oil. The financial uncertainty is partially attributable to the innovative aspects of oil shale processing. Although fundamental innovations are not required, oil shale facilities will require new integrations of proven technologies, and these integrations increase the uncertainty in estimating the costs of oil shale facilities. The large throughputs required for today's facilities also add to the uncertainty. These technical uncertainties, which lead to a high uncertainty around the high cost of oil shale, have resulted in the cancellation of all proposed shale projects except for one 10,000 bpd facility. The economic viability of this project has been increased by a price guarantee from the U.S. government.

THE PICEANCE BASIN

Figure 2 illustrates the geographical distribution of the oil shale deposits that underlie vast areas of the United States. Devonian and Mississippian deposits occur in large areas of the eastern United States, but most of these deposits are too thin and of insufficient richness to be of commercial interest. The deposits of the Green River Formation, located in northwestern Colorado, northeastern Utah, and southern Wyoming, are the thickest and richest oil shale deposits in the world.

Distribution of Green River Formation Oil Shale

Most Green River Formation oil shale occurs in four basins—the Piceance, Uinta, Green River, and Washakie. The locations of these basins are shown on the map of the Green River Formation in Fig. 3. Although the Piceance Basin is the smallest of the four basins, it contains most of the oil shale of commercial interest. Figure 4 shows the resource distribution within these basins. The 1200 square mile Piceance Basin makes up only 3.5 percent of the Green River Forma-

[4]For example a recent estimate by Exxon Corp. placed the capital cost of a 50,000 bpd facility at 4.9 billion dollars, see *Synfuels*, March 26, 1982.

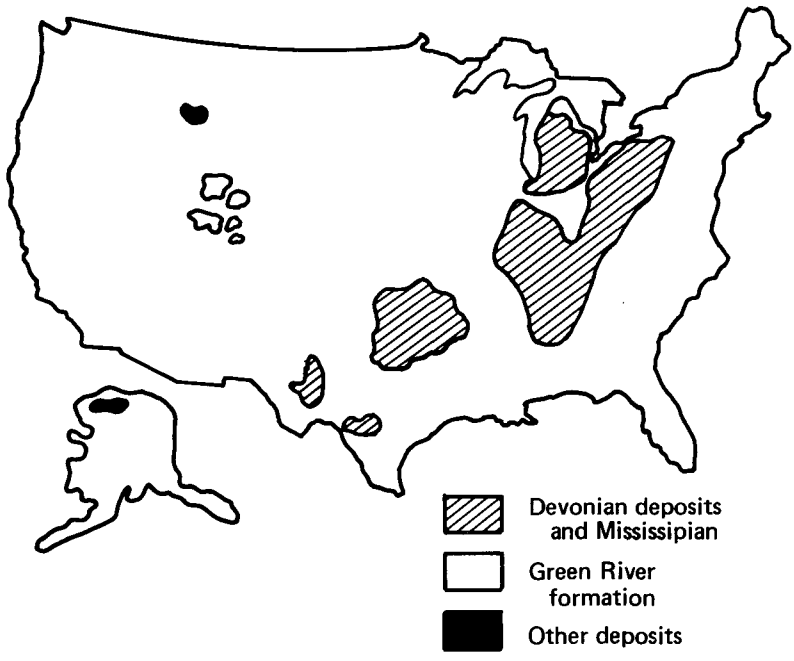

Fig. 2—U.S. oil shale deposits

tion, but it contains about 90 percent of the deposits that are at least 30 ft thick and average at least 30 gallons per ton (gpt). The Piceance Basin also contains 65 percent of the shale that is at least 15 gallons per ton.[5] Deposits of this lower grade shale in the Piceance Basin are thick and contiguously distributed and therefore of considerable commercial interest. Deposits of low grade shale in the other basins are thin and scattered. Only the rich (30 gpt) deposits in the Uinta Basin are of commercial interest. Wyoming deposits are of insufficient quality to be developed.

[5]The grade of shale is based on a measurement called the Fisher Assay. This is a reproducible method of measuring the oil yield from shale. It is not necessarily the maximum possible yield. The grade of shale is important because extracting oil from lower grades requires more mining and processing than extracting oil from high grade shales. A study by Cameron Engineers compared the costs of developing shale oil from equally accessible deposits of 30 gallon-per-ton shale and 15 gallon-per-ton shale. Depending on financial assumptions, the cost for developing 15 gallon-per-ton shale was 20–35 percent greater than the cost of developing 30 gallon-per-ton shale. See Cameron Engineers, 1976.

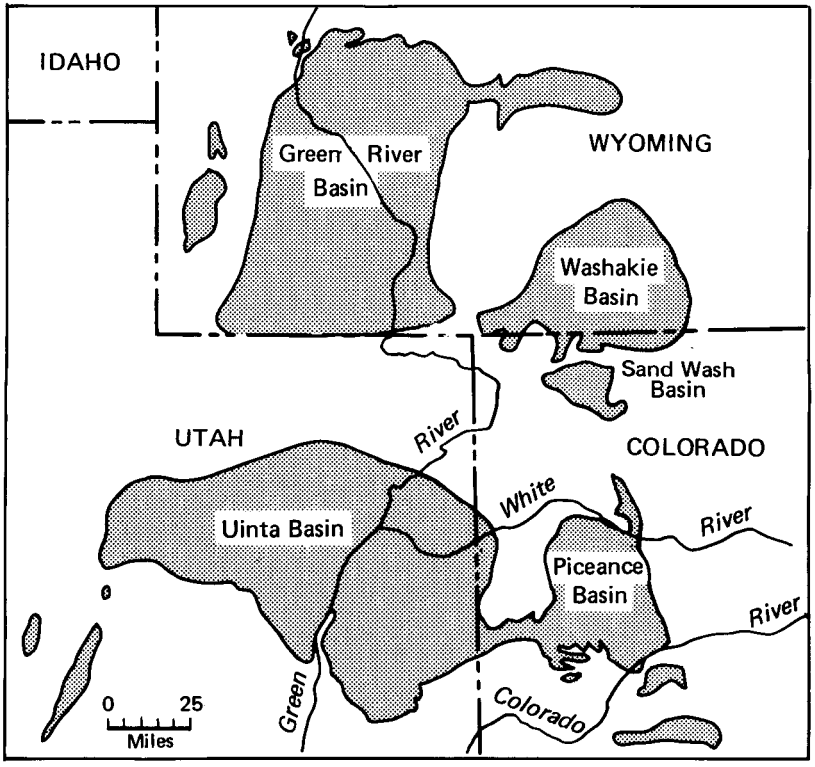

Fig. 3—The Green River Formation

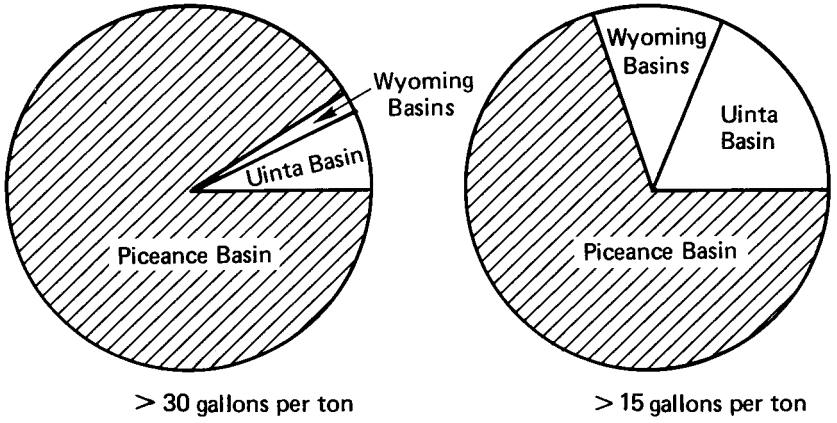

Fig. 4—Resource distribution in the Green River Formation

Piceance Basin oil shale represents an immense potential source of liquid fuels. Figure 5 shows a size comparison of Piceance Basin oil shale (cutoff grade of 15 gallons per ton) with world, middle eastern, and North American oil reserves and the amount of time that each of these deposits could provide the United States with 15 million barrels per day[6] (bpd) of liquid fuels. Although oil reserves are undoubtedly more accessible than shale, even with moderate recovery factors, the Piceance Basin resource is large enough to be considered as a potential replacement for foreign oil. The figure also illustrates the small size of North American oil reserves relative to others. Piceance Basin shale could play an important role in replacing this source as it becomes depleted.

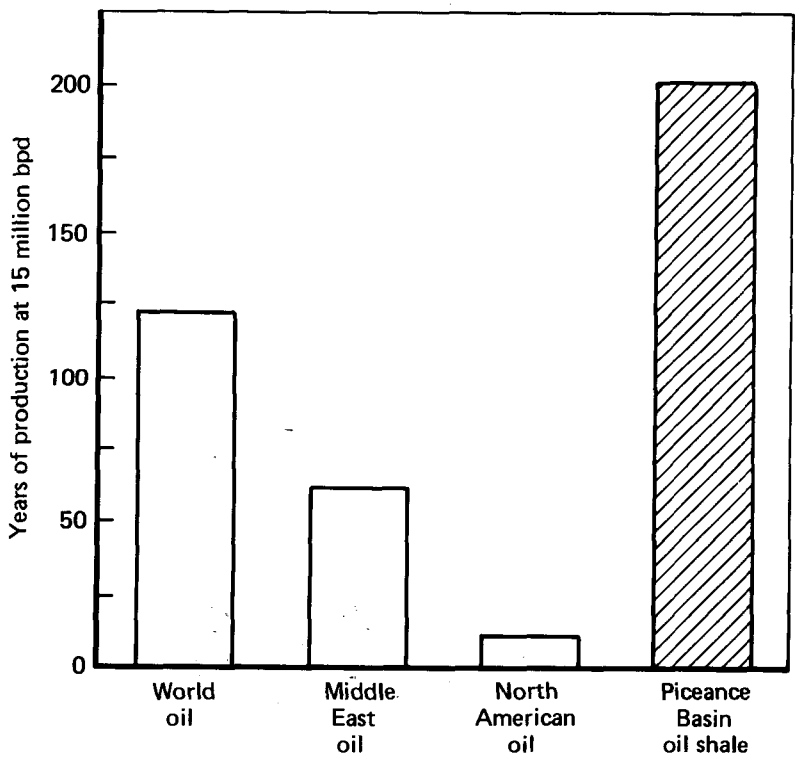

Fig. 5—Comparison of Piceance Basin shale with world oil reserves

[6]15 million bpd is typical for U.S. consumption during the last few years. Oil reserves in Fig. 5 were taken from Colorado Energy Research Institute, 1981, p. 18. Oil shale data in Fig. 5 were taken from U.S. Congress, Office of Technology Assessment, Vol. 1, 1980, p. 92.

Distribution of the Piceance Basin Resource

Oil shale occurs in thick contiguous deposits throughout most of the Piceance Basin. The central and northern portions of the basin contain the bulk of the resource. Figure 6 shows an outline of the basin and contour lines for deposits of 400, 800, 1200, and 2000 ft thicknesses, averaging at least 20 gallons per ton.[7] Deposit thicknesses in the central basin range up to 2000 ft. Thickness decreases closer to the edges, and there are no deposits of the indicated thickness in the southernmost portion. Deposits averaging at least 25 gallons per ton are also thickest in the center of the basin. Figure 7 shows contour lines for deposits of this grade.[8] Shale averaging 25 gpt has been found to occur in deposits as thick as 1500 ft in the center basin, which also contains the thickest deposits of shale averaging 30 gpt. The thickness of this rich shale is substantially less than that of shale

Fig. 6—Thickness of shale that is at least 20 gallons per ton

[7]This figure is based on Lewis, 1974.
[8]This figure is based on Cameron Engineers, Inc., 1976, p. 42.

Fig. 7—Thickness of deposits averaging 25 gallons per ton

between 20 and 25 gpt; however, deposits of 30 gpt shale have been found to occur in thicknesses up to 500 ft.[9]

Although the thickest and richest deposits are located in the central and northern portions of the basin, there are important deposits in the southernmost portion of the basin in a geological formation of rich shale called the Mahogany Zone. The quantity of this southern basin shale is small compared with that in the northern and central basin However, some of this shale is rich (averaging at least 30 gpt), fairly accessible, and of considerable commercial interest.

Extracting Piceance Basin Oil Shale

There are two well understood techniques that can be used to extract oil shale: underground mining (often referred to as room-and

[9]See Donnell, 1961, p. 872.

pillar) and surface mining. Other techniques such as modified in-situ processing are as yet unproved.[10] Surface mining is the only technique that can lead to extraction of a large fraction of the thick center basin deposits. Without considering waste disposal or processing area requirements, 90 percent of a deposit may be recovered.[11] When waste disposal and other operational constraints are considered, the percentage recovery can be much less. In room-and-pillar mining, only a thin seam is extracted, and a substantial amount of shale must be left in pillars to provide support. Typically about 50 percent of a 60 ft shale seam can be extracted with room-and-pillar mining. Surface mining is also free from many of the hazards of underground mining. The cost to extract a unit of rock is greater in an underground mine than in a surface mine; however, with underground mines it is possible to extract only the desired ore. Surface mining requires overburden removal, which means a considerably greater quantity of rock may have to be mined. Thus the ratio of overburden to ore thickness is an important factor in assessing the feasibility of surface mining.

The choice of mining technique depends on the resource extraction objectives, the ratio of overburden thickness to ore thickness, the topography, and other factors. Underground mining is the preferred method of extracting the rich Mahogany Zone deposits in the southern portion of the basin. The average thickness of these 30 gallon-per-ton deposits is less than 90 ft.[12] This implies that recovery factors of 33 to 50 percent can be obtained with underground mining. The topography of the southern basin also favors underground mining. The steep cliffs should facilitate access to underground mines and make surface mining more difficult. Surface mining this portion of the basin would require removal of overburden that is substantially thicker than the Mahogany Zone.

The factors affecting the choice of extraction techniques are considerably different in the center of the basin, which contains substantial deposits of 30 gpt shale; but the immense size of the Piceance Basin resource is due to center basin deposits of 20 gpt shale that are 2000 ft thick. This shale is characterized by favorable overburden to ore ratios (below 1.0 throughout most of the central basin). Efficient sur-

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[10]True in-situ (TIS) processing involves fracturing and heating the shale while it is still in the ground. In modified in-situ (MIS) processing a small portion of the shale is mined to increase the void volume needed for rubblization. See U.S. Congress, Office of Technology Assessment, Vol. 1, 1980, for a more complete description.

[11]Ibid., p. 245.

[12]Donnell, 1961, pp. 881-882.

face mining may therefore be feasible, and that is the only technique that can lead to recovery of a large fraction of a thick deposit.

Underground mining may be possible for the rich (30 gpt) center basin deposits but may be considerably more expensive than underground mining in the southern portion of the basin. The central basin is a large plateau and does not provide the same easy access to underground mines provided by the cliffs in the southern portion. There is also evidence of methane gas in the center basin, which could greatly increase the costs of underground mining. The rich deposits are also deeper in the center of the basin, implying larger haulage costs and requiring that more shale be left in the pillars to support the mine. The structural integrity of center basin shale is also an issue of great uncertainty. An analysis for one particular site indicated that the center basin shale was highly fractured and would not support efficient underground mining.[13] Thus underground mining costs in the center of the basin may be significantly higher than in the southern portion of the basin.

Ownership of the Piceance Basin Resource

The Piceance Basin is made up of both private and federal land holdings. The federal government owns most of the center and northern basin, and most private holdings are confined to the southernmost portion of the basin. Figure 8 illustrates this division. It also shows the 400, 800, 1200, and 2000 ft contour lines for shale averaging at least 20 gallons per ton. Ownership division roughly corresponds to the division of deposit type. The federal government owns most of the thickest and richest deposits, which make up 80 percent of the resource. All of the federal land is controlled by the Department of the Interior except for a small Naval Oil Shale Reserve located in the southeastern corner of the basin. Private lands are confined to the thinner deposits in the southern portion of the basin.

There is enough oil shale on private lands to establish a substantial industry; however, extensive use of federal lands will be required if oil shale is to represent a serious alternative to imported oil. Because the commercially attractive deposits on private lands are thin and rich, underground mining is the preferred technique. If we assume an underground mine consists of 30 gallon-per-ton shale, and that 50 percent of a 60 ft seam can be extracted, an underground mine for a

[13]See U.S. Congress, Office of Technology Assessment, Vol. II, 1980, pp. 47-48.

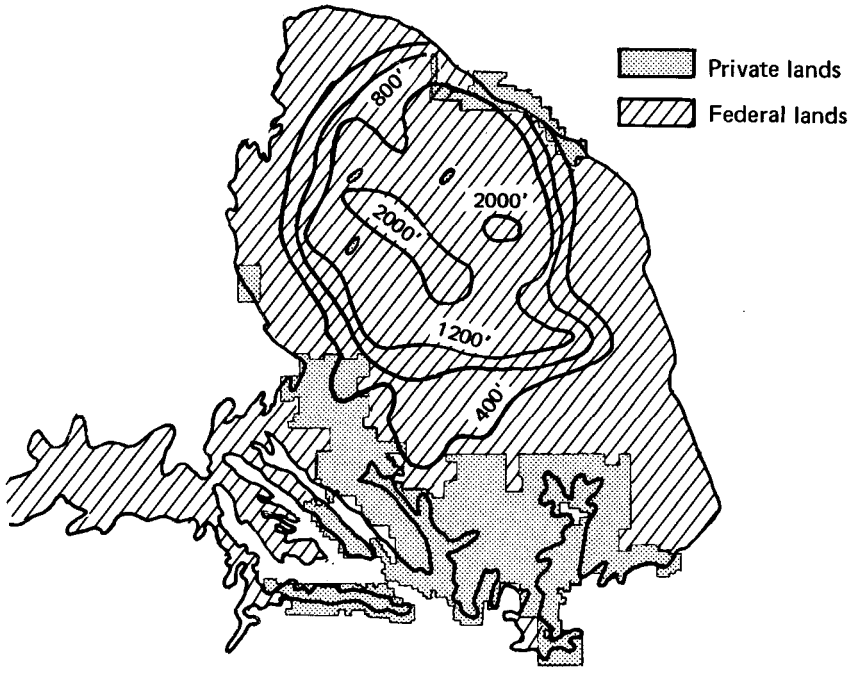


Fig. 8—Ownership of the Piceance Basin

50,000 bpd plant would consume 0.75 acres per day. The Piceance Basin contains approximately 170,000 acres of private oil shale lands. An upper limit on the potential of these lands would be a one million bpd industry operating for 30 years. This is an upper limit because not all private lands contain 60 ft seams of 30 gpt shale,[14] and not all of the land is accessible to mining. Production will also be limited by ownership distribution within the private lands. Many of the plots are too small or too irregularly shaped to allow efficient development.

