

ASSESSMENT OF RESEARCH NEEDS FOR
SHALE-OIL RECOVERY

FOSSIL ENERGY RESEARCH WORKING GROUP - III
(FERWG-III)

Submitted by: S. S. Penner, Chairman of FERWG
Energy Center and Department of Applied
Mechanics and Engineering Sciences
University of California, San Diego
La Jolla, California 92093

March 1981

Contract Sponsors: DOE Office of Energy Research, Fossil Energy, Resource Applications, Environment. DOE Program Managers: J. Powers, P. A. Petzrick, I. Wender. DOE Contract Number: DE-AC01-79ER10007.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, make any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

**Portions of this document may be illegible
in electronic image products. Images are
produced from the best available original
document.**

ABSTRACT

The Fossil Energy Research Working Group (FERWG), at the request of E. Frieman (Director, Office of Energy Research) and G. Fumich, Jr. (Assistant Secretary for Fossil Fuels), has reviewed and evaluated the U.S. programs on shale-oil recovery. These studies were performed in order to provide an independent assessment of critical research areas that affect the long-term prospects for shale-oil availability. This report summarizes the findings and research recommendations of FERWG.

MEMBERS OF FERWG-III (1980)

Dr. William S. Bergen, Consulting
Engineer (alternate member with
P. B. Weisz)
Engineering Department
Mobil Research & Development Corp.
P. O. Box 1026
Princeton, New Jersey 08540
(609) 737-3000

Professor Jon Clardy
Department of Chemistry
Baker Laboratories
Cornell University
Ithaca, New York 14853
(607) 256-7583

Dr. Louis E. Furlong, Manager
(alternate member with R. R. Lessard)
Project Development & Planning in Synthetic
Fuels Research
Exxon Research & Engineering Company
P.O. Box 101
Florham Park, New Jersey 07932
(201) 765-1852

Mr. John M. Hopkins, President
(alternate member with A. E. Kelley)
Energy Mining Division, Room 406
Union Oil Company of California
461 South Boylston Street
Los Angeles, California 90017
(213) 486-6437

Mr. Arnold E. Kelley, Vice President
(alternate member with J. M. Hopkins)
Engineering and Development
Union Science & Technology Division
Union Oil Company of California
P.O. Box 76
Brea, California 92621
(714) 528-7201

Dr. Richard R. Lessard, Director
(alternate member with L. E. Furlong)
Coal Research Laboratory
Baytown Research & Development Division
Exxon Research & Engineering Company
P.O. Box 4255
Baytown, Texas 77520
(713) 428-5764

Professor Alex G. Oblad
Department of Mining & Engineering
University of Utah
Salt Lake City, Utah 84112
(801) 581-6647

Professor S. S. Penner (FERWG
Chairman)
Director, Energy Center, B-010
University of California, San Diego
La Jolla, California 92093
(714) 452-4284

Professor John Ross
Department of Chemistry
Stanford University
Stanford, California 94305
(415) 497-9203

Dr. Robert P. Sieg, Manager
(alternate member with J. R. Thomas)
Synthetic Fuel Division
Chevron Research Company
P.O. Box 1627
Richmond, California 94802
(415) 237-4411

Dr. John R. Thomas, President
(alternate member with R. P. Sieg)
Chevron Research Company
P.O. Box 1627
Richmond, California 94802
(415) 237-4411

Dr. Malcolm A. Weiss
Deputy Director
MIT Energy Laboratory, E19-439
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139
(617) 253-3441

Dr. Paul B. Weisz, Manager
(alternate member with W. S. Bergen)
Central Research Division
Mobil Research & Development Corp.
P.O. Box 1025
Princeton, New Jersey 08540
(609) 737-3000

EX OFFICIO MEMBERS OF FERWG-III (1980)

Dr. Arthur E. Lewis, L-207
Oil Shale Project Manager
Lawrence Livermore Laboratory
University of California
P.O. Box 808
Livermore, California 94550
(415) 422-6453

Dr. Paul A. Petzrick, Director
Office of Shale Resource Applications
U. S. Department of Energy
12th and Pennsylvania Avenues
Mail Stop 334, Federal Building
Washington, D.C. 20585
(301) 633-8660

Dr. John Powers
Director for Research &
Technical Assessment
U.S. Department of Energy
Mail Stop J-309, GTN
Washington, D.C. 20545
(301) 353-2651

Dr. Irving Wender
Acting Director for Advanced Research
& Technology
Office of Fossil Energy
U.S. Department of Energy
4800 Forbes Avenue, Room 236
Pittsburgh, Pennsylvania 15213
(412) 621-4500, ext. 262

FOREWORD

During the third year of operation, FERWG was asked by E. Frieman (Director, Office of Energy Research, DOE) and G. Fumich, Jr. (Assistant Secretary for Fossil Energy, DOE), to conduct an "independent assessment providing for identification of the long-range research needs associated with shale-oil recovery, using both aboveground and in situ recovery techniques." The DOE objectives for FERWG are defined in Appendix A. The assessment of shale-oil recovery technologies was administered through a DOE contract to the Energy Center at the University of California, San Diego, in La Jolla, California.

Members of FERWG performed an extensive schedule of site visits to shale-oil process development units and facilities, as well as to university and DOE laboratories, in order to familiarize themselves with current and planned research programs. Site-visit reports and evaluations, with emphasis on identified process and fundamental research needs, were prepared by participating FERWG members after each site visit. These site-visit reports are reproduced in Appendix B.

FERWG members held numerous discussions with the Director of the Office of Energy Research, the Assistant Secretary for Fossil Energy, members of their staffs, DOE program managers, directors of laboratories and development engineers who are involved in oil-shale research and development (R&D) in both industrial and governmental organizations, and university-based scientists and engineers who perform research related to shale-oil recovery processes. In addition, FERWG received written comments from experts on shale-oil recovery in response to the draft letter that appears in Appendix B.

The Executive Summary is followed by an introductory discussion (Chapter 1) in which we present the FERWG study objectives, describe essential operating features of selected shale-oil recovery processes, and summarize the research recommendations derived from our site-visit evaluations. More detailed research recommendations are discussed in Chapters 2-7.

The costing of shale-oil recovery processes formed the subject of separate workshops. The results derived from these activities are summarized in Chapter 9.

The research recommendations made in this report have no bearing on one of our nation's most urgent initiatives for energy security, namely, the construction of first generation commercial

modules for promising shale-oil recovery processes. These commercial modules should be built, without awaiting the results of R&D investigations which we recommend, in order to provide operating experience that is required for successful near-term commercialization, as well as baseline data for developing acceptable environmental control strategies.

Our research recommendations cover a wide spectrum of activities in shale-oil recovery technologies, ranging from fundamental science to process engineering. They have not been constructed to satisfy the desires of either the scientist or the development engineer. Adequate research support for programs relating to shale-oil recovery technologies may aid commercial implementation of the right technologies over the long term and may also be valuable in the definition and identification of new or different technologies that merit commercialization.

The members of FERWG acknowledge, with thanks the advice and assistance given by many individuals in government, industry and the universities. The following people, among others, have contributed to our discussions, evaluations, and final recommendations: T. F. Adams (LASL); F. Allhoff (DOE); S. B. Alpert (EPRI); J. Appleton (Bechtel); R. Boade (Sandia/Albuquerque); A. A. Boni (Science Applications); R. L. Braun (LLL); D. Brown (Fluor); A. K. Burnham (LLL); B. M. Butcher (Sandia/Albuquerque); J. H. Campbell (LLL); W. J. Carter (LASL); W. Chappell (University of Colorado at Denver); F. Cook (University of Colorado at Denver); T. P. Cook (Fluor); K. Cooper (LASL); L. S. Costin (Sandia/Albuquerque); G. F. Dana (DOE/LETC); J. Deutch (MIT); J. Dienes (LASL); S. Dorrance (DOE/LETC); J. DuBow (Colorado State University); J. N. Edl, Jr. (DOE/LETC); W. Eichfeld (DOE/CMTC); H. J. Ettinger (LASL); H. L. Feldkirchner (IGT); J. P. Fox (LBL); R. Franklin (DOE); E. Frieman (DOE); J. Fruchter (Batelle); G. Fumich, Jr. (DOE); R. Gash (Rio Blanco); J. H. Gibbons (OTA); K. Gorman (DOE); D. Grady (Sandia/Albuquerque); H. Guthrie (Urban Institute); T. E. Hakonson (LASL); A. E. Harak (DOE/LETC); B. Harney (DOE); M. Harper (LASL); R. Heckman (LLL); W. Hecox (Colorado Department of Natural Resources); H. Heinemann (LBL); R. Heistand (Paraho); L. M. Holland (LASL); L. Icerman (New Mexico State University); J. C. Janka (IGT); D. Johnson (DOE/LETC); J. B. Jones, Jr. (Paraho); E. Kane (Chevron Research); B. Killian (LASL); J. Kindler (IIASA); M. Kipp (Sandia/Albuquerque); J. H. Knight (Superior Oil); L. Kronenberger (Exxon USA); W. E. Little (DOE/LETC); J. P. Longwell (MIT); L. Margolin (LASL); K. Markey (Friends of the Earth, Denver); R. D. Matthews (IGT); J. Maziuk (Mobil Research); R. Meglen (University of Colorado at Denver); R. Mellon (LLL); A. K. Miller (Sandia/Albuquerque); W. Morris (LASL); D. J. Murphy (Rio Blanco); B. Olinger (LASL); W. A. Olsson

(Sandia/Albuquerque); D. M. Pascoe (Colorado Department of Natural Resources); K. Petersen (University of Colorado at Denver); H. Pforzheimer, Jr. (Paraho); P. Phillips (Environmental Defense Fund, Denver); J. Pitts (University of California, Riverside); T. Pollaert (Lurgi); T. G. Priddy (Sandia/Albuquerque); R. F. Probstein (MIT); D. V. Punwani (IGT); M. Ray (LASL); E. Redente (Colorado State University); W. S. Reveal (EPRI); D. Rogers (Occidental Oil Shale); A. J. Rothman (LLL); P. Rutledge (U.S. Department of the Interior); A. Sass (Occidental Research); J. T. Schamaun (Sandia/Albuquerque); J. Shaw (MIT); D. Sheesley (DOE/LETC); D. Shelton (Colorado Department of Natural Resources); T. A. Sladek (Colorado School of Mines Research Institute); W. T. Slick, Jr. (Exxon USA); E. Stenehjem (Denver Research Institute); A. Stevens (Sandia/Albuquerque); H. M. Stoller (Sandia/Albuquerque); B. Sudduth (DOE/LETC); P. B. Tarman (IGT); T. Thoem (EPA); H. E. Thomas (DOE); B. Travis (LASL); N. Vanderborgh (LASL); A. Vickery (Colorado Mountain Club); J. Virgona (DOE/LETC); L. Warne (Sandia/Albuquerque); J. H. Weber (DOE/LETC); B. Wenzel (DOE/CRTC); R. E. Wildung (Batelle); E. Williams (LASL); and J. Yerushalmi (EPRI).

TABLE OF CONTENTS

| | <u>Page</u> |
|--|-------------|
| LIST OF ILLUSTRATIONS | xii |
| LIST OF TABLES | xiii |
| EXECUTIVE SUMMARY | xiv |
| NOMENCLATURE | xix |
| | |
| CHAPTER 1 OVERVIEW OF SHALE-OIL RECOVERY TECHNOLOGIES | 1 |
| 1.1 Introduction | 3 |
| 1.2 Summary Remarks on Recovery Processes of Oil from Oil Shale | 5 |
| 1.3 Mining Procedures for the Recovery of Shale Oil | 7 |
| 1.4 Oil and Gas Recovery from Oil Shale | 9 |
| 1.5 Upgrading of Shale Oil | 22 |
| 1.6 Environmental Effects of Shale-Oil Production | 26 |
| 1.7 Summary of Research Recommendations Derived from Site Visits | 26 |
| | |
| CHAPTER 2 PROCESS-DEVELOPMENT AND RESEARCH RECOMMENDA- TIONS FOR ABOVEGROUND RECOVERY | 31 |
| 2.1 Introduction | 31 |
| 2.2 Process-Development Recommendations | 31 |
| 2.3 Research Recommendations Relating to Aboveground Retorting | 37 |
| | |
| CHAPTER 3 PROCESS RESEARCH RECOMMENDATIONS FOR <u>IN SITU</u> RECOVERY | 41 |
| 3.1 Overview | 41 |
| 3.2 Status and Technical Uncertainties of MIS | 43 |
| 3.3 Retort Preparation | 43 |
| 3.4 Resource Recovery | 45 |
| 3.5 Gas Cleanup | 46 |
| 3.6 Process Control | 46 |
| 3.7 Containment of Process Gas in the Retort (Separa- tion from the Mine) and Reduced Leaching from Spent Shale | 47 |
| 3.8 Conclusions | 47 |
| | |
| CHAPTER 4 RESEARCH RECOMMENDATIONS ON MINING | 49 |
| 4.1 Introduction | 49 |
| 4.2 Open-Pit Mining | 49 |
| 4.3 Underground Mining for Surface Processing | 49 |
| 4.4 MIS Mining | 51 |
| 4.5 Need for A Large-Scale Facility for Mining Research | 53 |

TABLE OF CONTENTS (Continued)

| | <u>Page</u> |
|---|-------------|
| CHAPTER 5 INSTRUMENTATION IN SHALE OIL RECOVERY | 54 |
| CHAPTER 6 RESEARCH RECOMMENDATIONS RELATING TO ENVIRONMENTAL ISSUES | 58 |
| 6.1 Introduction | 58 |
| 6.2 Air Quality | 59 |
| 6.3 Water Availability and Quality | 60 |
| 6.4 Spent-Shale Disposal | 61 |
| 6.5 Ecological Baseline Studies | 65 |
| CHAPTER 7 WATER AVAILABILITY AND CONSUMPTION | 66 |
| 7.1 Water Consumption | 67 |
| 7.2 Water Supplies | 73 |
| CHAPTER 8 EASTERN SHALES | 82 |
| CHAPTER 9 COMMENTS ON SHALE-OIL COSTING AND R&D TO ASSURE SUCCESSFUL OPERATION FOR UNTRIED TECHNOLOGIES | 83 |
| APPENDIX A FERWG-III STATEMENT OF WORK | AA-1 |
| COMMENTS BY REVIEWERS | AA-4 |

TABLE OF CONTENTS (Continued)

| | <u>Page</u> |
|--|-------------|
| APPENDIX B SELECTED REPORTS OF SITE VISITS, CONFERENCES AND DISCUSSIONS | AB-1 |
| <u>AB-1</u> FERWG Participation at the 13th Oil Shale Symposium, Golden, Colorado (April 16-18, 1980) | AB-2 |
| <u>AB-2</u> FERWG-III Site Visits to Paraho Development Corp., Anvil Points Facility; Union Oil Company Operations near De Beque, Colorado; Occidental Petroleum Corp., Logan Wash Site; Discussions of Regulatory Aspects with P. Rutledge, Depart- ment of the Interior (May 5, 1980) | AB-10 |
| FERWG-III Discussions at the University of Colorado at Denver, Center for Environmental Sciences, the Oil Shale Task Force (May 6, 1980) | AB-10 |
| <u>AB-3</u> FERWG Discussions of Water Requirements for Shale-Oil Recovery (May 10, 1980) | AB-23 |
| <u>AB-4</u> FERWG Site Visits to the Laramie Energy Tech- nology Center (June 3, 1980) and Lawrence Livermore Laboratory (June 4, 1980) | AB-32 |
| <u>AB-5</u> Shale-Oil Development and Cost Estimates (July 8, 1980) | AB-43 |
| Appendix I: The Union Oil Retorting Process | AB-57 |
| Appendix II: The Lurgi-Ruhrgas (L-R) Process | AB-75 |
| Appendix III: The Superior Oil Process | AB-96 |
| Appendix IV: An Exxon Plan for Commercializing Synthetic Fuels | AB-118 |
| Appendix V: The Rio Blanco Programs | AB-140 |
| Appendix VI: The Chevron Process for Shale- Oil Recovery | AB-142 |
| <u>AB-6</u> FERWG Activities Relating to Environmental Impact Assessments of Shale-Oil Recovery (July 1980) | AB-152 |

TABLE OF CONTENTS (Continued)

| <u>Title</u> | <u>Page</u> |
|--|-------------|
| <u>AB-7</u> FERWG Report on "Oil Shale: The Environmental Challenges", Vail, Colorado (August 11-14, 1980) | AB-171 |
| <u>AB-8</u> Costing of Oil Shale: Comparisons of O.T.A. and Industry Estimates (August 15, 1980) | AB-176 |
| <u>AB-9</u> Discussions on Rock Mechanics with Experts from Sandia/Albuquerque and Los Alamos Scientific Laboratory (September 30, 1980) | AB-190 |
| <u>AB-10</u> Site Visit to the Institute of Gas Technology for Discussions of Eastern Shales (October 1, 1980) | AB-197 |
| <u>AB-11</u> Report of Instrumentation Peer Review of the DOE Oil-Shale Program (October 28-30, 1980) | AB-226 |

LIST OF ILLUSTRATIONS

| <u>Figure Number</u> | | <u>Page</u> |
|----------------------|--|-------------|
| 1.1-1 | Oil-shale deposits of the Green River formation in Colorado, Utah, and Wyoming | 4 |
| 1.4-1 | Processes involved in oil-shale exploitation | 10 |
| 1.4-2 | Schematic diagram illustrating the Tosco II process for oil recovery from oil shale, which was operated during 1967 on a 10 ³ TPD scale | 16 |
| 1.4-3 | Union B process, showing indirect heating of shale | 17 |
| 1.4-4 | Lurgi-Ruhrgas (LR) process for producing hydrocarbons from oil shale | 18 |
| 1.4-5 | Paraho process for extracting shale oil | 19 |
| 1.4-6a | Superior Oil multi-mineral process | 20 |
| 1.4-6b | Conceptual view of a circular grate retort | 21 |
| 1.4-6c | Cross-sectional view of a circular grate retort | 21 |
| 1.5-1 | Upgrading of oil from oil shale to syncrude using a gas combustion process | 23 |

LIST OF TABLES

| <u>Table Number</u> | | |
|---------------------|--|----|
| 1.1-1 | Estimates of shale-oil resources of world land areas (in 10^9 B) | 6 |
| 1.4-1 | Historical overview of shale-oil reserves (in B_e = barrels of oil equivalent) and production | 11 |
| 1.4-2 | Technical aspects of shale-oil recovery processes | 12 |
| 1.5-1 | Physical properties of shale oil derived from a Fischer assay of Colorado oil-shale samples | 24 |
| 1.5-2 | Physical properties and heating values of shale oil | 25 |
| 1.7-1 | Summary of research recommendations derived from site visits (based on data in Appendix B), in addition to the following common problems: materials handling, spent-shale disposal, revegetation of spent shales | 27 |
| 1.7-2 | Basic research needs identified during site visits | 29 |
| 2.1-1 | Aboveground retorts; other (non-U.S.) surface retorts (e.g., Petrosix, Kiviter, Galater) are also available for license | 32 |
| 4.1-1 | Mining operations for shale-oil recovery | 50 |
| 6.3-1 | Water types, sources, and cleanup procedures | 62 |
| 7.1-1 | Net water consumption for producing upgraded shale oil | 68 |
| 7.2-1 | Supportable shale-oil industries according to different authorities | 74 |

EXECUTIVE SUMMARY

Nothing in this report should be construed to justify delays in one of the most promising and most urgent initiatives to secure the energy future of the nation: the construction of a significant number of commercial modules for diverse shale-oil recovery procedures.

Funding for basic, applied and exploratory studies on shale-oil recovery systems by the Department of Energy (DOE) should be used to support the development of technologies for the efficient production of liquids from shale, using either aboveground or in situ shale-oil recovery processes. Shale-oil recovery processes require an integrated systems approach in which all aspects of the technologies (shale mining, sizing or fracturing, feeding, retorting, off-gas utilization, liquids refining, spent-shale disposal, environmental impact controls, etc.) are properly considered and optimized.

We summarize below important research areas for which more detailed justification is presented in the following chapters.

A. Aboveground Retorting: Process Development (Chapter 2)

- Confirmation of spent-shale leaching, compacting, stabilization, and vegetation procedures.
- Handling of raw shale fines.
- Confirmation of retort scale-up procedures.
- Carbon-value utilization for spent shales.
- Effective utilization of low-Btu gases.
- Fundamental and applied research should be pursued on separations of liquid streams and solids from the reaction products formed during shale-oil recovery. These studies are needed in order to improve overall systems efficiency and to reduce processing costs. Vapor/liquid/solid equilibria should be better defined, especially in regions near the critical points.
- An augmented and integrated effort must be made to solve, control, or avoid physical and chemical materials problems that are likely to be encountered in the development of a variety of shale-oil recovery technologies (e.g., in combustion and heat-transfer equipment).

- Clean-up systems must be developed for multi-phase mixtures of gases, liquids, and solids.
- Development of novel and efficient shale-beneficiation procedures may prove to be useful.

B. Aboveground Retorting: Fundamental Research (Chapter 2)

- Scale-up and optimization of shale-oil recovery processes require improved understanding of processing steps, including two- and three-phase flows with heat and mass transfer and chemical reactions.
- Fundamental work on the flow of solid oil shale under process conditions, including wetting and plastic flow.
- Fundamental research is needed on the escape from shale particles of kerogen and its subsequent conversion to gas and oil, both within the particle and in the vapor phase.
- Additional work is needed on the characterization of a wide range of individual shales as they relate to different shale-oil recovery processes for particular shales. These studies will require the maintenance of a carefully selected shale-sample bank.

C. Research Relating to In Situ Processes (Chapter 3)

- Mining and retort preparation represent important areas of study for improving MIS technology.
- Economical, improved methods should be developed for treating large volumes of low-Btu gases.
- Improved methods of process control, including ignition, should be developed.
- Process-gas containment within the retort and reductions in the leaching of spent shales are important areas for research.

D. Mining (Chapter 4)

- A sufficiently large facility should be dedicated to the purpose of developing improved mining procedures (Chapter 4) for aboveground retorting and for MIS.

E. Instrumentation (Chapter 5)

- A meaningful program for instrumentation development must include verification of measurement procedures.
- Improved instruments should be developed for the measurement and control of all phases of the shale-oil recovery technologies, including the characterization and control of effluents to the atmosphere or regional hydrology.

