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An Economic and Ecologic Comparison of the Nuclear Stimulation of Natural Gas Fields with Retorting of Oil Shale

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Final report 6 June 1975

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This study discusses two possible alternatives for the national dilemma with regard to energy fuel. The methods that will be addressed are: the recovery of natural gas by nuclear stimulation and retorting of oil shale to obtain crude oil. The findings are summarized from the limited employment of both methods in the Piceance Basin of Western Colorado. Particular emphasis is given to a review of the related literature. The similarities and differences of each method have been examined first with regard to ecologic considerations and second from the standpoint of economic considerations. Finally, each method was contrasted in the light of which would be the most economical and which would do the least amount of permanent damage to the ecology.

The study concludes that given a fixed amount of fiscal assets and the need to do minimal harm to the environment nuclear stimulation of natural gas fields is the more logical option.

AN ECONOMIC AND ECOLOGIC COMPARISON OF THE NUCLEAR STIMULATION OF NATURAL GAS FIELDS WITH RETORTING OF OIL SHALE

A thesis presented to the Faculty of the U.S. Army Command and General Staff College in partial fulfillment of the requirements of the degree

MASTER OF MILITARY ART AND SCIENCE

by

WILLIAM A. WISE, CPT, USA
MAPA, University of Oklahoma

Fort Leavenworth, Kansas
1975

ABSTRACT

This study discusses two possible alternatives for the national dilemma with regard to energy fuel. The methods that will be addressed are: the recovery of natural gas by nuclear stimulation and retorting of oil shale to obtain crude oil. The findings are summarized from the limited employment of both methods in the Piceance Basin of Western Colorado. Particular emphasis is given to a review of the related literature. The similarities and differences of each method have been examined first with regard to ecologic considerations and second from the standpoint of economic considerations. Finally, each method was contrasted in the light of which would be the most economical and which would do the least amount of permanent damage to the ecology.

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TABLE OF CONTENTS

Page

CHAPTER I

OVERVIEW

This chapter will introduce the problem of selecting one of two methods of obtaining energy fuel. Given a fixed amount of fiscal resources and the need to do the least amount of damage to the environment one method should be selected.

INTRODUCTION TO THE PROBLEM

This nation's supply of energy continues to be of growing importance and concern to everyone including government and industry. Among the methods of supplying energy to our nation are two that will be addressed in this study:

a. Recovery of natural gas by nuclear stimulation.

b. Retorting oil shale (Marlstone) for the production of synthetic crude oil.

This aspect of the problem with regard to the far reaching dilemma of energy fuel will be addressed in this study. Two viable solutions will be reviewed and compared particularly in the area of economy and ecology. The use of a cost-benefit ratio will aid in this examination. The conclusion that will be drawn will be that industry and government should place its economic assets on one method or the other. It should be realized that consequences will be far reaching. The Piceance Basin in Western Colorado offers an outstanding opportunity to examine the two methods in a fairly controlled environment. Note that both methods have been considered for a number of years.

INTRODUCTION TO NUCLEAR STIMULATION

The supply of natural gas is no longer in relative abundance simply because the requirements for its use have outstripped the ability of the industry to supply it by conventional means. Under these circumstances the search for new supplies through innovative technology becomes an obvious requirement of both the producing industry and the government.

Of all the possible domestic alternatives for natural gas supply, the use of nuclear explosives to stimulate very low permeability gas reservoirs is one of the most significant for short term contribution. The Bureau of Mines has estimated that perhaps as much as 317 trillion standard cubic feet of natural gas could be mined by this technique in the Rocky Mountain area alone.[1] By comparison the total United States reserve is only about 260 trillion standard cubic feet. This fact makes a strong case for nuclear stimulation. A test is being carried on in Western Colorado in the vicinity

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[1] B. Rubin, et al., An Analysis of Gas Stimulation Using Nuclear Explosives (Lawrence, California: Lawrence Livermore Laboratory, 1972), p. 2.

of the town of Rifle to determine the feasibility of this method of production.

The nuclear stimulation of gas wells began with the inception of Project Plowshare immediately after the Second World War. The first attempt took place in the Pictured Cliffs Formation in northwestern New Mexico with the El Paso Natural Gas Company working in conjunction with the U.S. Government. "Gasbuggy," as the attempt was called, was detonated in 1967. It produced a chimney about 160 feet in diameter and 325 feet high and contains 2.2 million cubic feet of void volume. The top of the chimney is 3,900 feet below the surface at the top of the 286-foot thick gas-bearing Pictured Cliffs Formation.[2]

Project Rulison in Western Colorado followed the "Gasbuggy" attempt. Project Rulison was a joint experiment sponsored by Austral Oil Company, Inc., Houston, Texas, the U.S. Atomic Energy Commission, and the Department of the Interior, with the Program Management provided by Geonuclear Corporation of Las Vegas, Nevada under contract to Austral. Its purpose was to study the economic and technical feasibility of using underground nuclear explosions to stimulated production of natural gas from the low productivity, gas-bearing Mesa Verde formation in the Rulison Field.

The nuclear explosive for Project Rulison was detonated successfully at 3:00 PM on September 10, 1969, at a depth of

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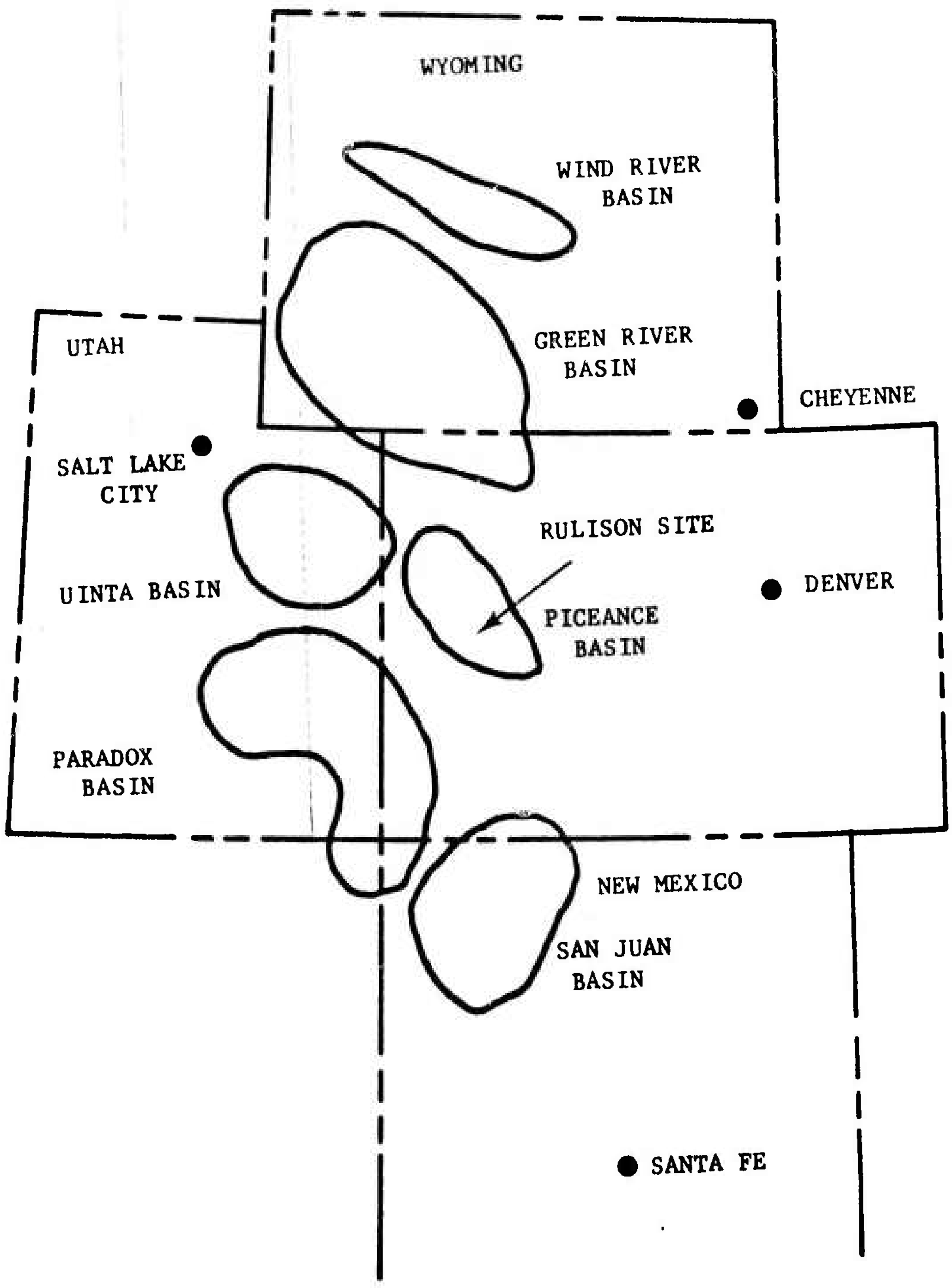
[2]E.W. Chew, et al., Chemical Considerations in Nuclear Stimulation of Gas Reservoirs, (Minneapolis, Minn.: AGA Distribution Conference, May 7, 1974), p. 10.


WYOMING
WIND RIVER BASIN
GREEN RIVER BASIN
UTAH
CHEYENNE
SALT LAKE CITY
RULISON SITE
UINTA BASIN
DENVER
PICEANCE BASIN
PARADOX BASIN
NEW MEXICO
SAN JUAN BASIN
SANTA FE

STUDY AREA

8,425.5 below ground level and was completely contained. The well head of the emplacement well is at an elevation of 8,154 feet above mean sea level and is located in Garfield County, Colorado. The data produced by Project Rulison will be examined in this study to gain an economic comparison.

The question of radioactivity in natural gas from nuclear stimulation is a major concern of people not familiar with the question. The problems of safely handling and using the gas appear minor to those who have studied radioactivity produced with present techniques in nuclear stimulation. Future improvements in understanding and procedures can be expected to result in actual radiation exposure being substantially below the current assessments by the Atomic Energy Commission.

Contaminated ground water is not expected to migrate away from the chimney during gas production since gas inflow will tend to inhibit radionuclide migration. When movement occurs, it will be so slow as to allow decay to concentrations below the radiation protection guides within a fraction of a mile.[3]

The only radionuclides expected to be present in detectionable quantities in flared gas during production testing are tritium and krypton-85. The average airborne

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[3]Roy B. Evans, Public Health Evaluation, Project Rulison (Las Vegas, Nevada: Southwestern Radiological Health Laboratory, 1973), p. iii.

concentrations are expected to be three or more orders of magnitude below the concentration guides for the general population at the nearest populated locations which is about three miles from the Rulison well head.[4]

RETORTING OF OIL SHALE

The second method in question is that of retorting oil shale for the production of synthetic crude oil. Oil shale is a rock of sedimentary origin that contains virtually no oil but a solid organic material known as Kerogen which, upon destructive distillation, yields shale oil. The Synthetic Liquid Fuels Act, which was passed by Congress in 1944, directed the Bureau of Mines to build and operate experimental plants to produce liquid fuels from oil shale and other substances.

When oil shale is raised to a temperature of 500°C the organic hydrocarbon in the marlstone undergoes a thermal decomposition which forms oil and gas. The process is often referred to as "cracking." This partial distillation procedure leaves the remaining shale in a coke-like form that is the residue. One of the salient environmental considerations will be how to dispose of this material.

Mining of the shale will be a very important aspect of the problem. There is no doubt that in the future, strip mining will be considered, however at the present time a room

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[4] Evans, p. 2.

and pillar system is being used for the test. Low-cost mining is a basic requirement if a commercial oil-shale industry is to receive any attention. This concept was the first objective of the Bureau of Mines. A mine was developed at Anvil Points, Colorado in the base of a 500 foot, near-vertical cliff of oil shale 3,000 feet above the Colorado River and the valley floor in the area of the Piceance Basin. The current system employs the use of natural shale pillars, about 60 feet square and 60 feet apart supporting a roofstone. Using this material from the Mahogany member of the Mesa Verda formation the current yield is about 15 gallons per ton of shale. The output will be examined in depth at another point in this study, but it may be noted that three tons of material will generate about one barrel of synthetic crude oil. At present the Bureau of Mines is testing a gas-combustion retort which is a continuous, thermally efficient process capable of high throughput and high liquid product recovery. The first of these systems was installed at the Anvil Points site in July of 1953 and was put into operation to provide engineering and cost data. This information has been used to project the design of industry-scale plants. This prototype will process up to 300 tons of oil shale a day and will provide an adequate supply of oil for refining studies.

The two units that will be used in this study are:

a. The Oil-Shale Plant located nine miles west of Rifle, Colorado.

b. The ARCO Plant in the same area of Colorado.