The potential role of the federal lands is a multi-million bpd industry that could operate indefinitely. The source of this potential is the thick deposits of 20–25 gpt shale. These lands also contain substantial deposits of 30 gpt shale, but their great depth arises from shale of 20–25 gpt. These grades are more expensive to process, but they constitute the bulk of the resource. Surface mining is the only technique that can produce important recoveries of these federal deposits. Thus,

[14]See Donnell, 1961, for the thicknesses of 30 gpt shale on private lands.

the feasibility of a multi-million barrel-per-day industry is tied to the feasibility of surface mining.

In summary, the Piceance Basin contains a vast potential source of liquid hydrocarbons. Recovery of a large fraction of this resource depends on the feasibility of surface mining the central basin, which is owned by the federal government. Therefore this report concentrates on the effects of federal policies on oil shale surface mines. In particular, it examines federal land use policies that could divide the basin into a series of smaller resources. These policies are discussed in the next section of this report. Their effects on surface mining are analyzed in Sec. III. The report is concluded with a discussion of the results and an illustrative land use strategy that could allow efficient development of the resource.

II. RESTRICTIONS ON THE USE OF FEDERAL LANDS

THE MINERAL LEASING ACT OF 1920

The development of a multi-million barrel-per-day shale industry will require extensive surface mining of federal lands. Many of the rules governing the use of federal mineral lands are determined by the Mineral Leasing Act of 1920. This act empowers the Secretary of the Interior to grant leases to private developers. The Act also specifies that no lease can be more than 5120 acres (eight square miles) and that no single developer can obtain more than this total acreage. These restrictions prevent any single developer from locking up a high percentage of the resource.

The Prototype Leasing Program

The current leasing rules have been in place more than 60 years, but only four oil shale leases have been granted. Five lease applications were filed in 1920 and three were issued. All were subsequently withdrawn. The Teapot Dome oil leasing scandal quickly followed, and as a result shale leasing was temporarily suspended. President Hoover withdrew oil shale lands from leasing consideration in 1930. Since that time there have been numerous attempts to initiate leasing programs. It was not until 1974, with the initiation of the Prototype Leasing Program, that six leases were offered for bid;[1] two each in Wyoming, Utah, and Colorado. No bids were submitted for the Wyoming tracts and they were withdrawn. The Colorado tracts, C-a and C-b, are located in the Piceance Basin. The locations of the six prototype tracts are illustrated in Fig. 9.

Restrictions on the Use of Off-Tract Lands

Attempts to develop the Utah tracts raised a land ownership dispute between the state of Utah and the federal government. Attempts to develop Tract C-b raised important geological issues. The original development plans called for multi-layer room-and-pillar mining. De-

[1]An excellent discussion of the history of shale leasing is provided in U.S. Congress, Office of Technology Assessment, Vol. II, 1980.

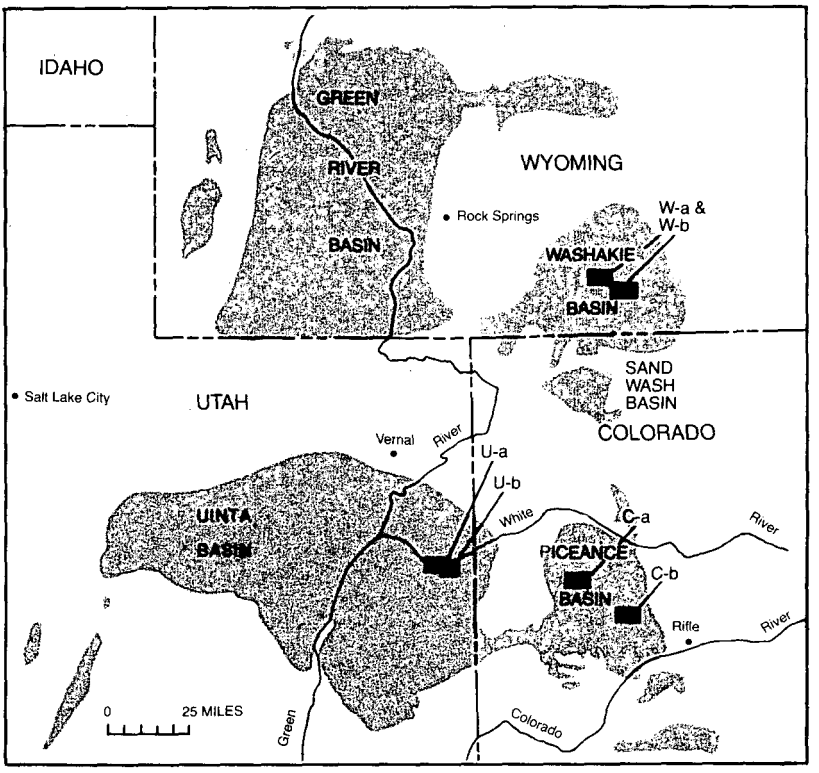


Fig. 9—Locations of the prototype tracts

tailed investigations revealed that the C-b shale was of insufficient strength to support efficient underground mining. Given the uncertainties about center basin geology, this result raised important questions about underground mining in that region.

The most important issue was related to the development plan for Tract C-a. The developers considered both surface mining and multilayer room-and-pillar mining. Surface mining was chosen because approximately five times more shale could be extracted than with room-and-pillar mining.[2] The development plan required off-tract lands for both process facilities and oil shale wastes. A schematic of the

[2]See Rio Blanco, *Detailed Development Plan,* Vol. 3, 1976; Rio Blanco, *Revised Detailed Development Plan,* Vol. 2, 1977, p. 2-9-2.

proposed layout is illustrated in Fig. 10. Because the Piceance Basin is a contiguous federal oil shale resource, lands near Tract C-a are also federally owned oil shale lands. Waste disposal outside the basin was prohibitively expensive, so the developers requested the use of federal basin lands for waste disposal and process facilities. The land requested, consisting of 6400 acres, was larger than the lease itself and contained more shale.[3]

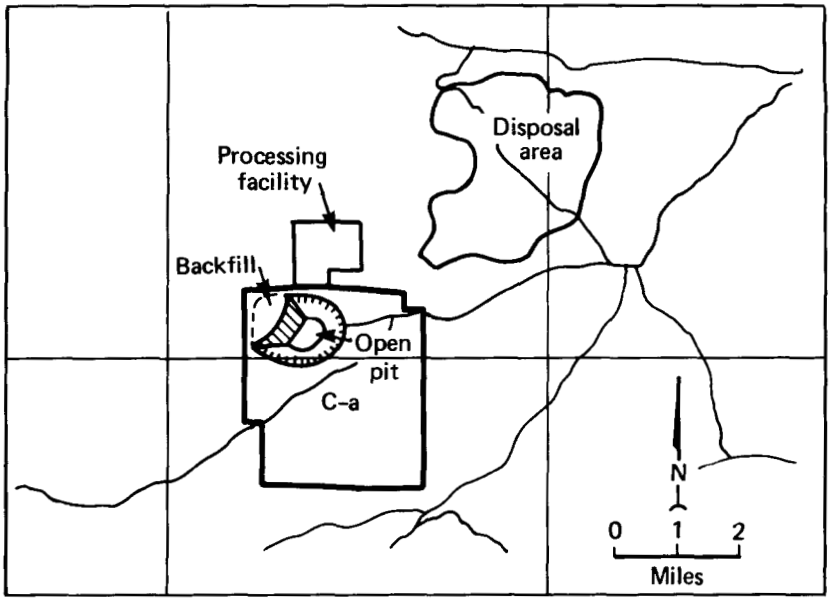


Fig. 10—Proposed Tract C-a development

The Department of Interior determined that use of federal oil shale lands for waste disposal and process facilities would be a violation of the Mineral Leasing Act of 1920.[4] This resulted in a series of Congressional resolutions calling for amendments to the Mineral Leasing Act of 1920. These resolutions have been debated since 1975. Recently a single exemption allowing off-tract lands for Tract C-a development was approved.[5] This amendment allows only a single

[3]See U.S. Congress, Office of Technology Assessment, Vol. II, 1980, p. 46.

[4]Use of private off-tract lands might have been acceptable but the haulage distances were very great.

[5]*Interior Department and Related Agencies, Appropriations for Fiscal Year 1983*, 96 Stat. 1999, Public Law 97-394, December 30, 1982.

exemption and does not change the general restriction on the use of off-tract lands.

CONCERNS ABOUT CURRENT LEASING PRACTICES

Oil shale leasing issues have been the subject of continuing debate for decades. Because most of the federal oil shale lands are yet to be leased, this debate will probably continue. It has been dominated by three issues: (1) the lease size and waste disposal restrictions imposed by the Mineral Leasing Act of 1920, (2) the rate at which leases should be granted, and (3) the potential resource fragmentation that could occur if the basin were divided into a series of leases. The first two issues involve specific aspects of existing legislation and have received most of the attention. The third issue involves the general applicability of leasing as a means of developing federal oil shale lands.

Concerns About Off-Tract Lands and Lease Size

The events associated with Tract C-a development have directed the debate toward the issue of off-tract lands and the 5120 acre limitation. There has been concern that these restrictions, which were written more than 60 years ago for all federal mineral lands, were not suitable for development of the unique Piceance Basin resource. Arguments for maintaining the restrictions have been based on the desire to avoid large giveaways of federal land. A 5120 acre lease can contain enormous quantities of shale. For example, one containing a 1000 ft thick shale deposit averaging 20 gpt could supply a 200,000 bpd shale plant for more than 100 years. Those favoring relaxed restrictions have argued that efficient development is not possible without larger leases or off-tract lands for waste disposal.

Concerns About the Rate of Leasing

The rate at which federal oil shale lands should be leased has been a subject of debate for many decades. The current cost of shale oil relative to the price of foreign oil has reduced the intensity of this debate. However, it is likely to be resumed if shale becomes competitive. In the past, those against rapid leasing have argued that, de-

pending on the value of the shale, rapid leasing would either be unnecessary or a massive giveaway. They also argued that leasing should be delayed until the shale on private lands is exhausted. Those in favor of accelerated leasing argue that the scattered distribution of private lands implies that individual developers are limited to at most one or two plants. These developers would be reluctant to take the risk on a first oil shale plant unless they could be guaranteed access to more land. At the present time there is no active leasing, and only the four "prototype" leases exist.

A somewhat neglected aspect of the debate is the relationship between leasing rate and the type of industry that may emerge in the Piceance Basin. Rapid leasing might encourage a dispersed industry of many developers on separate leases. Leasing at a slower rate would limit the number of developers and development sites. This might contribute to a more centralized industry.

Concerns About Resource Fragmentation

There has been concern that application of the current leasing policy could fragment the oil shale resource and preclude the possibility of a highly centralized industry. To a large degree, the federal lands in the Piceance Basin constitute a single contiguous resource. Boundaries associated with leases could fragment this resource. Because the federal lands could accommodate more than a hundred 5120 acre leases, a "checkerboard" pattern could develop. Even moderate changes in the lease size limitation would not avert this pattern.

When coupled with other factors, boundaries created by application of the Mineral Leasing Act of 1920 would fragment the resource and disperse the industry attempting to develop it. This will limit the size of individual projects and encourage developers to initiate new projects rather than expansions of existing ones. The single lease per developer provision may imply that once a developer obtains a lease he is excluded from participating in projects on other leases. Together with anti-trust concerns, this could discourage large joint ventures.[6] The limitation of one lease per developer also implies that developers may not have had oil shale experience. Given the innovative processes required to produce shale oil, these developers may be unwilling to make large investments in a first-of-a-kind plant.

A decentralized pattern has already developed on private lands and to some extent is already an industry tradition. Almost all potential

[6]A recent attempt by Mobil Oil to organize a large joint venture has raised serious anti-trust concerns, see *Synfuels,* July 16, August 13, and August 20, 1982.

shale developers have considered individual plants, but few have attempted to organize large centralized projects or develop plans for expanding projects established by other developers. Figure 11[7] shows the scattered distribution of previous design plans. Industry has already established a decentralized pattern, and organized efforts would be required to reverse it. Typically, individual developers have not contemplated plants of more than 50,000 bpd, and even these have been estimated to cost several billion dollars. They are unlikely to be able to marshal the financial resources needed for projects of considerably greater capacity.

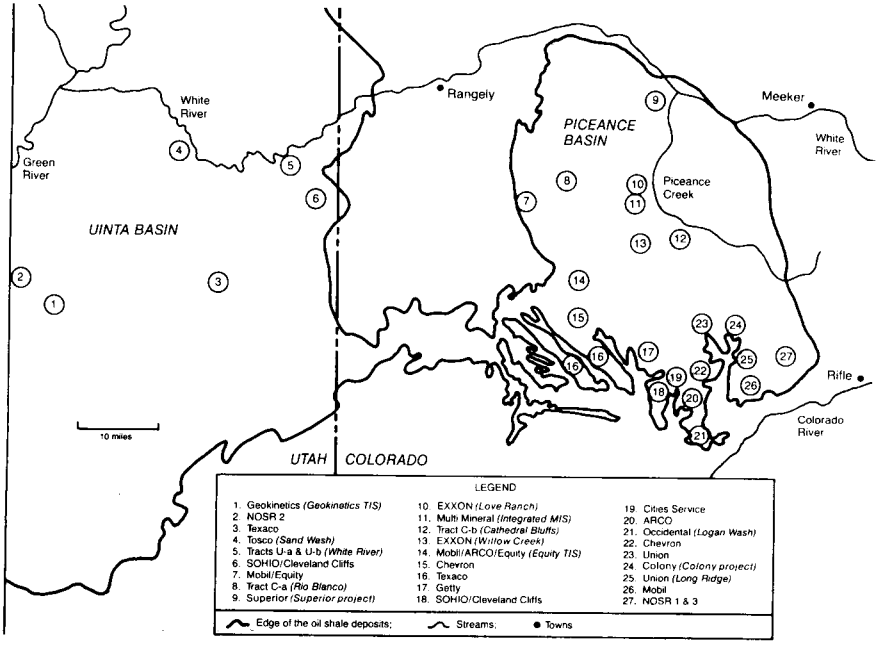


Fig. 11—Proposed oil shale projects

Although current land utilization policies may fragment the resource and industry, this will not necessarily have an adverse effect on all aspects of development. An industry consisting of many small projects could be more competitive than a highly centralized industry.

[7]U.S. Congress, Office of Technology Assessment, Vol. 1, 1980.

A fragmented industry might also employ a more diverse portfolio of technologies. This diversity could, in the long run, lead to greater efficiency. However, the great thickness of the Piceance Basin shale deposits suggests that geographically concentrated development may offer some advantages. In addition to considerations of lease size and off-tract lands, a comprehensive review of land use policies should consider the potential benefits of a concentrated industry and attempt to separate these benefits from aspects of the industry that are not dependent on this concentration. Such an analysis would insure that leasing practices do not preclude potentially advantageous development options.

THE POLICY PROBLEM

If oil shale is to represent an alternative to foreign oil, or a constraint on its price, it must be extracted in large quantities at the minimum possible cost. If it is to help alleviate the problems arising from an energy emergency, there must be an industry surge capacity that can be implemented in the minimum possible time. There are three major policy problems that should be investigated. The first is to determine the relationship among lease size, waste disposal restrictions, and the amount of oil shale that can be extracted. The second problem is to determine if current policies, which could fragment the industry and constrain the size of individual projects, increase the cost of extracting oil shale by precluding the use of economies of scale when they exist. The third problem is to determine if current leasing policies have an adverse effect on the time required to increase the capacity of an oil shale industry.

Analysis of these issues is complicated by the need for policies to be relevant in a variety of economic and political situations over an extended period of time. Current policies have been in place more than 60 years, and political concerns have made them difficult to change. Thus any analysis should be applicable to many situations, including today's, with little economic incentive for development, and future conditions that may one day motivate the development of a large industry. Because such an industry could be decades away, the results should be interpreted with allowance for unforeseen advances in technology.

Given the magnitude of uncertainty, a detailed analysis is both irrelevant and impossible. It is desirable to analyze policies with tools that are consistent with the available level of detail and are insensitive to changes in external conditions. Such general tools are of course

less accurate for any given situation but remain relevant under various conditions. Of course, no analysis methods can accommodate all situations, and any results must be tempered with a recognition of the overriding uncertainties.

In the next section of this report we analyze the effects of these federal policies on oil shale surface mines. In particular, we analyze the effects of federal policies on the amount of oil shale that can be recovered, the costs of recovery, and the extent to which oil shale can contribute to meeting the needs arising from a national energy emergency.

III. ANALYSIS

Three aspects of surface mining are considered in this analysis: (1) lease size and waste disposal restrictions effects on resource recovery, (2) the effect of project size and ability to expand projects on the cost of extracting shale, and (3) current land use policies effects on the time required to expand an oil shale industry.