F. Environmental Studies (Chapter 6)

- A reliable air-dispersion model for the complex terrain in oil-shale country is urgently needed. This model must consider the likely atmospheric transformation of emissions produced by oil-shale operations. An immediately required task is gathering and evaluation of meteorological data and/or confirmation of currently available baseline information.
- The effectiveness of existing control technologies that are being tested in ongoing pilot-plant programs should be assessed to define those areas where further developments and improvements will be required. The direction of future research clearly depends on defining the adequacy of available techniques.
- A major research effort is needed to understand the physicochemical processes which determine the leachability of spent shales for different types of processes.
- Land restorations should be used to provide improved information on water and mineral migration, the long-term viability of plants, adequacy of the soil for farming processes, and the physical integrity of the soil as functions of time.
- As an aid in establishing performance criteria for the shale industry, a major risk assessment needs to be done for oil-shale products and by-products. The real hazards associated with currently envisioned emission levels must be better defined quantitatively. This assessment should include toxicological evaluation of products and by-products arising from diverse processes.
- Environmental effects will generally reflect variables in shale type and in process technology. These process-specific variations in pollutants must be identified and understood.

G. Water Supplies (Chapter 7)

- Sufficient water can be made available at acceptable cost to sustain shale-oil production at large levels (e.g., 2×10^6 BPD*). However, social objectives make it desirable to minimize diversion of water to shale-oil processes from other regional uses. Therefore, long-range research should be undertaken to accomplish each of the following:
 - (a) Reductions in water consumption associated with environmentally acceptable disposal and revegetation of spent shale and with treatment of re-tort off-gases.
 - (b) Assessments of the potential of increasing long-term regional water supply through weather modification and inter-basin transfer.
 - (c) Improved definitions of regional hydrologies, including surface and sub-surface water supplies.

H. Refining[†]

- Existing or modified down-stream refining facilities should be used for experimental refining of shale-derived oils to produce commercially-usable liquids for use in transportation and stationary power plants.

I. Eastern Shales (Chapter 8)

- A long-range research program to define the potential utility of Eastern shale-oil recovery should include the following types of studies: more extensive resource estimation, environmental studies designed to produce the same type of data base that is needed for the recovery of shale oil in the West, definitions of regional geology and geochemistry, identification of improved mining procedures, shale-feed preparation, retorting techniques, product upgrading, gas purification, and careful assessments of process economics.

* BPD = barrels per day.

† FERWG supports the recommendations made in the study "Refining Synthetic Liquids from Coal and Shale," Energy Engineering Board, Assembly of Engineering, National Academy Press, Washington, D.C., 1980.

J. Costing of Shale Oils (Chapter 9)

- Reliable cost estimation will not be possible until first-generation plants have been operated successfully. In the meantime, the procedures that are customarily used by engineering constructors should be refined and updated periodically.

K. Prioritization of Research Recommendations

- While FERWG members have not arrived at an agreed upon priority ordering for research recommendations, fundamental research relating to surface recovery of oil shale, problems associated with spent shale disposal, and environmental studies are viewed as priority items for which augmented federal funding is well justified at the present time.

Most of the FERWG members consider programs dealing with (a) improved resource assessments, (b) collection of needed environmental data, and (c) the development of processing technologies suitable for oil recovery from Eastern shales as appropriate for near-term federal support. A minority group within FERWG views R&D recommendations on Eastern shales as premature and unjustified.

NOMENCLATURE

B = barrel (42 gallons)

BPD = barrels per day

TPD = (short) tons per day

MIS = modified in situ recovery processing of oil shale

CHAPTER 1

OVERVIEW OF SHALE-OIL RECOVERY TECHNOLOGIES

The objective of the development of shale-oil recovery processes is primarily that of providing replacement fuel for the transportation sector.

Shale-oil recovery, using surface mining and surface retorting, is currently not being supported on an appreciable scale by the federal government. Industrial developments leading to perhaps 400,000 BPD by 1990 are consonant with the President's energy plan and probably compatible with current construction plans of Union, Chevron, Tosco-Exxon, Rio Blanco, ARCO, Paraho, Occidental-Tenneco, Equity, Superior Oil, etc. Much larger and more rapid, integrated regional development plans have been proposed, which could begin to affect U.S. transportation-fuel supplies as early 1985-87. Development schedules leading to 2×10^6 BPD of shale oil by 1995 are conceivable. Even more rapid commercialization may be envisioned under an all-out crash program, which would require the following initiatives: environmental constraints (regional air pollution to protect both wilderness areas and residential communities, problems of water pollution and regional hydrology, socioeconomic impacts created by the influx of about 70,000 people per 400,000 BPD production, concentration of toxic chemicals in selected plants, land reconstruction, etc.) must be assessed on schedules that will yield believable answers within a year or two; permitting upward of 100 (permits, renewals, and modifications) must be further facilitated through federal, state, and local agreements; adequate authority must be delegated to one or two people to proceed. Water supplies are highly flexible (currently available technologies use ~ 2 to ~ 5 B of H_2O per B of oil produced).

The resolution of important policy issues lies beyond the scope of the FERWG-III activities.* However, analyses of policy issues may provide a useful framework for the technical questions and R&D issues which we shall discuss in detail. In any case, it appears likely that rapid commercialization will be enhanced by a concomitant and adequately funded R&D program of suitable scope and depth. We preface the discussion of R&D problems with brief comments on the nature of shale oil and U.S.

* It has been suggested by some FERWG members that an effective program plan for rapid shale-oil commercialization in the U.S. would involve the following steps: (a) development of a Piceance Creek Basin regional plan for a schedule of very rapid commercialization; (b) funding of environmental studies at an adequate level to obtain required baseline data within two years; (c) development of a meaningful program of public education in order to alleviate unfounded worries concerning environmental degradation; (d) leasing or selling of rich governmental lands to the private sector on condition of commercialization within a predefined development schedule. Until very recently, Piceance Basin development was not viewed as an important component of our national response to an energy-supply crisis.

Large-scale entry by the private sector may require, among others, the following three governmental initiatives: (a) an allowed schedule of rapid capital write-off in order to ameliorate the impacts of the very large required capital costs; (b) guaranteed immunity from, or full compensation for, retroactive environmental control measures that are found to be in the public interest after program initiation ("grandfathering" of shale-oil recovery processes); (c) guaranteed purchase prices (e.g., for delivery to the Department of Defense) in order to eliminate the possibility of deliberate price undercutting by producers who are presently requiring excessively large payments for crude in view of their own low production costs. Loans, loan guarantees, or joint ventures may be needed, especially for smaller producers.

resources, summary remarks on the processing of oil shale, mining procedures, retorting, upgrading, and environmental issues. This brief tutorial should aid readers in appreciating the context in which our R&D recommendations are made.

1.1 Introduction

Oil shale is the colloquial term for a sedimentary rock which contains the solid hydrocarbon kerogen, often in tightly-packed clay, mud, and silt. Kerogen is decomposed at elevated temperatures with the formation of oil that is suitable for refinery processing. However, removal of objectionable nitrogen compounds and other impurities is required. About 1.5×10^5 TPD of rich oil shale (corresponding to more than double of the material currently handled in the largest underground ore mines and about nine times larger than the lifting capacity in underground coal mines) will be required for retorting in a 10^5 BPD operation.

A. Resources

The Colorado-Utah-Wyoming deposits (see Fig. 1.1-1) have been estimated¹ to contain 1.43×10^{12} B with yields of 10 to 25 GPT of shale (about 3.5 to 8.6 weight-percent); about 0.80×10^{12} B are in the Piceance Creek Basin in Colorado, 0.23×10^{12} B in the Utah Uinta Basin, 0.40×10^{12} B in Wyoming (the Green River and Washakie Basins). In 1965, it was suggested that only 80×10^9 B were "recoverable under present conditions." There are also large deposits of carbonaceous shales in the Eastern and Central areas of the United States with such low oil contents that they were classified¹ in the past as marginal or sub-marginal for production. In fact, Hubbert² concluded that "the organic contents of the carbonaceous shales appear to be more promising as a resource of raw materials for the chemical industry than as a major source of industrial energy." The usually-quoted (1965) resource assessment of Duncan and Swanson,¹ as summarized by Hubbert,² is the following: the total world-wide recoverable

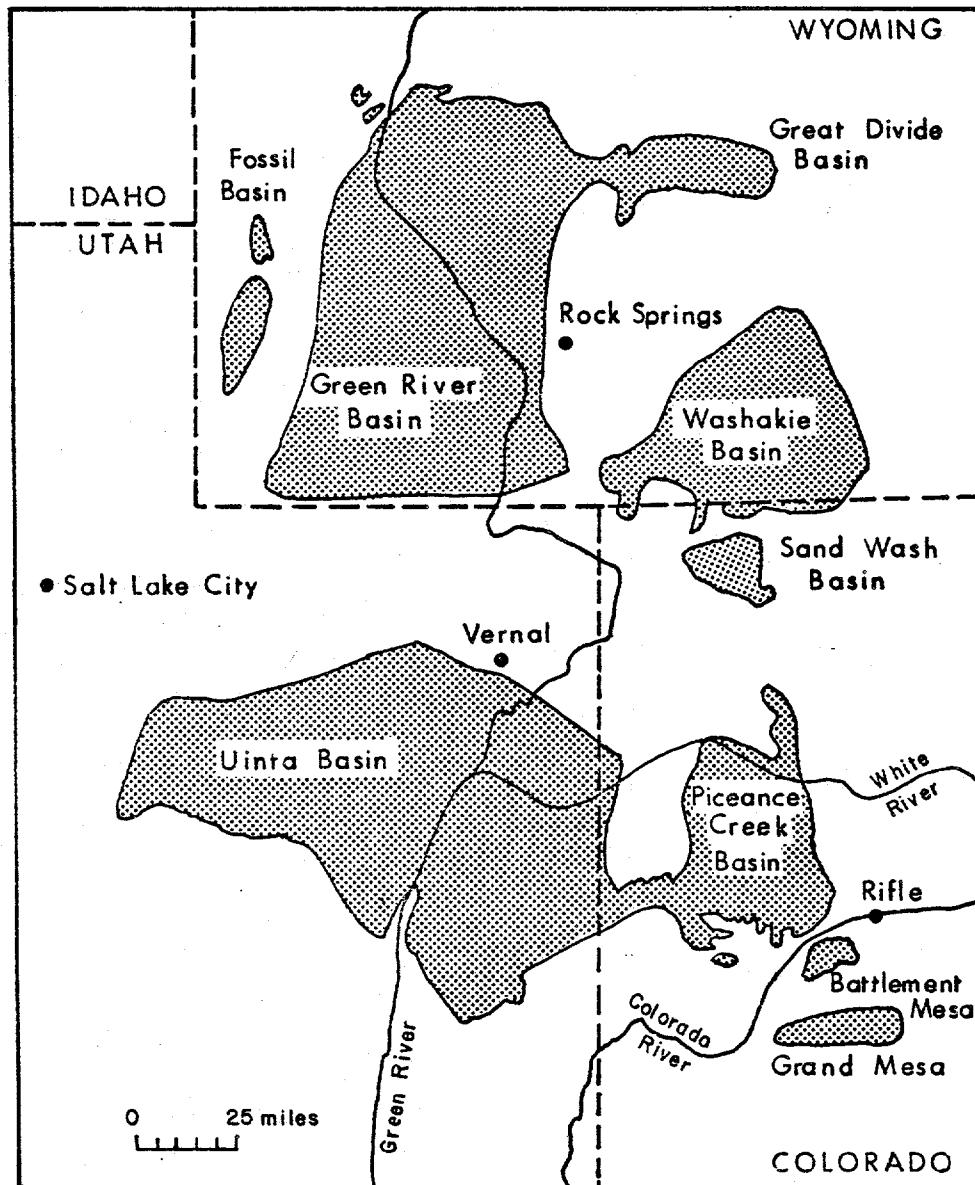


Fig. 1.1-1 Oil-shale deposits of the Green River formation in Colorado, Utah, and Wyoming.

oil from oil shale is about 190×10^9 B while the total world-wide resource amounts to about 2×10^{15} B. Duncan and Swanson's¹ Table 3 is reproduced here as Table 1.1-1. Reference to these data shows that the total North American deposits with 25 to 100 GPT (about 8.6 to 34.5 weight-percent of oil) may amount to about as much as 3×10^{12} B of shale oil. Probably more than 75% of these resources are located on currently (1973) unleased federal lands.

1.2 Summary Remarks on Recovery Processes of Oil from Oil Shale

Oil production from the kerogen in oil shale is more difficult to accomplish than oil recovery from the tar sands. Because the shale is not porous, the development of in situ recovery techniques requires fracturing (except, possibly in the particularly porous formations associated with the leach zone) of the shale before oil removal. In situ recovery of shale oil from oil shale is further discussed in Chapter 3. Conventional aboveground retorting may be used by applying a variety of procedures. Neither aboveground nor in situ recovery procedures have been developed to large-scale commercial use.

Extensive environmental impact-assessment studies for various proposed mining and retorting procedures have been performed. Nevertheless, many questions remain. These relate to such problems as the following: (a) air quality deterioration from preset standards in wilderness and other areas; (b) the fact that water availability may ultimately limit regional industrial development; (c) the possibility that small concentrations of kerogen-derived hydrocarbons may prove to be carcinogenic; (d) water-table contamination may be produced as the result of leaching of minerals from the spent oil shale. Acceptable methods for disposal and replanting of spent shale must be developed.

An important factor in the creation of a mature oil-shale industry relates to the availability of run-off water. It has been estimated that from ~1 to $\sim 2.5 \times 10^5$ acre-feet of water per year are required for the production of 1×10^6 BPD of

Table 1.1-1 Estimates of shale-oil resources of world land areas (in 10^9 B);
reproduced from Duncan and Swanson (1965).¹

| Continent | Known Resources (1965) | | | | Possible extensions of known resources | | | Undiscovered and unappraised resources | | | Total resources | | |
|------------------------------|------------------------|---------------|--------------|-------------|---|--------------|-------------|---|--------------|-------------|-----------------|--------------|-------------|
| | 10-100 GPT | 25-100 GPT | 10-25 GPT | 5-10 GPT | 25-100 GPT | 10-25 GPT | 5-10 GPT | 25-100 GPT | 10-25 GPT | 5-10 GPT | 25-100 GPT | 10-25 GPT | 5-10 GPT |
| Africa | 10 | 90 | small | small | ne ^a | ne | ne | 4,000 | 80,000 | 450,000 | 4,000 | 80,000 | 450,000 |
| Asia | 20 | 70 | 14 | ne | 2 | 3,700 | ne | 5,400 | 106,000 | 586,000 | 5,500 | 110,000 | 590,000 |
| Australia and New Zealand | small | small | 1 | ne | ne | ne | ne | 1,000 | 20,000 | 100,000 | 1,000 | 20,000 | 100,000 |
| Europe | 30 | 40 | 6 | ne | 100 | 200 | ne | 1,200 | 26,000 | 150,000 | 1,400 | 26,000 | 140,000 |
| North America | 80 | 520 | 1,600 | 2,200 | 900 | 2,500 | 4,000 | 1,500 | 45,000 | 254,000 | 3,000 | 50,000 | 260,000 |
| South America | 50 | small | 750 | ne | ne | 3,200 | 4,000 | 2,000 | 36,000 | 206,000 | 2,000 | 40,000 | 210,000 |
| Total | 190 ^b | 720 | 2,400 | 2,200 | 1,000 | 9,600 | 8,000 | 15,100 | 313,000 | 1,746,000 | 16,900 | 326,000 | 1,750,000 |

^a ne = no estimate.

^b Of the approximately 2×10^{15} B here indicated, 190×10^9 B were considered recoverable under 1965 conditions, corresponding to the sum of the resource estimates given in the first column.

oil from shale. A 7-year development schedule (1981 through 1987) leading to a 0.5×10^6 BPD industry may thus imply the consumptive use of 0.5×10^5 to 1.3×10^5 acre-feet/y of run-off water by 1987. In view of existing treaties on the allowable salinity levels of Colorado River water delivered to Mexico and of limitations set by agricultural use in California's Imperial Valley, the long-term availability of these amounts of surface water has been questioned in the past. However, our studies indicate that water supplies will not become limiting at the indicated production levels. Substantial underground water deposits (sufficient to support a 0.5×10^6 BPD industry for as long as 50 years) have been found in the oil-shale regions. The extent to which this stored water (which is a non-renewable source) can be used is currently unclear.

There are significant social stresses anticipated in the Colorado region, especially if a regional oil-shale development boom is coupled with a coal-development boom. Furthermore, cost estimates of oil from oil shale have recently been increased significantly (see Chapter 9 for a brief discussion of costing). As the result, it is conceivable that the entire oil-shale development plan will fail again, as it has repeatedly in the past, unless there is a firm national commitment to develop the oil-shale processing technologies, with adequate incentives to permit profitable private ventures for the first few plants.

1.3 Mining Procedures for the Recovery of Shale Oil

Among the mining procedures considered for oil recovery from oil shales are the following:

(a) Room-and-pillar mining is suitable for tabular bodies of room height but leaves about 40% of the rock in place while exploiting the other half. This procedure is an inefficient method of resource development but is nevertheless economically suitable for tabular seams, particularly if the seams are narrow. It has been demonstrated in oil shale by the U.S. Bureau of Mines and by several industrial organizations.

(b) Open-pit mining is suitable for application to deposits with small ratios of overburden to oil shale. The large thickness and extent of oil shale may permit open pit mining on a large scale.

(c) Cut-and-fill mining may be preferable to room-and-pillar mining when underground mining is required. In this procedure, the shale is removed continuously in layers, spent shale being employed as a floor for subsequent operation.

(d) Block caving is a procedure in which the ore is undercut, supporting pillars are removed, and the ore is subsequently extracted.³ As the ore is drawn out, the overlying blocks fall and spall. The ore is removed through raises and drifts.³ This procedure has been used successfully for copper (65,000 TPD at San Manuel) and molybdenum (60,000 TPD) mines. It is probably not practical for oil shale because oil shale is not highly fractured.*

(e) In sublevel caving, a drill-blast-haul sequence is used in which overlying material "caves" as ore is extracted. This procedure has been judged to be well adapted for mining of homogeneous oil-shale deposits.³

(f) Simultaneous recovery of oil, nahcolite (NaHCO_3), and alumina from oil shale has been proposed by the development of conventional mining procedures.⁴ Nahcolite may be useful for sulfur removal from stack gases with the production of Na_2SO_4 .

(g) In situ recovery requires fracturing and distribution of void space in deposits to allow hydrocarbon removal, generally after creation of a well-defined void fraction as in MIS (modified in situ recovery). Fracturing of the shale must produce

*Underground mining is discussed in "A Technical and Economic Study of Candidate Underground Mining Systems for Deep, Thick Oil-Shale Deposits," prepared for the U. S. Department of Interior, Bureau of Mines, by Cameron Engineers, Inc., Denver, Colorado, October 1976.

sufficient voids to allow retorting in place and oil recovery from wells. Rubbling may be accomplished by mechanical means or by chemical or nuclear explosions (see Chapter 3 for further comments). The broken shale will generally be distributed in size over a very wide range. Heating to remove gas and oil may be accomplished by hot steam injection, as well as by partial combustion; extraction with light hydrocarbon-solvent vapors has been suggested. Successful techniques for fracturing and subsequent in situ recovery have not been developed on a large scale, although substantial prototype studies are currently in progress for modified in situ recovery procedures (see Chapter 3 for further comments). Procedures have been developed for calculating the pressure distribution in fractured shale beds with gas flows.⁵

1.4 Oil and Gas Recovery from Oil Shale

The complete cycle for oil recovery is shown in Fig. 1.4-1, which has been reproduced from a 1968 U.S. Bureau of Mines report. The alternative paths involving either in situ processing or conventional aboveground recovery are clearly indicated.

Details concerning recovery up to 1973 may be found in a summary paper by Hendrickson.⁶ A historical overview of shale-oil production and of reserve estimates is given in Table 1.4-1. Technical aspects of shale-oil recovery processes are summarized in Table 1.4-2. The Tosco II process is shown schematically and described in Fig. 1.4-2; several other retorting procedures are described in detail in Appendix B in connection with our site-visit reports and are briefly summarized in Figs. 1.4-3 to 1.4-6.

Retorting or recovery efficiencies are expressed in terms of a Fischer assay. This is a retorting technique in which a 100-gram sample of oil shale is heated at a specified rate in an airtight aluminum retort, attaining a temperature of 932°F after 40 minutes. This temperature is then maintained for 20 minutes. As the kerogen decomposes, the pyrolysis products (shale oil, water,

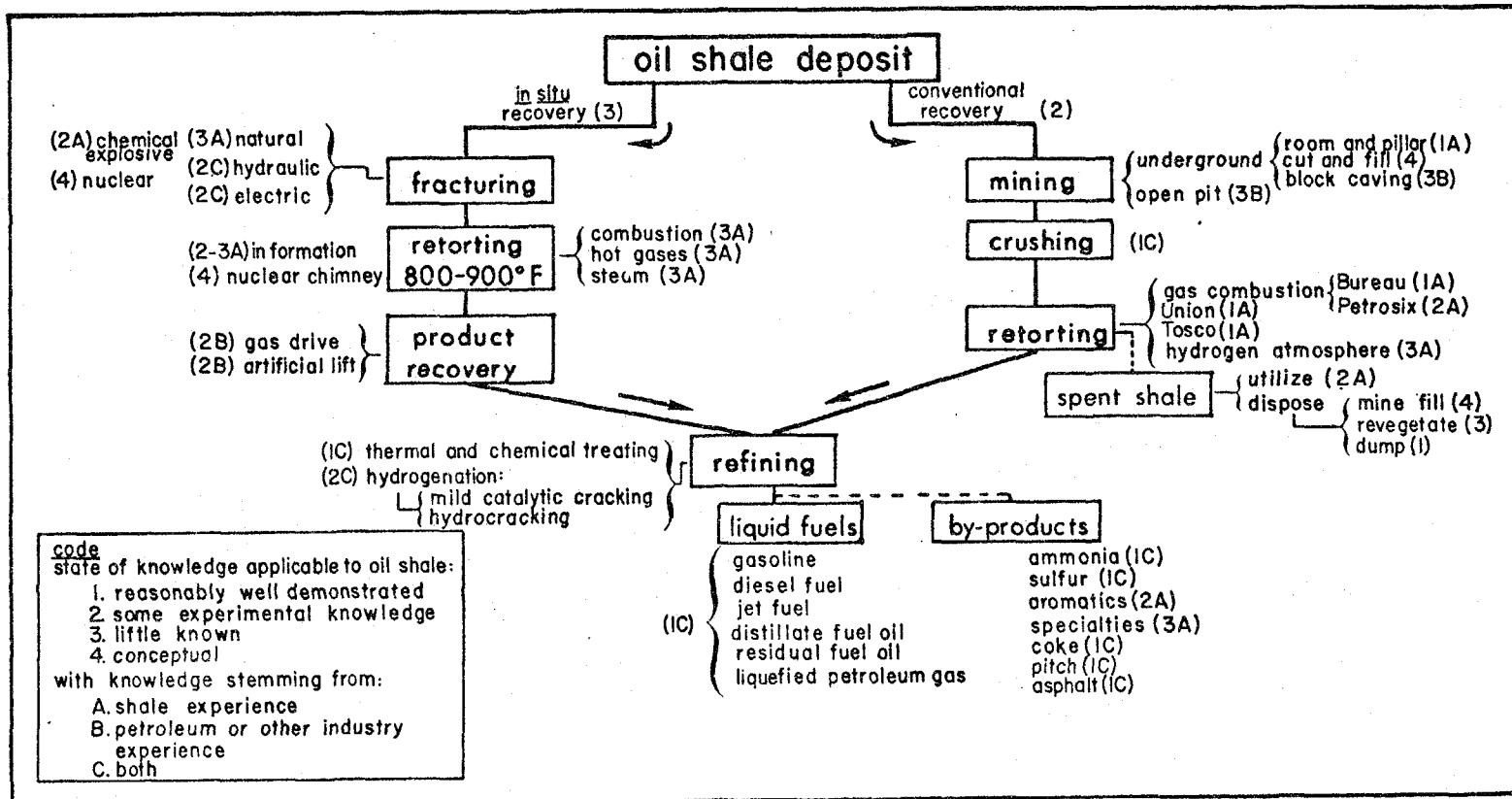


Fig. 1.4-1 Processes involved in oil-shale exploitation; reproduced from Prospects for Oil Shale Development in Colorado, Utah, and Wyoming, U.S. Department of the Interior, U.S. Government Printing Office, Washington, D.C., 1968.