METHOD OF EXAMINATION

An in-depth study of the economical and environmental aspects and problems are formulated so that within the test area of the Piceance Basin a positive decision could be made with regard to the application of fiscal assets to one method or the other. It will be necessary to draw some comparison to energy output of the two fuels so that a supported assumption can be used for the comparison of a given quantity of natural gas to a given quantity of synthetic crude oil. This will require that a common basis be generated at some base level of energy output.

A means of comparison will be the cost of repairing the environmental damage of one method against the cost of repairing the environmental damage by the other. This will require that some assumptions be accepted. For the purpose of the study these assumptions will be grounded upon data which is based on other like projects. The repair of strip mining in soil similar to the Green River shale will provide an excellent point for the study of damage in this area. This information will be applied to raw data obtained from test project being carried on at this time by the American Oil Company at Rifle, Colorado. This company is demonstrating how and at what cost an arid or semi-arid area like Western Colorado can be completely reclaimed after strip-mining so that the balance of the present eco-system will receive minimum or negligible damage. A consideration in this regard is that the strip-mined area in this region could be improved as a result of mining. This possibility is due to a release of the minerals from underground which may positively affect the vegetation on the surface. The second variable in this comparison will be the major ecological problem generated by the production of tritiated water and air as a result of the underground detonation of the nuclear device in the stimulation of natural gas.

It has been noted there are pointed tradeoffs to be considered when comparing the two energy resources. The common ground of economy and ecology are the most likely and most valid areas in which to juxtapose nuclear stimulation and retorting oil shale. The methods of applying fixed energy producing values on equated amounts of each of these is only superficial, but it provides the base method from which the economy end of the spectrum may be viewed. It may be readily seen that these two areas in question overlap considerably. For example, the costs of repair of ecological damage may become a very large factor when viewing a given source of fuel with regard to its economical assets.

The material used to examine both systems in question has been gained as a result of research into two prior studies, in addition to this, information was obtained from unpublished sources. The ultimate source stems from work in the University of Oklahoma Geology Department.

The subject is treated by considering the advantages and disadvantages of both means of achieving a viable source of energy at a marketable price. Both sources have extreme ecological drawbacks, on the one hand there is the question of radioactivity by the nuclear stimulation of natural gas fields. This question will be examined and compared to the destruction of the Western Colorado land surface by mining and retorting oil shale. But again, interacting with the question of ecology is the economical one. With the vast amount of research and technological development needed to be financed it is very possible that only one system should be supported, or at the very least some priority should be established.

Techniques differ from one another in the scope of their application, some being appropriate only to very narrowly defined contexts; others playing a part in a wide variety of inquiries. This examination will be sufficiently general to be common to both methods. The aim will be to describe and analyze both methods. As a given system is described it may be observed in the light of both its economical and ecological aspects. Some questions will be treated independently where possible. Secondly, the two methods and the two study criteria will be analyzed on common ground. Nature provided that common ground in the Piceance Basin.

The basic means of this examination will be empirical and although very little actual development has taken place, and none of it on the full scale level, considerable research has gone into both means of obtaining energy.

It is this experience that has been obtained over the last few years of research in the two methods in question that must be objectively viewed and used to place value priorities on the methods.

In the case of nuclear stimulation a model was constructed so as to allow the comparison of live swine to humans. This model studied the results and reactions of the swine living and eating in an environment similar to that of man. The study was carried on under the supervision of the Las Vegas Environmental Lab, and the idea was generated by the University of Oklahoma. This test proved extremely useful, in that most data surrounding the stimulation method has been theoretical. While the El Paso Natural Gas Company had, in fact, stimulated some low permeability gas-bearing sandstone formations there has always been (and will be in future) some reservations about the use of tritiated radioactive gas. It is this type of model that may dispel some of those natural misgivings.

Chapter I introduced the problem of selecting one of two methods for obtaining energy fuel. Chapter II will review the published and unpublished literature with regard to the two methods in question.

CHAPTER II

REVIEW OF RELATED LITERATURE

This chapter will generally be organized into a review of material that has been published in the two areas that are being studied. This will be limited to the comparison of economy and ecology of the methods in question. Oil Shale will be reviewed with regard to published material, this investigation will be followed by an examination of the location of the unpublished material on the subject.

The question of stimulation of natural gas fields by nuclear detonation will be discussed with regard to the published material and this will be followed by unpublished material. The location of unpublished material in both cases will be pointed out.

The first section in this chapter will discuss literature related to oil shale research.

OIL SHALE RESEARCH LITERATURE

An excellent study in the area of retorting oil shale was carried on at the Colorado School of Mines by T. A. Sladek. This study entitled A Determination of the Composition and Temperature Dependencies of Thermal Conductivity Factors for Green River Oil Shale was written in 1970. It was financially supported by the Sinclair Foundation, the National Science

Foundation and the Atlantic-Richfield Company. The temperature characteristics of Green River Oil Shale are of considerable economic significance. Sladek points out that to obtain a usable hydrocarbon from the material, either the entire formation must be heated IN SITU through fracturing and injection of a high temperature fluid, or the shale must be mined and retorted on the surface. In either case the rate at which the shale can be heated to the pyrolysis temperature range is most important when considering the economics of the method.

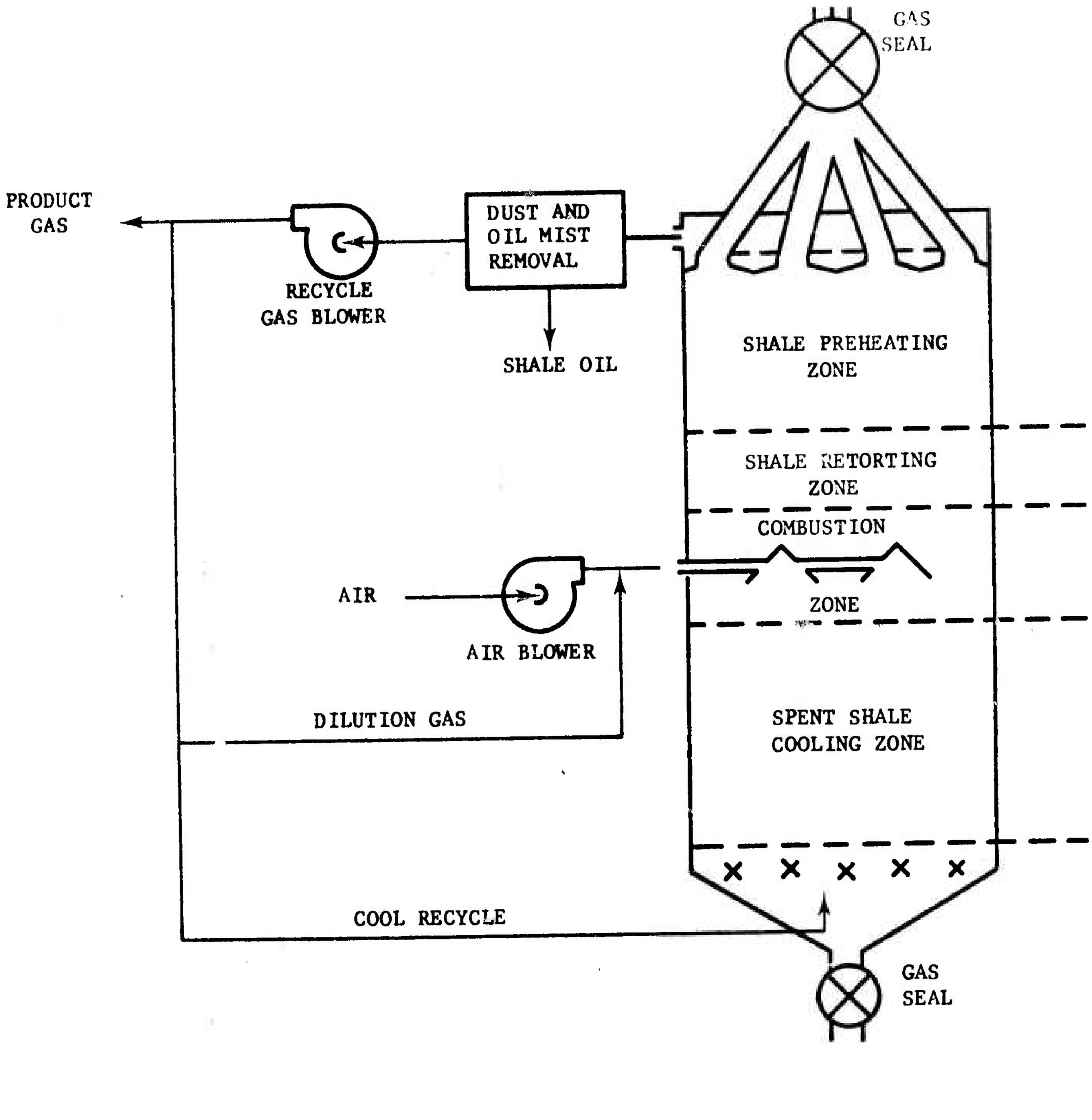
A second study done at Colorado School of Mines was completed in 1974 by H. Bonilla, Correlation of Hydrocarbons in Gilsonite, Tar Sand Red Wash Crude Oil and Oil Shale from the Green River Formation. This study compares and correlates the hydrocarbons, or derived hydrocarbons in the area of study. This work also shows the availability and reserve of hydrocarbons in producing material in the area of Western Colorado.

A series of excellent studies have been carried on by R. J. Cameron in the various areas of interest dealing with oil-shale technologies. Cameron is the chairman of Cameron Engineers and concludes that oil-shale is a viable option with regard to the energy fuel problem. Cameron's research and speeches on the vast energy potential of shale deposits has helped pave the way to commercial development. One of the papers by this author deals with the question of "Water Limitations." This paper concludes that water use will not limit the size of the oil-shale industry. Cameron contends that "If water does become a limiting factor then industry has the capability to modify its technology so that excessive amounts of water will not be utilized." Cameron has also studied the problem of salinity, and concludes that the down-stream irrigation projects are the major contributor to the Colorado River salinity, not the oil-shale industry. (In another study conducted by Cameron the use of spent shale is considered.) Cameron shows how this material can be re-vegetated. The study shows how the primary overburden could be used to provide a growth condition and also demonstrates how silt could be dredged out of the Gunison and Colorado Rivers to provide a top cover for the spent shale.

R. T. Stone conducted a study in the area of a Proto-type Oil Shale Leasing Program. Stone is the Oil Shale Coordinator for the Department of the Interior, and the Environmental Impact Statement dealing with the Oil Shale program was published by Stone's office in 1972. The statement supported the possible use of shale as a source of energy fuel.

A series of excellent studies have been conducted in the area of what kind of retort to use in the process of removing the hydrocarbons from the shale. The first of the research retorts used in reducing the petroleum from oil-shale was designed in the 1920s and is referred to as the "NTU" named for the Nevada-Texas-Utah Company. Some NTU's are still in use today. They make use of the fact that rich oil shale will burn, thereby providing heat to cook or retort the remainder in a fixed chamber. The main drawback to the NTU is that it operates on a highly inefficient "batch" system. It is loaded, fired and dumped, and this cyclic process proves slow and costly. The U.S. Bureau of Mines opened the first continuous flow oil-shale development project at Anvil Points near Rifle, Colorado in 1944. It tested one of the earliest gas-combustion retorts. The retort is a vertical vessel through which crushed shale is pushed down by gravity and hot, recycled gases move up from the bottom. The combustion of the gases and some residual carbon in the spent shale results in rising hot gases that heat the raw shale to retorting temperature. Oil vapors and gas rise to the top of the retort where they are removed. In the tests by the Bureau of Mines it was determined that oil from this retort has a low viscosity and this must be up-graded before it can be piped to refineries.