Analysis of these issues is complicated by many economic and political uncertainties. Because these factors are difficult to predict, we base our investigation on only a few basic geological and engineering parameters, but even those values are subject to uncertainty.

THE EFFECTS OF LEASE SIZE ON RESOURCE RECOVERY

The most intensely debated aspect of current land utilization policies is the restrictions on lease size and use of off-site lands for waste disposal and process facilities. This section examines the effects of these restrictions on the amount of oil shale that can be recovered from a surface mine.

Assumptions

The analysis is based on a geometrical model of an oil shale surface mine. The assumed lease layout for all cases is illustrated in Fig. 12. The lease is partitioned into two squares, one for the process facilities and one for the mine. Conceptual design studies for shale process facilities have generally shown that plants with a capacity of 50,000–100,000 bpd occupy about one square mile (640 acres). Larger leases can be expected to produce more shale, so we have assumed that one such facility is required for each 5120 acres. For a lease size of 10,240 acres, 1280 acres are dedicated to the process facilities. Figure 12 also shows that the mine is assumed to be surrounded by a thin perimeter zone separating it from the lease boundary.

The basic geological and engineering assumptions are summarized on a cross section of an oil shale surface mine shown in Fig. 13. The bases for these assumptions are two detailed site-specific studies of oil

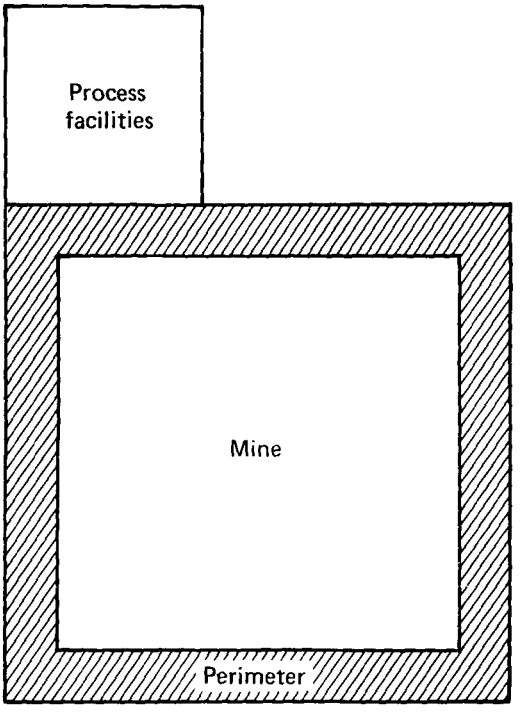


Fig. 12—Assumed lease layout

shale surface mines.[1] These studies indicated that in order to maintain structural stability, the walls of a surface mine must be sloped at angles between 37° and 45°. Our analysis uses the intermediate value of 41°. The working slope must accommodate equipment and haul roads and must have a more gradual slope of approximately 19°. Oil shale waste, consisting of overburden and the inorganic part of shale, is a granular material that cannot be supported in piles with slopes greater than 14°. Another option is to backfill waste into the pit, where it can be supported by the mine walls. The front of the backfilled waste pile must trail the working face by at least 500 ft. This distance is referred to as the working distance. Blasting and heating cause shale waste to occupy 25 percent more volume than in-situ shale. This factor, called the expansion

[1]Banks et al., 1975; Rio Blanco, Vol. 3, 1976.

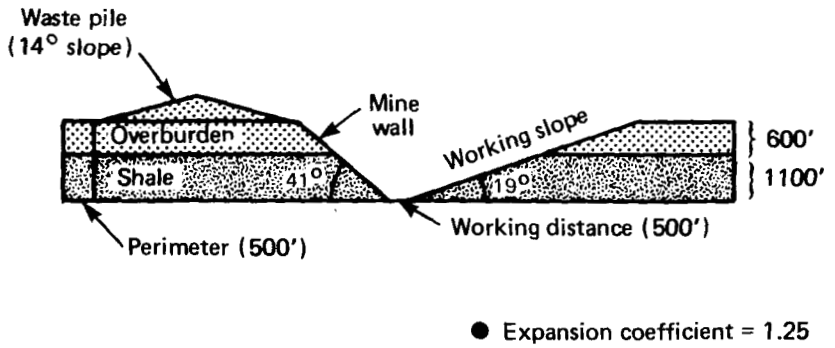


Fig. 13—Assumptions used for surface mining analysis

coefficient, is therefore 1.25. Finally, we have assumed an overburden thickness of 600 ft and an 1100 ft deposit. These thicknesses are typical of deposits averaging 20–25 gpt located in the central basin.

Methodology

The relationship among lease size, waste disposal policy, and resource recovery is evaluated by means of a three-dimensional geometrical analysis of each factor limiting recovery from a surface mine. Appendix A presents a detailed review of this methodology. The major factors limiting recovery are related to the process facilities, the mine walls, and the requirement for on-site waste disposal.

Process Facilities. Process facilities must be placed on the lease, and shale beneath them cannot be extracted. The Mineral Leasing Act of 1920 prohibits the use of off-tract federal lands for these facilities. We have assumed that the size of the process facilities increases directly with lease size. This assumption decouples the process facilities from the analysis by assuming that 12 percent of the resource is lost for all lease sizes.

Mine Walls. To ensure structural stability, surface mines must be constructed with gradual slopes, and shale beneath these slopes cannot be extracted. The percentage of the resource trapped beneath these walls is determined by the ratio of the mine area to the mine depth. For deep mines occupying small areas, this percentage is large. A smaller percentage is lost in shallow mines occupying large areas. The great thickness of the central basin deposits implies that this

factor could considerably reduce the amount of shale that can be recovered.

On-Site Waste Disposal. The limitations resulting from on-site waste disposal can be understood by considering the steps required for mine development. Figure 13 illustrates a mine that has just achieved final depth. The mine expands to the right with newly generated waste being returned to the pit. Before this point, waste must be stored out of the pit, but on the lease. Because the deposit depth is independent of lease size, large leases can better accommodate this initial storage than small leases. If a lease is too small, the full mine depth cannot be reached. The severity of this problem is illustrated in Fig. 14, which shows that one cubic foot of in-situ shale will require 10 ft^2 of area for the resultant spoil pile. The area required for initial out-of-pit storage is much larger than the area used for the initial mine opening.

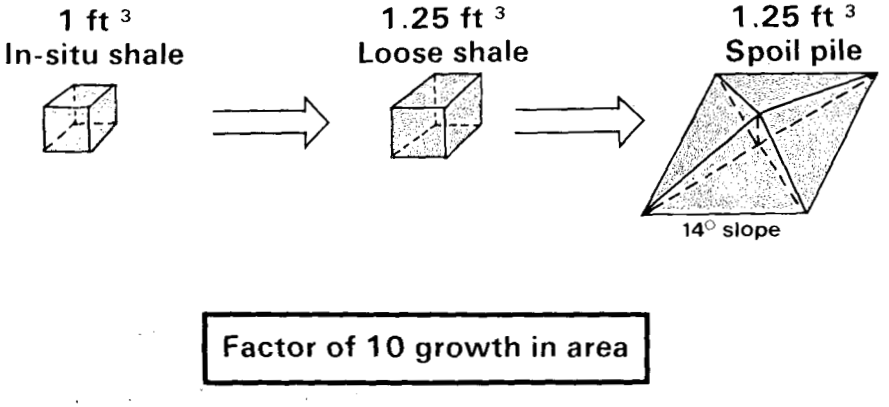


Fig. 14—Shale waste occupies large areas

On-site waste disposal may also create additional economic constraints. As shown in Fig. 13, the mine expands to the right until lease perimeter is reached. At this point substantial quantities of shale still remain on the left side of the lease, beneath the original disposal pile. To extract this shale, the original disposal pile must be transferred to the opposite side of the mine. Costs associated with this multiple handling procedure usually prevent this practice. Practical mining operations usually require a single handling of waste. Shale underneath the original waste pile therefore cannot be extracted. This

constraint is economic rather than regulatory, but it does not affect recovery when off-site disposal of waste is allowed.

Results

Figure 15 illustrates the resource recovery that can be obtained from a 5120 acre lease. The first frame shows the initial deposit, which consists of 600 ft of overburden and 1100 ft of shale. The second frame illustrates complete recovery. Each barrel represents 10 percent of the resource. The third frame shows that shale beneath the process facilities is not extracted, reducing the recovery by over 10 percent. The fourth frame shows that shale trapped beneath the sloped mine walls represents about 40 percent of the resource. This loss, combined with the loss due to the process facilities, reduces recovery to about 50 percent, obtained without consideration for oil shale waste. The Mineral Leasing Act of 1920 requires on-site disposal of waste, limiting the recovery to only 20 percent, as shown in the fifth frame. If the economic constraint of single handling is combined with the regulatory constraints, total recovery is only 10 percent, as shown in the last frame.

Recovery factors of 10 percent will drastically reduce the potential of oil shale. Figure 5 showed that the Piceance Basin resource was larger than world oil reserves. This comparison is repeated in Fig. 16, but with a recovery factor of 10 percent for oil shale. With a 10 percent recovery factor, the oil shale resource is only comparable to North American oil reserves and is far smaller than world oil reserves. To obtain even this limited potential, the entire basin would have to be leased and every lease fully developed. Practical considerations will undoubtedly reduce basin-wide recovery below that shown in Fig. 16.

The low recovery for a 5120 acre lease is a result of an unfavorable area-to-depth ratio, which in turn results in large deposits of shale left beneath mine walls. The initial mine opening (see Fig. 13) will occupy a considerable portion of the mine, further limiting the capacity for waste storage and the total amount of shale that can be extracted. Increasing the area-to-depth ratio by increasing lease size lessens the effects of these problems. Larger leases therefore allow for extraction of a higher percentage of the resource.

The relationship between lease size and percent recovery is illustrated in Fig. 17. The uppermost curve, labeled "off-site disposal," is based on the assumption that off-tract lands will be available for oil shale waste. This is the case where only the process facilities (12 percent for all cases), mine perimeter, and sloped mine walls limit recov-

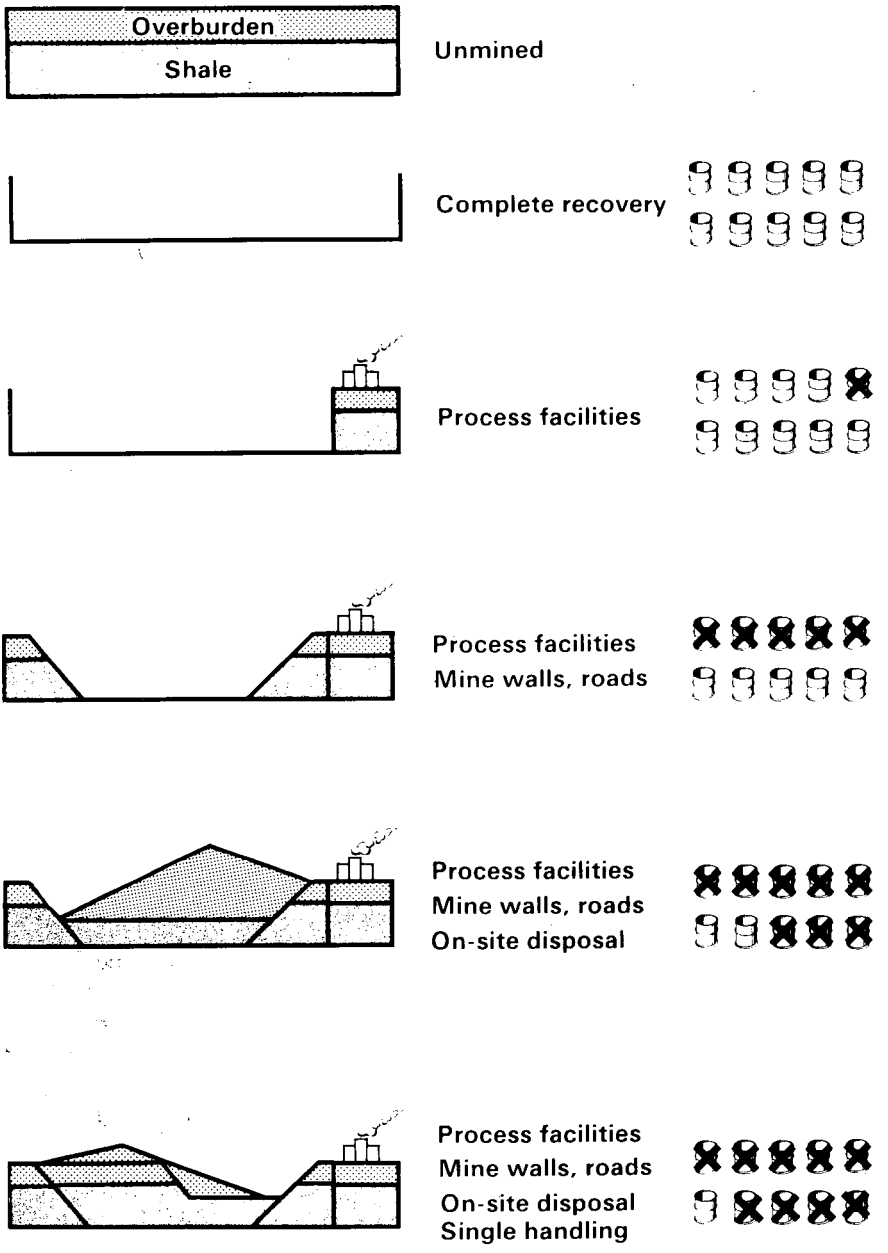


Fig. 15—Resource recovery from a 5120 acre lease

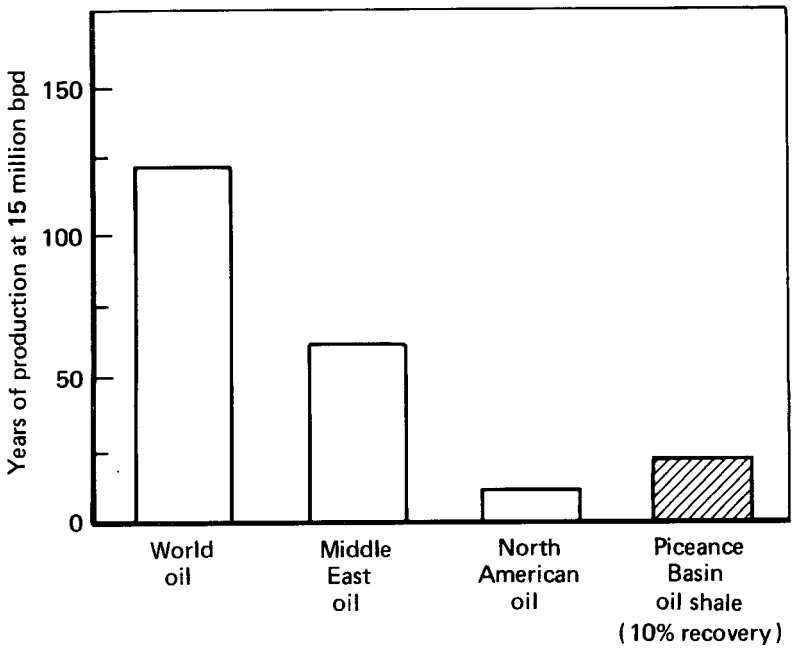


Fig. 16—Resource comparison with 10 percent recovery

ery. The conditions for this curve correspond to the fourth frame in Fig. 15. The curve labeled "on-site disposal" represents the recovery that can be obtained under current regulatory constraints. Obtaining this result requires multiple handling of waste. The conditions for this case correspond to the fifth frame in Fig. 15. The curve labeled "single handling" shows the recoveries that can be obtained without multiple handling of waste. This corresponds to the sixth frame in Fig. 15.

Figure 17 shows that existing policies severely reduce the amount of shale that can be recovered and that larger leases or off-site disposal alleviate this problem. Existing policy is represented by the point above a lease of 5120 acres on the branch labeled "on-site disposal." Obtaining this recovery requires multiple handling of waste. When the constraint of single handling is imposed, the recovery is only 10 percent; and off-site disposal offers a five-fold advantage. Recovery with off-site disposal is comparable to the recovery that can be obtained with single handling on a lease 10 times the size of the current 5120 acre requirement. This leasing option preserves the limitations on the amount of resource that can be owned by any developer.

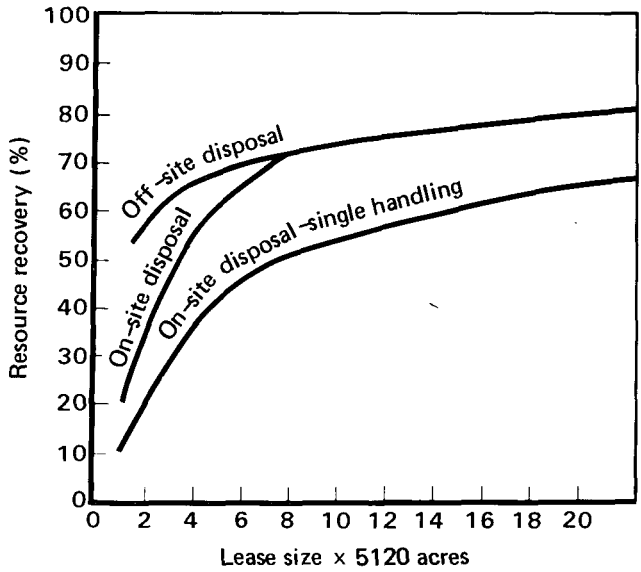


Fig. 17—Recovery increases with lease size

However, Fig. 17 does not provide a complete basis for comparing the effects of policy alternatives on resource recovery. The results do not include the land utilized for off-site disposal. Oil shale waste occupies vast areas. Figure 17 does not include shale that may be made inaccessible by disposal piles. The cost of hauling waste out of the basin may be prohibitive and disposal lands are likely to contain vast quantities of shale.[2] The amount of land required for disposal varies with lease size. This relationship is shown in Fig. 18, which shows the amount of off-tract land, measured as ratio of disposal land to lease size, required to obtain recoveries on the curve labeled "off-site disposal" in Fig. 17. For a 5120 acre lease, the disposal lands are larger than the lease itself, which is consistent with the requirements established in the site-specific studies. Figure 18 also shows that for leases greater than about 40,000 acres there is sufficient land available for waste that no additional off-site area is required. In other words, the waste from an area currently being mined can be

[2]The proposed disposal site for Tract C-a contained more shale than Tract C-a. See U.S. Congress, Office of Technology Assessment, Vol. II, 1980, p. 46.