Table 1.4-1 Historical overview of shale-oil reserves (in B_e = barrels of oil equivalent) and production. The data compiled in this table are based on information contained in articles by Charles H. Prien and by F. L. Hartley and J. Hopkins.

| Country | Estimated reserves; shale-oil contents | Time Period | Maximum Production |
|--------------|--|--|--|
| Sweden | $2.5 \times 10^9 B_e$ 12-15 GPT | Small plants during the twenties; production from 1944 to 1966. | 2×10^6 TPY of shale; 0.55×10^6 BPY of oil |
| Scotland | $600 \times 10^9 B_e$ ~ 22 GPT | 1859-1962; peak production during 1913. | 3.3×10^6 TPY of shale |
| France | $500 \times 10^6 B_e$ 10-24 GPT | 1840-1957; maximum throughput during 1950. | 0.5×10^6 TPY of shale |
| Spain | $280 \times 10^6 B_e$ 30-36 GPT | 1922-1966; maximum production during 1960. | 1×10^6 TPY of shale |
| Germany | $2 \times 10^6 B_e$ ~ 12 GPT | World War II to the present time. | -- |
| South Africa | $\sim 4 \times 10^{12} B_e$ 20-100 GPT, 55 GPT average | 1935-1962; maximum production during the fifties. | $\sim 0.3 \times 10^6$ TPY of shale; 0.28×10^6 BPY of oil |
| Australia | $270 \times 10^6 B_e$ 80-180 GPT | 1865-1925 and 1942-1952 in New South Wales | 0.1×10^6 TPY of shale (1935); 0.35×10^6 TPY of shale (1947) |
| | | 1910-1935 in Tasmania | 0.041×10^6 TPY of shale; 0.085×10^6 BPY of oil |

Table 1.4-2 Technical aspects of shale-oil recovery processes.*

| <u>In Situ</u> (IS) and Modified <u>In Situ</u> (MIS) Shale-Oil Recovery | | |
|--|---|--|
| Developer | Process designation | Novel design features |
| Occidental Petroleum Corp. MIS process for recovering oil from Colorado shales. | MIS (modified <u>in situ</u>) | About 20% of the underground shale is mined before fracturing to create voids. Retorting involves downflow combustion of residual coke with air. |
| Geokinetics process for recovering oil from Utah shales. | IS (true <u>in situ</u> retorting) | Adequate void space and proper distribution are obtained by heaving shallow beds with chemical explosives. When adequate void space is present, <u>in situ</u> retorting may be done. Rich oil shales in surface locations are retorted by horizontal combustion after explosive fracturing. |
| Aboveground Retorting of Mined Shale | | |
| Chevron processes for shale-oil recovery from Colorado shales (see Appendix VI of Section AB-5 for further details). | The Chevron B oil-shale retorting process has been designed to yield data on retorting kinetics, oil yields and qualities, spent-shale recovery, scale-up, etc. Product gases have high Btu contents (750 Btu/SCF initially and 950 Btu/SCF after acid-gas removal). The process utilizes fluidized-bed conversion. | |
| Lurgi process for retorting oil-rich chalk from Northern Germany (1938). | A tunnel kiln was used for retorting. | |
| Lurgi-Ruhrgas (L-R) processes (see Appendix II of Section AB-5 for further details). | Hot solids (e.g., spent shale) are used as heat carriers to retort the shale in a mixing-screw-type retort. Oil yields are above 95% of Fischer assay. Gas made in the process has a high heating value because air is not used for retorting and product-gas dilution is therefore minimal. | |

*Information summarized in this table has been taken, in part, from "Oil Shale--An Alternative Energy Source Whose Time Has Come" by Fred L. Hartley and John M. Hopkins, Union Oil Co., 461 South Boylston Street, Los Angeles, CA 90017, August 1980.

Table 1.4-2 (continued)

| Developer | Novel design features |
|--|--|
| Lurgi-Ruhrgas (L-R) processes (continued). | <p>Both a one-TPD and a 25-TPD have been operated recently. The L-R circulating system includes the following components: (a) a lift pipe to convey and heat the circulating, fine-grained heat carrier; (b) a collection bin to separate the combustion gas from the hot heat carrier; (c) a screw feeder which mixes the hot heat carrier and raw shale feed to induce retorting; (d) a surge hopper which provides surge capacity and time to complete retorting.</p> |
| Paraho processes for retorting Colorado shale. | <p>Downward (gravity) flow of shale is employed. Two operational procedures have been developed: (a) indirect heating by using hot recycle gas or (b) direct heating involving combustion of recycle gas and partial combustion of oil shale within the retort. Mixtures of oil droplets and vapor are produced at the top of the retort. Oil yields are about 93% of Fischer assay with direct heating and higher with indirect heating. Low-Btu gas (~100 BTU/SCF) is produced with direct heating and high Btu gas (~10³ BTU/SCF) with indirect heating. A 10.5-ft outer diameter, 75-ft high retort was run intermittently from 1974 to 1978.</p> |
| Rio Blanco processes for recovering shale oil from Colorado shales (see Appendix V of Section AB-5 for further details). | <p>Applications of MIS and of Lurgi-Ruhrgas technologies are being developed for shale-oil recovery.</p> |
| Superior Oil Co. process for recovering shale oil from Colorado shales (see Appendix III of Section AB-5 for further details). | <p>A circular grate retort is used for oil-shale processing. An adiabatic, fixed-bed retort has been designed to simulate the conditions encountered by solids traveling through the processing zones in a 200 TPD circular grate, moving bed. Product oil yields are greater than 98% of Fischer assay. The circular grate equipment has water seals between a stationary hood at the top and bottom windboxes.</p> |

Table 1.4-2 (continued)

| Developer | Novel design features |
|--|---|
| Tosco II process for retorting Colorado shale (see Fig. 1.4-2 for a detailed description). | <p>Oil shale is crushed to \geq 0.5-inch diameter, preheated with hot flue gas, and then fed to a horizontal rotating pyrolysis drum where heat is transferred from 0.75-inch diameter spherical ceramic balls to raw shale at retorting temperatures of \sim950°F. About two tons of balls are used per ton of shale processed. The oil vapors are condensed and cooled gases are subsequently recovered. The cooled ceramic balls are separated from the retorted shale in the drum and returned to the ball heater. Hot flue gas from the ball heater is used to preheat the raw shale to about 500°F and lift it to the separator. More than 100% of Fischer assay of the oil are recovered. A 1,000-TPD of shale plant operated from 1965 to 1972. Scale-up to about 11,000 TPD is under design.</p> |
| Union Oil Co. Retort A for processing Colorado shale. | <p>Upflow of crushed shale is used. Heat is supplied by burning the coke residue remaining on retorted shale. Between 1955 and 1958, a plant was operated that produced up to 800 BPD of oil from 1200 TPD of shale. Subsequent refining led to production of 13,000 B of gasoline and other liquid fuels.</p> |
| Union Oil Co. Retort B for processing Colorado shale (see Appendix I to Section AB-5 for further details). | <p>Upward flow of shale is used according to a procedure developed in a 3-TPD of shale pilot plant. A reciprocating piston within a feed cylinder pumps crushed solid shale upward through an expanding conical vessel. Recycle gas is heated by external combustion and flows counter-current to the shale and heats the shale. The retorted shale forms a free-standing pile at the top. A rake rotates above the surface of the pile to move the retorted shale down from the pile into an exit chute. Somewhat more than 100% Fischer assay are recovered as oil and gas. Liquid products trickle through the cool incoming shale and a liquid-vapor mist is carried away from the retort by circulating, cooled gases. The gas and</p> |

Table 1.4-2 (continued)

| Developer | Novel design features |
|---|---|
| Union Oil Co. Retort B for processing Colorado shale (continued). | liquid separate from the shale in a slotted wall section of the lower cone. A solids pump is located near the base of the lower cone and is at all times totally immersed in relatively cold product oil. The upflow system, as developed in this process, minimizes the oil residence time at high temperatures and thus reduces polymerization, condensation and coking. Furthermore, retorting occurs in a low-pressure regime and thus minimizes particle agglomeration, which may readily occur especially for very rich shales. |
| Chinese retorts operating at Fushun and Mao Ming, China, on relatively low-grade shale (~15 GPT). | The shale flows downward; heat for converting kerogen to shale oil is supplied by combustion of residual coke produced by retorting. The retort size has been limited to about 150 TPD of shale. Operational units have been in existence since about 1929. These units involve downward flow of shale. |
| Kiviter (U.S.S.R.) retort for processing Baltic kukersite (~ 50 GPT). | The shale feed (1- to 5-inch diameter) flows downward in narrow, parallel chambers where the shale is heated and retorted. Heating is effected by burning gas issuing from a central chamber located between the retorts; the burnt gases flow across the retorts to collection chambers. The two streams of retorted shale are combined and carbonaceous residues are burned off. The decarbonized shale is cooled by recycle gas and then discharged through water seals. The retorts process about 5,500 BPD of oil. |
| Galoter (U.S.S.R.) process for retorting Baltic kukersite (~ 50 GPT). | Hot spent shale is used to retort the shale feed (up to 1-inch diameter) in a rotary kiln. The carbon residue on the retorted shale is burned to supply heat for retort operation. The total USSR production of shale oil has been estimated to be about 25,000 BPD of oil. |
| Petrosix (Brazil) process for retorting Brazilian Irati shale. | Gravity flow of shale and hot-gas recycle (indirectly heated mode) are used to effect retorting. A plant producing about 25,000 BPD is under construction. A demonstration unit has been operating since 1972 at 2200 mt of shale per day. |

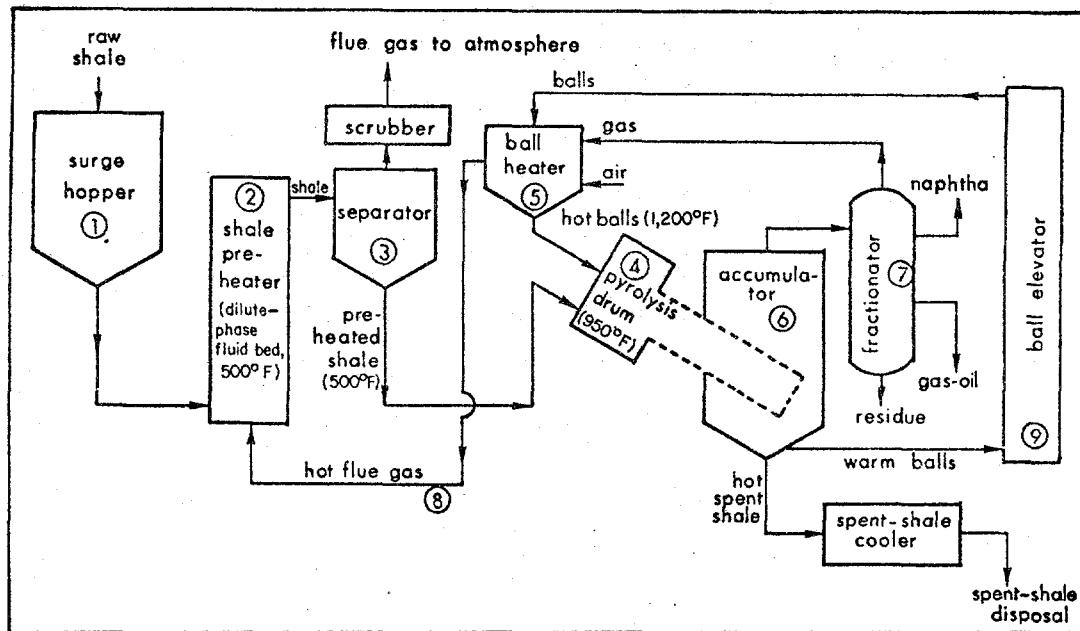


Fig. 1.4-2 Schematic diagram illustrating the Tosco II process for oil recovery from oil shale, which was operated during 1967 on a 10³ TPD scale.

Shale is crushed and processed through a surge hopper (1) before introduction to a preheater (2), where it is exposed to hot flue gases. It then passes to a separator (3), where flue gases are removed, and then to a pyrolysis drum (4) for mixing with ceramic balls from a ball heater (5). The hot shale ceramic-ball mixture enters a drum for efficient retorting in the accumulator (6), with the hydrocarbon vapors exhausting to the fractionator (7) for gas, naphtha, and gas-oil recovery. Flue gases (8) passing through the ball heater are used to preheat the shale. The ceramic balls, which have moved from the ball heater (5) through the pyrolysis drum (4) and the accumulator (6), are raised back up to the level of the ball heater (5) during passage through the ball elevator (9). The overall retort efficiency is over 100% according to a Fischer assay.

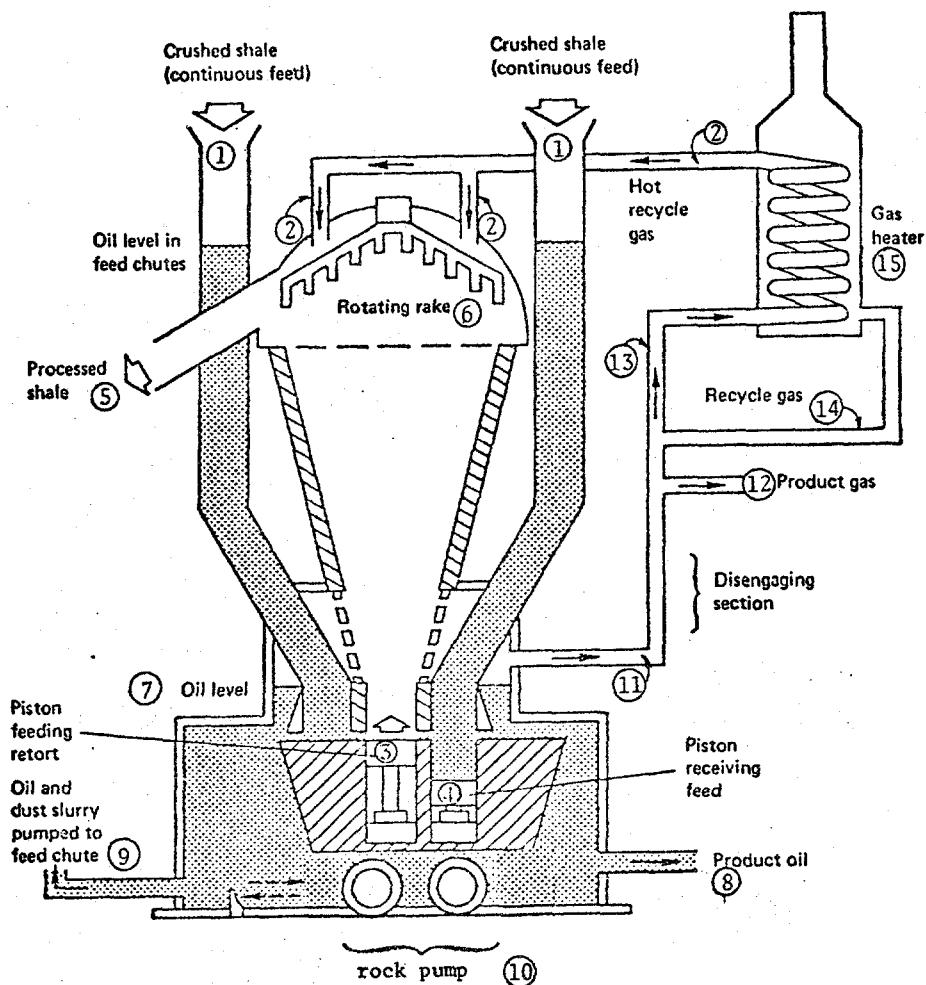


Fig. 1.4-3 Union B process, showing indirect heating of shale (Duir, 1977; Hopkins, 1976).

In the Union B indirect retorting process, crushed and screened shale is fed continuously (1) and is heated by hot recycle gas (2) in countercurrent flow. The shale is pumped upward in the conical, expanding chamber from the base through a piston solids pump which feeds the retort (3) after the shale has entered through this same piston receiving the feed (4). The solids pump in commercial applications will consist of a 10-ft diameter piston and cylinder assembly which alternately feeds shale to the retort and then moves over to take on a charge of raw shale; this solids pump is mounted on a movable carriage and is completely enclosed within the feeder housing and immersed in product shale oil. A complete cycle of the solids pump requires 1.5 to 2.0 minutes. The shale travels upward and spent shale is discharged (5) below a rotating rake (6) that serves to distribute the downward flow of hot recycle gas (2). The product oil flows down through the moving shale bed toward an oil pool (7) at the bottom of the retort. The product oil is withdrawn from the oil pool (8) and an oil and dust slurry is pumped from the base to the feed chute (9). The oil pool serves as a seal and prevents air from leaking into the retort. The oil pool also serves as a settling basin for entrained fines. Dual locations of the rock pump are indicated (10). The product gases exit (11) from the base of the retort and are then divided into separate streams (12, 13, 14). One stream (14) is burned in a gas heater (15) with air and the hot combustion products are used to heat the recycle gas that is returned to the retort. Thus, the recycled gas stream is not diluted by combustion products. The absence of combustion within the retort allows close temperature control and there have been no reports of clinker formation within the retort; oil recovery has been ~100% of Fischer assay.

A prototype rock pump is being designed to process ~5/8-inch size 35 GPT of shale and produce 10,000 BPD of oil; this unit is a scaled-up version of a ~1200 TPD unit operated during 1955-58. The retort will be 75 ft high, 35 ft in diameter at the top, and 10 ft in diameter at the bottom, with carefully-designed, sloping retort walls. The retort unit size is limited because pistons are not commercially available with diameters larger than 10 ft. Use of the Union B retort requires strong shale. Shale grades of 40 GPT experience a 12% compression for a pressure differential of 1 psig, thereby reducing the gas flow. It has been proposed to mine the entire mahogany zone with an average shale grade of 34.5 GPT. The product oil contains 2000-5000 ppm of solids.

The Union B retort has the following advantages: short shale residence time at high temperatures, minimal agglomeration even for rich shales; high mass velocities and throughputs per unit volume; low solids contents of the processed oil. A solid adsorbent step has been used to remove arsenic compounds. Liquid yields are ~100% Fischer assay and a high Btu gas (~900 Btu/SCF) is produced. Liquid product quality is excellent because retorting occurs at low temperature, low residence time, and in an oxygen-free environment.

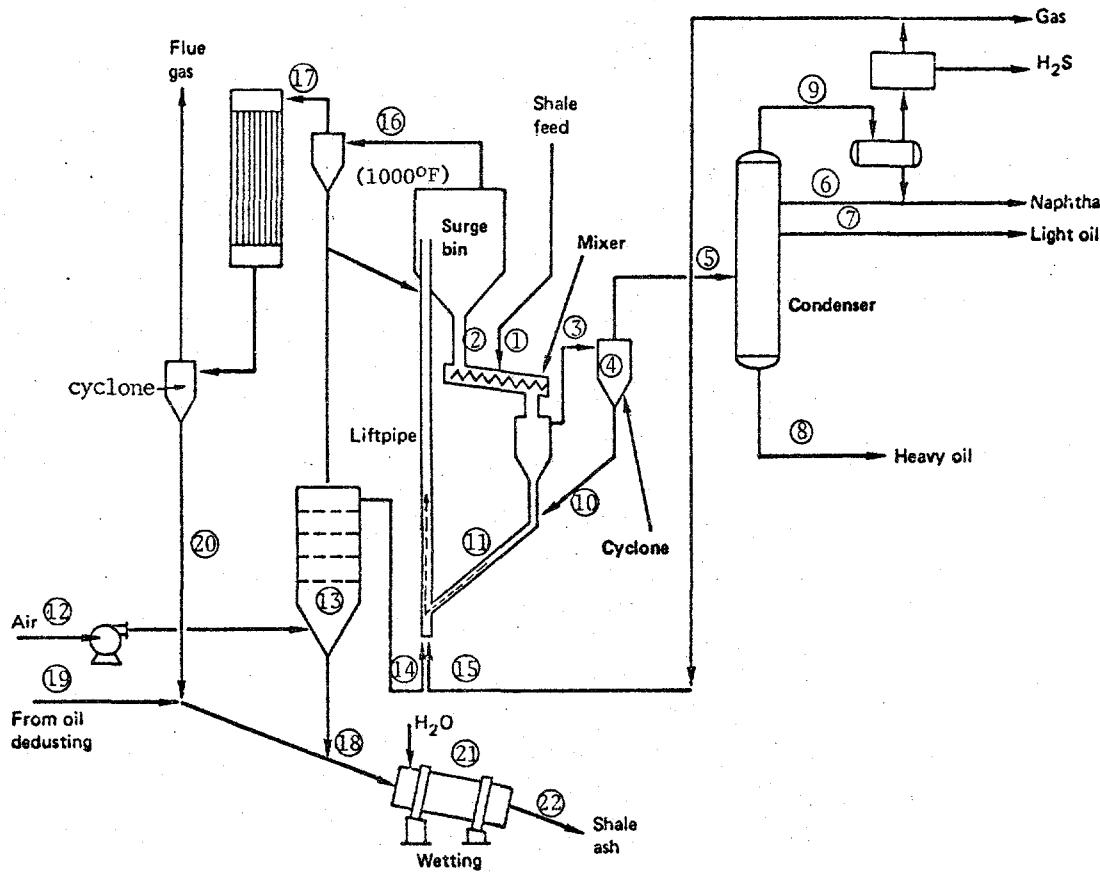


Fig. 1.4-4 Lurgi-Ruhrgas (LR) process for producing hydrocarbons from oil shale (Cameron Engineers, 1975; Sladek, 1975).