A second type of retort was designed by the Union Oil Company in 1956 and was developed and tested at the company's Parachute Creek Mine in Western Colorado. This retort is often referred to as an inverted gas-combustion retort or rock pump. The gases enter at the top of the retort and flow downward while the raw shale is moved upward by a rock pump. As in the Bureau of Mines retort, the heat is supplied by the combustion of the carbon on the spent shale. The shale oil condenses on the cool, incoming shale and flows over it to an outlet at the bottom of the retort. At the completion of the test Union abandoned the plant, forwarded

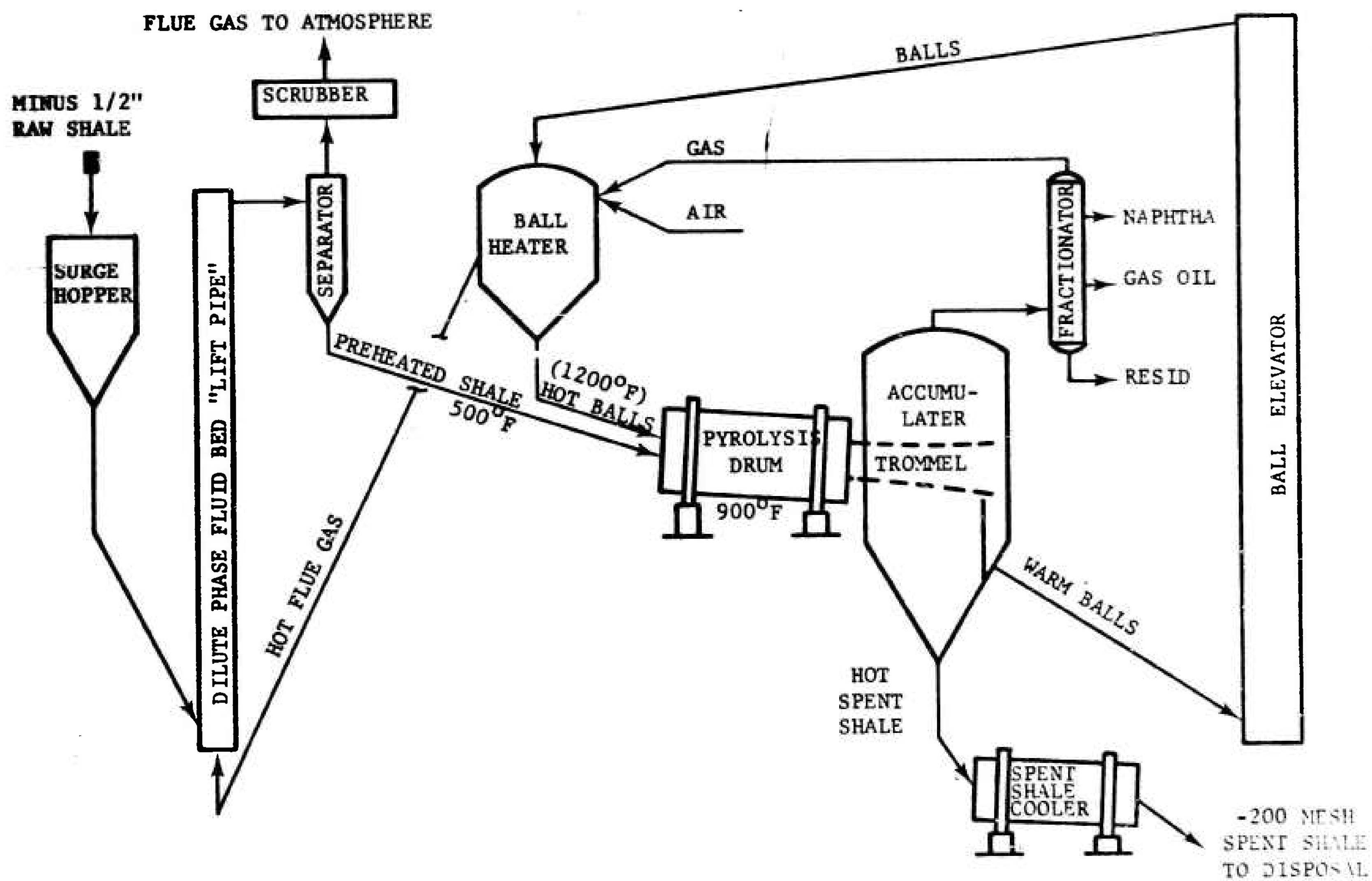

GAS
SEAL
PRODUCT
GAS
DUST AND
OIL MIST
REMOVAL
RECYCLE
GAS BLOWER
SHALE OIL
SHALE PREHEATING
ZONE
SHALE RETORTING
ZONE
COMBUSTION
ZONE
AIR
AIR BLOWER
DILUTION GAS
SPENT SHALE
COOLING ZONE
COOL RECYCLE
GAS
SEAL

NTU RETORT

a report to the Bureau of Mines stating that when economic conditions warranted this plant could produce 50,000 barrels-per-day.

A third method of retorting oil shale was developed by a Denver-based Corporation headed by J. B. Jones. This corporation is supported by 17 major oil companies and is chartered under the name Paraho. They are testing their retort at the Bureau of Mines facility at Anvil Points. This retort has the widely accepted advantages of a continuous, vertically descending, bed of granular material. The inability to maintain continuous movement has been a major problem with previous gas-combustion test programs. The Paraho retort can be used by any of the member companies.

The Oil Shale Company (TOSCO) studied a completely different system of retorting. Unlike the gas-combustion retorts, the TOSCO II is a rotary type retort that uses hot ceramic balls to heat the shale in the retorting process. The raw shale is crushed to a size of $\frac{1}{2}$ inch or smaller, the smallest size used in any retort, and then preheated before being fed into the retort with the ceramic balls, the balls transfer heat to the shale, thus eliminating the need for internal combustion, and the oil vapors and gas rise to the top of the retort where they are removed. TOSCO (a consortium of oil companies with Atlantic Richfield as the operator) contend this retort will be the first in commercial use.



TOSCO II RETORT

A study conducted by Sunshine Oil Company dealt with a process known as In-Situ. This study contends that not all oil shale retorting need be done above ground. For years environmentalists had tried to turn the thinking of the researchers in the direction of processing the shale underground. This in-situ (in place) process is achieved by heating the shale underground which eliminates both the mining step and the large processing step. Generally, the Sunshine in-situ development would involve the drilling of several wells, some to introduce heat into the underground shale deposit and some to draw up the oil and gas produced by retorting. Although the research included two major attempts, the only one of any value appeared to be the introduction of hot natural gases or superheated steam. About 10,000 barrels of crude oil were produced during the test but the process was considered economically unsound. One problem in the development of the in-situ process is permeability, Sunshine noted that lines of communication must be opened in solid rock to allow the passage of gases and liquids. The final report stated that the in-situ process deserved an extensive test but a time frame of about 10 years was needed. The Occidental Petroleum Company questioned the Sunshine report and stated that they could have an in-situ process ready for commercial use within 3 to 5 years.

The Occidental process is a combination of in-situ and retorting. In 1972 a series of reports by Occidental contended that they were producing 30 to 40 barrels a day. Occidental demonstrated that their process does not require drilling wells or using explosives for permeability, a large room is dug in the shale deposit, then explosives are detonated in the room to fill it with rubble. From the surface above the mine, air and fuel are forced into the room where the explosives are detonated. This brings the shale to retorting temperature. The shale oil then seeps through the rubble and gathers in a sump where it can be pumped from the mine. This semi-in-situ process avoids many of the pit falls of the problems to environment generated by the mining/retorting methods accomplished on the surface.

Some studies conducted in areas other than the basic production techniques deal with a wide range of related subjects. A regional development and land use study conducted for the Colorado West Regional Planning Commission concluded that Colorado may have little choice in the matter of oil shale development. As a result of the critical need for energy the shale may be used as almost a matter of national survival.

The Oil Shale Regional Planning Commission was organized in July of 1971 by the commissioners of Rio Blanco, Garfield and Mesa counties, this commission completed a series of studies and disbanded on 1 May 1974. At the final meeting of the commission, the members outlined 15 conclusions that were reached during the three years that it had remained in existence. The studies were jointly funded by the Interior Department of the State of Colorado and by the collective oil shale industries. The research team was comprised of the University of Denver Research Institute and Bickert, Browne, Coddington and Associates of Denver. The Commission generally supported the building of some type of oil-shale industry but within strict limits:

a. Control community planning.

b. Control on the growth of existing towns.

c. Encouragement of the use of existing facilities.

d. Requirement of the use of public type transportation.

e. No unrestricted use of the flood plane.

f. Continued public meetings and public awareness programs.

g. Rigid and high standards on mobile homes.

h. Encouragement of the use of undeveloped land as opposed to irrigated meadows.

In summary it may be noted that much study has gone into the oil-shale industry as a possibility of solving a portion of the nation's energy fuel dilemma. In the next section the literature with regard to nuclear stimulation of natural gas fields will be reviewed.

LITERATURE RELATED TO NUCLEAR STIMULATION OF NATURAL GAS

Both government, private industry and independent research organizations have contributed to the knowledge and application of nuclear explosives to the stimulation of natural gas fields.

The Southwestern Radiological Health Laboratory conducted The Public Health Evaluation of Project Rulison. The funds for this test came from the U.S. Department of Health, Education and Welfare, Public Health Service, Environmental Health Service, Environmental Control Administration and the Bureau of Radiological Health. Not only did these organizations commit the funds but in most cases reviewed the tests and assisted in the operation of the work. The Evaluation was initiated in July of 1969, at the Southwestern Radiological Health Laboratory in Las Vegas and this research is to be an on-going program until the parent agencies determine there no longer is a valid need for the tests. The results of the preliminary tests are published by R. B. Evans and D. E. Bernhardt and the latest production testing was up-dated and printed in February 1973. The analysis presented in the paper indicates that the Project Rulison operation can be conducted well within the radiological guidelines outlined by the Atomic Energy Commission. In addition, the environmental surveillance program proposed by Southwestern should be capable of detecting levels of environmental radioactivity well below the AEG guidelines.

An Analysis of Gas Stimulation Using Nuclear Explosives was published by B. Rubin, L. Schwartz and D. Montan in June of 1973. Their study was carried on under the funding of the Atomic Energy Commission. The study was conducted at the Lawrence Livermore Laboratory in Livermore, California. The study is centered around the Gasbuggy and the Rulison Projects and it outlines the need for low cost energy fuel. The research demonstrates that it is possible to fill this gap by the use of nuclear stimulation of natural gas fields of low permeability.

Miles Reynolds of the Austral Oil Company in Houston, Texas published Project Rulison-Summary of Results and Analysis in December 1971. It shows that the technical feasibility of stimulating the Mesaverde Formation in the Rulison Field is logical. This study provided the data on continuous chemical and radiochemical flow, explosive yield calculations and a surveillance of public health and safety assurances. Unpublished material for Austral Oil Company was generated by the Oak Ridge National Laboratory. These assess the potential radiation exposure that might result from the distribution and use of Rulison gas under various marketing conditions. These studies confirm that exposures from the use of Rulison gas are only a small fraction of the total average annual exposure to man from all sources (100-125 MREM.)

A. A. Moghissi, et al., conducted a study on The Background Information for the Development of a Radiation Standard for Tritium in Nuclear Stimulated Natural Gas. This research was carried on under the aegis of the Environmental Protection Agency and Western Environmental Research Laboratory, Las Vegas, Nevada. The study develops a radiation standard for tritium in natural gas by showing the relationship between the tritium concentration in the gas and the annual dose received by the people resulting from the usage of the gas. The study points out the uncertainties associated with the input parameters. The study also outlines results of experiments in the transfer of tritium from natural gas into food cooked under realistic conditions, also the contribution of heating with tritiated gas in an area with limited ventilation was considered.

Data on dose assessment of Rulison gas that has not been published was conducted in 1973 by D. E. Bernhardt who is the Project Leader of the Plowshare Dose Assessment Team. The information gained will be used in this study to demonstrate and support other material in the overall concentration of tritium in Rulison gas.

A paper entitled Project Rulison issued by the Department of the Interior was published on the First of May 1969. This research explains the need and reasons for the Rulison experiments and gives the objectives that are to be obtained in the project:

a. Comparison of gas production rates before and after detonation.

b. Measurement of the amount and kinds of radioactivity that are recovered.

c. Assessment of ground motion effects to establish yield limits.

Gas Analysis Results for Project Rulison Calibration Flaring Samples is the title of a study published by C. F. Smith of the Lawrence Radiation Laboratory at Livermore, California. The results of chemical and radiochemical analyses are presented and discussed. Seven samples were used from the flaring of produced gas on 1 August through 4 October 1970. The most significant radionuclide observed was tritium, present in the gas at 176 picocuries per standard milliliter. Methane contain 82 percent of the gaseous tritium, hydrogen 11 percent, ethane 6 percent and the fractional remainder is contained in the heavier hydrocarbons.

The significantly lower concentration of CO_2 present in the earliest samples taken is explained in the study in terms of a dilution effect resulting from the long-term release of inactive CO_2 in the chimney. Although this study is excellent in many aspects the radial gradient in the CO_2 concentration negates the comparison of earlier and later observations.

W. E. Nork and P. R. Fenske completed a study on Radioactivity in Water. This study generated information on the Rulison Project. This work points out that the ground water in the Mesaverda Formation is quite possibly immobile. If this is the case all radioact vity will reside essentially in place unless artifically removed, and will decay eventually to concentrations below conventionally detectable levels. For the source term concentrations given in the Rulison detonation, six to eight half-lives decay time or about 75 to 100 years are required to reach tritium levels that will not be conventionally detectable and about 16 to 20 half-lives decay time, or about 450 to 550 years to reach strontium-90 non-conventionally detectable levels.