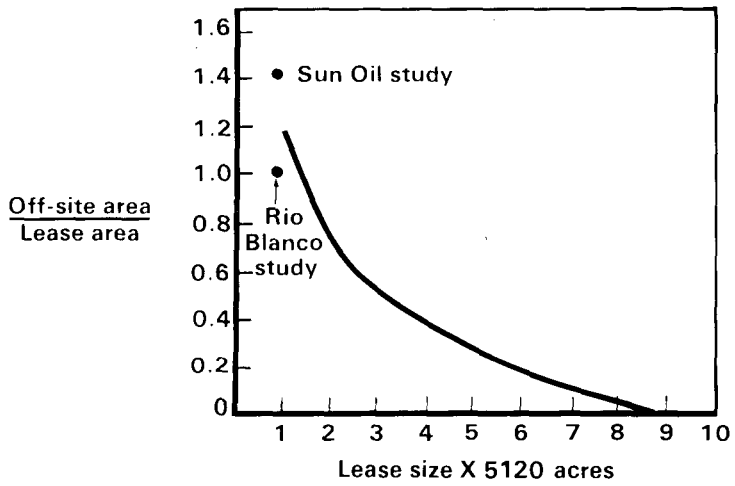


Fig. 18—Off-site disposal requirements decrease with lease size

held on adjacent areas and later removed and backfilled to permit mining of areas previously covered by waste (this would violate the economic constraint of single handling for a small portion of the waste generated).

Basin-wide resource recovery will be affected by both leasing and disposal policies. With leases limited to 5120 acres, off-site disposal increases the recovery for the lease; but depending on the amount of shale on disposal lands, it may not greatly increase basin-wide recovery. This is illustrated in Fig. 19, which shows the effect of off-site disposal and four other leasing policies on the long term utilization of 102,000 acres (20 leases of 5120 acres each) that produce 1.5 million barrels of oil per day. All 102,000 acres are assumed to have 1100 ft of shale covered by 600 ft of overburden. The bar labeled "Size 1" is based on the assumption that the existing regulations will be maintained and that the land is divided into twenty 5120-acre leases. Dividing the land into two leases (each of 10 × 5120 acres) or one lease (of 20 × 5120 acres) can considerably enhance the long term potential of oil shale. The option of maintaining lease size and allowing off-site disposal is not as effective because shale beneath the disposal piles is not extracted.

The values presented in Fig. 19 are based on single handling of

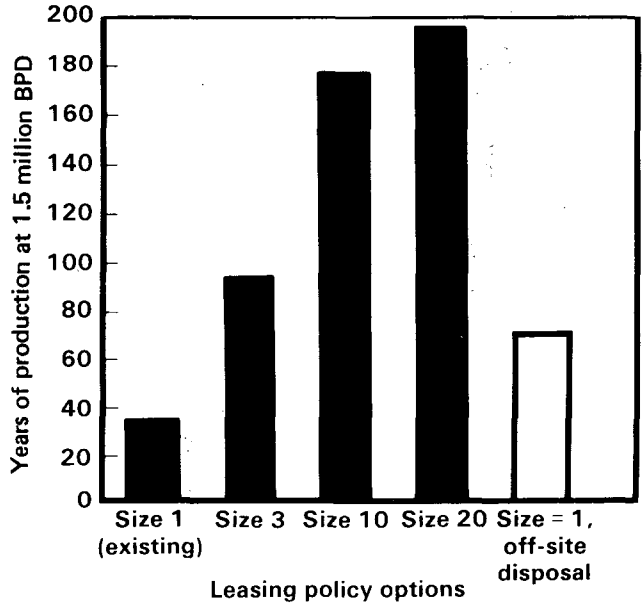


Fig. 19—Long term implications of leasing policy (20 × 5120 acres)

waste. If we assume multiple handling, and if lease regulations could be altered to later extract shale on the disposal lands, large leases would still allow greater recovery than small ones with off-site disposal. Dividing the basin into several small leases would scatter shale process facilities throughout the basin, making it difficult to connect the many small mines. At best, they could be joined to form a highly irregular shape, which would lead to much lower recoveries. If the comparison were based on multiple handling, the quantity of waste requiring such handling would be considerably larger for the case of off-site disposal. Although this would not alter resource recovery, it would affect the economics of the process.

The results presented in Fig. 19 can be interpreted differently by fixing the production time and production rate, and determining the amount of land required. Figure 20 indicates that even if shale production does not require use of the entire resource, the most efficient use of land is achieved by a small number of centralized development projects.

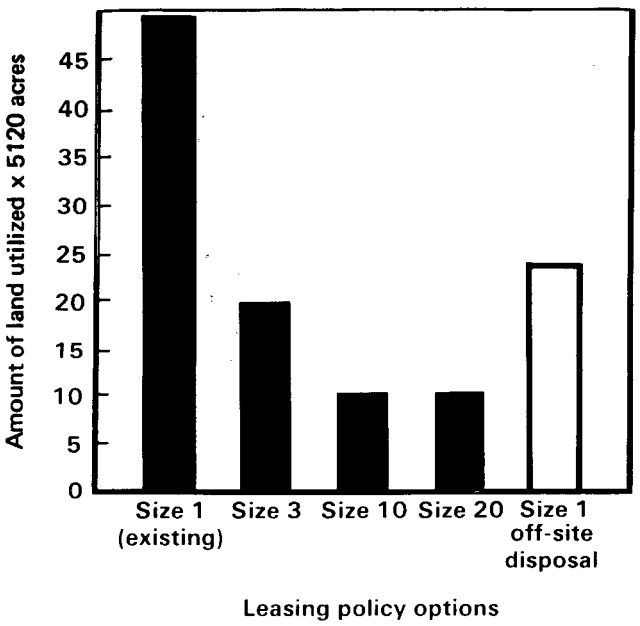


Fig. 20—Long term land use implications (1.5 million bpd for 95 years)

Sensitivity

The preceding section presents a first order analysis of the effects of lease size and waste disposal policy on resource recovery, which will also be affected by topographical and geological constraints. Because there are no actual oil shale surface mines, the values of the input parameters are uncertain. In addition, these values will vary among sites within the basin. We conducted sensitivity analyses to better understand the effect of these uncertainties.

Deposit and Overburden Thickness. The thickness of the deposits and overburden vary with location in the basin and with the cutoff grade. One example of the effect of this variation is illustrated in Fig. 21, which presents the percentage recovery for deposits with 300 ft of overburden and 500 ft of shale. This type of deposit is typical of deposits found on the western edge of the basin. The mine is shallower than that of the base case, so the area-to-depth ratio is larger, resulting in improved resource recovery for all lease sizes and waste disposal options. However, present leasing restrictions still reduce the potential

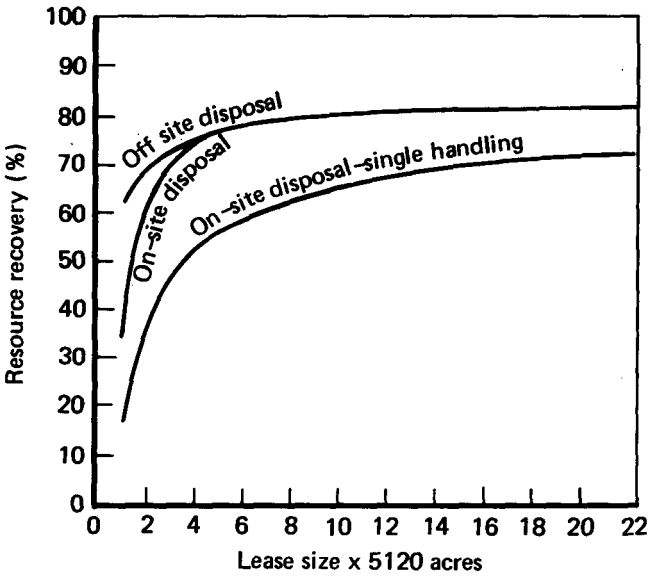


Fig. 21—Resource recovery from thin deposits (300 ft overburden, 500 ft shale)

resource recovery. An analysis of mines deeper than that chosen in the base case would have shown recovery factors below those presented in Fig. 17. The optimal leasing policy will depend on location in the basin. High recoveries for shallow mines, such as those on the western edge of the basin, can be achieved with moderate increases in lease size. High recovery factors for deposits in the center of the basin will require substantially greater increases in lease size.

Because the proposed policy of maintaining lease size at 5120 acres and allowing off-site disposal of waste has received a considerable amount of attention, sensitivity analysis for this policy is particularly important. Figure 22 shows the resource recovery associated with this policy for deposit thicknesses ranging between 50 and 2000 ft and overburden thicknesses of 300 ft and 600 ft. The two uppermost curves represent the recovery from the lease itself, and the curves labeled "basin-wide" include shale beneath the disposal piles in the computation. Because the lease size is the same for all the cases in Fig. 22, the area-to-depth ratio of the mine decreases with increasing deposit depth, which accounts for the decreasing recovery on the lease

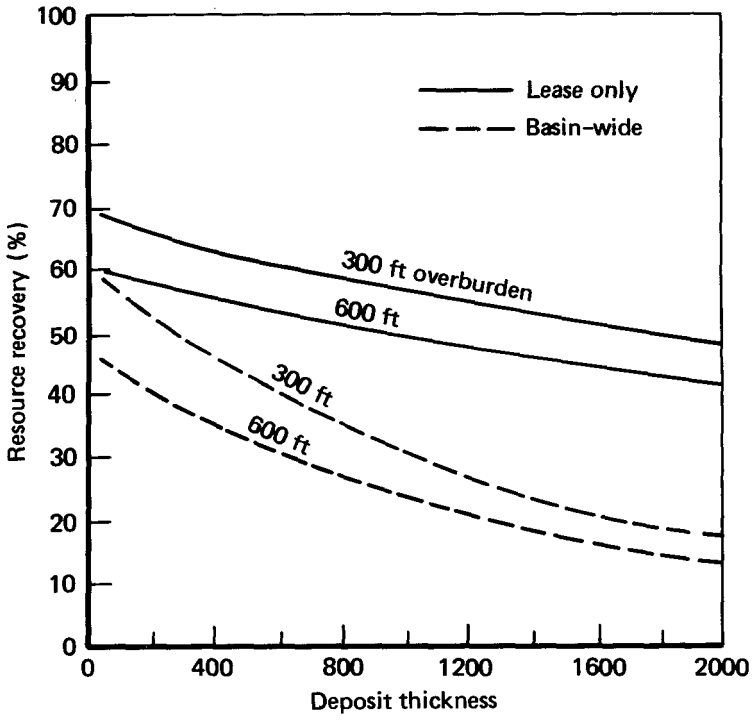


Fig. 22—Recoveries for 5120 acre leases with off-site disposal

itself. The "basin-wide" recovery is even more sensitive to mine depth because more land is needed for disposal sites and there is lower yield from the lease. Thus, maintaining lease size and allowing off-site disposal allows high recovery for the thin deposits located on the western edge of the basin, but not for the thickest deposits in the center of the basin.

Mining and Engineering Parameters. In addition to variations in overburden and ore thickness, mining and engineering parameters are subject to uncertainty. The values used in the analysis represent the authors' best judgment based on published results. To better understand the possible effects of the uncertainty surrounding these values, we conducted sensitivity analyses. The magnitude of the change in resource recovery resulting from a change in input parameters depends on the size of the lease under consideration and the particular

constraint being considered (e.g., single handling, off-site disposal, etc.). Figure 23 shows the results of our sensitivity analysis conducted for the specific case of a 15,360-acre (3 × 5120 acres) lease when on-site disposal and single handling are required. A 10 percent change in the expansion coefficient, from 1.25 to 1.275 (25 percent expansion to 27.5 percent), changes the resource yield by 8 percent of its base case value—from 30 percent to 32.4 percent recovery of the total resource. The resource recovery is only mildly sensitive to changes in values of the input parameters. A 10 percent change in any single input parameter results in less than a 10 percent change in yield. The two most sensitive parameters are the waste pile slopes and the shale expansion coefficient; both are characteristic of shale waste.

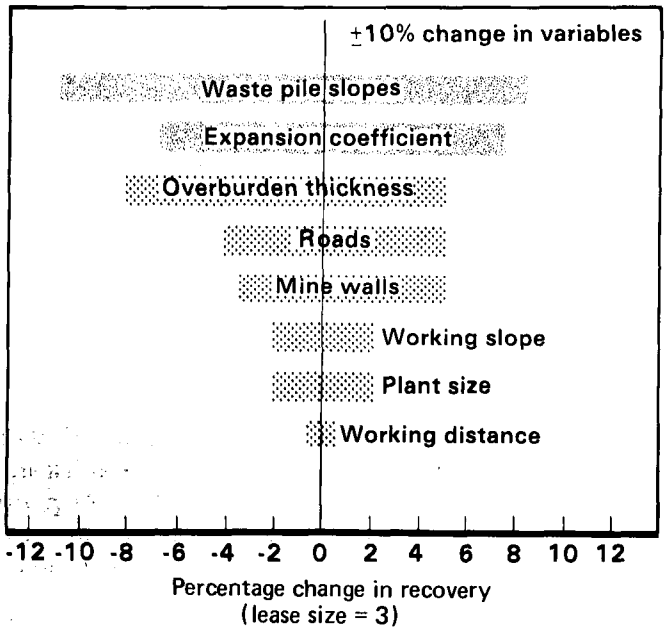


Fig. 23—Sensitivity analysis

EFFECTS OF PROJECT SIZE AND MINE EXPANSION ON COSTS

As stated in the previous section, present leasing arrangements coupled with anti-trust concerns, the high cost of oil shale facilities, and industry tradition may preclude the development of a geographically centralized industry. This would limit the size of individual projects and encourage developers to construct new projects rather than expand existing ones. This section explores how constraints on project size and expansion affect the cost of extracting oil shale. Although extraction costs are only one component of the cost of producing shale oil, they can represent more than 30 percent of the selling price.[3]

Assumptions and Methodology

The methodology and assumptions used in this section are an extension of the geometrical analysis used in the preceding section. Values of the mining parameters are identical to those shown in Fig. 13. In addition, we have assumed that mining operations will not be constrained by lease size. The most important new assumption involves a parameter called the "stripping ratio," which is a measure of mining efficiency. We used it to avoid the uncertainties and inherent difficulties in performing a financial analysis that would be relevant to a wide variety of economic situations. The stripping ratio is defined by the following formula:

$$\text{Stripping ratio} = (\text{overburden mined})/(\text{ore mined})$$

Stripping ratio can be calculated analytically, and it reflects the costs of surface mining. It is often used by industry as a quick method for determining the feasibility of surface mining. Using this parameter as an indicator of costs is undoubtedly less accurate than estimating costs directly. However, it is independent of external economic factors and is relevant for many situations.

Stripping ratio is correlated with mining costs because it is related to the total amount of rock (ore plus overburden) mined. Many surface mining costs are related to total rock, including crushing, wetting, drilling, blasting, and loading. This correlation was displayed in a detailed, site-specific, surface mining study performed by Suntech, Inc.[4] The results are shown in Fig. 24. The mining contribution to the

[3]See Weiss, Ball, and Barberg, 1979.
[4]Suntech, Inc., 1976.

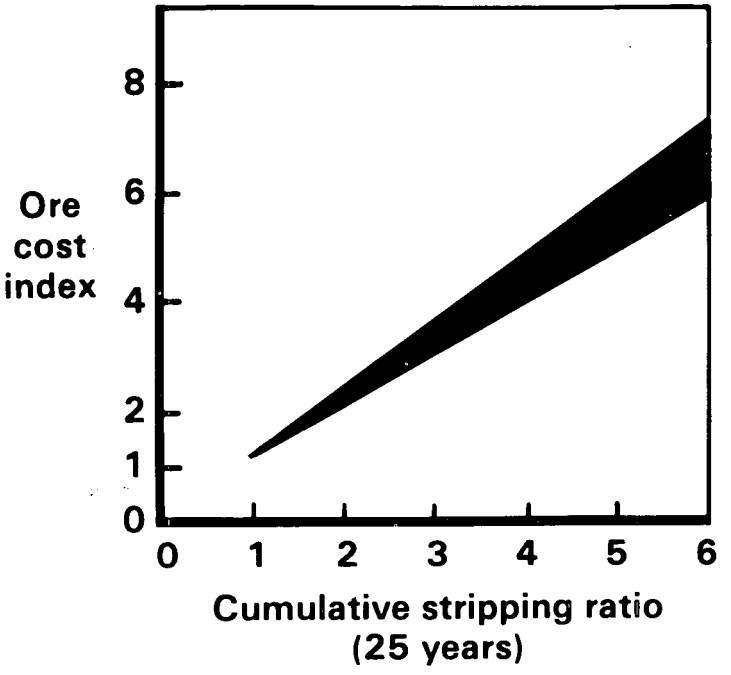


Fig. 24—Results of a site-specific study

price of oil correlated with the stripping ratio obtained after 25 years of mining.[5] These results are based on surface mines producing 500,000 and 1,250,000 tons of ore per day (equivalent to 250,000 and 625,000 bpd for 20 gpt shale). The Suntech study indicated some breakdown in the correlation for stripping ratios above 3 or 4 because of the increased haulage costs associated with extremely large mines. Stripping ratios do not reflect haulage distances. The correlation with costs breaks down when mines with greatly different haulage profiles are compared.[6] Stripping ratio therefore should be used only as a simple, rough indicator of cost trends. It has the advantage of being insensitive to external financial considerations, but it cannot be

[5]The Suntech study presented yearly cost totals and the annual amounts of ore and overburden mined. The results presented in Fig. 24 are derived by discounting annual costs by 10 percent per year. Different values of the discount factor only slightly alter the relationship shown in Fig. 24 and do not alter the conclusion that stripping ratio is a reasonable indicator of mining costs.