The LR process was developed during the 1950s for the low-temperature flash-carbonization of coal. It was applied to Colorado and European oil shales at Herten, F.R.G., in a 20 TPD plant, which has been disassembled. Larger plants of this type are currently under construction. Small ceramic balls were used for heat transfer in early work (LR I); the use of sand in the recirculating medium has allowed the production of ethylene from oil or naphtha (LR II); devolatilized spent shale is now used (LR III).

In the 20 TPD (LR III) operation, the shale was crushed to dimensions of 1/4 to 1/3 inch before feeding (1) to a mechanical (screw) mixer. In the screw mixer, the fresh shale feed is heated to 850-1100°F by intimate contact with 6 to 8 times the volume of spent shale arriving (2) from the surge bin. Retorting is completed in the surge hopper. Since rich shales disintegrate into a fine powder, the spent shale is supplemented by a sand feed when rich shales are used. A mixture of gas, oil vapors and dust is recovered from the mixer and passed (3) into a cyclone (4) for separation of dust from the fuel vapors. The fuel vapors (5) are then led to a condenser for separation of naphtha (6), light oil (7), heavy oil (8), and sulfur-containing fractions (9). Dust from the cyclone is combined (10) with spent shale from the mixer and fed (11) to a liftpipe together with air (12) that is compressed and heated by passage through spent shale (13) which has fallen from the surge bin. The heated and compressed air enters the liftpipe at 750°F (14) and raises the dust (10) and spent shale (11) to the surge bin. This lifting is accompanied by heating to about 1000°F with energy supplied by combustion of residual carbon remaining on the shale; if the amount of remaining residual carbon is insufficient, some of the product gas may be mixed (15) with the incoming air to provide a fuel-air mixture for combustion and heating. The heated shale from the surge bin (16) provides energy for the incoming compressed air (13) and is mixed with low-Btu flue gas (17) that may be used for auxiliary purposes. The spent shale (18) and dust from oil dedusting (19), as well as dust (20) carried in the flue gas and separated in a cyclone, are wetted down with water (21) to produce shale ash.

The following performance characteristics have been noted for the Lurgi-Ruhrgas process: the vapor products are not diluted by air, the oil yield is high (~110% of Fischer assay), combustion of residual carbon in the shale is nearly completed in the liftpipe, all of the mined shale is processed, emissions of SO₂ are minimized because of removal of this gas by reactions with alkali metal oxides, NO_x emissions are also reduced, the product is a pumpable oil, the spent shale is a stable product after water absorption, the overall water requirements are low, only commercially demonstrated process equipment (including the screw mixer) is used.

Scale-up of the screw mixer to handle up to 4400 TPD of rock is to be accomplished in commercial designs.

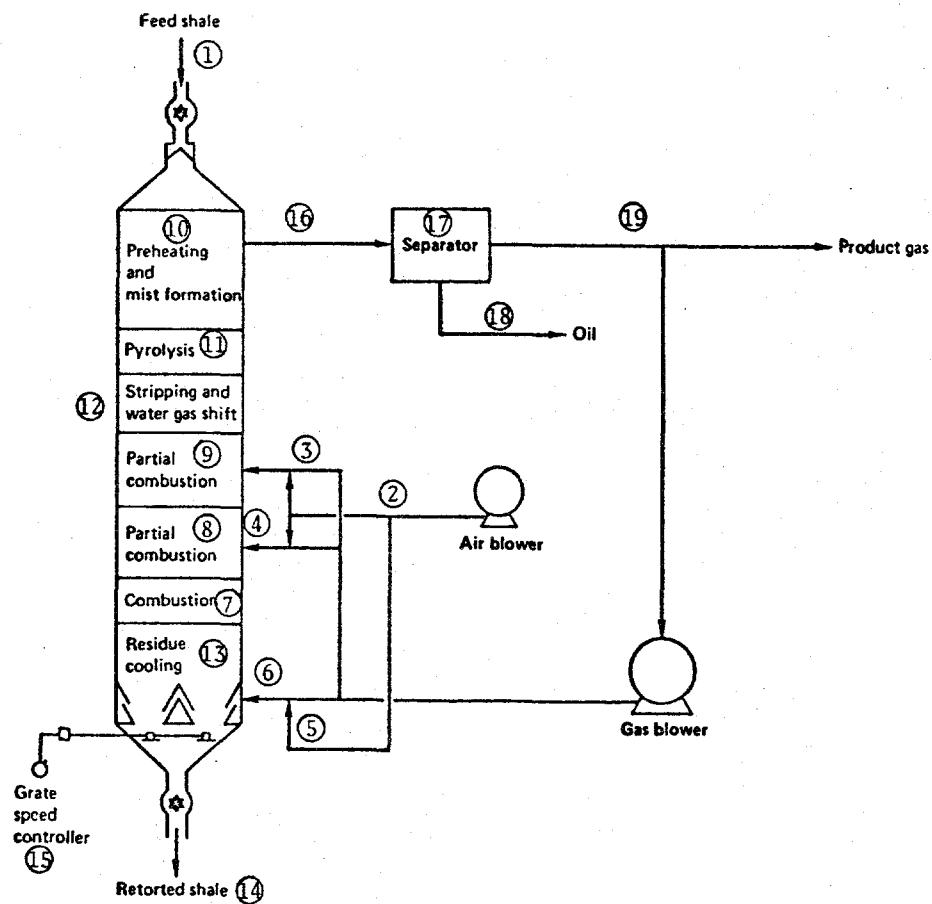


Fig. 1.4-5 Paraho process for extracting shale oil (Cameron Engineers, 1975).

Paraho has two retorts at Anvil Points (with internal diameters of 2.5 and 8.5 ft); these are stationary, vertical, gravity-fed, cylindrical kilns using direct heating of the shale with a residence time of ~6 hours in 25-ft long retorts (the height of a commercial retort will also be ~25 ft). Additional bed height of ~15 ft was available but was not used. The shale (with ~3-inch dimensions) is introduced at the top (1) through a rotating "pants leg" distributor. The operating pressure drop is 0.7 to 1.0 in/ft of bed. Compressed air (2) is introduced at three locations: near the middle of the retort (3), just below the center of the retort (4), and near the bottom of the retort (5) where it is mixed with product gas (6). Hot, rising gases are produced by burning of product gas (7) and by partial combustion of shale (8), (9) and move counterflow to the descending shale.

Heating of shale in the retort occurs throughout the retort in successive stages that may be classified as preheating and mist formation (10), pyrolysis of kerogen (11), and stripping of hydrocarbons from the shale accompanied by the water-gas shift reaction (12). About one quarter of the total residence time is believed to be spent in the retorting zone. Partial combustion of chars remaining on the heated shale (9) and combustion of added gas (7) provide the needed heat transfer for the retorting processes. After cooling (13), the retorted shale is removed at the bottom (14) through a grate speed controller with 0.5-inch grids (15). The fuel products are drawn off near the top of the retort (16) and passed through a separator (17) to produce oil (18) and product gas (19).

Injection of the gas-air mixture (6) (5) near the bottom of the retort allows recovery of much of the sensible heat from the spent shale. The temperature throughout the retort is controlled by adjusting the compositions of the gas-air mixtures (6) (5) and the air flow rates (3) (4) near the center of the retort.

The Paraho kiln will handle shale sizes up to 3 inches, thereby reducing the crushing and screening costs involved in processes requiring smaller shale sizes. The overall thermal efficiency is high because residual chars are burned and the hot, spent shale is cooled by the incoming gas-air mixture. The process is mechanically simple and cooling water is not required. The retort uses a rotating spreader made of carbon steel and a moving grate as the only moving parts. The shale grade has an important influence in the mist-formation zone (10) where a mist separator is employed. About 2% of the carbon remains on the shale. The flow-down retort is believed to be uniform. The bed porosity is about 40%, there are about 22,000 ft³ of gas per ton of rock, and 500 lbs of rock pass per ft² per hour in the existing retort. The off-gas is low-Btu gas (~140 Btu/SCF); if C₅⁺ compounds, H₂S and NH₃ are removed from this gas, the product will contain ~110 Btu/SCF.

It is claimed that Paraho spent shale becomes impervious after water treatment and compaction. The following spent-shale disposal scheme has been proposed: a liner of treated and compacted shale is filled with spent shale, covered with oil shale as a capillary barrier, and then topped with soil which could be revegetated. Water permeability through this reconstructed material was undetectably small for a simulated 2-inch rainfall.

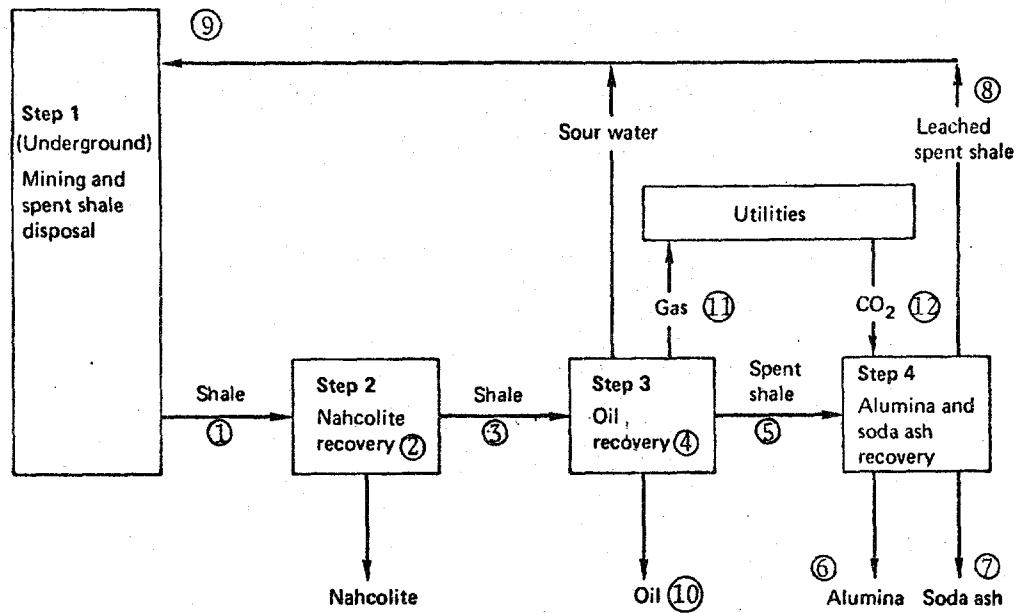


Fig. 1.4-6a Superior Oil multi-mineral process (Superior Oil, 1977).

In the 4-step Superior Oil multi-mineral process, mined shale ① containing brittle, discrete modules of nahcolite (sodium bicarbonate, NaHCO_3) is separated from the nahcolite ② by secondary crushing and screening, which is followed by "photosorting" to recover nahcolite product of greater than 80% purity. The remaining shale ③ is pyrolyzed ④ by using adaptations of the commercially developed McDowell-Wellman process, which is a continuous-feed, circular, moving-grate retort with good temperature control, separate process zones, and a water seal to eliminate contamination. Dawsonite $[\text{Na}_3\text{Al}(\text{CO}_3)_3 \cdot \text{Al}(\text{OH})_3]$ in the shale is decomposed in the retort to alumina and soda ash. The spent shale ⑤ is leached with recycle liquor and makeup water from saline subsurface aquifers; acid is then added to the resulting liquid to lower the pH so that alumina can be recovered after seeding ⑥. Finally, the soda ash is recovered by evaporation ⑦. The leached, spent shale ⑧ is returned to the mine ⑨ and the liquor trickles back to the processing of fresh shale.

The McDowell-Wellman pyrolysis process yields oil ⑩ and gas ⑪, some of which is burned for power production and for CO_2 generation; the CO_2 is injected ⑫ into the dawsonite-containing liquor to facilitate alumina and soda ash precipitation.

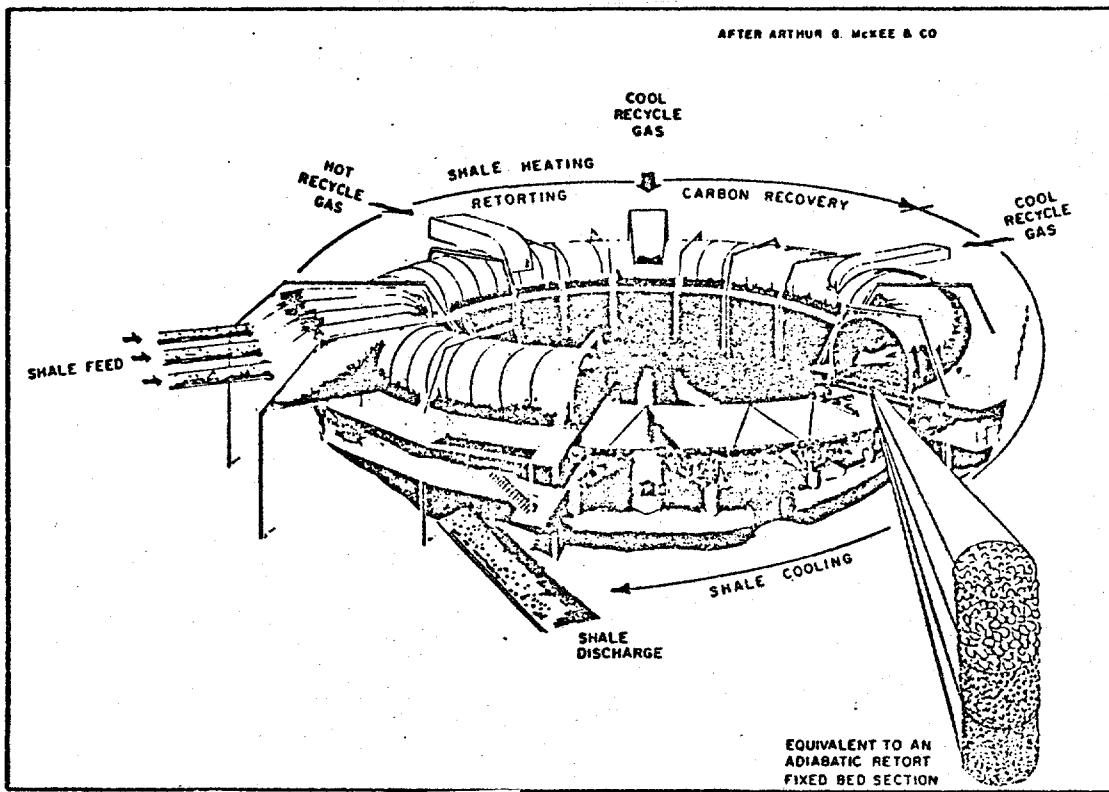


Fig. 1.4-6b Conceptual view of a circular grate retort.

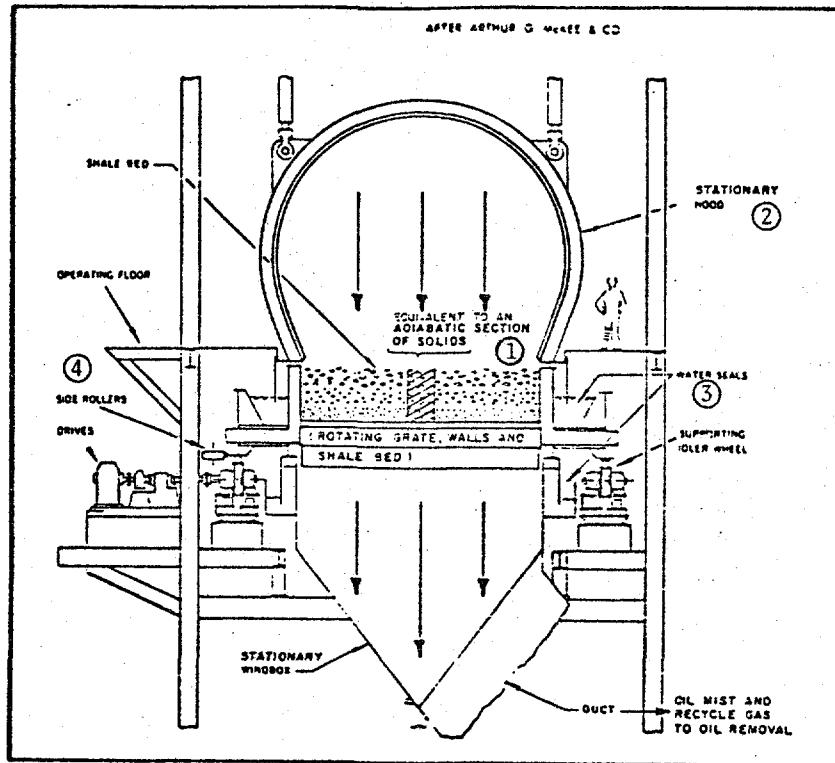


Fig. 1.4-6c Cross-sectional view of a circular grate retort.

Details concerning the Superior circular grate retort, which is an adaptation of the McDowell-Wellman process, are shown in Figs. 1.4-6b and 1.4-6c. Reference to Fig. 1.4-6c shows that the circular grate holding the shale bed and the retort walls (1) are rotated below a stationary hood (2) during shale processing. The retort is isolated through water seals (3) while rotation is facilitated by side rollers (4).

and noncondensable gases) are cooled to 32°F and collected. The shale oil is separated from the water by centrifuging in order to determine the shale-oil yield. Actual oil recovery may be somewhat greater or somewhat less than that obtained in a Fischer assay. The effect of thermal history on oil yield has been measured for selected shales.^{7,8}

1.5 Upgrading of Shale Oil

Upgrading of shale oil is being developed as an industrial technology. The now out of date U.S. Bureau of Mines process is illustrated in Fig. 1.5-1 for illustrative purposes only. The raw crude from the retorts [① in Fig. 1.5-1] is too viscous for piping and application and requires upgrading and purification (nitrogen-compound and sulfur removal) before use as feedstock at the refinery. The first step [② in Fig. 1.5-1] in upgrading involves fractionation to 650°F (40% of the total input) and coking (60% of the total input) to 900°F. Naphtha streams ③ and gas oil ④ are hydrofined using hydrogen (97% pure) from a separate hydrogen plant for syncrude production. Reference to Fig. 1.5-1 shows that 7.63×10^4 TPD of oil shale are converted to 5.93×10^4 TPD of burned shale in addition to 3.8×10^3 TPD of shale fines, 3.8×10^8 SCF/D of low-Btu gas, 5.29×10^4 BPD of raw crude; the ultimate products are 162 TPD of NH_3 , 74 TPD of S_x , 5.0×10^4 BPD of 43° API syncrude, and 820 TPD of coke, while 2.4×10^7 SCF/D of natural gas are consumed.

Physical properties of oil obtained from Colorado oil shale and Fischer assay products and calorific values are summarized in Tables 1.5-1 and 1.5-2, respectively. We note that the final product is of high quality, independently of the grade of ore from which it is recovered.

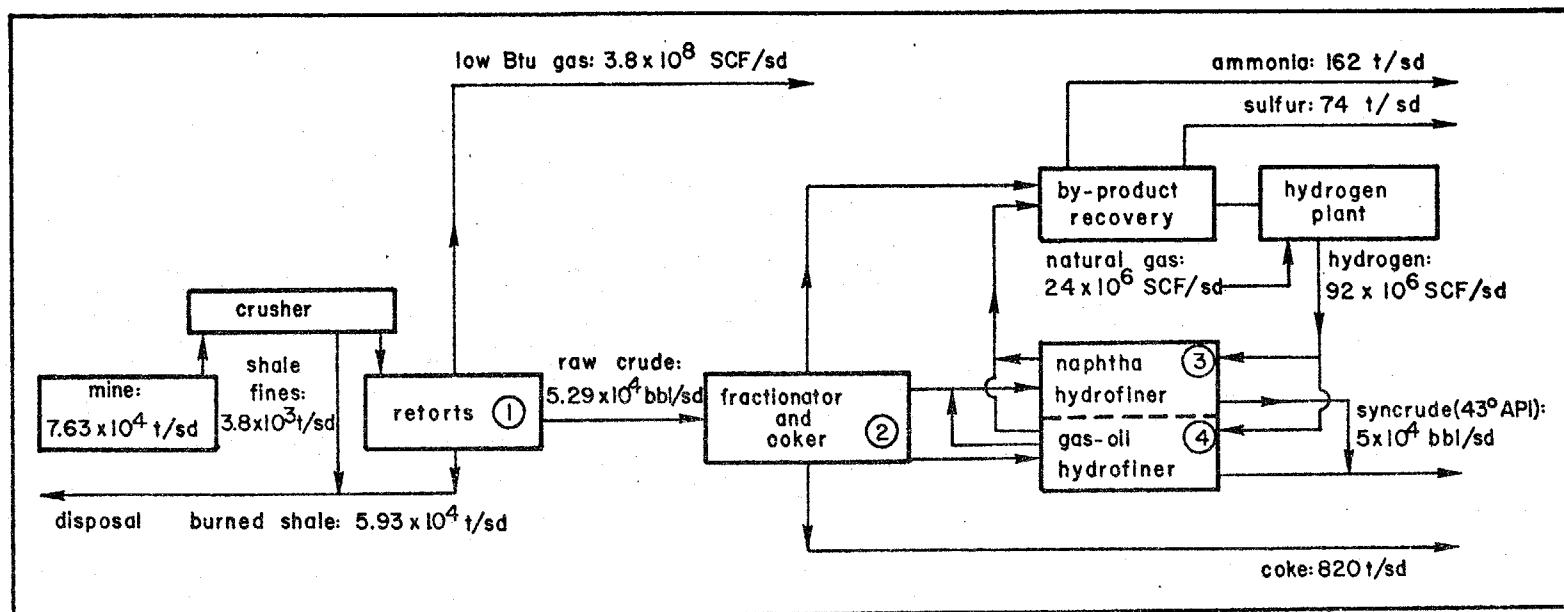


Fig. 1.5-1 Upgrading of oil from oil shale to syncrude using a gas combustion process; reproduced from R. G. Murray, "Economic Factors in the Production of Shale Oil," paper presented at the 74th National Western Mining Conference, Denver, Colorado, February 1971.