Some unpublished data of the post-event bioenvironment safety aspects of Project Rulison are available from the Battelle Memorial Institute. This material was gathered during the year after the Rulison Shot.

In 1971, F. Holzer and D. O. Emerson prepared a paper on the Possible Effects of Nuclear Detonations on Overlying Oil Shale and Mineral Deposits. This unpublished report demonstrates the potential damage to mines as well as to surface installations to be predicted in relations to ground motion. Although this involves some uncertainty for a given area, it was pointed out in the examination that the information from Rulison and "Gasbuggy" will give a large measure of confidence to predictions in the future. The paper examined a number of potentially harmful effects of proposed nuclear detonations in the Fort Union-Mesaverda Formation in a portion of the Piceance Basin on the overlying oil shale and mineral deposits. The salient points were:

--All detonations must be 200 feet or more below any of the oil, or mineral containing strata. Since fracturing is not expected to extend for more than 400 feet from the explosives, no fracturing is expected into the formation containing oil shale or other minerals.

--The depth of surface spall from a 100 feet explosion at a depth of 6000 feet as expected to be 170 feet.

--No surface separation will occur as a result of tension waves reflected from discontinuities between oil-rich and oil-lean layers as long as the parameters are maintained as prescribed by the Atomic Energy Commission.

In summary, Chapter II reviewed the literature related to the two methods that are being examined. In the next chapter the question of the ecologic considerations will be investigated.

CHAPTER III

ECOLOGIC CONSIDERATIONS

This chapter considers the impact of retorting oil shale with regard to damage to the environment. A second section of the chapter will view the problem of nuclear stimulation in the light of its ecologic drawbacks. The physical area that will be studied is the Piceance Basin of Western Colorado and its environs, which include the Book Cliffs. This portion of Colorado will be discussed at some length in Appendix A to this study entitled Geology.

This uplifted area of Western Colorado near the town of Rifle is a semi-arid region of ridges and valleys with steep cliffs of rock. The central oil shale producing area is the Book Cliffs to the east of the Piceance Basin. Here the population is only three persons per square mile.

OIL SHALE

This section of the study will consider the problem of oil shale operations of the environment in the examination area. It will be subdivided into the problems of: Revegetation, Air, Water, and Wildlife.

Revegetation

Wilderness animals are found in this area and the most common is the largest herd of mule deer in the world.[1] The mountain sage vegetation provides winter browse for this herd.

The vegetation impact associated with construction and operation of surface facilities, mining activities, overburden and processed shale disposal and development of utility corridors will vary considerably from tract-to-tract depending upon the development options considered. The physical characteristics of the individual tracts will also determine certain impacts.

Existing vegetation will be essentially eliminated from all land surface allocated to surface facilities, overburden storage, stockpiling, borrow areas and waste disposal associated with underground mines. Operations will also destroy the vegetation on small areas around the mine openings.

Utility corridor development will completely remove existing vegetation from portions of the corridor and much of the balance of the corridor areas will experience substantial trampling impact from mechanical activities. The vegetation of surface disturbed lands can be enhanced by several induced rehabilitation factors. Natural equilibrium may be attained by:

--Replacement of productive soil material and addition of fertilizer.

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[1]Evie Disante, Benchmark, Oil Shale Now (Denver, Colo.: Mountain Empire Publishing Co., 1974), p. 40.

--Formation of small basins or terraces for retention of natural runoff water.

--Planting of seed or seedlings of native species.

--Addition of irrigation water when initially planting.

--Protection from access by herbivores.

--Management after planting.

No rehabilitation of surface disturbed land can succeed without a proper medium of plant growth. Returning the productive soil to the surface after mining is critically important to revegetation, and in most areas revegetation may be achieved.

Revegetation is called for on areas when backfilling and surface placement of overburden has progressed to a point where workable areas are available for rehabilitation and when construction is complete in utility corridors and operations have progressed through areas that have been developed.

Revegetation for an area that has been strip-mined will be costly. The Colorado Open Space Council contends that the spent shale resulting from the TOSCO II process cannot be revegetated, however, ARCO environmentalists disagree. Their argument is based on a test that demonstrates the fact that spent shale is similar, if not identical to much of the soil in the oil-shale region. The natural forces of erosion and weathering of shale cliffs creates a soil like spent shale. Test plots were studied to determine if, in fact, spent shale can sustain vegetation.

Plot #1 at Colony, Colorado. This plot of 100 square feet was abandoned in 1970 after being seeded in 1967. In 1972 all three wheat grasses that were seeded were still growing, some had roots 3.5 feet deep and the grass was five feet tall. They are (in 1975) still growing and reproducing without water or fertilizer. Some new grasses and weeds have invaded the plot.

Plot #2 at Colony, Colorado. This plot of 100 square feet was planted in 1971 and has been watered each year since. It has 10 grass species common to the Western Colorado area, two native shrubs and one evergreen and all are living at this time (1975).

It has been determined that seeds for these grasses will have to be harvested in fairly large quantities due to the very low germination capability of native seeds. The impact of this action on the surrounding eco-system has yet to be determined. At this time the Soil Conservation Service is working to introduce native seeds to commercial seed producers. The cost to revegetate an area of one acre using 1975 dollars has been determined using the following data:

Equipment		$ 3,000
Water		1,500
Seeds		1,250
Manpower		2,500
Fertilizer		1,500
	TOTAL:	$ 9,750

This information was researched under the control of the University of Oklahoma Geology Department in 1971 and was updated prior to this study in 1975.

An average surface mine may cover a zone of about 4,000 acres, but processed waste can be filled into an area of one-fifth the mined zone which will be about 800 acres. Using these data it may readily be seen that the revegetation process may cost almost eight million dollars for one mine. If a mine is to generate one million barrels a day of synthetic crude oil the spent shale would cover one square mile every year.

To economize in this area it has been proposed that the miners be allowed to "layer" the spent shale over a narrow area which in some cases might be as high as 600 feet. This terracing method might not reach the final layer until 10-20 years from the processing date. This fact could offset the problem of revegetation; however, the feeling of the citizens in the area toward ecology as revealed in various articles in the Grand Junction Daily Sentinel this will not be the case.

Air

The question of whether or not environmental standards can be met by the oil-shale industry will be addressed in this portion of the study. This area of Colorado with its geographic pattern of hills and gullies has a dangerous trapping effect on emissions. The problem of inversions must be considered if a retorting plant is not to exceed the standard of the number of particulates per volume of air in the environs of the plant. A comparison to Denver was drawn which showed that air inversions could be kept within exceptable limits if the plateaus were used rather than the likely valley plants. On the plateaus in the Denver area emissions were dispersed to acceptable standards only on plants on or near plateaus. To date, no retorting plant operating over an extended period of time has failed to exceed the standards at some time during operation. The particulates in the air are the result of the crushing operation and the retorting process.

The potential impact of emissions of sulfur dioxide, particulate matter, nitrogen dioxide, hydrocarbons and carbon monoxide will need to be completely evaluated before air quality standards can be completely assessed. In addition point source emissions from the oil shale processing plants must be evaluated with regard to fugitive dust from the excavation, crushing, handling, and storage of the oil shale.

According to a study carried on by the U.S. Department of the Interior under the title Project Independence, air quality standards represent important constraints and must be resolved before large scale oil shale operations can get underway. This government study also points out it may be impossible to obtain the needed standards given the current state-of-the-art.

The Environmental Protection Agency has been examining the air quality question and an answer to the non-degradation of air quality will be necessary before plans for large scale operations can proceed.

Under the current Colorado State standards large scale development of oil shale may not be possible.

Water

Due to the lack of water in this area (7" to 9" a year) the question of water cost in dollars to the environment is not the only one. Whereas, water in some instances may be assigned an actual dollar value as in revegetation, in other cases, because of its scarcity and its location it can be seen that no value can be placed on it at all. In addition, all streams in the area flow downward to the all-important Colorado River. Any pollution added to the river water from the Piceance Basin would affect water uses in downstream states. The use of water is a very necessary input to the retorting of oil-shale and of the compacting of spent shale. When fresh water comes in contact with shale, open mines or spent shale it leaches out certain minerals, among these is halite. Halite increases the salinity of the river. The average annual salinity concentration of the Colorado River at Imperial Dam is about 800 mg/L. Salinity refers to the concentration of dissolved salt solids in water and is reported in milligrams per liter. The problem is that the

Colorado River salinity is on the rise and is expected to reach about 1,300 Mg/L by the year 2000 according to a study conducted by the Water Resources Council in 1972.

Colorado Public Law 93-320 entitled Colorado River Basin Salinity Control Act was signed into law in June 1974. Title II of the Act authorized the Secretary of the Interior of the State of Colorado to construct, operate and maintain four units to achieve water quality improvement.

Tests noting the exposure of halite to fresh water which was to be introduced to the Colorado River and corrected to a factor of a million-barrel per-day plant point to a sharp increase in salinity. By examining the salinity at Imperial Dam and applying the same upstream factor, a probable rise of 1.5 to 2 percent is seen. This assumes that no improvement will be made to the process of TOSCO II and that strip and open pit mining will be conducted, followed by revegetation. A desaltation plant would add to the expense of the already expensive process, but that idea is the only viable option at this time. A planning figure of $.43 per 100 gallon may be used as an input although this varies with the system of desaltation that is selected.

The oil-shale industry also faces potential salinity problems that could come from beneath the ground. Vast quantities of underground waters, as much as 25 million acre-feet, lie under the Piceance Creek Basin. The water at the top of these aquifers is generally fresh (e.g., the Windgate

Sandstone strata). But, as one studies the lower strata of these aquifers (and immediately above the aquiclude) the salt content is extremely high. The first of the Colorado public land oil-shale tracts rests immediately over one of the high salt aquifers. The location of the aquifers was fixed by electric log readings carried on in 1970 by a team of geologists from the University of Oklahoma. If an oil-shale mine opens one of these lower aquifers the hydrostatic pressure of the aquifer will drive a vast amount of salt water into the mine, possibly more than can be pumped out. Although in any case when it is pumped there is still the problem of what is to be done with it. The Director of the Colorado Geological Survey concludes that unless the salinity problem is resolved the chance of a full scale oil-shale operation is almost out of the question.

Wildlife

The impact on fish and wildlife due to prototype development is expected to cause local rather than regional changes. However, if the industry matures the magnitude of the impacts will increase. The following information on oil-shale development will provide an overview of some of the severe problems of oil-shale production as it affects the eco-system in the Piceance.

The scope of the 1-million-barrel-per-day industry visualized by about 1985 includes: 108,000 new inhabitants, including associated urban development; an expanded road, pipeline, and power transmission system; and water consumption of 124,000 to 194,000 acre-feet per year (depending on various contingencies, consumption could be as little as 76,000 or as high as 295,000 acre-feet per year).[2]

The cumulative regional effects on fish and wildlife will stem from the following causes: reduction in water quality, including siltation, various effluents, increased salinity and possible accidental spills of oil and other toxic substances; reduction in water supply (drying of springs, seeps, and headwater streams through alluvial water-table drawdown); increased urbanization and associated increases in road mileage, traffic, powerlines, solid and liquid wastes, hunting, fishing, camping, and off-road recreational vehicle use; increased noise from construction, equipment operation, and blasting; vegetation removal on up to 80,000 acres; and the filling of 15 to 50 canyons with spent shale (depending on disposal methods). These aspects are examined for cumulative impacts on the following broad classes: Threatened species; big game; raptors, small game and other small animals; and fish.[3]

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[2] U.S. Department of Interior, Project Independence, Oil Shale: Prospects and Constraints (Washington: U.S. Government Printing Office, 1974), p. 229.

[3] Project Independence, p. 230.

Those species dependent on limited habitat or remoteness from harassment will suffer most. Filling of canyons with spent shale will destroy habitat for falcons and the spotted bat. If colonies of burrowing rodents are destroyed, any black-footed ferrets in the area will be displaced and probably destroyed. Reduced water quality or impoundments in waters inhabited by the Colorado squawfish, Colorado River cutthroat trout, bony-tail chub, and humpbacked sucker will result in further population declines for these species. Habitat subject to noise and disturbance will be lost to peregrine and prairie falcons.

Mule deer (estimated over recent years to be approximately 30 to 60,000 head in the Piceance Basin) will be reduced a minimum of 10 percent by disturbance and by displacement and competition as their habitat is destroyed. The extent of reduction will depend on whether disturbed areas are revegetated with winter browse species. Where antelope frequent areas affected by development, a similar reduction is expected. Animals such as the elk, moose, bear, and mountain lion, which are less tolerant of human activity, will be denied a greater amount of habitat because of avoidance of noise and human activity. This will lead to the virtual disappearance of such wilderness species from the region directly or indirectly affected by oil-shale development. Hunting pressure will increase and harvest of game species will probably have to be reduced by more restrictive hunting regulations.