[6]A qualitative discussion of the relationship among stripping ratio, haulage, and other cost components not reflected by stripping ratio is presented in App. B.

viewed as a substitute for definitive cost analysis when that type of analysis is required.

Stripping ratio is defined as the amount of overburden mined per unit of ore, so the ratio of overburden thickness to ore thickness may appear to produce the stripping ratio. However, for practical mining operations, several other parameters also affect the stripping ratio:

- Overburden thickness
- Ore thickness
- Mine wall slopes
- Mine width
- Production rate
- Mine lifetime

The stripping ratio cannot be lower than the ratio of overburden thickness to shale thickness. The other parameters increase its value. Because mine walls must be sloped to maintain stability, the upper portion of a mine (which contains overburden) will be wider than the deeper portion (which contains shale). Sloped mine walls therefore increase the stripping ratio. These effects can be minimized if the mine is extremely wide. In a realistic mining operation, however, an initial layer of overburden must be removed before any oil shale is extracted. The quantity of initial overburden increases with mine width.[7] Wide mines may be acceptable if the production rate is sufficient to allow initial overburden removal in a time that is short compared with the lifetime of the mine.

The effects of these parameters can be better understood by considering the difference between the cumulative and annual stripping ratios. Figure 24 shows the relationship between costs and cumulative stripping ratio, which represents the total amounts of waste and ore mined. This differs from the stripping ratios obtained during individual years. Annual stripping ratios vary with time. The source of this time dependence is illustrated in Fig. 25, which shows an oil shale surface mine at different stages of development. The first frame shows the initial deposit. The second frame shows the initial mining period, during which only overburden is mined and the stripping ratio is infinite. The amount of overburden mined before shale is extracted is determined by the slopes of the mine walls and the mine width. Using the values show in Fig. 13 we have assumed the mine walls are sloped at 41°. The working face is assumed to have a 19° slope. The mine width is a function of production rate. As mine depth increases, the stripping ratio decreases. At final depth (fourth frame), the stripping ratio reaches a steady-state condition. After this point, the cumulative

[7]Mine width is the dimension orthogonal to the mine cross sections in Fig. 25.

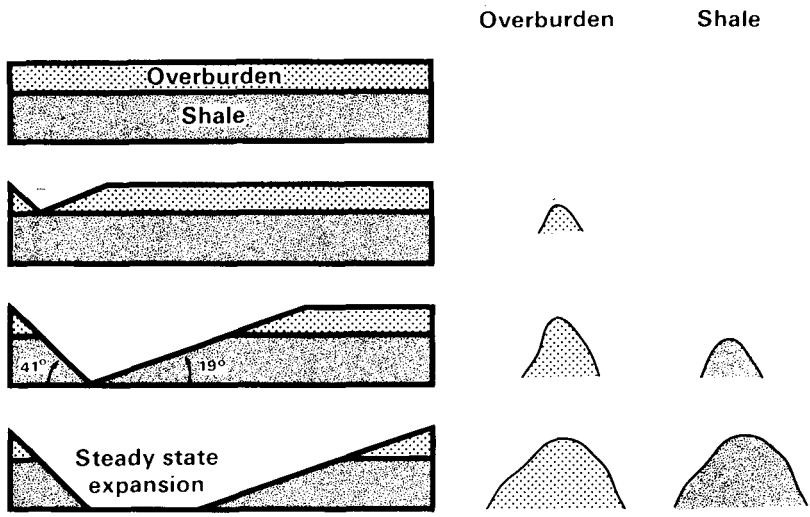


Fig. 25—Development of an oil shale surface mine

stripping ratio begins to approach the value of the steady-state stripping ratio.

Figure 26 illustrates the difference between yearly and cumulative stripping ratios with data from the definitive design plan of federal lease Tract C-a (this design plan was never implemented).[8] The bars represent annual stripping ratios. The curve marked "cumulative" represents the stripping ratios for the entire process up to that point. For example, after eight years the cumulative stripping ratio is approximately 1.50, consisting of the total waste and total ore mined through the eighth mining year.

We have developed an analytical model that calculates stripping ratios for oil shale surface mines. Model assumptions and algorithms are described in App. C. Figure 27 displays an overview of this model. Mine wall slopes, thickness of overburden and shale, shale grade (the amount of oil in gallons per ton), the steady-state production goal, and the mine width are inputs. Mine width is optimized in later steps. These input parameters determine the steady-state mine geometry, which allows for prediction of the steady-state stripping ratio and

[8]Rio Blanco, 1976.

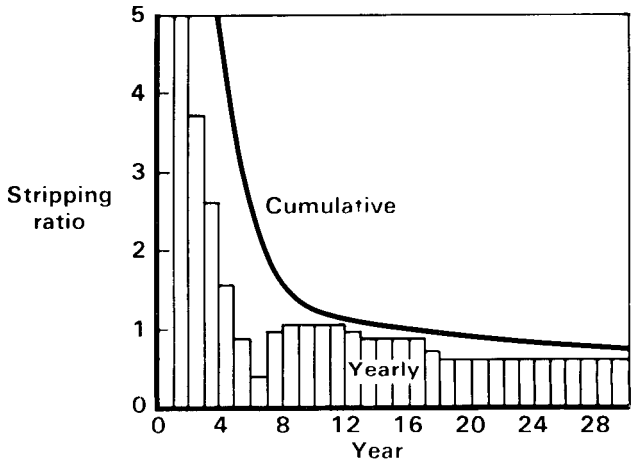


Fig. 26—Stripping ratios for Tract C-a

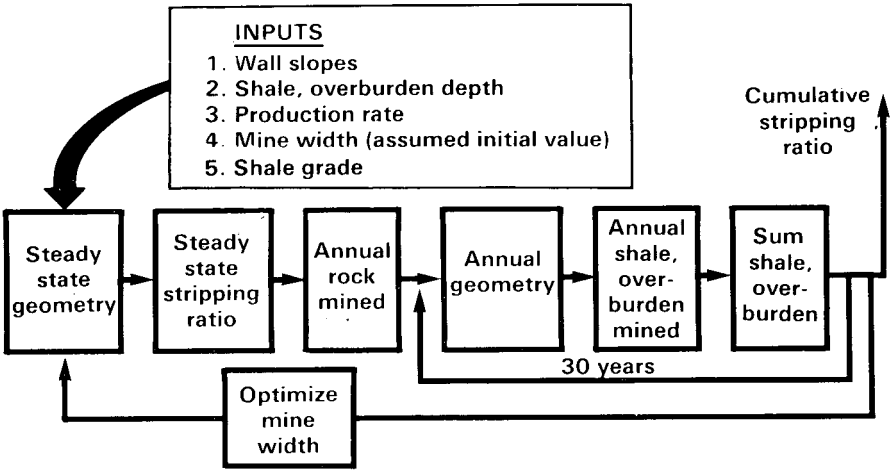


Fig. 27—The Rand Stripping Ratio Model

amount of rock (ore plus overburden) extracted during a steady-state mining year. We assume this extraction rate is constant for the entire mining process. A developer can of course remove the initial overburden at greater rates; however, such action would require the purchase of additional equipment for use during only the initial mining period. The large front-end investment would adversely affect the selling price of shale oil. The difficulty in accelerating the initial mining phase is also indicated in two site-specific studies showing the mining rate before steady state to be less than at steady state.[9]

Once the annual rock production is calculated, the geometry for each mining year can be predicted. The amount of shale and overburden extracted during each year is calculated and summed with previous years. The procedure is repeated for all mining years. We assume that 30 years represents the time used to evaluate the profitability of a particular development.[10] The procedure is repeated until an optimal value of mine width (determined by minimizing the cumulative stripping ratio) is found. We then use this procedure to examine the effects of project size and mine expansion on the stripping ratios obtained from oil shale surface mines.

Figure 27 indicates that shale grade, shale depth, and overburden depth are required input parameters for the model. These parameters are not independent. For any particular deposit, the thicknesses of shale and overburden are dependent on the grade specified. A high cutoff grade implies that only rich shale is included in the shale thickness, with low grade shale being counted as overburden. Reducing the cutoff grade means that lower grade shales, previously counted as overburden, can be included in the calculation of shale thickness. The extraction of lower grade shales will therefore result in lower stripping ratios than the extraction of higher average grade shales.

The great bulk of the shale resource occurs in thick deposits averaging between 20 and 25 gallons per ton. We have chosen the lower value of 20 gallons per ton as the shale cutoff grade. A cutoff grade of 25 gallons per ton would considerably reduce the size of the resource and would require mines of approximately the same depth as a 20 gallon-per-ton cutoff. Because we are interested in the long range effects of land utilization policies, we assume that improvements in processing technology will enhance the desirability of using lower grades. Finally, the assumption of shale grade is not critical to the analysis, which compares the stripping ratios for different project

[9]Rio Blanco, 1976; Suntech, Inc., 1976.

[10]This assumption was used in the Rio Blanco study. Sensitivity analysis in App. C shows that the results are only mildly sensitive to this assumption.

sizes, assuming constant grade for all projects. Higher cutoff grades would increase the absolute value of the stripping ratios but would not greatly alter the relative values among projects.

The thicknesses of 20 gpt deposits in the central basin are illustrated in Fig. 28,[11] which shows an east-west cross section of the central basin. The left edge of this cross section begins at the western edge and extends eastward, about two-thirds of the way across the basin.[12] The deposits fall into two broad categories: center basin and western edge. Deposits in the middle of the center basin have thicknesses up to 2000 ft and are covered by up to 700 ft of overburden. Deposits on the western edge of the basin are thinner and are covered by less overburden. In this analysis we consider one deposit on the western edge of the basin with 400 ft of overburden and 800 ft of shale, and another representing a deposit in the center of the basin with 700 ft of overburden and 2000 ft of shale. Figure 28 also shows lease Tract C-a located on the western edge of the basin; it is actually located to the north of the cross section in Fig. 28 but is shown this way to provide a rough indication of its characteristics.

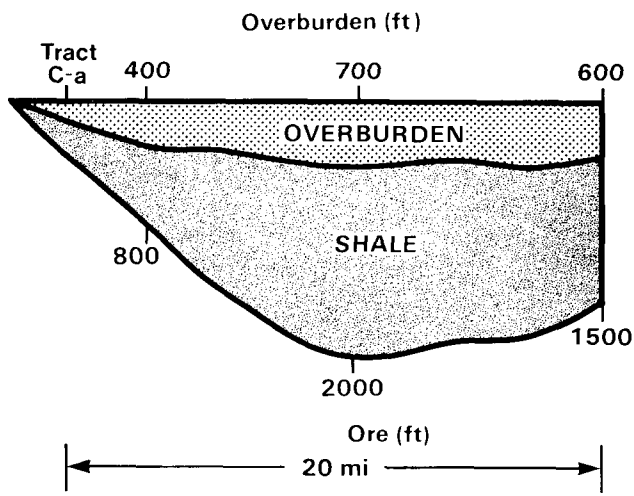


Fig. 28—Central basin cross section

[11]This figure was adapted from Lewis, 1980.
[12]For clarity, the depth scale in Fig. 28 differs from the horizontal scale.

Constraints on Project Size

If an active leasing program fragments industry capability, then the size of individual projects will be constrained by the financial resources of individual developers. Typically, a 50,000 bpd plant has been the largest one contemplated by individual developers, and even this has been estimated to cost several billion dollars.[13] Figure 29 shows the results obtained from the stripping ratio model for two 50,000 bpd plants: one with an 800 ft deposit and 400 ft of overburden, and the other a 2000 ft deposit with 700 ft of overburden. The former represents a lease on the western edge, and the latter represents a lease in the center of the basin. Figure 29 also shows stripping ratios obtained from the definitive plan for Tract C-a.[14] The close agreement of the Tract C-a data with those of the 800 ft shale deposit provides a validation of the model. The Tract C-a data also provide an indication of the stripping ratios required for the development to be seriously considered.

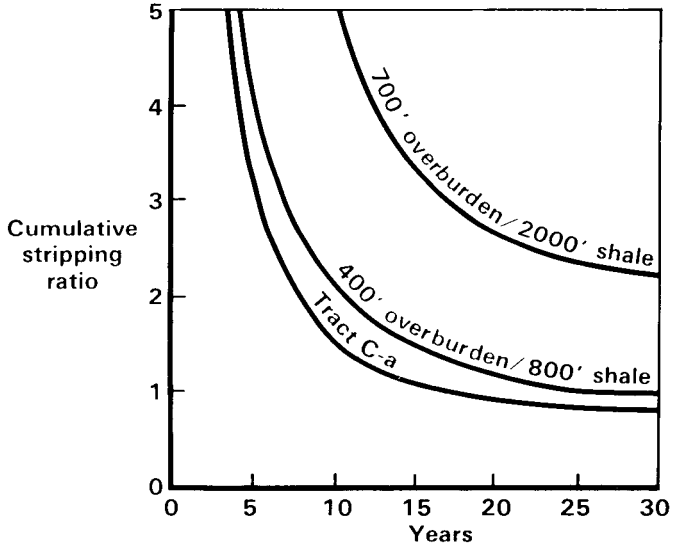


Fig. 29—Cumulative stripping ratios for 50,000 bpd

[13]Some developers have contemplated eventual expansion to 100,000 bpd after successful completion of a 50,000 bpd plant.

[14]Rio Blanco, 1976.

Stripping ratios for center basin deposits are higher than those on the western edge. It may therefore be more costly to extract center basin deposits because at a production rate of 50,000 bpd an individual developer would not open a mine wide enough to reduce the adverse effects of removing 700 ft of overburden. Our model predicts that for a 50,000 bpd mine in the center of the basin, a minimum stripping ratio is obtained with a mine width of 5000 ft,[15] which is insufficient to support the full resource depth and to minimize the adverse effects of the sloped mine walls. At 50,000 bpd, larger widths are not desirable because more initial overburden removal is required, but they become more practical with larger production rates, because more equipment is available for overburden removal. Figure 30 shows the effects of production rate on the cumulative stripping ratio obtained after 30 years of mining. The stripping ratio decreases with increased production. At rates of 250,000 bpd, the stripping ratios begin to approach the values that can be obtained on the western edge of the basin. Western edge stripping ratios also improve with production rate, but they are less sensitive to mine size.

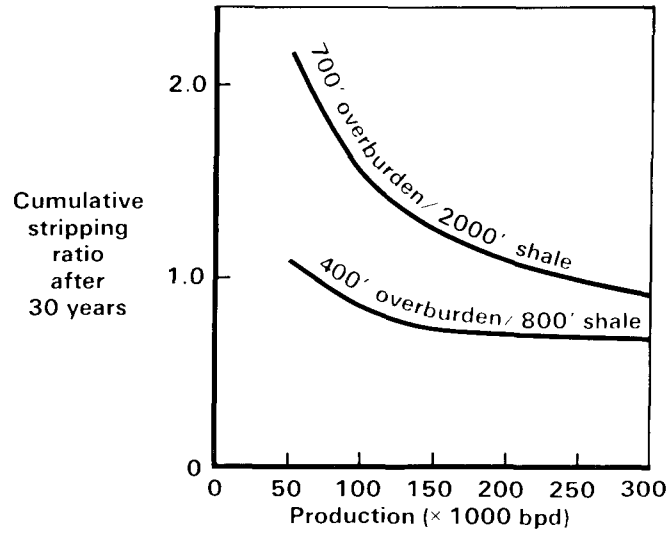


Fig. 30—Thick deposits require large production

[15]For the western edge deposit the optimum width is 4000 ft.

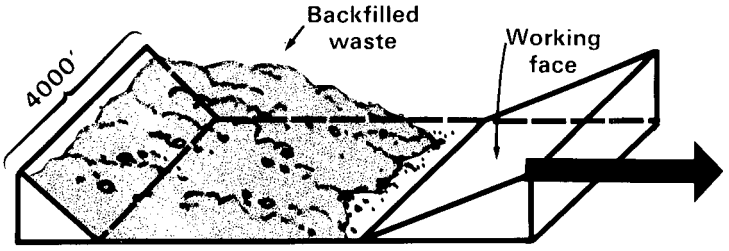
If the basin is divided into several tracts, it is unlikely that individual developers will be able to marshal the financial resources needed for the super-sized projects indicated in Fig. 30. Previous studies by individual developers have concentrated on 50,000 bpd plants at costs of several billion dollars. As of spring 1983, the only active shale project has a production goal of less than 10,000 bpd. A 50,000 bpd mine would require approximately 100,000 tons per day of 20 gpt shale. This is comparable to the largest surface mine in the United States. Special arrangements to concentrate industry capability will be required to extract center basin shale at favorable stripping ratios. Failure to do this could result in increased costs for extracting the bulk of the shale resource.

Constraints on Mine Expansion

Because the Mineral Leasing Act of 1920 limits developers to only one lease, present leasing practices could encourage the development of new mines rather than expansion of mines already under operation. A developer's participation in a mining operation on another developer's lease may violate this provision. Mine expansion will also be discouraged if it implies that mines will cross lease boundaries. Such constraints on mine expansion could result in increased costs for extracting shale.