Table 1.5-1 Physical properties of shale oil derived from a Fischer assay of Colorado oil-shale samples; reprinted from T. A. Hendrickson, "Oil Shale Processing Methods," Proceedings of the 7th Oil Shale Symposium, Quarterly of the Colorado School of Mines 69, No. 2, 45-69 (1974). Copyright © 1974 by the Colorado School of Mines.

| | Low-grade shale | Medium-grade shale | High-grade shale | Very high-grade shale | Ultra high-grade shale |
|---|-----------------|--------------------|------------------|-----------------------|------------------------|
| <u>oil shale</u> | | | | | |
| grade, GPT | 10.5 | 26.7 | 36.3 | 61.8 | 75.0 |
| <u>Fischer-assay oil</u> | | | | | |
| weight % of raw shale | 4.0 | 10.4 | 13.8 | 23.6 | 28.7 |
| specific gravity at 60°F | 0.925 | 0.930 | 0.911 | 0.919 | 0.918 |
| kinematic viscosity at 100°F, centistokes | 20.71 | 23.72 | 18.19 | 17.12 | 17.28 |
| gross heating value, 10 ³ Btu/lb | 18.51 | 18.33 | 18.68 | 18.51 | 18.44 |
| pour point, °F | 80 | 75 | 85 | 80 | 75 |

Table 1.5-2 Physical properties and heating values of shale oil; reprinted from T. A. Hendrickson, "Oil Shale Processing Methods," Proceedings of the 7th Oil Shale Symposium, Quarterly of the Colorado School of Mines 69, No. 2, 45-69 (1974). Copyright © 1974 by the Colorado School of Mines.

| Raw shale | 10.5 | 26.7 | 36.3 | 57.1 | 61.8 | 75.0 |
|---|--------|--------|--------|--------|--------|--------|
| grade, gal/ton | 10.5 | 26.7 | 36.3 | 57.1 | 61.8 | 75.0 |
| gross heating value, Btu/lb | 1,020 | 2,340 | 3,080 | 5,510 | 6,010 | 7,000 |
| <u>Assay products</u> | | | | | | |
| oil, weight % | 4.0 | 10.4 | 13.8 | 21.9 | 23.6 | 28.7 |
| water, weight % | 0.5 | 1.4 | 1.5 | 1.2 | 1.1 | 1.5 |
| spent shale, weight % | 94.4 | 85.7 | 82.1 | 72.3 | 70.4 | 63.6 |
| gas, weight % | 1.1 | 2.0 | 2.2 | 3.9 | 4.2 | 4.6 |
| gas, ft^3/t of shale | 66 | 337 | 445 | 1,051 | 1,073 | 1,207 |
| weight loss, % | ----- | 0.5 | 0.4 | 0.7 | 0.7 | 1.6 |
| <u>Gross heating values of assay products</u> | | | | | | |
| oil, Btu/lb | 18,510 | 18,330 | 18,680 | 18,580 | 18,510 | 18,440 |
| spent shale, Btu/lb | 80 | 250 | 330 | 1,160 | 1,090 | 1,250 |
| gas, 10^3 Btu/t of shale | 49 | 255 | 453 | 973 | 562 | 1,214 |
| gas, Btu/ ft^3 | 739 | 758 | 1,018 | 926 | 897 | 1,006 |

1.6 Environmental Effects of Shale-Oil Production

According to Hubbard,⁹ 20 to 40% of the raw crude weight, or 2 to 4% of the rock weight, are produced as water, containing organic and inorganic contaminants. For example, after in situ gas-combustion processing, the following typical inorganic substances were found: 1.04 or 3.10 g/l of sodium, 1.68 or 4.45 g/l of sulfates, 8.91 or 4.80 g/l of ammonium salts, 14.44 or 19.22 g/l of carbonates, 5.43 or 13.41 g/l of chlorides, at a pH of 8.61 or 8.69. The water may be reclaimed in arid regions or it may be disposed of. Environmental effects and their amelioration are discussed in Chapter 6.

The spent shale amounts to 85 to 90% of the rock processed. Water run-off from this spent shale (except possibly in the case of in situ recovery) has a high level of mineral contamination, amounting to as much as 45 g/l. Thus, run-off diversion and containment may be required. Probably complete reconstitution, including planting, of the spent shale will ultimately be required.

1.7 Summary of Research Recommendations Derived from Site Visits

During an extensive program of site visits and discussions with project managers and program participants, we were informed by active workers in the field (see Appendix B for details) of research needs and opportunities relating to oil-shale technologies. Process-research and basic-research recommendations identified during these site visits are summarized in Tables 1.7-1 and 1.7-2, respectively. Elaborations of some of these recommendations are contained in Chapters 2 to 8, where we present detailed discussions of the FERWG recommendations relating to R&D needs.

Table 1.7-1 Summary of research recommendations derived from site visits (based on data in Appendix B), in addition to the following common problems: materials handling, spent-shale disposal, revegetation of spent shales.

| Applications (<u>In Situ</u> Recovery) | R&D Requirements |
|--|--|
| well field design | identification of natural anisotropy |
| retort preparation | technically feasible methods for producing permeability, including optimal placement of charges and timing of explosions; tracer studies to define flow patterns |
| retorting efficiency | models of retort flow and performance (non-uniform sweep efficiency, physico-chemical aspects of retorting) |
| scaling of retorts retort abandonment | models for scaling to larger sizes retort sealing |
| Oxy's MIS program | effects of MIS on regional water quality particulate and other emissions to the atmosphere subsidence; leachability of spent shale; construction of by-pass water flows on-site upgrading of retort waters; low-Btu gas utilization |

Table 1.7-1 (continued)

| Applications (Aboveground Recovery) | R&D Requirements |
|--|--|
| Paraho retort | <p>removal and handling of fines</p> <p>scale-up to larger sizes</p> <p>diagnostic measurements to verify modeling studies</p> <p>low-Btu gas utilization</p> <p>spent-shale disposal and revegetation</p> |
| Union Oil operations | <p>revegetation of extensively decarbonized shale</p> <p>disposal of spent shale</p> <p>clean-up of multi-phase mixtures and the development of efficient separation procedures for gases, liquids and solids</p> |
| Lurgi process | <p>handling of spent shale</p> <p>development of useful models to allow quantitative predictions of retort performance</p> |
| Rio Blanco operations | <p>scale-up of retorts in MIS, including optimal location and timing of explosive charges</p> <p>effective utilization of low-Btu gas</p> <p>open-pit designs for miner safety and efficient operation</p> <p>adequate modeling of regional hydrology</p> <p>materials handling on a very large scale, including mining, crushing, feeding, and spent-shale disposal</p> |

Table 1.7-2 Basic research needs identified during site visits.

| |
|--|
| Baseline data for regional air quality. |
| Models for pollutant dispersal in the atmosphere that are suitable for application in the Rocky Mountain regions. |
| Management and reconstruction of piles of spent shale. |
| Toxicological studies to identify potentially harmful trace elements that are mobilized by shale-oil recovery. |
| Classification of microbial cultures and of plants that are adapted to the changed environments produced by shale-oil recovery. |
| Development of regional models to facilitate quantitative assessments of socio-economic impacts produced by the development of a shale-oil industry. |
| Proper regional management of water run-off, especially during the spring times. |
| Development of techniques for shale beneficiation, including the possible use of microbial cultures. |
| Studies on (a) pyrolysis of oil shale in evacuated chambers; (b) rock mechanics and rock properties; (c) thermophysical properties of heated shales under dynamic loading; (d) adsorption and desorption kinetics of H_2S on shales; (e) reaction mechanisms and rates in heated shales; (f) developments of improved instrumentation for diagnostic measurements. |
| Creation of a centralized repository for shale cores and associated properties. |
| Development of compliance plans for integrated regional development. |
| Identification and monitoring of non-criteria pollutants. |
| Identification, classification, and quantitative measurements of possibly carcinogenic materials associated with shale-oil technologies. |
| Creation of water-permeable areas by shale-oil recovery and the proper long-term management of these regions; leachate transports to aquifers. |
| Mapping and performance of regional hydrological networks. |

REFERENCES

1. D. C. Duncan and V. E. Swanson, Organic-Rich Shales of the United States and World Land Areas, U. S. Geological Circular No. 523, Washington, D. C., 1965.
2. M. King Hubbert, "Energy Resources," p. 199 in Chapter 8 of Resources and Man, W. H. Freeman and Company, San Francisco, California, 1969.
3. W. J. Reynolds, "Mining Considerations for In Situ Oil Shale Development," Report UCRL-51867, Lawrence Livermore Laboratory, Livermore, California, July 1975.
4. B. Weichman, "The Superior Process for Development of Oil Shale and Associated Minerals," Proceedings of the 7th Oil Shale Symposium, Quarterly of the Colorado School of Mines 69, No. 2, 25-43 (1974).
5. J. F. Carley, "Pressure Distribution in Beds of Oil-Shale Rubble," Report UCRL-51957 Rev. 1, Lawrence Livermore Laboratory, Livermore, California, March 1976.
6. T. A. Hendrickson, "Oil Shale Processing Methods," Proceedings of the 7th Oil Shale Symposium, Quarterly of the Colorado School of Mines 69, No. 2, 45-69 (1974).
7. N. D. Stout, G. H. Koskinas, J. H. Raley, S. D. Santor, R. J. Opila, and J. Rothman, "Pyrolysis of Oil Shale: The Effects of Thermal History on Oil Yield," Proceedings of the 9th Oil Shale Symposium, Quarterly of the Colorado School of Mines 71, 153-172 (1976).
8. J. H. Raley and R. L. Braun, "Oil Degradation During Oil Shale Retorting," paper presented at a Symposium on Oil Shale, Tar Sands, and Related Materials, Division of Fuel Chemistry, American Chemical Society, San Francisco, California, August 29-September 2, 1976.
9. A. B. Hubbard, "Method for Reclaiming Water from Oil-Shale Processing," American Chemical Society, Division of Fuel Chemistry Preprints 15, No. 1, 21-25, March-April 1971.

CHAPTER 2

PROCESS-DEVELOPMENT AND RESEARCH RECOMMENDATIONS FOR ABOVEGROUND RECOVERY

2.1 Introduction

Process research for aboveground retorting systems has been practiced intermittently over the past forty years. Spurred by developmental programs in private industry and various governmental and federally-funded laboratories, the science of Western oil-shale retorting has progressed to the point that several commercial demonstrations are now in the formative stage. At least five viable aboveground retorts appear available. Additionally, variations of the five basic retort systems expand substantially the commercial mix potential. Some of the basic systems considered are shown in Table 2.1-1.

Second generation retorts have been under development at Chevron and have been suggested by Shell at the pilot-plant stage. Semi-works plants are being planned for these systems.

2.2 Process-Development Recommendations

A. Process Needs

Even with commercialization at hand, process-development needs may be identified. Some of this work may require partial federal funding. Since existing processes are subject to industry patent rights, it may appear unjustified to supply federal funding to meet these research needs. However, at least 80% of this resource is owned by the government. Future royalties will offset governmental investments many times.

The remaining problem areas should not impede commercial development. Rather, resolution should enhance production. Identified

Table 2.1-1 Aboveground retorts; other (non-U.S.) surface retorts (e.g., Petrosix, Kiviter, Galater) are also available for license.

| Category | Heating Mode | Retort |
|----------|----------------|--|
| Direct | Gas Combustion | Paraho Superior Dravo |
| Indirect | Hot Gas | Paraho Union B Superior Dravo |
| Indirect | Hot Solids | TOSCO II Lurgi Chevron |

problems include: (a) confirmation of spent-shale leaching, compacting, stabilization, and vegetation procedures; (b) handling of raw shale fines; (c) confirmation of retort scale-up; (d) carbon-value utilization for spent shales; (e) effective utilization of low-Btu gases; (f) clean-up systems for multi-phase mixtures of gases, liquids, and solids.

Mining, upgrading, and refining research needs are discussed in other chapters.

Preliminary studies have begun in many of the identified problem areas and need not be repeated here. The development of adequate models is the responsibility of a licensee in producing saleable technology. Licensors and others may appropriately require operating models for verification.

B. Spent-Shale Handling

Research needs are discussed elsewhere in this report. Extensive work (done at Colony, Union, Paraho, and the Colorado State University) during the last decade to identify and resolve problems must be noted. This work has been coupled with retort-development activities utilizing freshly spent shale. Thus, a substantial data base exists at the present time.

Three types of spent shale will be generated from surface-extraction systems: (1) minus two-inch shale with residual carbon values, (2) minus 1/4-inch shale with residual carbon values, and (3) minus ten-mesh (approximately) shale with low residual carbon values. Each must be treated differently to provide an adequate lay-down system.

In the handling of spent shales for long-term storage, an adequate definition of laydown criteria is necessary. Each developer will work out plans through RCRA. To establish an adequate R&D program, guidance to developers is necessary.

Many developers will construct zero water discharge systems for both surface and underground processing. Spent-shale leaching and compacting systems are high water users. Research could significantly lower water-use projections.

Vegetation of spent shale has been studied to some extent. The long-term stability of revegetated spent shale piles under field conditions needs to be demonstrated and an adequate assessment is needed for projected reclamation plans.

C. Raw-Shale Fines

Several processes do not utilize raw-shale fines in the retorts. Fines are produced during normal crushing operations. Depending on the retort, fines are generally minus 3/8-inch materials and represent between 5 and 8% of the mined shale. The present gas combustion and hot gas systems reject fines. The TOSCO II and Lurgi processes utilize the full range of shale fractions that is fed to the retorts.

Early developers may build combinations of retorts to handle fines. Others may agglomerate fines for further processing. This latter approach will require a research effort. It is not practical to store these fines for a prolonged period because of their high oil contents.

D. Retort Scale-Up

Confidence in retort scale-up will be an important problem for initial retort developments. Multiple modules are currently planned for commercial plants. Most of the developers are projecting commercial plants in the 50,000 to 150,000 BPD range. Furthermore, retorting modules are expected to produce 5,000 to 20,000 BPD while processing 8,000 to 30,000 TPD of shale. A retort element is considered to be a commercial module. Multiple modules will be

constructed on selected plant sites to meet planned production goals.

Some of the developers have tested operational plants using shale throughputs of 24 to about 1,500 TPD.

Cost projections to build a single module plant range from \$100 to about \$500 MM in 1980 dollars. These are high-risk investments. A primary goal in the construction of these modules is the confirmation of scale-up designs by demonstrating operability of commercial modules. Construction costs and operating needs will also be evaluated or confirmed. Furthermore, once initiated, construction to full commercial size must progress to make these plants economically viable ventures.

We see few opportunities for research that will significantly influence construction of the initial commercial modules. Following operation of these units, it is likely that R&D applicable for second generation plants will be identified and pursued.

E. Utilization of Residual Carbon Value

Except for the Lurgi and similar processes, substantial residual carbon values will remain in the spent shale. Because of the amounts of the spent shales produced, these values are significant and warrant further research. On reviewing various processes, efforts should be made to utilize these energy values by process modifications that are specific and appropriate for each retorting system.

The costs of proceeding with research for each system will be significant. Furthermore, there will be a natural reticence to revise a retort system during the commercial-size design phase by utilizing untested schemes. Timing is the key element. In any event, this technology should be ready after initial modules are proven and before plants are expanded.

Paraho and Union have described plans for carbon utilization in spent shales. TOSCO II, Superior, and Dravo retorts can also accommodate changes of this type and further work on developing efficient processes for carbon burning appears to be justified.

A suitable method of financing must be found for these important but peripheral developments.

F. Low-Btu Gas Utilization

The Paraho process using the direct heating mode, the Superior process, and the Dravo direct retort system produce low-Btu gas (100-150 Btu/CF). For each 6×10^6 Btu/B of raw shale oil produced, approximately 1×10^6 Btu of gas are formed, most of which may be impractical to condense.

This gas is of little value unless it can be utilized locally. Since significant quantities of this gas are produced, large residuals are available beyond process needs.

Construction of power plants has been projected. Because the environment in the rich shale regions is fragile, it may be best to limit industry to the production of oil in order to maximize energy returns to the country at acceptable total environmental costs.

Research is needed to find effective means for utilization of energy of the low-Btu gas at acceptable total environmental impact levels, including utilization of scarce or expensive resources such as water and infrastructure. Alternatively, process designs may be modified to produce gases with higher energy contents.

G. Product Clean-Up Systems

Crushed and spent shales are dusty. Raw shale produces water when retorted. Gas is produced or provides the heat transport in all systems. These systems coexist in product streams and require clean-up. Separating these products effectively requires further study. Research in these areas will require active production facilities for simulation purposes. The results would be of value to all developers and to federal agencies.

In performing this work, a close examination of water produced in the retorts should be carried out. Fines separation from the

product liquid and gas streams may also demonstrate a needed technology gap.

H. Shale Beneficiation

Novel techniques for shale beneficiation should be pursued because they may lead to improved resource recovery and process efficiencies.

2.3 Research Recommendations Relating to Aboveground Retorting

Fundamental work on aboveground retorting can play an important role in providing a technical basis for the development and improvement of industrial processes and should be given high priority. Such fundamental work may provide insights into processes other than thermal retorting (e.g., physical separation and collection of kerogen concentrates by beneficiation processes). Support should be broadly based and continuous, as is appropriate for the very large, undeveloped resource under discussion. We are here not concerned with specific studies that will serve to improve a particular aboveground retorting procedure. Instead, the following recommendations deal with broad fundamental studies that we expect to impact all shale-oil recovery schemes.

Aboveground retorting involves complex processes between solids, liquids, and gases and their mechanical, physical and chemical properties. A great deal of basic information and fundamental understanding is missing on many components of these complex processes. We list here some of the problems which need to be solved in order to gain information and understanding, which, in turn, may lead to more efficient management of resources and process control under environmentally acceptable operations of aboveground retorting. Many of the research requirements listed here are of equal importance in modified in situ and in situ oil-shale processes.

A. Physical Properties of Oil Shale

Information is needed on thermodynamic and transport processes within oil shale, including thermochemical data of feed and product components at retort temperatures, thermal conductivities, thermal diffusivities, compressibilities, permeabilities to liquids and gases, and mechanical stability. Acoustic and dielectric properties of oil shale are needed in monitoring some of the rubblization techniques.

Substantial additional work needs to be done on the rheology of oil shale, both under in situ and aboveground process conditions. What are the plastic flow properties of these materials and what types and strengths of cohesive forces are involved in agglomeration. What are the extents and rates of changes? What is the flow of these solid materials under retort conditions, whether gravity flow or upward pumping are applied?

Research is needed on multi-phase flows of the solid, liquid and gaseous materials which occur in aboveground retorts.

There are serious practical problems, as well as fundamental questions that should be understood in order to effect efficient separation of fines (small, solid particles) from liquid products and from gaseous effluents.

Heat and mass transfer are important between the various phases in retorting and need to be understood for different shales over likely operating ranges of the state variables.

The condensation of oil to form mists and liquids affects gas and solids flows and contributes to the destruction of oil under some conditions. The multi-phase, turbulent flows that characterize retort hydrodynamics need to be investigated and may well prove to be important in quantitative retort modeling.

Thermophysical properties of shales (heats of formation, heat capacity, thermal conductivity, density, porosity, etc.) need to be correlated as functions of composition (mineral matter, organic constituents, moisture) and temperature. The data base for these studies should include raw shale, as well as partially retorted, gasified and burned shales at varying degrees of conversion. These

correlations are necessary for interpretation of results of retorting and retort modeling.

B. Chemical Properties

Much additional information is needed on both the organic and inorganic components of oil shales, including compositions, variability of compositions with deposits, and structures of organic and inorganic components. The chemical mechanisms and rates of thermal decomposition and degradation are insufficiently understood. Further studies are necessary on kerogen pyrolysis, mineral reactions, and oil-degradation mechanisms (including coking and cracking). The role of inorganic components as catalysts is unknown. The chemistry of nitrogen and sulfur, as well as that of trace elements in both organic and inorganic components, is important for process development, refining, and pollutant control. Combustion processes involving solids, liquids and gaseous products need to be determined accurately, including adequate descriptions of reaction kinetics. Better knowledge of the kinetics of residual carbon burn-up is necessary for optimization of shale-oil recovery processes.

Measurements of rates of production or change of various species need to be made for drying, retorting, gasification, and combustion. These data should be used to develop empirical kinetic expressions for important reactions taking place and to make inferences as to mechanisms. The kinetics will be needed for reactor modeling and data interpretation. A good understanding of mechanism will allow limited extrapolations beyond the available data base.

The needed basic research should encompass experimental and theoretical work, including extensive modeling of complex systems in order to define the effects of generic process variables on hydrocarbon products, spent and burned shales, and gaseous and liquid effluents. This information will be valuable to developers of industrial processes, as well as to those responsible for defining environmental regulations.

C. Materials Handling

Another important area for fundamental research is materials handling. All shale processes require the handling and movement of large quantities of solids, liquids and, in many cases, almost equally large masses of gas. Correlations need to be developed which describe solids transport, cyclone collection, and fluidization behavior of solids encountered in shale processing. These correlations must account for the wide size distributions of irregularly shaped particles obtained when shale is crushed by various approaches.

Solids may be moved during processing by gravity flows, mechanical transport, or suspension in fluids. Although crushed oil shale, when cold and dry, flows freely through pipes and other parts of a retort system in accordance with generally understood engineering principles, it often fails to do so under processing conditions. The effects of the presence of liquids and of hot products formed from kerogen on the surfaces or interstitially in oil-shale particles should be studied to determine their influence on cohesiveness and flows. The generation, condensation and evaporation of liquids (oil and water) under conditions encountered in processing must be better understood.

Solid properties important in disposal and compaction of spent or burned shale, and changes caused by different process conditions, must also be better defined.

Promising methods for materials handling in oil-shale recovery involve applications of fluidized bed and entrained solids processing. While these technologies are well advanced in such applications as catalytic cracking of oil on well controlled solid catalysts, they remain to be applied successfully to shale retorting for which the solids are not well controlled with respect to physical and chemical properties. Fundamental research should be done in this area. These studies should include work on the physical and chemical properties of various shales as they relate to process conditions in fluidized and entrained-solid combustors.