Loss of habitat, reduced water supply, increased hunting pressure, and casual shooting will reduce populations of such animals as hawks, eagles, bobcat, raccoon, and ring-tail cat and force displacement and increased competition for remaining food and water. The sage grouse, a scarce but highly prized game bird, will probably almost disappear from the oil shale regions of Colorado. Reductions in small prey species such as rodents and rabbits will also cause reductions in populations of predators.

Drying of streams, degrading of water quality, and/or water diversion will cause reductions in, or change in desirability of, fish populations. Species especially vulnerable to changes in physical conditions or water qaulity (temperature, pH, toxic substances) include trout and whitefish as well as the threatened species mentioned above. Although fishing may be retained by stocking and other management steps, there will be a long-term decline in high-quality fishing, which depends on natural-spawned fish growing to good size in a relatively undisturbed environment.[4]

In summary the ecologic considerations of an oil-shale operation are many and varied. In the following section the problem of the ecologic considerations of nuclear stimulation will be examined.

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[4]Project Independence, p. 232.

NUCLEAR STIMULATION

This section will discuss nuclear stimulation of natural gas fields in the light of what damage it might do to the environment.

The application of nuclear explosives to stimulate natural gas production from low yield gas reservoirs has been demonstrated to be a feasible technology. Both the Gasbuggy and Rulison Projects have shown this feasibility, but regardless of the economic implications of the application of this technology, certain environmental and public health questions must be satisfactorily answered before nuclear stimulation of natural gas can be applied routinely. In the cavity which is formed as a result of nuclear explosives a large number of radionuclides are produced which, if released into the surrounding environment, would present a substantial environmental and public health hazard. As has been pointed out earlier the majority of these radionuclides are short-lived and would decay substantially if there is an appropriate time delay before exploitation of the gas well. Testing of the Rulison well was initiated in October of 1970 and after four intermittent flow periods was concluded in April 1971. The first flows were made at rates varying from 2 to 16 million standard cubic feet of gas per day (MMSCFD) These tests spanned a three day period of time and were made for the purpose of calibrating the U.S. Public Health Service offsite surveillance program.[5] Tracking and measurement of the gaseous radioactive effluents from flaring were carefully done to confirm that the production testing would be carried out with the assurance that the health and safety of the population nearby would be protected.

Following the calibration flow period, three production flow tests were made for the purpose of determining the post-shot production characteristics of the Mesa Verde formation in the interval stimulated by the nuclear explosives.

A total of 455 MMSCF of gas, including diluents which were present, was produced from the Rulison Project in 108 days of flow testing. This volume is equivalent to about 10 years of production from a conventionally stimulated well in the Rulison Field. The 455 MMSCF of gas was saturated with water vapor at separator and was diluted with carbon dioxide and hydrogen. All of the gas samples taken were analyzed for certain radioactive components. The concentrations of the gaseous isotopes, tritium and krypton-85 declined in an expected manner and were only about two percent of their initial concentrations at the conclusion of the flow testing. Only 2,824 Ci of tritium were produced from the well during the flow tests.[6] This is only about 28 percent of the expected 10,000 Ci predicted to result from the nuclear

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[5]Roy B. Evans, Public Health Evaluation, Project Rulison (Las Vegas, Nevada: Southwestern Radiological Health Laboratory, 1973), p. 8.

[6]Evans, p. 10.

explosion.[7] Essentially all of the gaseous tritium was removed from the cavity by the end of the testing. An accounting of all the tritium created could not be made, however, because of the large quantity of tritiated water still being recovered at the conclusion of the testing and an unknown volume of water remaining in the cavity.[8]

As has been explained the tritium is a by-product of the result of a number of reactions subsequent to the explosion of the nuclear device it is introduced into molecules of methane and the other high hydrocarbons which constitute the natural gas. Tritiated water present in the cavity is easily removable from the gas prior to its transfer to and use by consumers. Using conventional means and the current state-of-the-art it has been found that the separation of tritiated hydrocarbons and non-radioactive hydrocarbons is not commercially feasible. The most logical approach at this time is to flare a few cavity volumes of gas until the level of tritium becomes acceptable. This level is referred to as Maximum Permissible Concentration.

The results of various experiments carried out to estimate the radiation dose which may be received by people as a result of the domestic consumption of tritiated natural gas will serve to demonstrate the perimeters of the problem. These experiments were carried out by the University of Oklahoma in conjunction with the Western Environment Research

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[7] Evans, p. 9.

[8] Evans, p. 14.

Laboratory at Las Vegas and they represent significant findings with regard to the use of tritiated gas. Various foods were cooked in both an oven and on top burners of a standard domestic gas range. The amounts of tritium in cooked food was measured, a variety of foods were used so that cooking time would vary. Of the total amount of tritium in gas used to cook a food item, the percent found in the food was remarkably consistent for both oven and stove-top cooking. The average transfer was 0.4 percent and no item investigated exceeded 1.1 percent.

In the second part of this investigation four minature swine of about 70 kg each were housed in a trailer. The trailer was heated by a gas space heater with all combustion products vented directly into the trailer, again this gas was tritiated methane. The trailer ventilation was adjusted to give a carbon dioxide concentration in the trailer of 0.5 percent, this is the Threshold Limit Value for carbon dioxide. A fundamental assumption is that levels of carbon dioxide as low as three percent in the air cause adverse health effects and that 10 percent carbon dioxide concentration leads to the loss of consciousness within a short period of time. Therefore, air changes in the trailer were applied to maintain the carbon dioxide level at 0.5 percent. This also equated to a normal well-built home with windows and door shut. This level of carbon dioxide governed the intake of tritium by fixing the intake of carbon dioxide. The chemical reaction for the combustion of methane is:

$$CH_4 + 2O_2 \rightarrow 2H_2O + CO_2$$

It was also assumed that all inhaled tritium was absorbed and none exhaled. When tritium concentrations normalized to the body of an average man they resolved to 15 nCi/L.

The experimental conditions were conservative in that it is inconceivable that a large segment of the population would be exposed continuously to carbon dioxide levels of 0.5 percent.

The extension of the findings to the entire year would assume a year around environment of gas consumption which is also conservative. On a yearly basis the associated radiation dose would be 1.5 MRAD/year which is well within AEC limits. No negative effects were noted in the swine or in the following two generations.

The radiochemical composition of gas produced by nuclear stimulation is relatively simple. The device explosion produces tritium, which is radioactive hydrogen, and krypton-85, as well as other radioactive fission products. The two isotopes mentioned have the greatest radiological significance, the remainder either being trapped permanently underground, decaying rapidly to insignificant levels or being produced in small quantities.[9]

Of these two isotopes, tritium and krypton-85, tritium

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[9]E. W. Chew, et al., Chemical Considerations in Nuclear Stimulation of Gas Reservoirs, (Minneapolis, Minn.: AGA Distribution Conference, May 7, 1974), p. 6.

is a much greater to radiological health importance. Krypton is not retained to any significant extent by the body. The primary mode of exposure is from submersion in contaminated air. On the other hand, tritium, uses as its primary exposure water vapor that has been tritiated. This is a product of combustion of gas which distributes itself throughout human body water. The whole-body radiation exposures for immersion and skin absorption for tritium and krypton-85 in equal concentrations in the air is 50 times less for krypton-85 than for tritium.[10] This consideration then is very important when viewing both the economical and environmental aspects of the stimulation and production of natural gas fields.

The question of radioactivity in natural gas from nuclear stimulation is a major concern of many people not familiar with the question. To most of those who have studied radioactivity produced with present techniques in nuclear stimulation, the problems of safely handling and using the gas appear minor. Nevertheless, future improvements in understanding and procedures can be expected to result in actual radiation exposure being substantially below current assessments.

Several careful assessments of the potential radiation exposure to consumers of natural gas produced following

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[10] Chew, p. 10.

nuclear stimulation have produced unequivocal evidence that human radiation exposure would be much less than we commonly accept in the other areas of our lives. Oak Ridge National Laboratories found that if gas containing one picocurie per cubic centimeter (0.028 microcuries per standard cubic foot of gas) were distributed for all gas used in the Los Angeles Basin, the maximum human exposure would be 2.2 millirem per year and the weighted average would be 0.5 millirem per year. In comparison, incremental radiation exposure from a cross-country jet flight is about 2 millirem, from a luminous dial wristwatch about 1 millirem per year,[11] from a single diagnostic x-ray about 50 millirem and living in a brick rather than a frame house adds 20 millirem per year. The average radiation exposure from natural sources varies from about 70 millirems per year to over 200 millirem per year at various locations in the United States.[12] These comparisons reveal that additional exposures from widespread use of natural gas containing 0.028 microcuries/CF of tritium would be quite low and quite safe.

Low levels of natural radioactivity are present in natural gas today due to radon-222. A few preliminary dose

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[11]U.S. Environmental Protection Agency, Estimates of Ionizing Radiation Doses in the United States 1960-2000. Rockville, Maryland: August, 1972, p. 40.

[12]Op. Cit., p. 40.

assessment studies for the average radon concentration in natural gas have concluded that no significant health effects result from the use of such gas.[13] Understanding is still not adequate for meaningful comparison of tritium exposures due to projected nuclear stimulation development to radon daughter exposures from natural radioactivity.

The initial tritium activity at the wellhead is expect d to be less than 2 microcuries/CF, the average concentration for the first year of production would be less than 1.3 microcuries/CF, and radioactivity concentrations in succeeding years would be substantially lower. Assuming no farm taps near wellheads during early years of production, mixing in available pipelines would result in much lower tritium concentration in natural gas delivered to consumers.

In comparison to the many and varied problems of an oil-shale operation the question of nuclear stimulation of natural gas fields seem to be fewer and less complex. In the next chapter the economic enigma of the two methods will be viewed.

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[13] C. J. Bar, et al., Contribution of Radon in Natural Gas to the Dose From Airborne Daughters in Homes, Proc. Noble Gases Symposium, Las Vegas, Nevada, September 24-28, 1973.

CHAPTER IV

ECONOMIC CONSIDERATIONS

This chapter will compare nuclear stimulation of natural gas fields to retorting of oil shale in the light of economic considerations. The first section of the chapter will address the economic view of retorting oil shale.

OIL SHALE

The study area in Colorado is an area of 9,560 square miles and it is a prosperous and diversified economic region depending largely of recreation, ranching and manufacturing. The population in this area is presently growing at a three percent annual rate but the area may see additional oil and gas activity and coal development. The oil shale land is concentrated in a sub-area founded by the small towns of Rangely, Grand Valley, Rifle and Meeker.

The Department of the Interior initiated a program in 1974 to stimulate the possible development of oil shale.

The Interagency Oil Shale Task Force has examined the prospects for expanding shale oil production to meet the objectives of Project Independence. Analysis is presented under two categories: (1) Business as Usual; and (2) Accelerated Development.

The "Business as Usual" situation postulates a continuation of the pre-embargo structure of those relationships through 1990. It is necessary to understand how the energy and impact outputs can be expected to change as expectations about the price of foreign oil changes. The "Accelerated Development" situation postulates NEW government actions to change resource, constraints, and production process factors. It is also necessary to understand how energy and impact outputs can be expected to be changed by these actions, acting simultaneously with changes in foreign oil prices.[1]

As discussed in this analysis, the rate at which oil shale can be developed depends upon a number of interrelated factors. Initially, it will depend on the availability of venture capital that can expect only a minimum acceptable rate of return. As the industry matures, however, profitability should increase and other factors will become more important than venture capital. Eventually a point will be reached, beyond which no matter how profitable the operations might be, expansion will not be possible due to other non-economic limitations.[2]

No shale oil production is expected at a world crude oil price of $4.00 per barrel since the rate of return at this

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[1]U.S. Department of Interior, Project Independence (U.S. Government Printing Office, 1974), p. 3.

[2]Project Independence, p. 3.

price would be less than 10 percent and would not attract venture capital.

Under Business as Usual and a world oil price of $7.00 per barrel, oil shale development is projected to reach 250,000 barrels per day by 1985 and 450,000 barrels per day by 1990. Under these conditions, the minimum expected rate of return would be 15 percent. This schedule of production is expected to respond to normal economic inventives and to the relaxation of some physical constraints.

Under Accelerated Development, the estimated return on investment for world oil price of $11 per barrel is about 20 percent. Higher crude oil prices will increase the return on capital, but is not expected to stimulate higher production. This is due to non-economic limits inherent in oil shale development.