Mine expansion represents an opportunity to reduce the costs of extracting oil shale. Figure 29 indicates that a considerable portion of surface mining costs can be attributed to initial overburden removal. This initial period is extremely important in financial analyses, where downstream costs are heavily discounted. Expansion of existing mines may be a way to increase production without high stripping ratios during the initial years. One mine expansion method is illustrated in Fig. 31, which shows a 50,000 bpd mine located on the western edge of the basin. The stripping ratio model predicts that the optimal width is about 4000 ft. Narrower mines produce higher stripping ratios because of the sloped mine walls, while wider mines are less favorable because of initial overburden removal. Although this mine was optimized for 50,000 bpd, it could be expanded when steady-state conditions are achieved. Ultimate capacity is limited by the area (projection of the area in the mining direction) of the working face and the rate at which a given area can be mined. At 50,000 bpd the mine face advances at 0.80 ft/day. A study by the Sun Oil Company[16] indicated 0.15 tons per square foot per day might be an engineering

[16]Banks et al., 1975, p. 5-129.



Working face advance rate

	Engineering limit
50,000 bpd	(130,000 bpd)
0.8 ft/day	2.1 ft/day

Fig. 31—Mine expansion capability
(400 ft overburden, 800 ft shale)

limit on the extraction rate. This is equivalent to a working face advance of about 2.1 ft/day. A mine initiated for 50,000 bpd can be expanded to a total capacity of 130,000 bpd.

Figure 32 compares the cumulative stripping ratio for an expanded mine[17] and a new mine. An expanded mine achieves steady-state stripping ratio immediately, but a new mine must go through the development phases, which produce very high stripping ratios. This is particularly important because front-end costs make the greatest contribution to the cost of mining.

Mine expansion can also provide opportunities for development of the thick deposits in the center of the basin. The benefits described in Fig. 31 for the 800 ft deposit are also applicable for thicker deposits. An even more advantageous option for developing the center basin would be to develop mines on the western edge of the basin and allow them to expand toward the center of the basin, exposing the thick center basin deposits without requiring a large front-end investment for removal of the thick overburden covering these deposits. This approach could dramatically decrease the cost of extracting center basin

[17]The expanded mine represents a production increase from 50,000 bpd to 100,000 bpd.

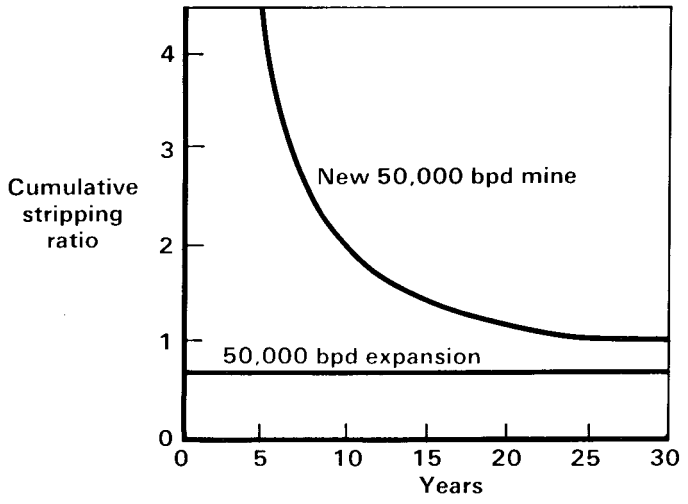


Fig. 32—Mine expansion results in favorable stripping ratios

shale. The inability to cross lease boundaries might prevent this development option.[18]

Present leasing practices often do not legally forbid mine expansion, but they may discourage it. High-production mines reach boundaries faster than low-production mines. If, for example, lease size is maintained at 5120 acres (with off-site disposal), a square mine on such a lease might be 13,000 feet on a side.[19] The length of the mine shown in Fig. 31 would be about 5000 feet when it first reached steady state. If the mining rate is maintained at 50,000 bpd, then the edge of the lease would not be reached for 27 years. However, if the mine advanced at 2.1 ft/day (130,000 bpd), then the boundary would be reached in 10 years. This period of time may not allow an investor to amortize his investment in the required process facilities. Another factor inhibiting mine expansion is the capital required for increased production. As with center basin deposits, it may be difficult for a single developer to marshal the financial resources required to fully exploit an existing mine. Bringing in partners may also be

[18]The developers of Tract C-a pointed out that their tract might be a logical place to initiate a mine that could be expanded toward the center of the basin. See Rio Blanco, Vol. 1, 1976, p. 2-2-9.

[19]This area is less than 5120 acres because of requirements that the process facilities be located on site. See Fig. 12.

problematic. Unless a partner's process facilities can be sited nearby, there may be very large haulage costs. Partners may also be under a legal obligation to develop their own leases rather than use ore from another. Large partnerships could also raise antitrust concerns.

INDUSTRY SURGE CAPACITY

The dependence of the United States and Western Europe on foreign oil has increased concern over the possibility of sudden reductions in oil supplies. If such a reduction were to occur, it would be desirable to increase domestic production of liquid fuel as rapidly as possible. Given the lead times required for oil shale facilities, it is unlikely that shale could play a very large role in a short term cutoff. However, if long term reductions were to occur, then shale might have a role in replacing foreign oil. This section examines the relationship between land utilization policies and feasibility of rapidly expanding an industry developed under these policies. The capability for rapid expansion is referred to as surge capacity.

Constraints on Surge Capacity

Increasing the capacity of a shale industry would require expansion of mine capacity, increased numbers of process plants, and an expansion of the entire infrastructure required to operate a shale industry. Land use policies and their effect on mining are only one component of this problem. However, mines may represent the longest lead time item in an oil shale facility. Expansion of mine capacity is therefore a potential bottleneck in the expansion of the entire industry.

There are two methods of increasing the mine capacity of an oil shale industry. The first is to develop new mines and the second is to expand existing mines. New mines will not make a great contribution to alleviating the effects of an energy emergency. The time required to develop them will preclude any rapid increase in production. Figure 33 shows results obtained from the Rand Stripping Ratio Model for a 50,000 bpd mine (when steady state is achieved) on an 800 ft deposit covered by 400 ft of shale for shale extracted for each mining year. During the first two years only overburden is removed and no shale is mined. The proportion of shale mined increases continuously until the mine reaches steady-state conditions in year 10. This lengthy period does not include the time for site preparation, which must take place before mining can begin. Site preparation times must be added to the

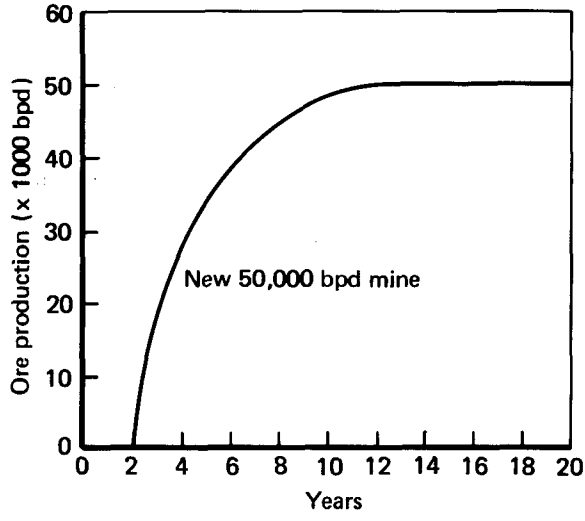


Fig. 33—Yearly production for a mine that produces 50,000 bpd at steady state

values presented in Fig. 33 to obtain the total time required for a given level of production.[20]

The only method of expanding mining capacity quickly is to avoid the lengthy period required for overburden removal. This can be achieved by using exposed faces in existing mines. This procedure was demonstrated in Fig. 31, which shows that a 50,000 bpd mine, located on the western edge of the basin, could be expanded to 130,000 bpd without requiring initial overburden removal. Increased capacity is achieved as soon as additional mining equipment can be brought in. This expansion might be constrained by lease boundaries, but it may be reasonable to assume that boundaries would be altered in an energy emergency. However, if an emergency were to occur during the early stages of an oil shale industry, there may be only one or two operating surface mines. Expansion of these mines from 50,000 bpd to 130,000 bpd would not affect national energy supplies. Even if existing land use policies could be changed after an emergency, a small oil shale industry could not be rapidly expanded into a large one.

[20]Site preparation time includes the time required for site exploration, engineering studies, ordering equipment, and other activities. See Suntech, Inc., 1976, for additional details.

Potential Surge Capacity

Under present leasing arrangements and incentives, the surge capacity of a small industry will be limited by the area of the exposed faces in existing mines. Advanced planning, or a different set of incentives, could achieve additional surge capacity by expanding the sidewalls, as shown in the plan view of a mine in Fig. 34. However sidewalls may not be available to provide this capability. Under normal operations backfilled waste would block access to these walls. This waste would have to be removed before mining the sidewalls, which is equivalent to developing a new mine and would take several years. If sidewalls are to provide additional surge capacity, then additional waste (beyond that needed for initial pit development) must be stored out of the pit and away from the mine before expansion is desired.

Sidewall expansion can dramatically increase the surge capacity of an operating mine. Figure 35 shows the volume of waste that must be stored out of the pit to obtain a given level of surge capacity from a

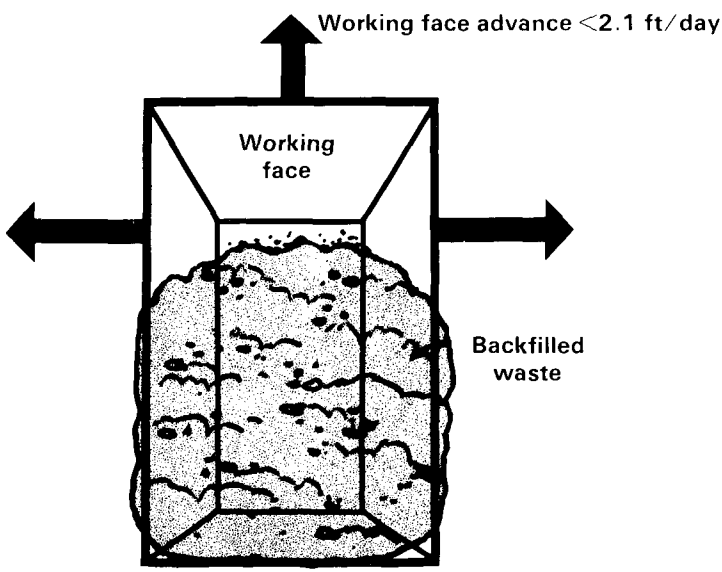


Fig. 34—Sidewall expansion

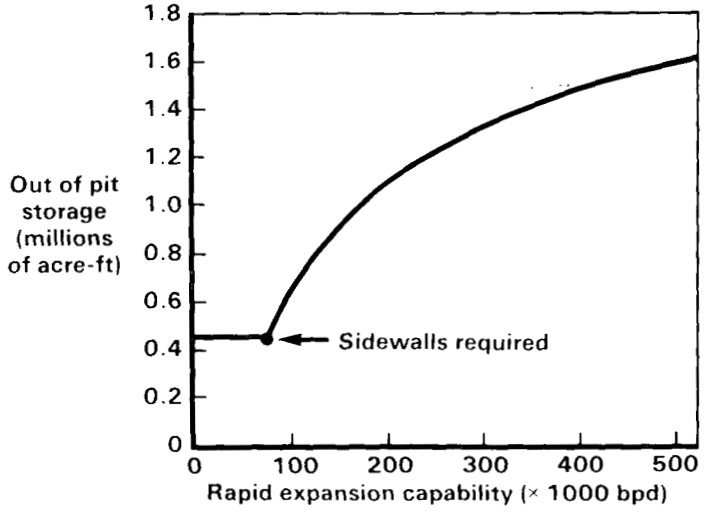


Fig. 35—Rapid expansion capability

50,000 bpd steady-state mine located on the western edge of the basin. For initial development, 450,000 acre-ft must be stored out of the pit. The first 80,000-bpd expansion occurs along the original mine working face and no additional out-of-pit storage is required. Additional surge capacity requires additional out-of-pit storage. With proper incentives, such out-of-pit storage could drastically increase the expansion speed of a small oil shale industry.

Under the present leasing arrangements there is no incentive to store additional quantities (beyond that required for initial development) of waste out of the pit. Out-of-pit storage requires larger haulage profiles and is more expensive than storage in the pit. Without off-tract lands, out-of-pit storage would not produce the desired effect, because waste would have to be stored next to the mine and would continue to block sidewall expansion. Off-tract lands, and incentives to place additional waste on these lands, are required to make the sidewalls represent additional surge capacity. One method of motivating additional out-of-pit storage is through federal financial incentives. Another is to allow developers to sell exposed mine faces as a commodity. In this latter method, sidewalls could be purchased by other companies that wish to expand an operating mine. The possibility of future sales may motivate developers to keep sidewalls free

from backfilled waste. However, realizing this incentive requires that new companies be able to site process plants on federal land near the expanded mine and that lease boundaries not constrain expansion. In any case, advanced planning and a flexible leasing policy will be required.

IV. IMPLICATIONS

RESTRICTIONS ON LEASE SIZE AND OFF-TRACT LANDS

The most intensely debated aspect of current land use policies is the restrictions on lease size and use of off-site lands. Our analysis showed that the 5120 acre size limitation, when coupled with the requirement for on-site waste disposal, will severely reduce the amount of oil shale that can be recovered. This will preclude the development of a large industry and the use of oil shale as a long term alternative to foreign oil. Larger leases, or off-site land for disposal of waste, could greatly increase the resource recovery from a lease. However, off-site lands may themselves contain large quantities of shale, and their use for waste disposal will render the shale inaccessible. When these lands are included in an assessment of resource recovery, the option of maintaining lease size at 5120 acres and allowing off-site disposal is less favorable than allowing leases that are many times larger than 5120 acres.

The sensitivity analysis illustrated important distinctions between the thick center basin deposits and the thinner deposits on the western edge of the basin. Current leasing policies severely reduce recovery from both types of deposits. However, for a given lease size, recovery is higher on the western edge of the basin than in the center. This implies that the policy option of maintaining current lease size and allowing off-site disposal will be more effective on the western edge than in the center basin. The only method of obtaining high recovery in the center basin is very large leases. Policies that lead to high recovery in one area of the basin may not produce high recovery in other areas. No single lease size or waste disposal policy is ideal for all deposits, but current restrictions severely limit the potential of the resource, and new restrictions will have the same effect unless they are tailored to the requirements for developing particular deposits.

CONSTRAINTS ON PROJECT SIZE AND MINE EXPANSION

The limitation of one lease per developer, anti-trust concerns, and industry tradition will constrain the size of individual projects. These constraints may considerably increase the cost, as measured by the

stripping ratio, of extracting the bulk of the shale resource, which is located in the center basin. Production levels of at least 250,000 bpd are required to extract center basin shale efficiently. The 50,000 bpd projects typically contemplated by individual developers result in much less efficient mining operations. Efficient extraction of center basin shale will require special efforts to concentrate industry capability. The analysis also indicated economies of scale for the thinner deposits located on the western edge of the basin. However, for these deposits, a 50,000 bpd production rate did not have important adverse effects on mining operations. Projects of 250,000 bpd are only slightly more efficient.

The factors limiting project size will also encourage developers to begin new projects rather than expand existing ones, increasing extraction costs, because expansion offers the opportunity of increased production without the expensive process of initial overburden removal. The benefits associated with mine expansion occur for both center basin and western edge deposits. Any exposed mine faces represent a potential resource. Unless there are geological barriers, expansion is preferable to starting a new mine. An efficient development pattern should allow mines to migrate continuously to minimize initial overburden removal.

SURGE CAPACITY

The role that shale can play in helping to alleviate the adverse effects of an energy emergency is limited by the lead times required to construct oil shale facilities. It is unlikely that shale can influence the effects of a short term reduction in oil supplies. However, in the event of a permanent reduction, it might be desirable to expand shale production as rapidly as possible, even if several years were required for this expansion.

Increasing the capacity of an oil shale industry in such an emergency would require expansion of all parts of the industry. Mining is one critical component of this problem. Our analysis showed that because of the long lead times required to develop new mines, oil shale would not be much help in meeting the effects of even a long term energy emergency. Development time can be reduced by expanding existing mines rather than sinking new ones. Unfortunately, the expansion potential of an existing mine developed under normal operations would probably not be large enough to influence national energy supplies. Expandability can be increased by storing waste beyond that required for initial pit development out of the pit and away from the

mine, before an emergency. This would expose the sidewalls, which could then be mined without initial overburden removal. This practice is currently prevented by restrictions on the use of off-site lands. However, even with off-site waste disposal there is no incentive to keep sidewalls clear because storage in the pits is the least expensive disposal option.

The incentive needed to keep sidewalls free from backfilled waste can be generated by market forces that favor mine expansion during normal operation. Under normal operations, increasing the mining rate on the working face offers the economic benefit of increased production without initial overburden removal. Sidewalls offer the same potential benefit. If sidewalls are viewed as a salable commodity, developers may have incentives to keep them clear of backfilled waste. Boundaries and other factors that discourage expansion on the working face will also discourage sidewall expansion. This will reduce the value of sidewalls and the incentive for extra out-of-pit storage.

OBTAINING MAXIMUM RESOURCE USE

The analysis has identified several factors that could reduce the potential of Piceance Basin oil shale. A policy that minimizes these factors could increase the potential of the resource, but there are several concerns about the desirability of large scale oil shale production.