CHAPTER 3

PROCESS RESEARCH RECOMMENDATIONS FOR IN SITU RECOVERY

3.1 Overview

In situ processes involve extraction of oil from the rock in place. This procedure is attractive because its use would avoid the cost and environmental consequences of removing oil shale from the ground and disposing of spent shale. The principal problem is that most oil shales are effectively impermeable to the heat transfer fluids that are used to decompose kerogen, and the conductivity of the rock is too low to permit heating by conduction.

Most in situ processes depend on the ability to produce adequate permeability by some process such as explosive fracturing or on finding sites where adequate permeability exists or can be produced by the dissolution of locally occurring soluble minerals. Attempts to date have not shown the feasibility of using these methods in general.

Several possibilities utilizing special circumstances have been shown to be useful or to have technical feasibility. One of these (Geokinetics) involves explosive fracturing at such shallow depths that the overburden is permanently displaced upward, thereby providing adequate permeability. Air is injected and a burn front is propagated horizontally to produce shale oil. Control of blasting to obtain uniform and adequate permeability may need some improvement. Loss of gases through cracks to the surface is a serious operational hazard and an environmental problem, as well as a process problem. Product collection and gas-handling problems are similar to those encountered in modified in situ processing.

Another true in situ process that shows promise is RF heating. Some configurations of electrodes may allow quite uniform heating of oil shale. With uniform distribution of heat in a

volume, the kerogen decomposes and generates sufficient gas pressure to drive out shale oil through the pores that were previously occupied by kerogen. Feasibility of this process remains to be demonstrated in the field. Water may interfere and prevent uniform heating. Suitable electrodes and power supplies need to be optimized and the economics further evaluated. The total electric power consumption is ~ 400 $k_e h/B$ of raw shale oil.

Modified in situ (MIS) processes are defined as those in which some rock is removed by mining to make a limited amount of space underground (generally 20-30%). This space is then distributed in broken rock by a combination of blasting and mining processes to produce an underground retort. A combustion process is used to drive a flame front downward through the retort and produce oil, which is collected at the bottom and by condensation of vapor in the off-gas. An alternative approach involves construction of the retort in a geometry that is suitable for horizontal movement of the flame front.

Several companies (e.g. Occidental Petroleum and the Rio Blanco Oil Shale Company) have conducted field tests of this method. The rock mined to make space underground may be processed in surface retorts.

Of the in situ operations, MIS is the most promising available at this time. The level of activity by industry has been strongly influenced by direct and indirect government support. Occidental Oil Shale, Inc. receives both money and technical aid for research and development at Logan Wash. The work by the Rio Blanco Oil Shale Company on tract C-a and Cathedral Bluffs on tract C-b is supported, to a substantial degree, through lease provisions. Firm statements concerning commercial readiness should preferably be based on successful operation of large-scale demonstration units.

3.2 Status and Technical Uncertainties of MIS

Construction and retorting are the two basic processes occurring in MIS. These must be integrated into a system underground that produces shale oil at competitive cost and provides acceptable recovery of the total resource in place. At the present time, seven individual retorts have been constructed and retorted with varying degrees of success. No integration of multiples into a practical system has yet been attempted.

Major problems that must be resolved before MIS technology may be judged to be ready for commercial applications include the following: (a) retort preparation (sweep efficiency of retorts), (b) resource recovery, (c) gas cleanup, (d) process control including ignition, (e) containment of process gas in the retort (i.e., separation from the mine), (f) efficient and environmentally acceptable management of process water, and (g) long-term stability of retorted shale to leaching. There are almost certainly feasible technical solutions to all of the listed problem areas.

3.3 Retort Preparation

The basic requirement in construction of a retort is to obtain a porosity that is adequate for gas flow and sufficiently uniform in permeability so that a high fraction of the bed will be swept by the retorting flame front. An additional requirement is the construction of retorts of the required size (large) at acceptably low costs. Large blocks that cannot be retorted effectively must be avoided; the presence of fine material, which causes a high pressure drop and prevents easy draining of absorbed oil, must also be minimized.

Construction methods may utilize both blasting and drawing technology to distribute void space in broken rock. To date, only blasting into mined void has been used. Drawing involves the

movement or flow of broken rock within and through an underground opening. In this process, the rock may be further broken and the space redistributed. Utilization of drawing processes may make possible the development of low-cost methods of producing retorts with uniform permeability.

Workers at Occidental have experimented with various geometries of mined void space and have developed an elaborate blasting sequence utilizing carefully controlled delays to obtain a reasonably uniform permeability in their latest retort (#6). However, attempts to retort #6 with high sweep efficiency were not successful, probably because of collapse of the overhead sill pillar during retorting. Analyses of flow data available before collapse indicate that the sweep efficiency should have been better than that actually obtained (65% estimated). Although total recovery from Retort #6 was only 40% (54,000 B out of 133,300 B in place), the results seem to indicate that the method used can be made technically successful for a single retort. There are different opinions on whether the cost is acceptable on a commercial basis. Allan Sass of Oxy has stated that currently estimated costs are sufficiently low to make MIS commercially viable at the present time and cites a company commitment of $\$100 \times 10^6$ since 1977 for commercial production of 94,000 BPD on Federal tract C-b jointly with Tenneco (Cathedral Bluffs Oil Shale Co.).

Fundamental studies of the behavior of explosives and of rock compression during early times are in progress with the objective of improving our understanding of rock fracturing. The available methods of calculation are not readily applicable to oil shale during unloading following explosive compression. In addition, the presence of omnipresent fractures, bedding planes, and other flaws critical to the process cannot be considered realistically in this approach. Fortunately, mining techniques can be used to determine empirically the appropriate hole spacings and explosive loads that are needed to fracture the rock to appropriate size.

Alternative approaches to retort construction are possible by utilizing mining and drawing techniques, but these methods have not been applied to oil shale. A substantial experimental and developmental program in an active mine will be required to investigate applicability of these methods.

Commercial development of MIS technology may well depend on the successes achieved in retort preparation. A sustained program will require access to a suitable mine in oil shale; this problem is further discussed in Chapter 4.

3.4 Resource Recovery

The resource recovery achieved is the product of the fraction of oil recovered in processing an underground retort and the fraction of the resource that is contained in retorts. Unless retorts are closely spaced, both vertically and horizontally, a substantial part of the resource will not be recovered. Resource recovery using MIS will exceed resource recovery using room and pillar mining and surface retorting only when room and pillar mining is not suitable for the geometry of the resource. Resource recovery for MIS may also be competitive if the cost of MIS is low enough to allow processing of part of the resource that cannot be economically processed by other methods.

Safe operation will depend on the ability to maintain retort integrity and isolation for close spacing of retorts. Here, again, advances in mining and underground processing technology are required to provide both safe operation and close spacing of retorts.

3.5 Gas Cleanup

A large amount of gas must be handled in an MIS retort. This gas has a very low energy content and making it acceptable for release may lead to an appreciable incremental cost for shale-oil recovery; existing technologies may have to be improved.

In a process using a mixture of 30% steam and 70% air as the inlet gas, the mass of dry outlet gas will be almost 60% of the mass of shale processed. On a volume basis, the gas amounts to 420 m^3 (15,000 SCF) at STP of dry outlet gas per Mg of shale processed. Technologies exist for cleaning and upgrading of retort gases but economical methods for treatment of this huge amount of gas are essential for commercial process success.

3.6 Process Control

Good progress has been made in understanding the effects on shale-oil yield of inlet gas compositions and flow rates, particle sizes, shale grade, and retorting rate. Further progress is needed in each of the following areas: (a) control of retorts with moderate permeability contrast, (b) ignition under field conditions, (c) monitoring and control of retorts when operational problems arise (for example, selective channeling in the retort), (d) effects of water influx on yield and performance, (e) effects of large changes in shale grade, (f) variations in chemical compositions of the shales used, (g) diagnosis of retort outputs and other diagnostic procedures, (h) use of retort models for design and process control.

3.7 Containment of Process Gas in the Retort (Separation from the Mine) and Reduced Leaching from Spent Shale

Process gases contain large amounts of CO and H₂S, which could be lethal if significant flow occurs into occupied mines. Increases in the lengths of retorts and/or the rates of retorting are desirable from a commercial standpoint and will result in closer spacing of retorts. If larger retorts are used, larger pressure differences and reduced ease of containment will accompany commercialization. Cementation of spent retorts may decrease the likelihood of accidental releases by closing the spent retort and preventing it from becoming a source of toxic gases, leaching by groundwater of spent shales, or producing ground movements in the mine that could open flow paths. Containment is a development problem that may require substantial advances in the technology of underground engineering if it is to be done successfully.

Current research dealing with these problem areas is supported by DOE. To achieve near-term resolution of problems, continuation and perhaps augmentation in R&D support will be required.

3.8 Conclusions

Almost all of the present oil-shale budget of DOE is devoted to support of the MIS process, with the exception of generic and specific environmental studies relating to aboveground processing. A substantial part of these funds is earmarked for industry under the PON programs and additional money is being spent in the field by workers from government laboratories offering direct technical support. Under this program, Occidental will construct and operate Retorts #7 and #8 in FY81 and 82. Additional measurements will be made by DOE (Sandia) during this same period of time. Results obtained in the DOE support program will become public information while the results of privately funded R&D on fracturing will remain proprietary. Workers at the Rio Blanco Oil Shale Company

have recently operated their Retort 0 and are expected to operate Retort 1 during 1981.

Development beyond these currently defined plans is uncertain at the present time. It appears that the major industry thrust will deal with development and commercialization of surface shale-oil recovery processes. Continued R&D on MIS processes beyond 1981 or 82 may therefore depend on the role that DOE or another federal agency assumes in this area.

A balanced program is essential for success. Access to an experimental mine will be required. Much of the laboratory work on MIS is also applicable and pertinent to surface retorting. Both experimental mining and laboratory work on MIS should include the development of adequate understanding and of base technology that will be useful to the industrial concerns engaged in this type of resource recovery.

CHAPTER 4
RESEARCH RECOMMENDATIONS ON MINING

4.1 Introduction

An oil shale industry will require very large mining operations compared to present U.S. mining operations in the coal or metal industries. The amount of rock that must be mined is shown in Table 4.1-1 for underground mining, open-pit mining and MIS.

4.2 Open-Pit Mining

Open-pit mining is probably most advanced because of developments in mining low-grade copper deposits and iron ore. It is suitable for much of the resource if it is done on a large scale and will allow low-cost removal of most of the resource. Research needs include studies of slope stability, dewatering on a large scale, methods of placement of spent shale in the pit, and a plan for location of pits for maximum resource utilization and minimum environmental costs. This information will be useful in developing federal leasing policies.

4.3 Underground Mining for Surface Processing

The thickness and extent of oil shale present a new mining problem for mining engineers. Low cost methods for mining thick beds of oil shale with high resource recovery are primitive or nonexistent. Room-and-pillar mining methods have been developed and are suitable for beds 60 feet thick. This method may be applied

Table 4.1-1 Mining operations for shale-oil recovery.

| Mining Method | Grade, GPT | Special assumptions; material mined in mine development, i.e., for access, ventilation, shafts, etc. is not counted. | Amount mined in TPD for 1×10^6 BPD shale-oil recovery |
|--------------------|------------|---|--|
| underground mining | 30 20 | net retort recovery = 95% | 1.47×10^6 2.21×10^6 |
| open-pit mining | 20 | stripping ratio = 0.5:1; net retort recovery = 95% | 3.32×10^6 |
| MIS | 20 | 25% is mined and not retorted; net retort recovery efficiency = 48% = (sweep efficiency of 80%) x (retort recovery of 60%) | 1.46×10^6 |
| | 20 | 25% is mined and retorted at the surface ; net recovery efficiency = 60% (48% from MIS and 95% from mined shale, i.e., 40% of the shale oil is produced in surface retorts) | 0.88×10^6 |

to somewhat thicker beds with further development. Roughly half to two-thirds of the bed may be recovered with this method. It is relatively low in cost and applicable to relatively thin beds of high grade oil shale (30 GPT or more) in the southern part of the basin. Research and development is needed to find methods suitable for the thicker beds and to improve the fraction that can be extracted.

The great bulk of the resource occurs in the north central part of the Piceance Creek Basin, where oil shale of 20 GPT or more is from 400 to 2000 feet thick. Even in the southern part, substantial amounts of oil shale are in beds 100 or more feet in thickness.

No method exists for underground mining that meets the requirement for high resource recovery at low cost. A substantial improvement in mining technology is required to provide the basis for wise development of this huge resource in the decades and centuries to come. A broadly based approach is required, including studies of rock mechanics, fracture and flow properties of oil shale during drawing operations, methods of roof control and controlled subsidence and disposal of spent shale (both underground and on the surface). Regional problems, such as maintenance of ground water purity and control of methane and H_2S production in mines, should be studied.

This work is necessary to provide a basis for efficient future recovery of the enormous available resources.

4.4 MIS Mining

An important requirement in mining for MIS is a low-cost production method that will produce underground retorts with uniform permeability. A second requirement is development of underground technology to allow the construction and operation of retorts in a safe and efficient manner.

A method for producing single retorts involves the mining of openings (rooms for example) and blasting of rocks into these openings. A large retort requires multiple rooms and support pillars to prevent premature collapse. Blasting then requires a complicated and precise sequence of detonations to destroy the pillars and blast into the rooms in proper sequence. Precise distribution of explosives is needed to obtain acceptable distribution of porosity. This method may be difficult and expensive to control on a production basis but technical feasibility has probably been achieved by Oxy and DOE at Logan Wash.

An alternative procedure is to utilize drawing methods for material removal and distribution of porosity. In this method, rock is broken by blasting into an open or partially open space. Broken rock or rubble is then allowed to flow (by gravity) out of the opening through draw points, where they are removed to the surface to offset underground volume changes. The gravity flow or drawing operation will cause further breakage of rock and redistribution of void space. These methods are suitable for large-scale, low-cost mining operations. In several mining methods, draw operations are used and variations appear suitable for use in the construction of retorts. This technique has not been applied to MIS. The method may allow the low cost construction of suitable retorts.

Construction and operation of many MIS retorts in a mine in a safe and efficient manner will require substantial advances in underground technology. Efficient resource utilization will require close spacing, both horizontally and vertically. The need to process the retorts rapidly and the preference for tall retorts both lead to the requirement of increasing the pressure in the retorts. Small separations between retorts and large pressure drops may make it more difficult to keep retort gases out of the mines.

Other problems include mine dewatering, retort abandonment, ground control and subsidence, product collection and removal, and resource recovery.

Basic advances in mining technology are essential in proceeding toward large-scale commercialization of MIS processing.

4.5 Need for A Large-Scale Facility for Mining Research

There are many shared problems in underground mining of oil shale and in mining associated with MIS. Most of these require for study a mine where mining research can be done on a substantial scale in the field. Laboratory and theoretical work will be needed to support field experimentation, but field experimentation in a mine is essential. Experiments of this type are not generally compatible with the operation of a commercial production mine. The magnitude of the resource and the benefits to be achieved justify establishing a central mining facility and providing an operating budget and an institution to operate it.

An "Oil-Shale Mining Institute" might be established to operate the facility and to perform supporting laboratory research and theoretical work. It could be managed by a university or a group of universities in collaboration with interested industrial participants. In addition to investigating innovative approaches including automated techniques and otherwise advancing the state of mining technology in oil shale, this institution would serve the important function of providing a source of trained mining engineers for the country.

CHAPTER 5

INSTRUMENTATION IN SHALE OIL RECOVERY*

All of the methods proposed for shale-oil recovery involve complex processes and many operations: mining, retorting (in situ, modified in situ, or aboveground) to effect oil and gas recovery, separations, environmental monitoring of surface restorations, and mine security. The need is very apparent for adequate instrumentation to assure safe, reliable, and efficient operations of all phases of these complex processes. There is also need for process instrumentation to monitor and control sequential operations in shale-oil recovery. Finally, there is need for instrumentation in research and development accompanying the growth of the industry. A multi-billion dollar oil-shale industry is projected and that entire industry, including research, development and process control, needs to be backed up with adequate basic research and the instrumentation necessary to perform the research. We endorse recommendations derived in prior studies by NRC/NAE and other committees, in which a strong case is made for adequate funding of basic research in science, engineering and instrumentation in order to promote and support the development of the oil-shale industry. There is no doubt that the various processes can and will be made to work. There is, however, much room for improved instrumentation to facilitate operational steps.

The total 1980-81 budget of the oil-shale research and development program of the Department of Energy was \$36 million, of which approximately \$32 million are allocated to field operations.

*For a listing of instrumentation needs in fossil energy processes, see "Instrumentation and Control for Fossil Energy Processes," May 15, 1980, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California.

There remains then about \$4 million which is placed under the title of Instrumentation. However, it must be recognized that what is meant by that title includes a composite of measurements, surveillance experiments, and some instrumentation. The funds actually available for research and development on instrumentation are a small fraction of the \$4 million. Instrumentation for research and development for environmental monitoring and studies is funded through other sources. Major parts of the entire instrumentation program, including field measurements and surveillance, are carried out at Sandia/Albuquerque and the Lawrence Livermore Laboratory.

The primary impetus for the development of new instrumentation must come from a need, either in process development or in research. The need should be connected with specific measurements. However, it is important to recognize that such a need is often not possible to predict and, once the need develops in a given funding situation, there are seldom adequate funds to satisfy identified requirements. We, therefore, recommend that a defined fraction of research and development funds be reserved for instrumentation needs that are likely to develop.

The process instrumentation used in oil-shale recovery to date was primarily developed for the oil industry and related areas such as coal conversion. A review of standard instrumentation techniques is given in a report from the Argonne National Laboratory ("Overview of Coal Conversion Process Instrumentation," ANL-FE-49628-TN01). This review includes discussions of standard instrumentation for flow measurements, temperature measurements, level sensing, pressure measurements, analytical instrumentation of all types including spectroscopic and chemical analytical techniques, and measurements of density, viscosity and thermodynamic properties. Much of this standard instrumentation can and is being used in the processing and recovery of oil from shales.

The developing oil-shale industry has a number of special requirements for instrumentation. We cite here a few examples for the purpose of illustration.

1. Rubblization. Modified in situ oil-shale technology depends on effective rubblization of large volumes of shale deposits. It is essential to characterize, measure and control blasting performance. Important characteristics of the rubblization process include fragment sizes and void and permeability distributions. Techniques have been devised for the use of attenuation and phase-shift measurements on short and long wavelength electromagnetic radiation to determine important characteristics. Interpretation of the measurements depends on an analysis involving tomographic techniques. The method has not yet yielded unambiguous results. One problem with this technique, as well as with other procedures based on acoustic measurements, is the result of the fact that the method has not been tested on rubblized volumes of sufficient size with known void and particle fractions in order to calibrate and determine the accuracy of the techniques. The rush to support the field program has hampered adequate backing of laboratory and small-scale studies. Research and development is essential on a variety of techniques to measure the results obtained after specified blasting procedures have been applied.

2. Aboveground Retorts. Small-scale studies on aboveground retorts have yielded to date useful information on flame front propagation, control of the burning process, and measurements of oil and gas yields. A variety of thermal profiling instruments is available, including ultrasonic temperature probes, sliding thermocouples, and "radio bugs" applied in gas canisters. Effluent gas compositions from the retort are monitored by gas-chromatographic or mass-spectrometric methods. The application of a variety of available spectroscopic techniques to small-scale retorts and

process-size retorts is recommended as a rapid method for chemical composition and temperature measurements, possibly within the system and certainly for oil and gas products.

A useful addition is instrumentation for on-line estimates of oil yields from shale that is being conveyed (perhaps a combination of a nuclear density meter and a reflectance measurement could be applied for this purpose).

3. Environmental Monitoring. It is important to develop techniques with agreed upon reliability to monitor environmental effects associated with an oil-shale industry. Monitoring of gaseous effluents requires rapid, efficient techniques which can be used to cover large areas. Study of the migration of various effluents, such as impurities leached from spent mines, will require the development of sensitive analytical methods. Process water remains a difficult and largely undefined analytical problem. It is important that adequate sampling methods be developed and agreed upon to determine procedures for measurements, in particular for environmental monitoring. Permeability distributions can be measured by tracer techniques in which a radioactive species is released at one point and measurements are then made at other points in the shale-oil formation in order to determine velocities of gas flows and residence times in shales. The technique is useful but there have been difficulties in interpretation because of the lack of calibration under appropriately controlled conditions.

CHAPTER 6

RESEARCH RECOMMENDATIONS RELATING TO ENVIRONMENTAL ISSUES

6.1 Introduction

Careful consideration of environmental concerns is crucial to an impending oil-shale industry. Relatively untested technologies will be located in an undeveloped area. Excellent summaries of the many environmental issues are contained in "An Assessment of Oil Shale Technologies," OTA Report M-118, June 1980, and in "Oil Shale: The Environmental Challenges," Oil Shale Task Force and DOE, August 1980. In this chapter, the focus is on the key environmental issues for which further research could have a significant impact. The discussion is not meant to represent a summary or review of all of the environmental problems which need to be addressed.

After evaluating issues and concerns, it is our view that many of the problems can be solved through the application of existing control technologies. On the other hand, we also feel that many of the questions being raised cannot be definitively answered until commercial modules begin operation. It is time to move from laboratory studies to field studies and from problem identification to solutions of problems and control testing. During this transition interval, ongoing research studies need to be expanded and new areas of activity need to be explored. These should be coordinated to provide maximum information flow to the commercially-sized facilities. While a number of potential problems has been raised, there is inadequate information on the real level of risks posed by the development of this industry. The ultimate size can best be decided when realistic risk-assessment capability is available.

In this chapter, we highlight those areas where vital risk information is lacking and further research is needed to help guide the growth of the shale industry, especially as it grows to significant size.

6.2 Air Quality

Of all the environmental areas of concern, air quality could be the limiting constraint on the ultimate size of the industry. According to estimates prepared at the EPA, an industry of 400,000 BPD might result in SO₂ levels approaching the current air-quality guidelines in nearby Class I areas. Workers at the EPA readily admit that this estimate involves the use of a simplified regional model. This situation indicates that research is urgently needed in two areas.