Thus, positive Government actions and a stable world price of oil of $11 rather than $7.00 per barrel will create the economic and institutional climate necessary to call forth higher levels of shale oil production. By 1985, 1 million barrels per day could be attained. By 1990, production could reach 1.6 million barrels per day.[3]

According to the Task Force Report expected capital expenditures for a single year for Business as Usual will total $450 million dollars, this figure compares to $1.25

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[3] Project Independence, p. 4.

billion for Accelerated Development. The cumulative capital that is extrapolated from the above figures is a total of $2.5 billion by 1990 for Business as Usual in Development for the same time period.[4]

The ability to generate sufficient venture capital can act as a short term constraint on both Business as Usual and Accelerated Development. Analysis indicates shale oil production will yield only a marginal return on investment of about 15 percent discounted cash flow at a world price of $7.00 per barrel. Returns would increase to about 20 percent at $11 per barrel. All costs in this analysis are based on 1973 dollars. This analysis shows that initial development of the new industry will depend on the availability of large amounts of venture capital that can expect to yield only a minimum acceptable rate of return on the investment.[5]

This is a particularly serious constraint when real costs are rising rapidly. Currently, a one year delay in construction will result in a 20 percent or more increase in capital investment. For a $500 million processing complex, this represents an additional $100 million the first year, $110 million the second year, and so on. In about 3.5 years, the original estimated cost of the plant has doubled to $1 billion. Inflation is a serious problem for any capital intensive development such as oil shale or coal conversion

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[4] Project Indpendence, p. 5.

[5] Project Independence, p. 22.

since costs associated with such construction may be rising faster than can be offset by higher product prices. This, in turn, will cause the expected rate of return to fall. At some time, the return will be so low that alternative investments will be made.[6]

For example, every company has the need to replace worn out or obsolete facilities. Due to inflation, the money normally used for this (depreciation) may be inadequate to pay for replacement. A dilemma is created; should a company use new funds to expand into an entirely new area such as shale oil or to replace existing facilities? In competition with more traditional energy sources, all synthetic fuels development may be delayed.

Once initiated, however, the real cost of shale oil production is expected to decrease significantly, as it has in other industries. Because of this, the economics of oil shale processing will probably not act as a long-term constraint, but will undoubtedly affect the rate at which a mature industry will develop. Certainly, low profit expectations have been a fundamental reason why oil shale has not been commercially developed to date. Future expectations concerning production costs, oil prices, the general state of the economy, and the availability of capital will establish the economic parameters. If, in combination, these are

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[6] Project Independence, p. 24.

judged favorable by private enterprise, oil shale development will be initiated.

The Task Force has concluded that industry will move rapidly forward with oil shale development if the world price of crude oil is maintained at $11 per barrel. In this case, economic incentive to attain the accelerated development schedule are provided by the market mechanism without government action.

Conversely, if the world price of oil stabilizes at $7.00 per barrel, it has been concluded that economic incentives are adequate to attract only enough venture capital for the Business as Usual development schedule.

Economic stimulants can be applied. The Task Force indicates that most effective method to remove or eliminate private risk is through a price floor or purchase agreement. Either would increase the attractiveness of a marginal rate of return and probably be necessary to accelerate development over the short-term, i.e., to 1980.

In summary, the most important short-term constraint on oil shale development is the availability of adequate venture capital. Over time, the profitability of development is expected to increase and venture capital will no longer be as significant as other relevant considerations.

RESEARCH NEEDS

In the preceeding chapters of this study, it was recognized that two major alternatives are being considered for oil shale development: (1) mining followed by surface processing; and (2) in-situ (in place) processing. It is suggested that initial development of oil shale will almost certainly follow the reasonably well-demonstrated route of room and pillar mining at moderate depths and retorting by one or more of the several better established processes. A major scaleup effort will yet be required: however, there is little reason to doubt that the industry will effective and expediently accomplish this phase of development in view of experience in other large-scale industries and the apparent high degree of interest displayed during the lease sales under the Department of the Interior's ongoing oil-shale leasing program. Added evidence is seen in recent announcements by two companies of their intentions to proceed with commercial development on their privately-owned properties. However, the industry is expected to place mining at depths below approximately 1,000 feet and in-situ processing in positions of lower priority due to the uncertainties yet to be resolved.[7]

The overall rationale for focusing research in the areas noted above stems from Government's responsibilities as custodian of the major part of the shale resource and in alleviating the Nation's energy-supply problems as expediently

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[7]Project Independence, p. 293

as feasible in an environmentally acceptable manner. Specific criteria for selecting principal research targets include recognition that:[8]

--Deep mining and in-situ retorting can be instrumental in greatly broadening the resource base.

--Increased opportunity in terms of resource base will promote more efficient utilization of the overall shale deposits and will help accelerate overall development.

--In-situ processing promises advantages in regard to safety, water economy, and environmental impact over the mining/above groud processing approach.

--Firm definition and earliest possible solution of environmental problems can well be a critical factor in the rate and extent of commercial development of oil shale, regardless of the technological route.

--Government has a "need to know" over the full range of development alternatives in order to plan and execute its duties effectively in administration of the public lands.

--Industry's principal thrust, at least initially, is expected to utilize relatively well-established techniques rather than covering the broader range of concern to Government.

Within the framework described above, the primary thrust of the research program must be directed toward ways of mitigated environmental damage, including techniques for

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[8] Project Independence, p. 294.

solid-waste management, vegetation and restoration of lands used as surface disposal sites for spent shale or otherwise disturbed, and biological investigations for the protection of fish and wildlife.

In summary in this section the considerations, constraints, and the direction of future research for the oil shale industry has been examined. In the following section nuclear stimulation will be viewed in generally the same vein.

NATURAL GAS PRODUCTION BY NUCLEAR STIMULATION

This section of the study is dedicated to the economic problems and issues surrounding the nuclear stimulation method of obtaining energy fuel.

The measured change in permeability of the paying strata is measured in millidarcys. This measure is used as a portion of an expression for gas deliverability from a well. This factor "K", prior to detonation, was measured in the lenticular sandstone formations of the Mesa Verde at 0.04 millidarcys and after detonation at 0.5 millidarcys. This is an example of the effectiveness of nuclear stimulation.

The cost of production of natural gas by nuclear stimulation is fixed to the cost of:

--Hole Emplacement.

--Detonation Service Manpower.

--Explosive Emplacement and Stemming.

--Reentry and Completions.

--Safety Program.

--Nuclear Device.

Application of the Rulison test results and analyses to the fieldwide reservoir characteristics that are known from other wells that have been drilled in the Rulison Field provided the basis for determining the potential gas reserve that could be attributable to stimulation and recovery by nuclear techniques. Based on the current gas wellhead price of approximately $0.24 per thousand cubic feet (kcf), a well cost of $1 million and a discounted average annual return on investment of 20 percent, a potential reserve of some two trillion cubic feet of gas was calculated. It was assumed in making these calculations that the necessary explosives with sequential firing capability would be available from the government. The wellhead price of $0.24 per kcf used in calculations assumed full commercial operation in the post-demonstration phase and did not include any differential to cover R&D costs. Natural gas price is regulated by the Inter-State Commerce Commission and is fixed at a maximum cost of $0.50. Natural gas sold on an intra-state basis has in some states gone to a level of $1.50 kcf. This indicates that the stimulation of natural gas can be economically sound and seemingly lucrative.

Another prime requisite for continued industrial investment in the nuclear gas stimulation prog am is the establishment by the Federal Power Commission of the pricing structure which will permit industry to recover its research and development costs during the demonstration phase of the program. Such action would provide a needed incentive to industry to come forward with added proposals for demonstration projects at a time of severe competition for available capital resources and would itself accelerate the process of effective gas recovery from low permeability formations.

To evaluate the radiation exposure to the population resulting from low levels of radioactivity in the gas two methods of distribution were conceived. If all the gas were uniformly mixed with gas from a source of fuel that had not been stimulated by nuclear detonation the average individual exposure could be maintained at 0.45 milliren per year. This method uses the year 2000 as the maximum mixing year with regard to stimulated gas.

Alternatively, the 0.50 trillion cubic feet of highly contaminated gas occuring during the first year of production might be collected into a separate pipeline and consumed in power plants. In this case, the average individual exposure would be less than 0.11 mrem/year. Average allowable exposure to individuals in the population at large is as recommended by the Federal Radiation Council and the Environmental Protection Agency.

The construction and detonation cost that a commercial venture would need to sustain are these:[9]

--Emplacement Hole. This includes site access, grading, drilling, casing emplacement to a depth-1,000 feet cost (allowance was made for drilling problems, the consideration being that one of six would not be completed). Cost: $520,000.

--Detonation Service Manpower. This includes technical personnel to supervise explosive emplacement, stemming, and to set up and operate firing equipment. The planned field development is one well per month. Cost: $40,000.

--Explosive Emplacement and Stemming. This includes equipment and labor personnel to emplace and stem the nuclear explosive device, in addition this includes cost of all downhole hardware and stemming material. Cost: $190,000.

--Reentry and Completions. This includes equipment and personnel to reenter the emplacement well and wellhead hardware to complete well production. Cost: $60,000.

--Safety Program. This cost takes into consideration personnel to evaluate hazards and perform those activities necessary to ensure health and safety of general public and project personnel, which includes equipment to monitor and document radioactivities during production, again this is based on an approximate field development rate of one well

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[9]B. Rubin, et al., An Analysis of Gas Stimulation Using Nuclear Explosives, (Lawrence, Calif.: Livermore Laboratory, 1972), p. 10.

per month. Cost: $130,000.

--Nuclear Device. This cost is based on AEC stated charge for 100 kt explosive with provision for sequential firing. The requirement for temperature and pressure protection is to 350°F, and 10,000 psi to all firing components. Cost: $1,380,000.

Total cost of the above items: $2,410,000. Costs are inflated from 1971 to 1976 at 5.5 percent per year.

Environmental and safety requires a monitoring system to be employed at the wellhead during the flaring. It consists of four basic elements:[11]

--STALLKAT (System to analyze low levels of krypton and tritium.)

--Freeze Trap.

--Particular Filter (with charcoal cartridge).

--Gamma Monitor.

The STALLKAT will analyze continuously the gas flow from the well for low levels of krypton and tritium. This system has a detector and a readout following continuous monitoring, it provides an instantaneous reading of the total amount of the radionuclides released. This system will permit the operator supervising the flaring to know if the concentrations of release exceed that which is expected.

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[11] Court Decision Converned with Postshot Flaring Program of the Project Rulison, U.S. District Court, Denver, Colorado, 19 March 1970.

The freeze trap is a device which is placed in the main flow line to monitor the moisture in the gas. It monitors tritium being released in water vapor form through the flare stack. This cannot be accomplished by the STALLKAT.

The particulate filter and activated charcoal cartridge is placed on the flow line. The filter determines if any particulate beta or gamma radiation is present in the gas. Since such radioactivity is not anticipated, the filter is merely precautionary. The activated charcoal cartridge will measure any iodine-131 present in the released gas.

A Geiger Counter is used to monitor gamma radiation. It is placed in the flow line to provide instantaneous monitoring of the gross gamma radiation level. This supplements the particulate filter, which is removed from the line in order to be analyzed.

In addition off-site monitoring is conducted by the Southwestern Radiological Health Laboratory which is an activity of the U.S. Public Health Service. All environmental surveillance for the duration of the Drillback and flaring is carried on both on the surface and by aerial monitoring. Mobile teams collected samples prior to release of any radioactivity. These samples included food and water used by wildlife, domestic livestock and humans. As shown earlier the emphasis must be placed on tritium levels.

Monitoring activities include air sampling, through fifteen stations established specifically for Rulison through four Air Surveillance Network stations of the Southwestern Radiological Health Laboratory network and eight thermoluminescent dosimeter in a five-mile radius of Surface Ground Zero.

Milk was sampled through the Southwestern Radiological Health Laboratory Milk Surveillance stations in eleven Colorado cities. The Southwestern Radiological Health Laboratory Rulison Water Surveillance Network is used to detect radiation in water supplies. Twelve municipal water supplies within twenty-five miles of SGZ plus five other water supplies have surveillance stations. Five private wells around the site, a special well on Battlement Creek, three springs, four reservoirs and nine streams were and are under surveillance.

The meteorological data gathering system includes a systrac radiotelemetered instrumentation array to measure surface wind speed and direction. During flaring, wind data are continuously recorded providing information on the local wind and information useful in placing manned sampling stations. Surface temperature and humidity will also be measured and recorded on site.