The requirements for achieving maximum resource potential are: extensive surface mining of federal land, large mines that are free to migrate, highly cooperative industry development efforts, and careful siting of process facilities and waste disposal piles. Clustering of process facilities in areas without substantial shale reserves will enhance resource recovery. These same considerations are even more important for waste disposal piles, because these piles may require more land than the process facilities. The importance of careful waste pile siting is increased by the need for extra out-of-pit storage to increase mine surge capacity.

A land use policy that simply maximizes resource potential may not be in the best interest of the nation. There are many concerns about development that should be considered when formulating land use policies, the most obvious being the current lack of incentive for shale development. This has created a trend toward smaller projects rather than the highly centralized developments highlighted in this analysis. Even with increased incentive, industry is not ready to develop 250,000 bpd projects and perhaps not even 50,000 bpd projects. The trend toward decentralization may also have certain advantages in

terms of competitiveness and innovation. Any changes in land use policies should be sensitive to these potential benefits and the present trend in the industry.

In addition to industrial and financial concerns, there are socioeconomic, environmental, and institutional concerns about the effects of shale development. The remote location of the Piceance Basin implies that a large industry will require the development of an extensive socioeconomic infrastructure that may take years. The environmental effects of oil shale development have long been a subject of intensive debate. Environmental concerns occur in almost all aspects of shale development, and these concerns have given strength to the argument that development should be paced so that additional information can be obtained about environmental effects.

The potential for technological advances in oil shale extraction also introduces uncertainties to the formulation of new land use policies. Our analysis was based on surface mining, because it is the only proven technique that can lead to large recovery factors. Advances in the in-situ technologies or other methods of mining and waste handling may introduce other options. Therefore, any new policies should provide the flexibility for unforeseen technological changes.

A balanced land use policy should allow for maximum resource utilization without dismissing the concerns about large scale development. A plausible strategy that would provide such a balance is illustrated in Fig. 36. It calls for the phased use of the federal land and phased development of the oil shale industry. An essential compo-

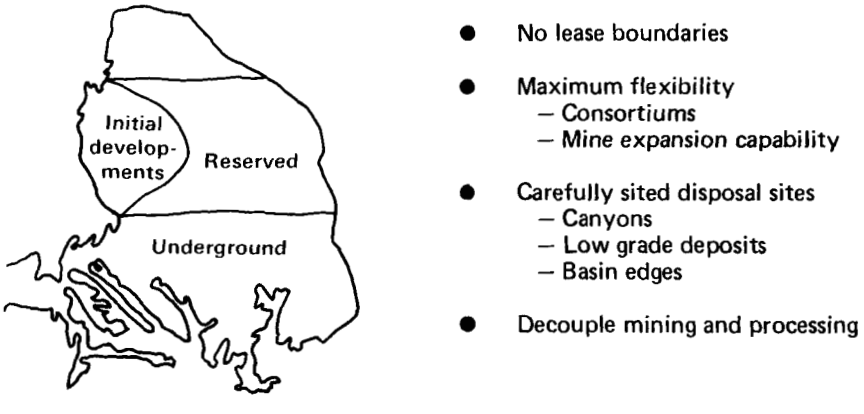


Fig. 36—A basin-wide development strategy

nent of this strategy is the designation of the central basin as a strategic oil shale reserve. Our analysis showed that this portion of the basin could not be efficiently developed without extremely large mining operations. At the present time industry is unprepared for these operations. Releasing this land for development would only fragment industry capability and cause developers to investigate extraction techniques that may have little ultimate potential. If initial development is confined to the private lands in the southern portion of the basin, easy access to underground mines may allow efficient operation of the small projects (10,000 bpd) needed to minimize financial risk while the industry is in the early stages of development.

Initial development of federal lands should be concentrated on the western edge of the basin, allowing the concentration of industry capability into one region. Efficient extraction operations could be conducted with projects on the order of 50,000 bpd. Mining operations could be initiated at this level and be expanded without concern for man-made boundaries. Waste disposal and process plants could be sited at the edges of the basin to avoid interference with mining operations. Favorable locations for waste disposal sites may also permit additional out-of-pit storage to provide a strategic surge capacity.

This strategy will undoubtedly require protection from anti-trust concerns and might produce an uncompetitive centralized industry. One possibility for alleviating this problem is to decouple the mining and process operations. Other than the need for geographical clustering, the analysis did not identify any need for large scale process facilities. Typically, oil shale developers have considered development of only complete shale oil production facilities. The possibility of selling ore to process facility operators has been neglected. There is apparently no technological obstacle to this separation. It would allow processing to be done in a highly competitive manner that could include both small and large developers. Mining operations might be less competitive; however, the possibility of competing firms operating within the same large mine has not been fully investigated.

POTENTIAL FEDERAL ACTIVITIES

Implementation of this type of strategy will require extensive planning, study, and negotiation among private firms and state, local, and federal governments. Because the federal government owns the land, it also has the responsibility for establishing the framework. Its development requires more detailed engineering work. Suitable sites for process facilities, waste disposal, and mines must be established.

Many of the land use issues that have been previously debated will also affect the feasibility of adopting such a strategy. A rapid release of federal lands would probably not maximize the resource potential but would fragment industry capability and produce man-made boundaries that may be difficult to remove. Federal actions consistent with obtaining maximum resource potential would limit the availability of federal lands and attempt to stimulate development of private lands. One of the major obstacles to development of private lands has been the small and irregular shapes of the private tracts, so land exchanges and use of federal land for storing waste generated on private lands may increase the possibilities of developing these lands. These types of actions are currently more important than the release of new federal lands.

Although there is no immediate need for more federal land, it must be available when needed. One factor inhibiting development of private lands is size of the private tracts. Many tracts are not large enough to sustain more than one or two plants. First-of-a-kind plants are often unprofitable and are only constructed if there is an expectation of more developments. Without federal land, developers may not have this confidence.

The unique characteristics of Piceance Basin oil shale create unique development problems and opportunities. Individual oil shale projects will be highly interactive. As an example, process plants from one development could interfere with the expansion of a mine from another project. Most studies have ignored these interactive effects. Analyses of constraints on shale production have concentrated on the upper limits on total production without considering the type of development pattern dictated by the constraint. We hope that this study has brought more important aspects of these interactions into sharper focus and suggested an approach to a rational development of the Piceance Basin.

Appendix A

RESOURCE RECOVERY

LEASE LAYOUT

We assumed that the lease could be divided into two squares—one for the process facilities and one for the mine. The process facilities occupy one square mile per 5120 acres. Figure A.1 illustrates this layout and shows a 500 ft perimeter. The symbol "W" represents the width (or length) of the mine.

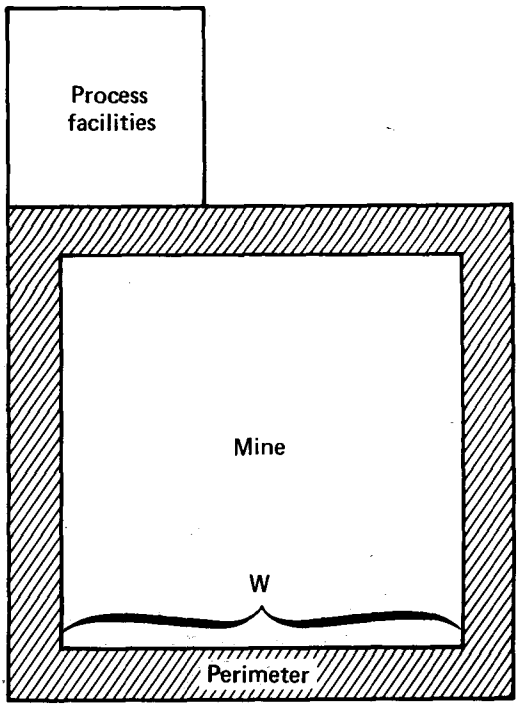


Fig. A.1—Lease layout

Our assumed base case lease has an overburden thickness of 600 ft and a shale thickness of 1100 ft. Figure A.2 shows these dimensions on a cross-sectional view of the mine.

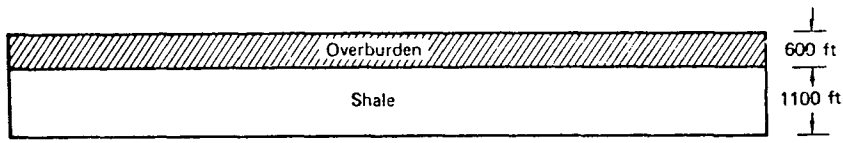


Fig. A.2—Lease cross section

RESOURCE YIELDS

Figure 17 showed resource yields that can be obtained under three different constraints. All results are based on a comparison of the volume of shale extracted and the total volume of shale in the lease. Resource recovery can be expressed mathematically by Eq. (A.1):

$$\text{Resource recovery} = \frac{\text{(Volume of shale extracted)}}{\text{(Total volume of in-situ shale)}} \qquad \text{(A.1)}$$

In all cases, the total volume of in-situ shale is assumed to consist of an 1100 ft thick seam underneath the entire lease. This volume (in cubic feet) is given by:

$$\text{Total volume of in-situ shale} = 2.4 \times 10^{11} N \qquad \text{(A.2)}$$

where $N \times 5120$ acres is the lease size.

The process facilities are assumed to occupy about 12 percent of a lease for all lease sizes. Here we assume that all shale underneath these facilities is lost, limiting recovery to no more than 88 percent.

Offsite Disposal

The curve labeled "off-site disposal" in Fig. 17 shows the limitations of 41° mine walls without considering the effects of storing shale waste on site. The volume of shale extracted is a four-sided, flat-top pyramid extending from a depth of 600 ft to a depth of 1700 ft. The total volume extracted (shale plus overburden) is a similarly shaped pyramid extending from the surface to a depth of 1700 ft. Figure A.3 shows a cross section of this volume. The total volume extracted is given by:

$$V = x^2h - \frac{2h^2x}{\tan\theta} + \frac{4}{3}\frac{h^3}{\tan^2\theta} \qquad \text{(A.3)}$$

where θ = wall angle
h = vertical height
x = width of the large base

The volume of shale removed is obtained by using Eq. (A.3) with the following values:

where $x = W - 2(600\text{ ft})/\text{Tan}\theta = W - 1380\text{ ft}$
$\theta = 41°$
$h = 1100\text{ ft}$

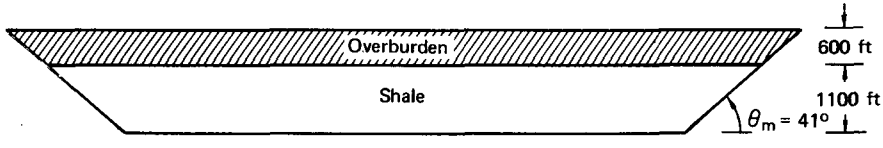


Fig. A.3—Cross section volume mined for "offsite disposal" case

With these values, the volume of shale (in cubic feet) extracted is:

$$V = (W - 1380)^2\ 1100 - (2.8 \times 10^6)(W - 1380) + 2.4 \times 10^9. \qquad \text{(A.4)}$$

W is the width of the mine; its value can be expressed in terms of lease size by using the geometry shown in Fig. A.1. This relationship can be shown to be:

$$W = 13{,}959\sqrt{N} - 1000\,, \qquad \text{(A.5)}$$

where N × 5120 acres is the lease size (W is in feet). This formula shows that for N = 1, the mine width is approximately 13,000 ft. Using Eqs. (A.4) and (A.5), the volume of shale extracted can be computed as a function of lease size. This can be inserted into the numerator of Eq. (A.1) to obtain the resource yield. For N = 2 (a 10,240 acre lease), the volume of shale mined is 2.9×10^{11}, whereas the total volume of shale on the lease is 4.8×10^{11}, for a recovery of about 60 percent, as shown in Fig. 17.

Single Handling

When on-site disposal and single handling of waste are required, the losses imposed by these constraints are as illustrated in Fig. A.4, which shows a cross-sectional view of the mine at three different stages of development.

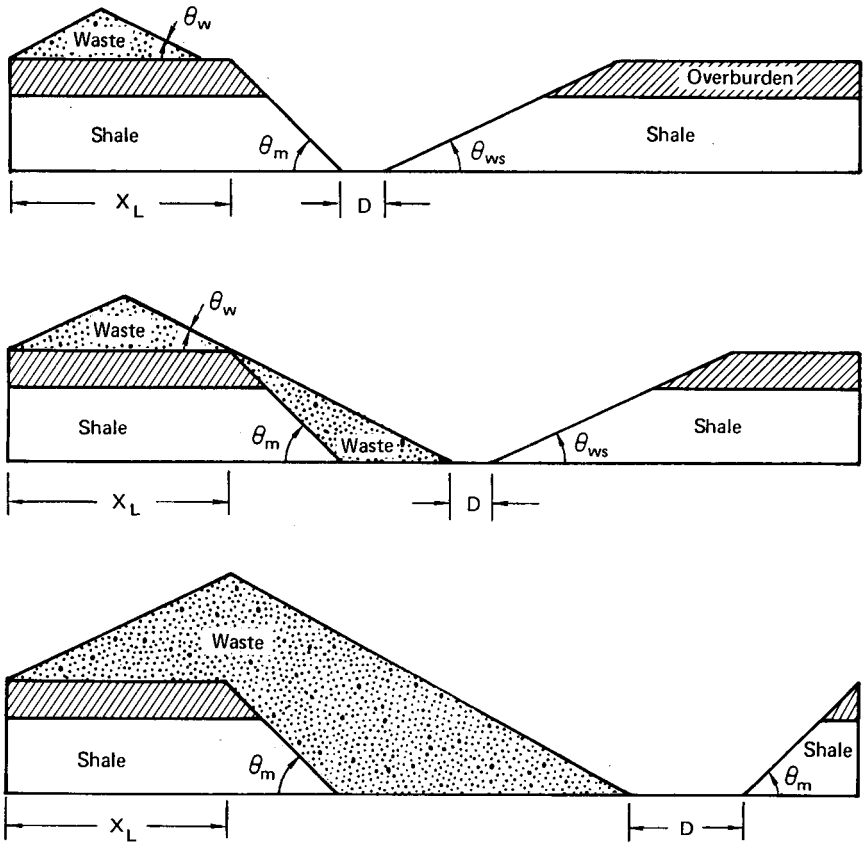
The first frame shows the stage at which the final depth and the required working distance of 500 ft are first reached. The second frame shows an intermediate stage at which the backfilled waste is wedge-shaped. The third frame shows the final stage for single handling of waste. The 500 ft distance separating the backfilled waste pile and the 19° working slope are maintained throughout the process. The working slope can be increased to the angle of the final walls (41°) at the end of the process. The mine cut is assumed to run in and out, across the entire width of the mine.[1]

The mine is allowed to progress through its various development stages as long as the following constraint is obeyed for all mine stages:

$$\text{Volume available for waste storage} > (K) \times (\text{Volume extracted}) \qquad \text{(A.6)}$$

where K = the spent shale expansion coefficient equal to 1.25. The volume available for waste storage in the pit is not large enough to satisfy this constraint for all stages (consider the first frame of Fig.

[1]This policy can severely limit the recovery from smaller leases. Alternative policies are discussed in the last section of this appendix.



θ_w = Waste pile angle of repose = 14°

θ_m = Mine wall angle = 41°

θ_{ws} = Working slope angle = 19°

D = Clear distance $\geq$ 500 ft

Fig. A.4—Mine development with single handling

A.4, where no volume is available in the pit but substantial mining has taken place). To satisfy the constraint, an area must be set aside for waste storage, here represented by the area above X_L. Because Eq. (A.6) must be maintained for all stages, in the absence of double handling of waste, the mine stage that requires the greatest value of X_L determines the size of X_L, which also determines the amount of shale not recovered. In general, the configuration shown in the second frame of Fig. A.4 will determine the required value of X_L.[2]

X_L determines the amount of shale lost because of the single handling constraint. The size of X_L is the largest value needed to ensure that Eq. (A.6) holds for all mine stages. Once this is determined, the total volume of shale extracted can be calculated. The geometry in the third frame of Fig. A.4 shows that the volume of shale extracted is a four-sided pyramid with a rectangular base. Using standard geometric formulas, this quantity can be calculated and inserted into Eq. (A.1).

Once the stage represented by the second frame of Fig. A.4 has been reached, the mine opening generally moves faster than the waste pile. This increases the working distance (the distance between the end of the backfilled waste pile and the beginning of the working slope) to a value greater than the required minimum of 500 ft. This is indicated in the last frame of Fig. A.4.

These illustrations also provide some insight into the sensitivity of yield in relation to lease size. The amount of shale lost is determined by an intermediate mine stage (the second frame of Fig. A.4), so the total quantity of shale lost is only mildly sensitive to the size of the lease. In other words, the absolute value of X_L does not vary rapidly with lease size. The larger the lease, the smaller X_L is as a percentage of the total mine width.

Double Handling

Double handling[3] of waste allows for the possibility of extracting the shale lost, as shown in the third frame of Fig. A.4. The mine usually expands faster than the waste pile, so the working distance at

[2]This can be shown by evaluating the rate of growth of the volume extracted and the resultant rate of growth of the volume available for waste storage. For most mine geometries, this occurs when the backfilled volume is in the shape of the wedge shown on the second frame of Fig. A.4. We have considered exceptions in our analysis.

[3]Increased recovery due to handling the waste more than twice was investigated and found to be insignificant.

the bottom of the mine is greater than the minimum requirement of 500 ft. This extra distance may allow for the waste to be transferred, as shown in Fig. A.5; however, two factors may prevent this transfer. First, the transfer divides the waste pile in two. This separation is a less efficient way to store waste because more area is required and results in a smaller working distance at the bottom of the mine. Second, the mine wall on the left now becomes the working slope with an angle of 19° (rather than the 41° before waste transfer). This process creates additional waste without increasing waste storage volume; it also reduces the working distance at the bottom of the mine. If these two factors reduce the working distance to below 500 ft, waste transfer cannot occur as shown. In such cases, yield can be increased by mining to depths less than the 1700 ft maximum (from the beginning of the process). This approach, however, may lower the recovery that can be obtained under the single handling constraint. Figure 17 shows the largest value obtainable under each constraint, even though both results may not be consistent with one mining operation.