A high priority research need is an improved transport model to estimate dispersion. This model should involve consideration of the uneven and mountainous terrain in the oil-shale region. It should also consider the reactive nature of the emitted gases. The development of this model has to be accompanied by intensive field gathering of meteorological data and an investigation of the atmospheric chemistry of emissions peculiar to the oil-shale industry. Since the model results will depend on the levels of emissions from a developing industry, it is essential that all available data on the actual emissions be validated for ongoing pilot and demonstration projects. While obtaining the data is required as part of permit agreements, there needs to be a concerted effort to organize and correlate the data which are becoming available and to reach conclusions and identify necessary work that needs to be done.

Another clear research need is for evaluation of the effectiveness of existing air emissions control technology for various shale processes. At first glance, it appears that technology developed for other industries should be applicable.

However, there exist serious disagreements among various factions and a coordinated assessment program is needed. Field tests should be done on the largest possible scale. The decision on whether to fund additional development work on air emission control technology should await these test results. There is also evidence that different retorts have rather different air emission profiles. The relationship between process and air-emission should be explored and clarified.

6.3 Water Availability and Quality

A frequently-mentioned problem for the oil-shale industry is that of water availability and maintenance of water quality. Several studies indicate that water availability is not a short- or medium-term problem. Workers in Colorado have estimated that an industry of $\sim 1.6 \times 10^6$ BPD could exist indefinitely without seriously affecting water availability.* Nevertheless, there is a long-range need to consider water availability and supply as a constraint on a growing industry. Ultimately, this problem may be solved by interbasin transfer of water, which requires long-range planning but little research activity. An alternative approach, which is not a high priority item at this time, is to minimize the consumption of water in processing. Water availability and needs are further discussed in Chapter 8.

The hydrology of the oil-shale region must be better understood. We support a research effort to develop hydrological models on both regional and site-specific levels. Acquisition of the necessary field data could be profitably combined with instrumental developments. These hydrological models should include a description of the difficult problem of unsaturated flow that will be caused by mine dewatering.

Water quality is a difficult and sensitive issue. It is worthwhile to distinguish a variety of waters involved in the

* It should be noted that the same data base has been used by others to arrive at estimates for water availability as sufficient for only 0.6×10^6 BPD production.

industry, as listed in Table 6.3-1.

As in the case of air emissions, it appears that impurities present in the process waters should be removable by applying conventional technology used in the petroleum industry. There has been relatively little test work done to date but the currently available public data do not support this expectation. Industry has proprietary research in progress addressing questions of water purification and there are indications that some of these data may soon be publicly available. These disclosures should prove valuable in coordinating and defining needed research programs. A decision on whether additional research is warranted should await these disclosures. Processes which do not generate dangerous sludges or require large energy expenditures for cleanup would be extremely valuable to the industry. There may ultimately be a premium on process technologies that minimize water use.

6.4 Spent-Shale Disposal

Whether shale is processed by a surface retort or modified in situ retorting, there are generic problems of spent-shale disposal and we prefer to consider these processes together. The two major concerns are leaching of harmful substances from spent shales and the long-term stability and reclamation of spent-shale piles.

The chemical and physical processes taking place in a spent-shale pile or in an abandoned retort are not well understood. Much of the information gained to date is derived from small-scale laboratory studies and has questionable predictive capacity for large shale piles. This is a difficult area of research because of long-term physical, chemical, biological, and biochemical changes that may occur within the shale piles. For this reason, short-term studies may only be of moderate utility.

Table 6.3-1 Water types, sources, and cleanup procedures.

| Type of Water | Source | Cleanup Procedure |
|-------------------------|-------------------------------|-----------------------------|
| mine water | mine dewatering | removal of inorganics |
| dirty process water | retort condensate | very difficult to implement |
| utility blow-down water | cooling towers, boilers, etc. | difficult to implement |

From the point of view of risk assessment, the major research need is for detailed information on whether and how substances migrate from spent shale. This research should emphasize molecular chemical phenomena. A great deal of analytical work is needed in this area. Several tests have indicated that leaching could be a serious problem. However, there is information from industry showing that the fear of leaching from shale piles may be exaggerated and that the measured leachate concentrations are functions of the tests used. Since many of the conclusions being drawn are in conflict, the various methodologies used to assess leaching potential must be reviewed and a better test protocol developed to reflect actual field conditions. Very high priority should be given to a large-scale, long-term field test, possibly in conjunction with a modular plant. Spent shale is not currently on the RCRA list of toxic substances but this does not guarantee that it will not be reclassified in the future. A hydrological and mass-transport model of spent-shale piles is urgently needed. At the present time, we do not know whether trace migration occurs primarily downward from leaching, upward from evaporative and capillary action, by general diffusion processes, or by combinations of these.

For every barrel of oil produced, approximately two tons of shale will be returned to the environment. This represents a tremendous dislocation of rock material and will be the most visible legacy of the oil-shale industry. The ultimate land reclamation goal must be a terrain suitable for long-term land use and not requiring custodial care. Specifically, this goal requires that the shale be disposed of in such a manner that the shale (a) maintains physical stability and is resistant to movements by wind and water erosion, (b) minimizes or eliminates deep leaching, (c) supports a diverse ecosystem, ideally the same or a substantially equivalent ecosystem as that present in the unperturbed natural habitat.

There are a number of information gaps and conflicting opinions where new research is needed to resolve questions of risks associated with shale disposal. Current studies are providing much useful information but are limited in their predictive capacity. For example, the status of an existing shale pile fifty years in the future is impossible to predict. A useful area of research would be the development of evolutionary models for the long-term behavior of spent shales.

We have also identified the following short-term research needs, which must be met for a variety of spent shales in order to account for a spectrum of likely process variables:

a. What is the minimum depth and quality of top soil needed to establish permanent vegetation?

b. Identification should be made of the effectiveness of liners, of processes associated with intentional leaching, and of the behavior of capillary barriers for protecting plants, aquifers and organisms from migrating salts and trace minerals; the development of novel approaches in these areas is to be encouraged.

c. What are the concentrations of trace minerals in plants and how does one perform believable risk assessments of their impacts on native animals?

d. Innovative engineering design studies should be performed on pile geometries, shapes, and pile stability and life; these should consider the local hydrology and stream flows to strive for minimum contact.

e. Reliable analytical methods should be developed to identify the valence states of the metals and specify the associated anions.

The question of the environmental stability and long-term behavior of abandoned MIS retorts is currently receiving adequate attention.

6.5 Ecological Baseline Studies

There is clear need to direct future environmental studies on oil shale into systematic ecological research that will provide quantitative measures of impact. Although there is a large body of data from existing baseline studies, many experts believe that these are inadequate and generally suffer from a lack of in-depth interpretation. Few studies in the Piceance Basin provide a sound basis for monitoring changes in the ecosystem caused by oil-shale development. The near-term need is for assessment of the available data to derive implications and then decide on the research needed to fill the gaps. There is not so much a data gap as a lack of systematic interpretation of the existing data.

CHAPTER 7

WATER AVAILABILITY AND CONSUMPTION

Water has received much public attention as an important potential constraint on the total level of shale-oil production sustainable in the Green River formation. Water supplies are limited in the arid area of the Green River formation, and water consumption is significant in all shale-oil recovery processes. But it is important to recognize that water-supply limits will not represent a physical/economic constraint. Sufficient water is available or could be made available at acceptable costs to sustain as large a shale-oil industry as may reasonably be expected to be developed. Water-supply limits may arise as the result of legal/institutional/socioeconomic constraints because it is not certain that our institutions will permit and our broad social objectives will allow the diversion of water to shale-oil production rather than to other end uses, both over the short and long terms.

An estimate cited in an OTA report¹ may be used for illustration, viz., irrigated agriculture along the White and Colorado Rivers in Colorado now "consumes about 549,000 acre-feet/year*" of water to produce 3% of Colorado's crop production". Colorado's total crop production is worth about $\$1 \times 10^9$ annually and total farm products are worth about $\$6 \times 10^9$ annually. Thus, irrigation water in northwestern Colorado yields at most about $\$0.18 \times 10^9$ worth of farm products each year; that same amount of water, assuming a consumption of 3 barrels of water per barrel of oil and an oil value of \$35/barrel, would sustain a shale-oil

* One acre-foot per year is equivalent to about 21 barrels per day.

industry producing about $\$0.136 \times 10^9$ worth of oil each day!*

The economics notwithstanding, it is generally agreed that the consumption of water in a shale-oil industry should be done with minimum impact on other activities in the region, particularly agriculture, and should not further degrade the quantity and quality of flow in the Colorado River. Therefore, the purpose of this section is to identify needs for new technical long-term R&D programs with the potential of increasing the water supply or reducing the amount of water consumed in producing a given amount of shale oil. The disposal or cleanup of contaminated water is discussed in Chapter 6. Legal, institutional and social issues and the choices to be made among competing end uses of water at fixed costs for supplies fall beyond the scope of this study.

7.1 Water Consumption

In Table 7.1-1, we have reproduced some of the data from Ref. 3 concerning water requirements for three types of shale-oil recovery technology. The water requirements listed correspond to water consumption, i.e. to zero-discharge water-management systems (except in municipal use) and cover the needs for all activities in the region, including increased populations associated with producing upgraded shale oil in the region.

Table 7.1-1 shows that demand generally ranges from about 2 to 5 B of water per B of upgraded oil produced; the exact

*The calculated ratio of shale-oil value to farm-products value is about 275, which is consistent with the data of Ref. 2 assuming predominant animal (rather than crop) raising and a mixed surface-in-situ shale-oil industry.

Table 7.1-1 Net water consumption for producing upgraded shale oil;
these data are taken from Ref. 3.

| | Surface Retort (direct heat) | Surface Retort (indirect heat) | <u>In Situ</u> Recovery (direct heat) |
|------------------------------|------------------------------------|--------------------------------------|---|
| Shale grade, GPT | 29-32 | 32-35 | 23-27 |
| Net water use, B/B of oil | 2.1-3.3 | 4.0-5.2 | 2.1-2.5 |
| <u>% of Water Use</u> | | | |
| Mining and handling | 9-18 | | 4-10 |
| Power generation | 8-12 | | - |
| Retorting and upgrading | 25-44 | | 51-69 |
| Disposal and revegetation | 26-40 | | 19-26 |
| Municipal use | 5-12 | | 6-16 |

amount depends on the particular processes used and on assumptions made. Significantly more accurate demand numbers are not likely to be available until detailed commercial plant designs are completed and operating experience has been obtained. Even then, there may be a residual error because of uncertainty about water requirements to establish and sustain revegetation on spent shale over the long term. It is worth noting that surveys of water demand given in Refs. 2, 4 and 5 also indicate requirements of 2-5 B of H_2O per B of oil, although there are important differences in detail. Thus, the authors of Ref. 2 assume no power generation accompanying surface retorting. The broad agreement is not surprising since all of the reviews depend heavily on the same basic data contained in specific site-development plans using various technologies.

A strategy to reduce water consumption must be developed with adequate consideration of all important factors, including total costs, commercial readiness, and environmental impacts. It may be useful to look for opportunities to reduce water demands by developing improved or new process elements (e.g. dry or wet cooling, seasonal storage to cool as well as store, etc.).

A. Mining and Handling

Water consumed during mining and handling amounts to 0.1-0.4 B/B of shale syncrude produced.³ Water is used to control dust generated during removal of the rock in place, crushing (for surface retorting), and transport of rock from point to point. Some reduction in water consumption can be obtained by using improved enclosures of crushing and conveying equipment and by road paving. No important need for long-term R&D to reduce water consumption in this step is apparent.

B. Power Generation

The water consumed in power generation amounts to 0.3-0.5 B/B and is used for evaporative cooling during the generation of electric power (ordinarily for on-site use) by burning off-gases from the shale retorts. The extent of use and method by which power will be generated at any particular site are not clear. Dry cooling, gas turbines, and power importation will all reduce local water use. Water consumption during power generation in areas where water is scarce is a topic of interest in the electric utility and other industries. Regional development plans include construction plans for power generation and also considerations of central power plants in the region vs. site generation/cogeneration. In these studies, regional water consumption should appear explicitly along with other variables.

C. Retorting and Upgrading

Water consumption for retorting and upgrading uses 0.6-2.1 B/B. Although data are given in Refs. 1, 3 and elsewhere for the combined retorting and upgrading steps, there is no particular reason for using this combination.* The steps are independent and there are many different possible upgrading and retorting processes. An obvious procedure for reducing local water consumption is upgrading (coking, hydrogenation, etc.) at remote locations, e.g. at a refinery away from the arid oil-shale region. Remote upgrading requires economical means for transporting raw shale oil away from the retort

*Limited data from Chevron⁶ on upgrading alone (via hydrogenation) show a process water consumption of 0.3-0.6 B/B plus unspecified cooling water consumption, which amounts to an additional 0.6 B/B assuming that 3% makeup water is required for the specified 20 B/B circulation rate.

through pipelines and techniques (e.g. pour-plant depressants or visbreaking) for making the oil fluid. Since there are strong driving forces to upgrade remotely if feasible, concern for water consumption alone will not be needed to justify further R&D.

Significant water consumption occurs during upgrading, especially for (a) cleaning of retort off-gases, (b) evaporation from retort cooling towers, (c) injection into underground retorts, and (d) generation and reaction of hydrogen for upgrading. Retort designs are being improved to reduce water consumption and to use water produced during retorting; R&D tends to be specific to the particular technology and thus unsuited to a broader long-term program. An exception is the treatment of retort gases. Removal of particulates and gaseous contaminants from very large volumes of gases is a pervasive, expensive, and water-consuming problem in shale-oil recovery. Although gas cleanup is a widespread problem in the process industries, its importance to shale oil merits a broad and long-term R&D program, which should include efforts to reduce water use.

D. Spent-Shale Disposal and Revegetation

Spent-shale disposal and revegetation use 0.5-1.7 B/B. The water is used to cool and wet the spent shale from the retort so that it may be placed compactly and securely in the disposal site. There is continuing consumption of water over the years to establish and sustain vegetation on top of a spent shale surface deposit. Considerable debate exists about how to carry out the disposal and revegetation steps in an environmentally satisfactory manner and about how much water will be required. Although there have been some experiments performed on relatively small scales, more work is needed, particularly

on a scale large enough to evaluate disposal designs confidently for different types of spent shale (differing, for example, in particle size, carbon contents, or temperature history). The main incentive for this work is to assure environmental protection rather than defining or minimizing water consumption; we strongly recommend support for this type of research in a comprehensive long-term program to reduce water use.

E. Municipal Needs

Municipal needs use 0.3 B/B and consist of off-site water consumption by the labor force, their families, and the associated infrastructure. These needs are ordinarily computed from other experience by applying appropriate population multipliers. A ratio of population increase to direct site operating labor of about 4 to 5 is often used. No special shale incentive for R&D is needed.

F. Conclusions

Both the principles and details of water consumption in shale-oil recovery are understood and consumption is subject to some control by widely applicable engineering methods, as discussed in Ref. 7. In general, water is a resource the consumption of which can be reduced by the substitution of other resources (e.g., investment in air heat exchangers or precipitators, electric power to operate blowers or precipitators). Long-term R&D to improve these engineering methods for particular application to shale-oil recovery will add little to a steadily advancing art. Exceptions unique to shale oil or having a particularly large impact on shale-oil recovery include R&D on (a) spent-shale disposal and revegetation and (b) retort-gas cleanup and utilization.

7.2 Water Supplies

From the standpoint of the individual shale-oil developer, especially at this early stage of commercialization, it is less costly to obtain more water on a long-term average basis than to make major process changes to consume less water,* although there is usually an area of tradeoffs between the most costly supplies of incremental water and the least costly water-saving process changes. For this reason, interest in the regional water balance has concentrated on (a) determining how much water is available in the region and how large a shale-oil industry may be supported by that available water and (b) strategies for increasing the amount of water available to the industry.

A. Water Availability

How much water is available depends less on the physical and economic facts than on the definition of availability. The authors of Refs. 1-5 use different definitions with accompanying lists of qualifications and assumptions. The results are shown in Table 7.2-1 and indicate widely varying estimates for the sizes of supportable shale-oil industries.

The key difference between the most conservative estimate (from the standpoint of shale-oil production) of a

*Success of potential shale-oil developers in obtaining supplies is illustrated by the estimate in Ref. 1 that "The (already acquired conditional water) rights of ... (shale-oil) companies ... could support an industry of nearly 8 million bbl/d ...". This quotation is unexpectedly followed by "and would be sufficient for the shale-oil production levels projected for the near term". However, Shaw⁸ points out that a practical question to an individual developer is the amount of water he can expect to receive as a result of purchasing or perfecting water rights. Western water laws provide many opportunities for delay, litigation, and other impediments to the use of the water being sought.

Table 7.2-1 Supportable shale-oil industries according to different authorities.

| | Colorado (Ref. 5) | OTA (Ref. 1) Probstein (Ref. 3) | Colorado (Ref. 2) | NAS/NRC (Ref. 4) |
|---|----------------------|------------------------------------|----------------------|---------------------|
| Supportable shale oil production 10^6 BPD | 0.5 | ≥ 0.5 | 1.3 | 2.6-7 |
| Water available, acre-ft/year | 70,000 | 85,000 | 140,000 | 500,000 |
| Water use, B/B | 3.0 | 3.6 | 2.4 | 1.5-4.0 |

0.5×10^6 BPD industry and the most optimistic estimate of an industry about ten times that size is that the latter assumes that "some agricultural rights" would be displaced, "many of which may be found to be attached to the actual lands that are acquired for oil-shale production". In contrast, the former (which includes production only in the State of Colorado) assumes no reduction in any "other existing or projected consumptive use".

The differences in estimates also reflect the fact that "... a million bbl/d (shale-oil) industry would require ... about 1% of the virgin flow of the Colorado River at the boundary of the Upper Basin ... and about 2% of projected consumption (by all users) in (the year) 2000 ...".¹ Since the water available for shale oil is usually calculated as a residual, after first estimating total supplies and then subtracting the sum of all other projected uses, small changes in either the supply or other-use estimates cause huge relative changes in the residual and thus in the size of the industry that can be supported. In particular, the available water is sensitive to assumptions about irrigation, which accounts for about 73% of current total water consumption in the Upper Colorado Basin and about 95% of consumption after reservoir evaporation, conveyance, and other "losses" which add up to about 23% of the total.⁴ Thus, a 5% overestimate in the Colorado⁵ projection of irrigation use in the year 2000 corresponds to about a 100% underestimate in projecting water available for shale-oil recovery.

Although the preceding table lists the best current estimates of availability, these estimates were aptly evaluated in an NAS/NRC study⁴ as follows: "No one can say, within very wide margins, how much (Colorado River Basin) water is likely to be available for new users (for shale-oil development) in any future year. The estimates range from far more than amounts that could be put to use to none whatsoever. Both conditions are sure to occur in the long term."

The uncertainties are caused not only by uncertainties about physical supplies and the levels of well-defined types of usage but also by non-technical, non-economic uncertainties, e.g. Federal and Indian water rights; interpretations of other "ambiguous treaties, compacts, and laws"; permissible long term flows and salinity of the lower Colorado River; importance attributed by the public to natural water flows for wildlife, recreation, and aesthetics.

B. Increasing Supplies Available for Shale-Oil Recovery

References 1-3 include current and knowledgeable reviews of the alternatives for increasing water supplies available for oil-shale development in the Upper Colorado Basin. Therefore, only a brief summary of these alternatives is necessary here. The alternatives fall into the following three broad categories:

- (i) Using less water for purposes other than shale-oil recovery (by purchase of irrigation rights, by improving efficiency of irrigation use, or by improving efficiency of municipal and other industrial uses).
- (ii) Using existing supplies more effectively (by constructing reservoirs and aqueducts to damp seasonal and year-to-year flow variations, by sharpening laws relating to existing water rights, by purchasing unsold water from federal reservoirs, by developing ground water supplies and desalinating where desirable, or by complete use of water brought on shale sites or generated there during mining or retorting).

- (iii) Increasing total supplies in the region (by weather modification or by interbasin transfers, although even study of the latter is inhibited by existing federal legislation).

The water quantities and costs attributable to these supply alternatives cover a wide range; Probstein's³ summary tabulation has a minimum of "nil" (for high-quality ground water) to a maximum of 79¢ per B of oil for some interbasin diversions. Some specific examples show that winter cloud seeding can, by conservative estimates,² increase runoff by about 10% at a cost of about 0.03 to 0.3¢/B of oil. In contrast, interbasin transfer (over distances of 400-800 miles from the Missouri, Yellowstone, or Columbia Rivers) would cost about 30-60¢/B of oil, assuming that the legal, institutional, and socioeconomic barriers to transfer could be overcome. Improving agricultural efficiency, primarily by piping and line ditches, could reduce consumption by 130,000 acre-feet/year at a one-time investment of \$700M.² If that water were all used for shale-oil recovery, it could support about 1×10^6 BPD of production at a cost of about 30-50¢/B of oil, depending on investment life and interest rates.

C. Impacts of Water Use for Shale

As noted previously, a million BPD shale-oil industry would consume only about 2% of the total water use projected for the year 2000 in the Upper Colorado Basin. Therefore, consumption alone would not cause major regional impact, although there would be incremental regional debits such as reduced flows and increased salinity of the lower Colorado River. Greater site-specific impacts will occur as a result of diverting surface flows, creation of new reservoirs and aqueducts,

disturbance of ground water aquifers, or other changes to the existing water system. However, the unfavorable impacts caused by water consumption alone should be minor compared to the potential impacts caused by contamination of surface and ground waters as a result of all shale-oil recovery activities.

D. Conclusions

The technology already exists for making more water available for shale-oil development, either by increasing total supplies or by increasing the efficiency with which water is used for other end-use purposes. Although the cost of that water is high by the usual criteria, the cost is not too high to constrain shale-oil production if water consumption were the ultimate limitation. The following long-term R&D programs, which we endorse, were recommended by the NAS/NRC study⁴ for increasing our understanding of regional water supplies :

"Geology and ground water. A detailed analysis of fractures in the Piceance Creek Basin is being completed by the U.S. Geological Survey and is being correlated with observations of ground-water movement. In large part, the occurrence and movement of ground water in the Piceance Creek Basin is controlled by fractures. Similar studies are needed elsewhere in the oil-shale region. Such information appears to be essential to dewatering operations and for water management. Hence, this knowledge is a necessity for understanding the effect of mining on the hydraulic system. A still more detailed analysis, based on subsurface measurements of fractures, would be desirable."