Effects of the Rulison detonation on the surrounding ecosystem were minimal, and no significant adverse effects were noted during the post-event observations. There was a temporary increase in turbidity and water color in Battlement Creek water immediately after the detonation, although this was at least partly caused by a local rain and hailstorm. In any case, the increase in turbidity was transient and caused no significant problems for water users. Pre-event measures taken to prevent entry of oil and other drilling wastes into the watershed were apparently effective.[12]

The present status of natural gas produced following nuclear stimulation is that no standards have been established for safe consumer use, so that no such gas may be sold. All gas produced in the experiments to date has been flare at the wellhead. Procedures for marketing products containing man-made radioactivity differ significantly from those for most other potentially hazardous materials. Any marketing of a consumer product containing manmade radioactivity is illegal until a standard is set or a specific permit is granted by the Atomic Energy Commission for its distribution. Whereas ambient air standards for chemical pollutants are generally set near the level where effects become noticeable, standards for exposure to manmade radioactive substances must be "as low as practicable." This generally means standards three to four orders of magnitude below those levels where adverse health effects have been demonstrated. These procedures are much more stringent than those applicable to natural radio-activity, radiation from electronic devices or radiation exposure incurrent in medical diagnosis.

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[12]R. G. Fuller, *et al.*, *Post-Event Bioenvironmental Safety Aspects Project Rulison* (Las Vegas: Southwestern Radiological Health Laboratory, March 1973), p. 20.

As yet, no application has been filed to trigger the rulemaking which must precede license procedures to sell natural gas containing manmade radioactivity and the government has not initiated the action of its own volition. Expenditure of the effort and money to carry out the complex government procedures involved in the regulatory process has not been judged justifiable in relation to potential income from sale of amounts of gas available from the three experiments performed to date. An intention to file an application to market the gas from the Rulison well has been announced but the time of filing is indefinite.

It is anticipated that all radioactive safety procedures, measurements and licensing will probably be a function of the producers, transmission companies and government agencies. Gas reaching distribution companies would contain license-exempt concentrations of radioactive materials. No legal requirements for radioactivity or special procedures are anticipated at the distribution level.[13]

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[13] Eddie Chew, Chemical Considerations in Nuclear Stimulation of Gas Reservoirs (Minneapolis, Minnesota: American Gas Assoc., 1974), p. 15.

CHAPTER V

CONCLUSIONS

In the final chapter of this study some conclusions are drawn with regard to the selection of one of the two methods of generating energy fuel addressed in the study. While it must be remembered that the test area was restricted to the Piceance Basin on Western Colorado the factors may be considered as general in most cases.

The seventeen year old technology of nuclear stimulation is very young in many respects, and this is also true of the retorting of oil shale although it has been known for about 30 years. Both have passed through meaningful steps of development. Objective assessment, based on economy and ecology indicates that a sound method may be selected.

To analyze the findings of this study and to realize some meaningful impact of it on the current critical energy enigma, it must be pointed out at the outset that if unlimited fiscal assets and resources were available much more technical research should be accomplished. This is due to the far reaching effects of these two systems. But considering the national energy posture, the interface of this posture with our national defense, and the immediate state-of-the-art to generate the needed energy, it may be seen by the percipient observer that a judicious selection, of one system or the other may be made based on the findings of this study.

Nuclear stimulation of natural gas fields is a safe method of obtaining energy. Its major drawback is its possible generation of uncontrolled or excessive radioactive material. Objective assessment indicates that potentially, nuclear stimulation can safely produce hundreds of trillions of cubic feet of natural gas at a cost that will be competitive with almost any source in the United States today. If the $0.24 mcf can be maintained or dropped (as nuclear devices become more available) it appears that the demand will far exceed the product. Economic data needed are the costs of:

a. Drilling construction and logistic support.

b. Fielding nuclear explosives on a routine basis.

c. Related safety programs.

It will be necessary during the early stages of actual production to greatly exceed required safety measures and these should include:

a. STALLKAT

b. Freeze Trap

c. Particulate Filter

d. Gamma Monitor

Public acceptance of both the technical feasibility experiments and the subsequent commercial development of the fields, will be a major factor in the development and use of the technology. In the Rulison Project several injunctions were sought initially to stop the detonation and subsequently to prevent the post-shot flaring program. In all instances the courts ruled that the experiment could proceed, thereby clearly establishing the propriety of AEC procedures and guidelines regarding release of radioactivity and carrying out peaceful nuclear explosions. Since Rulison, considerable effort has been made to work with groups in Colorado who opposed Rulison, as well as State advisory groups and environmental organizations, in an effort to acquaint them fully with planned precautionary measures and to acknowledge their criticisms.

Ultimately, public acceptance revolves around a few key points:

a. Public awareness of the shortage of fuel and other natural resources.

b. Direct benefit such as jobs and taxes.

c. An awareness that the radioactivity associated with products from nuclear detonations is extremely small.

The effects of the Rulison detonation on the surrounding ecosystem were minimal and no significant adverse effects were noted during the post-event observations. There was a temporary increase in turbidity and water color in Battlement Creek water immediately after detonation. In addition pre-event measures were taken to prevent entry of oil and other drilling wastes from entering the local watershed.

It must be recognized that for industry to assess accurately the required amount of capital investment and return on that investment, firm information is needed on:

a. The price to be charged by the AEC for the nuclear explosives.

b. The gas sales prices to be allowed by the Federal Power Commission.

c. The levels of radioactivity in the distributed gas to be allowed by the FEC, as based on standards to be established by the Environmental Protection Agency.

Present law permits the use of nuclear explosives in joint government-industry experiments. However, after the research and development is completed, a law must be passed to permit commercial use of nuclear explosives. In addition, information such as canister diameter and quantity of internal and external radioactivity produced per explosive will need to be declassified so that design of commercial production wells can proceed.

The comparison of nuclear stimulation with the several alternative ways of increasing gas availability shows that the cost of production, development and research, the required capital investment and the time needed to achieve a production capability of one trillion cubic feet per year are less than or competitive with conventional exploration, coal gasification or import of liquified natural gas. Gas sales prices from nuclear stimulation will be lower than from any other source except conventional exploration which must locate high permeability fields.

Although at some time in the future the need to retort oil shale may be necessary it does not appear to be likely in the immediate time frame. Oil shale is a tremendous reserve of oil, in fact, it is the world's largest reserve. However, it will be years before the technology to economically produce large quantities of shale oil is available. In order to expedite this development and provide an opportunity to study the environmental impacts of oil shale mining and extraction, some of the rich public shale land must be made available.

Analysis has established that it is possible to accelerate oil shale development. The findings of this study and the work accomplished by the Oil Shale Task Force under Project Independence have determined that expansion can only be accomplished if certain constraints are met:

--A world oil price of $11 per barrel, which should be adequate to attract initial venture capital. Alternatively, it may be necessary to remove economic risk through a floor price or purchase agreement.

--Resolving issues associated with "non-degradation" of air quality and the Colorado State standards for sulfur dioxide.

--Beginning leasing of public oil shale land in 1979.

--Establishing a leasing policy based, not on land area, but on recoverable resources.

--Clarifying legislation to specifically provide for offsite disposal of spent shale.

--Initiating a program to provide additional water storage in Colorado by the early 1980's, by either public or private funding or some combination of both.

--Establishing a mechanism for growth management, including a centralized system for information and coordination.

--Accelerating research on in-situ processing.

--Rapidly developing environmental control technology.[1]

The United States cannot include or depend on shale oil to supply any of the immediate energy fuel needs, but now is the time to prepare for good, logical environmental management of shale development for some operation in the future. The most troublesome impacts of the oil shale development are those that will occur from the growth of a major industry, employing thousands of workers. No decision to set such growth in motion, beyond the effects of the lease of six sites has been made, or will be made until the impacts of commercial scale production can be assessed.

The impact on the air, water, land, wildlife and the remote and primitive quality of the area on and around the sites will be at best extensive and possibly disastrous.

Private sector participation in the design of the program, the provisions incorporated in the lease to encourage timely development and the rapidly rising price of crude oil, all suggest convincingly that there is high interest in the

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[1]U.S. Department of Interior, Project Independence Potential Future Role of Oil Shale (Washington, D.C.: U.S. Government Printing Office, November 1974), p. 5.

prototype program. But uncertainty in estimates about the cost of production is very great and for some technologies, estimates are quite pessimistic.

Costs are estimated for an open pit mine and surface retorting oil scale process which is producing 200,000 barrels of oil per day to be at a selling price of between $8.00/bbl. and 16.00/bbl. There, prices depend on the choice between Business as Usual and Accelerated Development. This also assumes a recovery of 20 gallons of oil per ton of shale. In any case the cost of a unit of crude oil is far more costly than an equivalent unit of natural gas.

Even assuming best available control of particulate matter, sulfur dioxide, nitrogen dioxide, hydrocarbons and carbon monoxide the oil shale industry will not be able to meet the current Colorado Air Quality standards. In addition fugitive dust from excavation, crushing, handling will cause air pollutant emissions.

The impact on the wildlife of a 1-million-barrel-per-day industry visualized by 1985 will be extreme. This will include about 100,000 new inhabitants and will require urban development, road networks, a power transmission system and water consumption of 124,000 to 194,000 acre-feet of water per year. The cumulative regional effects on fish and wildlife will stem from the following causes:

a. Reduction in water quality.

b. Reduction in water supply.

c. Increased noise.

d. Vegetation Removal.

e. Reduction in Air Quality.

Filling of canyons with spent shale will destroy habitat for falcons and the spotted bat to the extent that it appears they might become threatened species in the entire region.

Mule deer will be reduced 10 to 15 percent or more by disturbance, displacement and competition as their habitat is destroyed. Due to the loss of habitat, reduced water supply, increased hunting pressure and casual shooting will reduce populations of such animals as hawks, eagles, bobcat, raccoon and ringtail cat and force displacement and increased competition for remaining food and water. The sage grouse, a scarce but highly prized game bird, will probably almost disappear from the oil shale regions of Colorado.[2]

Drying of streams, degrading of water quality and/or water diversion will cause reductions in, or change in desirability of, fish populations. Species especially vulnerable to changes in physical conditions or water quality (temperature, pH, toxic substances) include trout and whitefish as well as many others. Although fishing may be retained by stocking and other management there will be a long term

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[2] Project Independence, p. 229.

decline in high-quality fishing, which depends on natural-spawned fish growing to good size in a relatively undisturbed environment.[3]

The problem of hyperurbanization will impact on the sparsely developed area in a number of ways. The area is about 10,000 square miles and is a prosperous and diversified economic region depending largely on recreation, ranching and manufacturing. It is presently growing at a three percent annual rate, but the area may see additional oil and gas activity, and coal development. It appears that an annual growth rate of five percent is the maximum that can comfortably be accommodated in semirural regions in this area. The boom type growth exists above a threshold of seven to ten percent. After growth rates exceed ten percent, existing institution such as the schools, local government structures and labor market become inadequate or break down. If the oil shale boom is concentrated in the small area of the Piceance Basin the effective growth rate will be substantially higher. The problems of oil shale hyperurbanization are complex and interrelated and will be at best costly to surmount, if they can be overcome.

In summary nuclear stimulation appears to be far less complicated than retorting of oil shale as one immediate answer to the energy problem in the United States. Nuclear

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[3]Project Independence, p. 231.

stimulation could be, based on this study, the most economical method of generating needed energy fuel of the two systems in question. Finally, in both the short view and the long view nuclear stimulation will do far less damage to the environment than will the retorting of oil shale.

APPENDIXES

APPENDIX A

GEOLOGY

The Rulison Field is in the Piceance Creek Basin. The field is in the southwest limb of the basin. Upper Cretaceous beds in the area dip towards the northeast at the rate of approximately 150 feet per mile. Tertiary age beds in this area are relatively flat lying. Wells in the Rulison Field are productive of gas from numerous sandstone bodies in the Mesa Verde formation of Upper Cretaceous Age. The natural character of the Mesa Verde formation in the Rulison Field is several hundred feet of potential pay and the interbedded sand-shale stringers. This was supported by electric log tabulations of Austral Oil research (29-95 well).

The Mesa Verde formation in the Rulison Field area was deposited in a near shore environment that included marine, flood-plain, and coastal swamp conditions. This deposition setting resulted in rapid lateral and vertical variations in lithology. The Mesa Verde sandstone reservoirs in the Rulison Field are lenticular and for the most part have limited area extent. The lenticularity of the Mesa Verde sandstone reservoirs is the cause of entrapment of gas in the Rulison Field.

The Mesa Verde formation in the Rulison Field is approximately 2,500 feet thick. It is underlain by the

Mancos shale formation of generally the same thickness. It is overlain by the Fort Union, Wasatch and Green River formations of Tertiary age. These rocks predominantly shales and nonpermeable sandstones.

On the surface there are some outcroping of the Wasatch and Green River formations of the same Tertiary age. In addition to this there is a number of Quarternary age alluvial deposits in the valleys of the Colorado River and its tributaries and in terraces on the lower slopes of the Battlement Mesa. Some "Mud Flow" type deposits are present in some of the higher valleys.