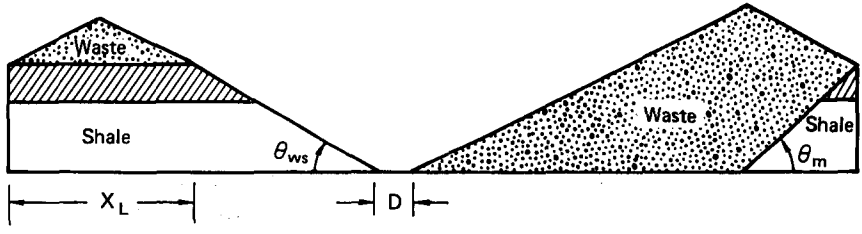


Fig. A.5—Waste transfer

Once waste transfer is completed, the mine can be expanded to the final configuration shown in Fig. A.6. If the full depth is mined, the volume of shale extracted is equal to that of the case labeled "off-site disposal." Figure 17 showed that this occurs for leases greater than about 40,000 acres. The mining depth for smaller leases was limited to less than the maximum of 1700 feet to increase the recovery obtained with double handling.

Alternative Mining Strategies

The mining policy in this analysis assumes a mine cut across its entire width, which reduces available volume for waste storage. For a

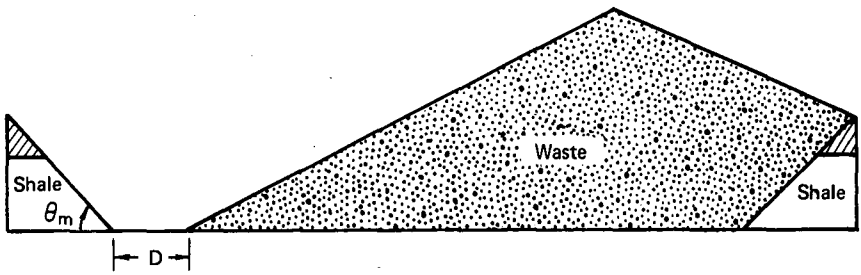


Fig. A.6—Final mine configuration

lease of 5120 acres, the total mine width is approximately 13,000 ft. The initial cut, shown in the first frame of Fig. A.4, has an opening of 7400 ft. The remaining 5600 ft × 13,000 ft area is not large enough to accommodate the waste. Thus, the total mine depth cannot even be reached for a lease this size.

To attempt to increase the yield from small leases, we explored several alternative mining policies. One possibility is to mine only a thin portion of the 1100 ft shale deposit. This approach is not as favorable as those that limit the width of the cut. Figure A.7 shows an example of such an approach for a lease size of 5120 acres. In this configuration, the strip marked "1" is mined and the areas marked "2" and "3" are used for waste storage. If double handling is allowed, the waste in strip 3 can be transferred into the open pit created from mining strip 1. Strip 3 can then be mined, with excess waste stored in strips 1 and 2. After strip 3 is mined, waste from strip 2 can then be stored on strips 1 and 3 and part of strip 2 can be mined. This procedure provides more recovery than can be obtained with a single cut across the entire lease. The practicality of mining a lease in this manner has not been investigated; but even if it is practical, the recovery will not increase very much. Using this method, we found that the recovery obtained with double handling is less than 20 percent for a lease of 5120 acres.

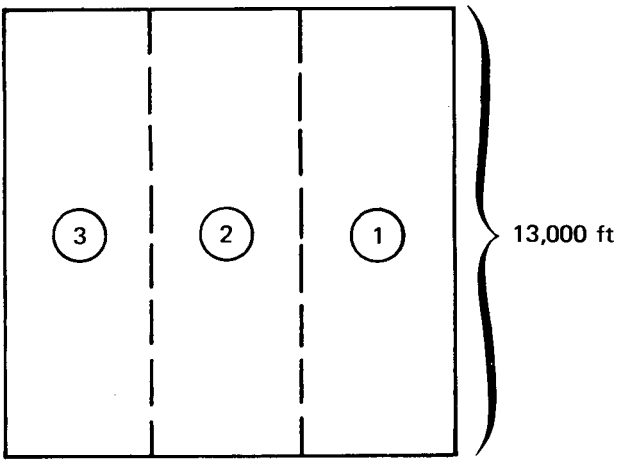


Fig. A.7—Mining in thin strips

Appendix B

THE LIMITATIONS OF STRIPPING RATIO

Stripping ratio accounts for most costs in a surface mining operation; however, the ultimate profitability of an operation cannot be determined by one simple parameter. Stripping ratio does not include all the factors going into a financial analysis. Notable exceptions are haulage distances and the costs incurred for initial mine development (power, roads, etc.). There has been some concern that these other costs could eliminate economies of scale. The main argument is the increased haulage distance required for larger mines. There are no operational oil shale surface mines, so there is no definitive evidence. However, we believe that for the production levels contemplated here, the available evidence points to the indicated economies of scale.

The Suntech study (Suntech, Inc., 1976) is perhaps the most complete engineering and cost analysis of an oil shale surface mine. It analyzes a mine on the western edge of the basin and considers production rates larger than 250,000 bpd. A 250,000 bpd mine is at the upper end of the production rates contemplated in this report. The two smallest cases in the Suntech study were 250,000 bpd and 625,000 bpd with mine widths of about 9000 ft and 15,000 ft, respectively.[1] As shown in Fig. 30, we would not expect any important difference in stripping ratio for these two Suntech mines. This is because stripping ratios for western edge deposits do not decrease greatly for production rates more than 150,000 bpd. We would therefore not expect any difference in mining costs. The Suntech study confirmed this result by showing that undiscounted mining costs were the same for the 250,000 bpd and 625,000 bpd cases. Thus the costs associated with haulage distances did not dominate the stripping-ratio cost contribution. One reason is that the somewhat increased haulage costs were balanced by economies of scale in initial mine development. Because increased haulage costs occur late in the mining process, discounting costs strengthens the case for economies of scale. The higher the discount factor, the more tendency toward economies of scale. However, independent of the discount factor, the

[1]In our report the 50,000 bpd center basin mine had a width of about 5000 ft and the 250,000 bpd mine had a width of about 9000 ft. Thus, haulage distances may be less important for our cases.

Suntech study indicates that stripping ratio is a good figure of merit for mine widths of up to 15,000 ft and, depending on the discount factor, perhaps up to 25,000 ft. These widths are well beyond the mine sizes contemplated in our study. Finally, Suntech studied mine widths of more than 100,000 ft. Stripping ratios are still relevant for these widths, but haulage distances take on increased importance.

The above arguments point to the need for site-specific cost analysis to determine optimal mine production levels. Haulage profiles must be defined and financial assumptions included. However, stripping ratios do drive costs; and for center basin deposits, stripping ratios are extremely sensitive to production rates up to about 300,000 bpd. Given the above evidence, we therefore expect the need for sizable mining operations to efficiently extract center basin deposits.

Appendix C

STRIPPING RATIO MODEL

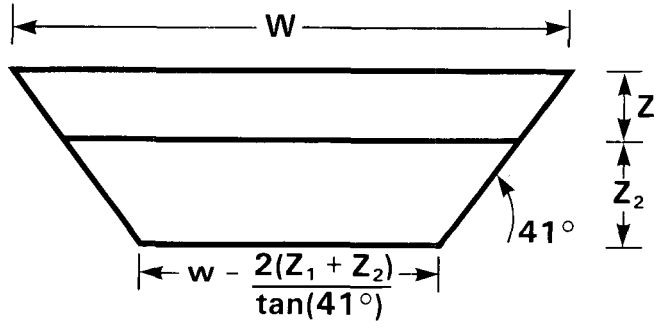
This appendix reviews the assumptions and algorithms used to derive the stripping ratio models presented in the text. The appendix is organized in a manner that follows the logic flow diagram shown in Fig. 27, which shows that the input parameters (wall slopes, shale depth, overburden depth, and production rate) allow prediction of mine geometry under steady-state conditions. This determines the rate at which total rock (ore plus overburden) is mined. With this value, mine geometry can be predicted for each of the 30 years of mining. The procedure is repeated until an optimal mine width, determined by the minimum in the cumulative stripping ratio, is found.

INPUTS

The inputs to the stripping ratio model are the slopes of the mine walls and the working face, the shale and overburden depth, the steady-state production rate, the average shale grade, and the mine width. Mine width is later optimized. We have assumed that the mine walls are sloped at 41° and the working face is sloped at 19°. Shale depth, overburden depth, and steady-state production rate are determined by the particular mine being studied. The thicknesses shown on the cross section in Fig. 28 are based on deposits averaging 20 gpt, and this value is used in the analysis.

STEADY-STATE CONDITIONS

The input parameters can be used to construct the dimensions of the steady-state mine working face. The vertical projection of the working face area is illustrated in Fig. C.1. The vertical projection is important because the mine is expanded horizontally. The sum $(Z_1 + Z_2)$ represents the mine depth. This depth is not necessarily equal to the depth of the overburden and shale. The inequality arises if the mine width is insufficient to support the full depth. This latter constraint is given by the following expression.



Z_1 = Overburden thickness

Z_2 = Shale thickness

Fig. C.1—Vertical projection of the steady-state working face

$$500 + \frac{2(Z_1 + Z_2)}{\tan(41°)} \leqslant W \qquad \text{(C.1)}$$

(All dimensions in feet)

This expression gives a constraint on mine depth assuming the requirement of a 500 ft mine floor. For the two cases analyzed in the text, total depths of 1200 ft and 2700 ft were required to fully exploit the resource. These depths require minimum mine widths of 3260 and 6711 ft respectively. Figure C.1 also illustrates why stripping ratios improve with higher production. As the mine width increases, the effect of the sloped mine walls decreases and the steady-state stripping ratio approaches the overburden to shale ratio. However, large widths increase the amount of overburden that must initially be removed, requiring a large rock mining rate. This corresponds closely with the production rate.

Using Eq. (C.1) to determine allowed mine depth (given mine width), the dimensions of the steady-state working face can be calculated. The area on the working face that is covered by shale is given by:

$$A_s = \left(W - \frac{2Z_1}{\tan(41°)} - \frac{Z_2}{\tan(41°)} \right) Z_2 \qquad \text{(C.2)}$$

where Z_2 is determined by Eq. (C.1). The area of the overburden on the working face is given by:

$$A_o = [W - Z_1/\tan(41^\circ)]\ (Z_1). \qquad (C.3)$$

The steady-state stripping ratio is given by:

$$\text{Steady-state stripping ratio} = A_o/A_s \qquad (C.4)$$

These formulas, and the steady-state production goal, permit calculation of the annual amount of rock (overburden plus shale) mined. This value is given by the following expression:

$$\text{Annual rock mined} = (2)\ (14\ \text{ft/ton})\ (365)\ (P)\ (A_o + A_s)/A_s \qquad (C.5)$$

where (P) is the production rate in barrels per day. The factor of 2 converts barrels per day into tons of 20 gpt shale.

MINING BEFORE STEADY STATE

We have assumed that the total quantity of rock mined is constant throughout the mining period. The quantity of rock given by Eq. (C.5) can be used to predict the mine geometry at various points in the process. We have assumed that the mine develops with a wedge shaped opening as illustrated in Fig. 25. The volume removed from the deposit is illustrated in Fig. C.2, and is given by the following formula:

$$V = WXZ - Z^2\left(\frac{X}{\tan(41^\circ)} + \frac{W}{\tan\theta}\right) + \frac{4}{3}\,\frac{Z^3}{(\tan\theta)\,[\tan(41^\circ)]}$$

$$\text{where:}\quad X = Z\left(\frac{1}{\tan(19^\circ)} + \frac{1}{\tan(41^\circ)}\right) \qquad (C.6)$$

$$\theta = \arctan\left[\frac{2\tan(41^\circ)\,\tan(19^\circ)}{\tan(19^\circ) + \tan(41^\circ)}\right]$$

The symbol θ is used only for notational convenience. This volume may consist only of overburden or may contain both overburden and shale. If $Z < Z_1$, then the volume contains only overburden and the stripping ratio is infinite. If $Z > Z_1$, then the overburden volume can be calculated from Eq. (C.6) with $Z = Z_1$. Subtracting the overburden volume from the total rock gives the amount of shale contained in the wedge.

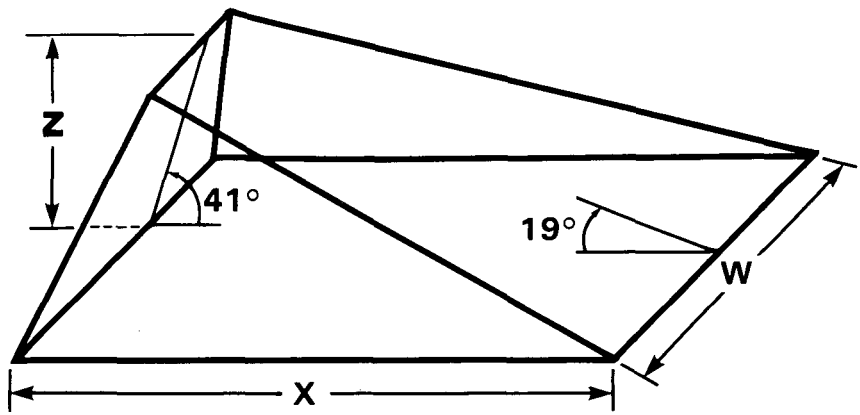


Fig. C.2—Volume of rock removed before steady state

Equations (C.5) and (C.6) can be used to calculate the cumulative stripping ratios obtained at each year in the process. This is done by solving the following equality for the depth of the wedge (Z):

$$(N)\begin{pmatrix}\text{Annual rock}\\ \text{mined in } ft^3\end{pmatrix} = \text{Volume of the mined wedge}$$

$$(2)\,(N)\,(14)\,(365)\,(P)\left(\frac{A_o + A_s}{A_s}\right) =$$

$$WXZ - Z^2\left(\frac{X}{\tan(41^\circ)} + \frac{W}{\tan\theta}\right) + \frac{4}{3}\,\frac{Z^3}{\tan\theta\tan(41^\circ)} \qquad (C.7)$$

where N = year number

$$\theta = \arctan\left[\frac{2\tan(41^\circ)\tan(19^\circ)}{\tan(19^\circ) + \tan(41^\circ)}\right]$$

Equation (C.7) defines the total volume mined up to and including mining year N. The amount of overburden and shale can also be calculated using the method discussed above. Thus the cumulative stripping ratio can be obtained for any year before steady state. The annual stripping ratios can be calculated by comparing cumulative stripping ratios from consecutive years.

MINE WIDTH OPTIMIZATION

The above procedure uses mine width (W) as an input parameter. This parameter is optimized by repeating the above procedure with different values of the mine width. The optimal value is the one that minimizes the cumulative stripping ratio after a given evaluation period. Smaller widths require less overburden removal but have less favorable steady-state stripping ratios. The optimal width will depend on the evaluation period used, the large widths being optimal for longer evaluation periods. The results presented in the text are based on an evaluation period of 30 years, based on the definitive design plan for Tract C-a, which considered an equivalent period. Choosing this time period resulted in a mine width of 4000 ft for the 800 ft deposit covered by 400 ft of overburden. Figure C.3 shows that the choice of 30 years does not critically affect the optimal mine width and that if the evaluation period were 20 years, the 4000 ft mine width is still favored over a 3000 ft width. The crossover point occurs at 16 years. Even if the evaluation period were as short as ten years, the choice of a 4000 ft mine width does not give very different results than does a 3000 ft width. Only when the evaluation period is short does the 4000 ft mine width become suspect. However, for these periods the stripping ratio is unfavorable at any width; and surface mining is not likely to occur.

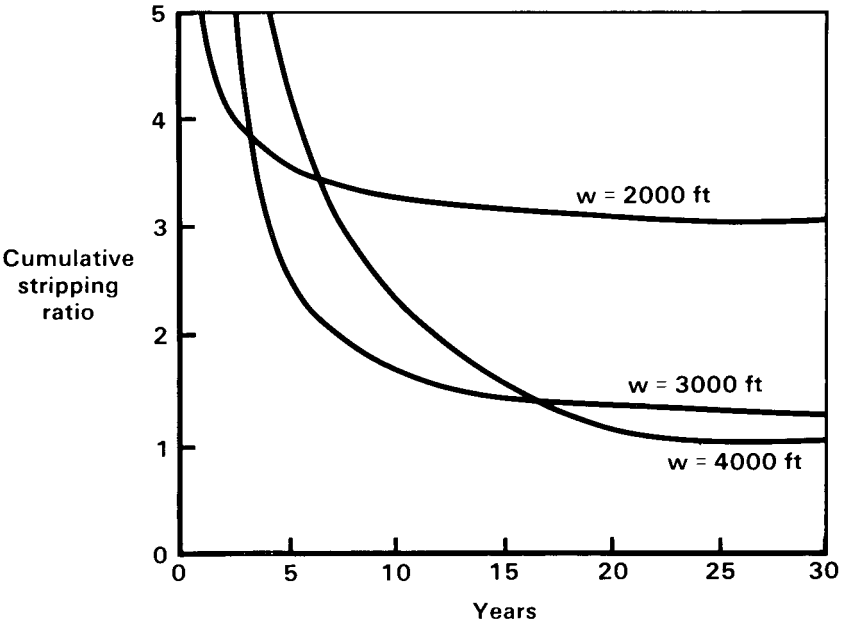


Fig. C.3—The effect of mine width

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