Most of the annual precipitation in the area runs off in small streams and flows or percolates through the alluvial fill or terrances into the Colorado River. Few springs are present where the underflow in the alluvium is deflected to the surface by the relatively impermeable bedrock.

There is a significant underflow through the alluvium of the valleys. The only water wells in this area with appreciable capacity are completed in the alluvial sand and gravel lenses in the valleys. This type of deposit is only characteristic of the Colorado River and some of the larger tributaries north of the Colorado River. The smaller tributaries on the Battlement Mesa generally flow on bedrock.

The median permeability of the gas-bearing Mesa Verde sandstone is approximately 0.5 md.

GREEN RIVER FORMATION

The Green River Formation oil shale is a sedimentary rock of the Eocene age occurring in Colorado, Utah, and Wyoming. The organic matter of the Green River Formation was derived mainly from microscopic algaes and other microorganisms and non-lacustrine organic substances like pollen and waxy spores that were deposited in two lakes located in the Uinta and Piceance Basin in Utah and Colorado respectively.

Oil shale is a heterogeneous substance consisting of a complex hydrocarbon called kerogen locked within a matrix of calcium and magnesium compounds. Kerogen is a solid at room temperature and is only sparsely soluble in the common organic solvents. Oil shale is a potentially valuable resource because, when the contained kerogen is heated it undergoes a chemical transformation to a polymer called bitumen.

APPENDIX B

CLOSSARY

A groove. This is a characteristic groove in the face of the Roan Cliffs which marks the top of the Mahogany Ledge which contains the richest oil shale. It results from the fact that the shale in that particular narrow stratum weathers and erodes easier than the strata above and below.

Aquifer. In oil shale deposits, this word has a special meaning. If it's the upper aquifer in the Piceance Basin, then it's potable water and must be protected. If it's the lower aquifer, then it's probably salty and its waters must be kept out ot the upper aquifer and streams because of the adverse effects on water quality that would result. The aquifers of the Piceance Basin are believed to contain some 25 million acre-feet of water.

Alluvial. A general term pertaining to deposits resulting from the operation of rivers, these are normally recent unconsolidated.

Areal. Pertains to the distribution, position and form of the areas of the earth's surface occupied by different kinds of rock, or different geologic units.

<u>Bench Scale</u>. This is the first stage of a commercial oil shale process, generally referring to a process conceived and developed within the laboratory.

<u>B groove</u>. Like the A groove, the B is another characteristic cleft in shale outcrops that marks the bottom of the Mahogany Ledge. Both the A and B sections are low in oil content.

<u>Christmas Tree</u>. The wellhead cap consisting of many valves and gauges.

<u>Cretaceous</u>. Of the nature of chalk and the name of the third and last period in the Mesozoic Era.

<u>Dawsonite</u>. This is a sodium aluminum carbonate found in potentially commercial quantities in the deeper and richer shales in the heart of the Piceance Basin. Alumina can be recovered from dawsonite and the alumina can then be refined into aluminum. The bulk of U.S. aluminum ores presently are imported.

<u>Destructive Distillation</u>. The process of decomposition whereby the original chitinous material of certain fossils has lost its nitrogen, oxygen and hydrogen and is represented by a carbonaceous material.

<u>Drill Back</u>. The reentering of a well after nuclear detonation.

<u>Evacuation Creek</u>. This is the name of a creek that cuts the oil shale country of eastern Utah and the spot where a particular member of the formation overlying the shale was first noted. The U.S. Geological Survey has recently redesignated the formation as the Uinta. It is the brown rock that overlies the Green River formation and of which most of the ridges in the Piceance Basin are composed. It contains no oil shale.

<u>Fines</u>. Refers to the smaller particles of oil shale coming out of the mine. Fines are generally pea sized on down and must be screened out from the feed of some retorts.

<u>Fischer Assay</u>. A standard laboratory method for assaying the oil that can be recovered from shale. It is not absolute. Some processes can recover more than 100 percent of Fischer assay.

<u>Flare Stack</u>. The vertical pipe at the wellhead where the natural gas is burned off.

<u>Flaring</u>. Burning of the natural gas in the open air at the wellhead.

<u>Green River Formation</u>. The deposit laid down in the bottom of ancient Lake Uinta about 50 million years ago. The deposit, up to 2,000 feet thick in places, required some 10 million years to form. The upper Green River formation contains the richest oil shale deposits.

<u>Halite</u>. One of the forms of rock salt, a mineral form of common table salt. It is found in the deeper shale zones in the heart of the Piceance Basin and such might be recovered in shale processing not so much because it is commercially valuable as because it would be a potential stream polutant if not recovered.

<u>Hydrocracking</u>. An oil refining process in which the large molecules of crude oil are broken into smaller molecules through the reaction with hydrogen. The process is used to convert heavy oil into lighter fractions such as gasoline.

<u>Hydrofracturing</u>. The term that describes the use of fluids pumped underground under very high pressure to drive fractures out through the rock. It is a natural gas recovery technique that may be used on a massive scale in tight natural gas reservoirs. It has also been used in some in-situ shale oil experiments.

<u>Hydrogenation</u>. This frequently is a synonym for hydrocracking though it may also mean replacement of an atom as well as addition. Thus, hydrogenation may be used to replace an atom of sulfur or nitrogen in a molecule of crude oil in both lower the pour point of the oil and remove the sulfur and nitrogen as by-products. In general, the more hydrogen in a molecule, the lighter it is, For example, water has two atoms of hydrogen to one of oxygen and is a liquid. Methane has four atoms of hydrogen to one of carbon and is a gas.

Kerogen. — Kerogen is the "oil" in the shale. It is a hydrocarbon which breaks down under heat to form synthetic crude oil.

Leached Zone. — This is a considerable thickness of the upper oil shale layers in the heart of the Piceance Basin where ground waters have leached out all or most of the sodium minerals once deposited therein. Such water is still there and is highly saline. The presence and extent of that ground water has been a major headache to prospective shale developers since its discovery.

Lenticular. — Lens-shaped formation.

Mahogany Ledge. — The name applied to the distinctive rich oil shale outcropping along the Roan Cliffs north of the Colorado River. The Ledge apparently is continuous across both the Piceance and Uintah Basin shale deposits. It contains some of the richest shales.

Mahogany Marker. — This is a rather thin section near the top of the Mahogany Ledge. It is high in volcanic ash content and because of its distinctive characteristics, is a signpost for exploratory drilling in areas where the shale is located far below the surface.

Marlstone. — Oil shale is not a shale but a marlstone. Both are rocks laid down as fine sediments. The chief difference to the layman is that shale readily splits along its layers. Oil shale does not readily break along the layers except for a few rather well delineated sections that probably record some spectacular event at the time they were deposited. One of these exists near the top of the mahogany ledge and forms the roof or "back" of most mahogany ledge shale mines.

Mesa Verde Formation

This formation lies at a depth of nearly a mile beneath the surface in the Piceance Creek Valley though it forms the tops of cliffs just north of Grand Junction, an indication of the geology of the basin. It contains significant coal deposits which have been mined in surface outcrops. Previous exploitation of the gas has been frustrated by the discontinuity and tightness of the gas-bearing sandstone layers.

Nahcolite.

This is the mineral form of baking soda. It is sodium hydrogen carbonate. The mineral is found in beds in the deeper deposits of the Piceance Basin and is intermingled with the shale throughout the basin. It is potentially commercially valuable for stripping sulfur from stack gases in such as power plants which burn high sulfur coal or fuel oil.

Permeability.

Capacity for transmitting a fluid.

Piceance Basin. To a cowman, the Piceance is that area west of the Grand Hogback, north of the Roan Cliffs, east of the Cathedral Bluffs and south of the White River that is drained by Piceance and Yellow Creeks. To a geologist, the Piceance Basin comprises a much larger area flanked by the Uncompahgre uplift on the south, the Douglas Arch on the west, the Grand Hogback to the East, and the Uintah uplift to the north. The cowman's Piceance contains the bulk of the oil in oil shale in the three-state area. The geologist's Piceance contains vast quantities of coal and natural gas in its Mesa Verde member as well.

Porosity. The ratio of the aggregate volumn of interestices in a rock or soil to its total volumn .

Pour Point. This is the temperature at which a hydrocarbon will pour. Generally, hydrogenation or hydrocracking--increasing the number of hydrogen atoms in the hydrocarbon molecule--will lower the pour point. A low pour point generally is required for pipelining.

Project Bronco. This is the name applied to a proposed insitu shale oil recovery experiment in which a nuclear explosive would have been used to fracture the shale. It was shelved for lack of industrial support in the face of underground water problems. While some Atomic Energy Commission scientists still would like to try the experiment, technical, political and social considerations make it extremely doubtful the test will ever be conducted.

Quaternary. The final period of the Cenozoic Era.

Radionuclide. Radioactive nuclei within an atom.

Retort. Both are designed to recover a volatile product through heating. Ovens, kilns and smelters are designed to do the nonvolatile solid such as iron, copper, or lime.

Room and Pillar. This is the mining technique envisioned in most shale development plans involving underground mining--and that's most shale development plans. In essence, it means mining out a room and leaving a supporting pillar. In a given room, 60 to 75 percent of the shale in a horizon will be mined out and 25 to 40 percent will be left in place as pillar to hold up the roof.

Salinity. This describes the amount of dissolved salts in water. It is a term that will be around perhaps forever because of the problems such salts cause and the limited supplies of water in the West.

Sequential Firing. Detonation of the nuclear devices, one followed by another with some time between them.

Shale Ash. As its name implies, this is shale that has been burned in the retorting process. It has been subjected to higher heat since the free carbon remaining after retorting has been burned. Such heating also converts some of the other minerals to their oxide forms and the resulting ash has been described as a low grade of cement. It is fairly hard when wet down and compacted.

Tailings. This is a term little used in oil shale. It can refer to the barren rock or low grade ore dumped near the mouth of the mine. In the uranium industry, it refers to the material left after the minerals have been removed. In oil shale, such residual material is called spent shale.

Tritiated. Affected by radioactive tritium.

Uintah Basin. The Uintah Basin is the western half of the great depression that was filled by ancient Lake Uintah. The lake was divided and the basin divided into the Uintah on the west and the Piceance on the east by the uplift of the Douglas Arch late in the life of the old lake.

Upgrading. In shale oil terminology, this generally refers to the various processes--hydrogenation, for example--to remove undesirable elements from the oil. Such undesirables include nitrogen and sulfur which are both air pollutants if left in such products as fuel oil and can poison catalysts in refineries. Once removed, these products are valuable in chemical and fertilizer manufacturing.

<u>Wasatch Formation</u>. This is the multicolored deposit underlying the Green River Formation. It does not contain oil shale, but like the other sedimentary deposits above and below it, it is a major contributor to river salinity.

APPENDIX C

LETTER SYMBOLS

BPM	=	barrels per minute
BH	=	bottom hole
BHF	=	bottom hole flowing
C	=	lithology factor for cavity radius calculations
C_h	=	factor for chimney height calculation
C_p	=	factor for permeable zone height calculation
C_r	=	factor for permeability zone radius calculation
d	=	day
D_b	=	depth of burial of nuclear device
f	=	equal probability factor
g	=	gravity
h	=	net pay thickness
h_c	=	height of nuclear chimney
h_p	=	height of permeable zone
h_t	=	height of sand lenses
k	=	permeability
k_r	=	radial permeability
kt	=	kiloton
k_Z	=	vertical permeability
L	=	length of sandstone lense
Md	=	millidarcy
Mg	=	molecular weight of gas
MMSCFD	=	million standard cubic feet of gas per day

MPC	=	maximum permissible concentration
NTP	=	normal pressure and temperature (14.7 psia + 60°F)
p	=	pressure
	=	picocuries per standard milliliter
P_d	=	pressure at well's drainage radius
P_e	=	pressure at well's maximum effective drainage radius
P_i	=	initial pressure
P_r	=	initial pressure of correlative layer
Psc	=	standard reference base pressure
psi	=	pounds per square inch
psia	=	pounds per square inch absolute
P_w	=	pressure at well bore
q	=	flow rate
q_f	=	flow rate after fracture
q_o	=	flor rate before fracture
r	=	radius
r_c	=	radius of cavity
r_d	=	radius of drainage
r_e	=	radius of maximum effective drainage
r_p	=	radius of permeable zone
r_w	=	radius of well bore
scf	=	standard cubic feet
SDB	=	scaled depth of burial
t	=	time
T	=	absolute temperature
TD	=	total depth
T_f	=	subsurface flowing temperature

T_{sc} = temperature at standard conditions

T_w = temperature at well datum plane

V = volume

W = yield of nuclear device, kilotons

x = horizontal distance

X = horizontal distance in east-west direction

y = horizontal distance perpendicular to x

Y = horizontal distance in north-south direction
effective porosity

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