"Hydrologic models. Detailed measurements of porosity, transmissivity, and other properties of the aquifers, particularly in the Piceance Creek Basin, are needed to construct a dependable model of the ground water and its relation to surface water. Models based on existing data have proved to be inadequate for predicting quantities of ground water encountered in dewatering operations. Better models are needed to predict the long term behavior of the hydrologic system. A program to gather this information should also routinely obtain measurements of water quality, which are needed for other aspects of environmental management."

"Water management. Research is needed on water supplies that can be made available for oil-shale development, including supplies that might be provided by further economies and improved management of present uses. The downstream effects of consumptive use, discharge, and losses by evaporation from reservoirs are not well quantified. Substantial amounts of ground water at comparatively shallow depth are evidently present and might be a basis for conjunctive management of ground water and surface water through systems of recharge. Still deeper ground water exists below the oil-shale deposits."

When water supply and water consumption are balanced in site water-management plans, it is not clear that the plans are always developed from a systems point of view, i.e. that the supply and cooling choices are designed to minimize cost and water consumption by considering all important on-site and off-site elements. Examples of these elements are evaporation from

storage reservoirs and ponds, provisions for natural seasonal and year-to-year flow variations, and legal or institutional constraints on withdrawal from specific sources. Systems optimization becomes more important as the regional water resources become more strained.

REFERENCES

1. An Assessment of Oil Shale Technologies, Congress of the United States, Office of Technology Assessment, June 1980.
2. "The Availability of Water for Oil Shale and Coal Gasification Development in the Upper Colorado River Basin, Summary Report," report to the U.S. Water Resources Council prepared by the Office of the Executive Director, Colorado Department of Natural Resources, Denver, Colorado, October 1979.
3. R. F. Probstein, H. Gold, and R. E. Hicks, "Water Requirements, Pollution Effects, and Costs of Water Supply and Treatment for the Oil Shale Industry," report prepared for OTA by Water Purification Associates, Cambridge, Massachusetts, October 1979.
4. "Surface Mining of Non-Coal Minerals, Appendix II: Mining and Processing of Oil Shale and Tar Sands," National Academy of Sciences/National Research Council, Washington, D.C., 1980.
5. "Colorado Oil Shale: The Current Status, October 1979," Office of the Executive Director, Department of Natural Resources, State of Colorado, Denver, Colorado.
6. "Refining and Upgrading of Synfuels from Coal and Oil Shales by Advanced Catalytic Processes," HCP/T2315-25, UC-90d, Chevron Research Company, Richmond, California, July 1978.
7. R. F. Probstein and H. Gold, Water in Synthetic Fuel Production, M.I.T. Press, Cambridge, Massachusetts, 1978.
8. John Shaw, personal communication, August 1980.

CHAPTER 8

EASTERN SHALE

8.1 Introduction

The Devonian shales in the Eastern part of the U.S. are known to cover about 400,000 square miles in Indiana, Michigan, Ohio, Kentucky, Tennessee, and Illinois. Only recently have these shales been considered as sources of synthetic fuels. Several companies and a number of state and federal agencies are currently conducting studies of these Eastern deposits. Among active groups are workers at the Dow Chemical Co., Phillips Petroleum Co., the Ashland Co., Pyramid Minerals, and the Institute of Gas Technology (IGT). Workers at IGT have been engaged in studying Eastern oil shales since 1972; this work has included resource characterization, process development, mining technology, environmental assessments, and economic evaluations. While it appears that technology used in recovering oil values from Western shales is applicable to Eastern shales, the yields are poor with respect to the organic content.

Recent research at IGT has led to the development of the Hytort process for the production of synthetic natural gas or synthetic crude from Eastern or Western U.S. shales. This process scheme involves heating crushed shales (1/8" - 1") to temperatures up to 1500°F in the presence of hydrogen at pressures up to 525 psig; conventional pyrolysis retorts for Western shales are operated at atmospheric pressure. The high temperatures and hydrogen at elevated pressures are needed to improve yields of both liquids and gases, particularly from Eastern shales. Details concerning the Hytort process are presented in Appendix AB-10.

Some of the richest Eastern shales have organic carbon contents almost as high as those of Western shales. However, the corresponding hydrogen contents are considerably less than those

of Western shales (at 13.5% organic content, hydrogen is less by 30 to 40%). The lower hydrogen contents for Eastern shales lead to lower oil production during conventional pyrolysis as compared with Western shales; Eastern shales are also more refractory than Western shales. For example, Fischer assays, for an organic content of 13-14%, show an oil yield of only 10 GPT for Eastern shale while the yield for Western shale is 30 GPT. Hytort conversions of organic material as high as 90% have been achieved in small-scale testing. This process will raise oil yields of Eastern shales to about 30 GPT, whereas a yield of only about 10 GPT is obtained in the type of conventional retorting used for Western shales. The range of hydrogen consumption is 2500-4000 ft³/ton for the Hytort step. Additional hydrogen is required to upgrade the raw shale oil to syncrude by conventional hydrotreating methods (up to 1700 ft³/B). The resulting syncrude is low in sulfur (less than 0.1 wt.% of S), contains less than 0.2 wt.% of N, and 80% of the product boils below 600°F. The high yields from Eastern shales can only be obtained by using large amounts of hydrogen. The potential attractiveness of the resource is therefore dependent on the availability of low-cost hydrogen. The deposits are close to large industrial, highly populated areas of the U.S.A. and also close to large supplies of water. The Eastern shales also appear to yield more environmentally acceptable spent shales after pyrolysis than Western shales since they show less leachable material. On the other hand, the sulfur contents of Eastern shales are much higher than those of Western shales. The Hytort process has been run in small laboratory size equipment at 100 lbs/hr and in a PDU with a capacity of 24 tons/day.

8.2 Recent Developments

A serious assessment of the potential for commercial development of Eastern shales has been performed for the Buffalo

Trace Area Development District of Northeastern Kentucky.* This study shows that directly accessible surface outcroppings over a 4-mile perimeter hold in excess of 1×10^9 B of shale oil and suggests that trace element contamination associated with leaching of spent shales will be similar to that of leaching coal deposits.

A costing study has been performed for a commercial process using either a variant of the Paraho (see Appendix AB-2 for details) or the IGT Hytort (see Appendix AB-10 for details) retorting technologies. The resulting cost estimates are substantially higher than corresponding studies for Western shales. On the basis of the results available to us, we estimate >\$55/B for hydrofined Eastern shale product as compared with ~\$35/B for hydrofined Western shale oil. Only the development of greatly improved process technologies will reduce the high current costs.

Most of the FERWG members believe that a significant federal R&D role on Eastern shales is justified at the present time for the following reasons:

i. The sociopolitical environment is more favorable in the East than in the West for large-scale commercialization of a synfuels industry.

ii. The Eastern shales lie in regions of the country where water supplies are ample.

iii. Industrial development is so unattractive at the present time that an adequate near-term (i.e., within 10 years) assessment of costs, environmental impacts, and technologies is

* FERWG is greatly indebted to Paul Petzrick for inviting FERWG participation at an extensive program review on March 5, 1981.

not likely to materialize unless adequate federal subsidies are received for evaluation.

As with other activities relating to synthetic fuels, FERWG recommends federal R&D support only to provide meaningful evaluations. Commercialization of Eastern shales, as well as of all other synthetic fuels processing, should be left to the private sector.

The types of studies that are needed for an adequate assessment of the merits of Eastern shales parallel the work done and in progress for Western shales. The following problem areas merit attention among others:

i. Mining and crushing problems resulting from the special properties of Eastern shales that lead to the production of large amounts of fines.

ii. Spent-shale disposal, including leaching and possible contamination of regional water beds by trace elements and chemical compounds.

iii. The design of optimized processing and retorting technologies to assure minimum product costs, with proper allowance of credits for byproducts in these optimized processing technologies.

iv. More extensive resource evaluations than have been performed thus far.

What fraction of the total federal R&D budget should be allocated to work on Eastern shales requires policy considerations that must involve, among others, estimates of the desired or likely near-term (i.e., within 10 years), intermediate term (10-20 years), and long-term (more than 20 years) developments of Eastern shales concurrently or subsequently to large-scale commercialization in the West and the needed R&D support for these more immediately realizable Western commercialization schedules.

CHAPTER 9

COMMENTS ON SHALE-OIL COSTING AND R&D TO ASSURE SUCCESSFUL OPERATION FOR UNTRIED TECHNOLOGIES

In order to understand the factors that will determine ultimate product costs and possible associated R&D needs, FERWG held two workshops on this topic, which are described in detail in Appendices AB-5 (pp. AB-43 to AB-56) and AB-8 (pp. AB-176 to AB-189). In addition, FERWG members participated in discussions on costing methodology with T. P. Cook and D. Brown of Fluor Corporation and with J. Appleton of Bechtel.

The cost assessments presented in Appendices AB-5 and AB-8 provide a reasonable estimation of currently-available data and procedures. The methodologies utilized by engineering and construction firms generally yield close estimates for all known and conventional components for which allowable contingency factors are small (2 to 5%). For new technologies, contingency factors may be as high as 50 to 100%. Sophisticated computer programs using Monte Carlo techniques are used in both financial risk analysis and in refining cost estimations. Cost estimates are made by searching for analogies with known technologies used in related or in different industries. Vendor inputs are used routinely.

Large discrepancies between cost estimates will inevitably occur when different contractors work with different goals and design objectives. In this connection, it should be noted that the differences in cost estimates for raw shale oil and for hydrofined shale oil will be of the order of \$10/B (in 1980 dollars).

The relations between inflation and price escalation are complex because they tend to be coupled with scope changes (produced, for example, by new environmental regulations) and with improved understanding of process technologies.

Price-demand elasticities will become important under accelerated development schedules for components that are needed at appreciable levels of total national output (e.g., heavy-walled vessels, shell-and-tube heat exchangers, pumps, compressors, etc.). Thus, staged development may have important bearing on actually required capital costs. Under a schedule of very rapid commercialization, it may become necessary to assign allocation-priority schedules for competing contractors and industries.

The difficult question of likelihood of operational success for an untried technology, or for a technology that has been scaled up from a much smaller size, cannot be assessed reliably in advance. It appears to be the general view of the engineering constructors, as well as of FERWG members, that the responsibility for operational feasibility and success rests with the sponsoring industrial groups. Accordingly, the needed R&D to assure successful development of new or untried components must be identified and pursued within the industry, preferably in cooperation with the constructors. The vexing issue of governmentally-supported R&D when loans, loan guarantees, joint ventures, or guaranteed purchase plans provide financial exposure for federal funds will require examination on a case-by-case basis and may properly lead to different initiatives when smaller contractors with limited financial resources are involved than for the major companies with large financial resources.

APPENDIX A
FERWG-III STATEMENT OF WORK

The objective of this project is to conduct an independent assessment providing for identification of the long-range research needs associated with shale-oil recovery, using both aboveground and in situ recovery techniques. This work is expected to include recommendations to DOE for research programs that can best contribute to the successful long-term development of new shale-oil recovery technologies.

The contractor shall provide the necessary personnel, facilities, services, materials, and documentation required to perform all of the required tasks.

In fulfillment of the project objectives, the contractor will be expected to work with both the academic community and industry. The assessment will consider all of the basic disciplines involved in the development of the shale-oil recovery, using both aboveground and in situ technologies. The researchers will be expected to gain first-hand familiarity with operational aspects of shale-oil technologies through site visits, interviews, examination of development studies and reports, and other means.

Typical of the kinds of long-range issues that will be addressed are the following:

1. How much cheaper or more efficient may we expect aboveground and in situ shale-oil technologies to be in the future, compared with those that are now in use or under development?

2. Can we identify the scientific and engineering directions that will be useful in making these technological improvements?

3. What are likely near-term and long-term environmental impact assessments for large-scale commercialization of these technologies?

4. What scientific and technical areas that are key to the success of ongoing shale-oil recovery R&D are still "open" areas for research, i.e., areas likely to profit from a broader or deeper look?

5. What disciplinary or interdisciplinary fields or research ideas should be supported because they hold long-range potential for generating innovative and useful technologies?

In complying with the objectives, the contractor shall perform the following tasks.

Task 1: Prepare a Detailed Work Plan

The contractor will prepare a work plan for DOE review and approval that will define the execution of the remaining tasks. This detailed work plan will include documentation of the following activities: (a) description of a methodology for obtaining independent assessments representing a wide diversity of views concerning shale-oil techniques; (b) site-visit requirements; (c) technical approach for evaluating research needs for each project. The work plan will be submitted for approval by the DOE technical representative. DOE comments shall be furnished to the contractor within 5 working days after receipt.

Task 2: Conduct Assessment

In accordance with the detailed work plan (Task 1), the contractor shall conduct the necessary research assessment activity. It is expected that a credible assessment will require use of a variety of information sources,

including site visits to shale-oil recovery projects to gain first-hand familiarity with currently available or developing aboveground and in situ technologies, including operational aspects; technical discussions with government, industrial, and research community specialists in shale-oil recovery; review of relevant technical literature; other means, as deemed appropriate, including the use of consultants from industry and the academic research communities. The contractor will submit to DOE an interim letter report describing each site visit and significant technical meeting during this assessment.

Task 3: Prepare a Final Report

The contractor will prepare a final report of this assessment for DOE. This report will include the following: purpose of study; study approach; list of consultants, if any, and other information sources; brief description of sites/projects visited; research needs identified, according to technology area, urgency, and expected benefit time-frame; and recommendations.

SCHEDULE

- Item 1 A detailed work plan in accordance with Task 1: June 1980.
- Item 2 A draft report of each site visit in accordance with Task 2: three (3) weeks after each site visit.
- Item 3 Final report, including identification of research needs for shale-oil recovery technologies, in accordance with Task 3: March 1981.



Lawrence Berkeley Laboratory

University of California • Berkeley, California 94720

March 5, 1981

Professor S. S. Penner
University of California
San Diego Energy Center
Mail Code B-010
La Jolla, California 92093

Dear Dr. Penner:

I have just received your letter of February 27 and the draft copy of your report entitled "Assessment of Long-term Research Needs for Shale Oil Recovery." Since I am about to leave town, I have not had a chance to read this report carefully, but have spent a couple of hours looking it over.

In general, I believe this report meets the high standards your other two reports have established. It will certainly be helpful in directing future research.

The question that bothers me and that I could not find addressed in my admittedly quick review of this report concerns the uniformity of the bitumen in different oil shales. While it is clearly stated that oil shales from different locations vary in their bitumen content, I wonder whether there is an answer to the characteristics of this bitumen when subjected to retorting. Does one get the same product distribution and the same quality products from oil shales from different locations? We know there are tremendous differences in this respect in different coals subjected to gasification or liquefaction and in tar sands. I would assume that the same holds true for oil shales, and the methods used for recovering oil from the bitumen may to some extent depend on the composition of the bitumen.

In reading the report, I found it most helpful to review some of the comments on site visits in the appendix. Perhaps more frequent references to specific items in the appendix would be helpful.

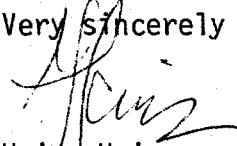
Professor S. S. Penner

March 5, 1981

Finally, an editorial comment: throughout the report, in situ shale oil recovery has the words "in situ" underlined. Is this really necessary or helpful? After all, in situ shale oil recovery contrasts to above-ground retorting. If one underlines one, one probably should underline the other. However, this is a rather nitpicking comment.

Best regards.

Very sincerely yours,


Heinz Heinemann

Staff Senior Scientist

HH:bc



United States Department of the Interior

GEOLOGICAL SURVEY

Conservation Division
Area Oil Shale Supervisor's Office
131 N. 6th, Suite 300
Grand Junction, Colorado 81501

March 23, 1981

S. S. Penner
Chairman, Fossil Energy Research
Working Group
Mail Code B-010
La Jolla, CA 92093

Dear Mr. Penner:

Thank you for the opportunity to review the draft report on Assessment of Long-Term Research Needs for Shale-Oil Recovery. We have only a few comments relating to specific needs as we see them which may be beyond the scope of the report.

Page 51 discusses the need for improved underground mining methods. Because of the large resource base depth and thickness, a method which can extract a high column with good areal recovery, perhaps with backfill, will be needed in the future.

Page 38 discusses the need for additional physical and chemical property data on oil shales. Incorporated in these studies should be investigations into the types and quantities of iron and sulfur containing minerals with particular attention to vertical and horizontal variations throughout the formation. In addition, low temperature, exothermic oxidation characteristics of oil shales should be investigated. These studies are recommended in light of new data supporting the concept of self-heating problems in raw shale storage piles.

Pages 37 and AB-25 discuss shale beneficiation, this technique shows little promise for resource recovery for Green River Formation oil shales with their highly cementitious carbonate mineral matrix. Research on beneficiation should be limited to small-scale laboratory studies.

Page AB-25 mentions microbial conversions on beneficiated shales. Prior bacterial studies on oil shale showed little promise of large scale application. Bacterial conversion of sulfur forms to sulfuric acid for carbonate leaching is not a valid consideration because

Green River formation oil shale's ratio of potential sulfuric acid to carbonate mineral content is not adequate to remove a significant amount of the carbonate minerals. Past studies including those by Melton of the USBM should be carefully reviewed before additional funds are committed.

Page XV discusses characterization of a wide range of individual shales as they relate to different recovery processes. An additional benefit of these studies would be a knowledge of shale properties that would assist in predicting processed shale properties to aid in developing processed shale disposal techniques.

Sincerely,



Peter A. Rutledge
Deputy Conservation Manager
Oil Shale

APPENDIX B

SELECTED REPORTS OF SITE VISITS, CONFERENCES AND DISCUSSIONS

This section contains edited copies of site-visit and other reports prepared by FERWG members. Some of the hand-out materials prepared by DOE contractors and others are included (without explication) to permit readers the construction of a coherent picture of work in progress.

FERWG PARTICIPATION AT THE 13TH OIL SHALE SYMPOSIUM,
GOLDEN, COLORADO
(April 16-18, 1980)

Submitted by: S. S. Penner (May 28, 1980)

The following FERWG members attended the 13th Oil Shale Symposium: J. Clardy, S. S. Penner, R. P. Sieg, J. R. Thomas, M. A. Weiss; also A. Lewis and J. Powers. Brief comments on the status of (modified) in situ recovery technology and on environmental studies have been prepared by FERWG members M. A. Weiss and J. Clardy, respectively, and are attached.

COMMENTS ON IN SITU RETORTING: 13TH OIL SHALE SYMPOSIUM

by Malcolm A. Weiss

Twelve papers dealing with in situ retorting* were presented at the April 16-18, 1980, Oil Shale Symposium at Golden, Colorado. The published abstracts of these papers are attached. In contrast, there was only one paper about a specific surface retorting* process, on which there is currently no active work being done. The difference in reporting reflects DOE (in situ) vs. private (surface) R&D funding rather than total levels of commercial interest in the U.S. The twelve in situ papers may be classified into four groups, as summarized below.

* This listing excludes papers confined to the treatment of retort products for environmental purposes.

Well Field Design: There were two papers (Loo, Dougan) concerned with optimizing the placement and timing of both injection and production wells in formations where the formation properties (especially permeability) are different in different horizontal directions or horizontally and vertically. The methodologies used were similar to those used for oil field flooding. Allowing for the presence of significant anisotropy seems to be important where the natural formation is retorted in situ without modification; the application considered here was the Equity project for injecting superheated steam into the permeable leached zone of some shale deposits. The effects of natural anisotropy should be minor when there is extensive mining and rubbing before retorting, as in a modified in situ process.

Retort Preparation by Blasting: There were two papers (Britton, Ricketts) dealing with one aspect of the key technical and economic issue in in situ retorting, namely, preparation of the retort. Both papers described the placement of blasting charges and the optimum timing of explosions to get the best uniformity of rubbing in the retort. Voids are created in the retort by lifting the overburden (as in the Geokinetics project, Britton) or by mining out (as in the Occidental project, Ricketts). The Ricketts paper was favorably received by the Symposium participants. Ricketts claimed that, on the basis of unspecified tracer and other diagnostic tests, the blasting of Occidental Retort 6 resulted in a uniformly rubbed retort of about 5 million cubic feet with 23% voids. This desirable result was the outgrowth of

a previous R&D program dealing with cratering in confined spaces, row and array tests, explosive type, and other blast variables. Retort 6 itself was blasted with a mixture of 500,000 pounds of ammonium nitrate and fuel oil in 400 holes, about 1.4 pounds of ANFO/ton of shale, all set off in precisely controlled sequences. At a subsequent site visit to Occidental, it was stated that 386,000 pounds of explosive were used at a ratio of about 1.07. With these high levels of drilling and explosives, blasting "overpowered geology" and natural formation conditions were unimportant.

The paper provided an impressive display of the capabilities of advanced blasting technology. There was no discussion of economics and it is not clear that the cost of all the mining, drilling, and blasting used would be acceptable in a commercial operation or that the size and uniformity of the rubble produced would in fact result in an acceptable yield of oil during retorting. An early sill failure distorted the retorting results.

Retort Operation, Modeling, and Analysis: Seven papers (Jacobs, Campbell, Gregg, Udell, Sandholtz, Burnham, Duvall) covered experimental or theoretical or both aspects of the in situ retorting process. Jacobs' laboratory work using superheated steam confirmed that retorting at relatively low temperatures and high residence times produces increased amounts of volatile and hydrogen-rich oils but at reduced yields. Duvall reported on combustion and heat-transfer rates initiated in the plane "fracture" between two large blocks of shale. A group of four papers from the Lawrence Livermore Laboratory covered combined

theoretical and experimental studies on controlling or interpreting the process of in situ retorting: Campbell discussed the results of two runs in a 6-ton retort, each with a step-grade change from 18 to 36 gal/ton but with differences in particle-size distributions and retorting rates, neither of which had a major effect on yields under proper retort control. Burnham and Sandholtz interpreted processes occurring during retorting, Burnham by measuring the concentration ratios of various sets of product molecular species to infer rates of degradation reactions and Sandholtz by measuring time-temperature profiles to determine rates of front movement and thus to infer flow patterns and void structure. A flow model proposed by Gregg was used to predict nonuniform flow and sweep efficiency in three configurations representing the Occidental Retort 5 (with a geometry inferred from tracer data on that retort), a hypothetical retort with higher permeability near the walls, and a large block imbedded in a matrix of small-size material. Finally, Udell developed a more elaborate model than earlier investigators of combustion retorting of small oil-shale cylinders and tested the model experimentally in both inert gas and combustion gas atmospheres.

Retort Sealing: The author of the remaining paper (Mehta) evaluated Lurgi spent shale (possibly an unrepresentative sample) as a component of cement to seal abandoned in situ retorts against water intrusion.

PAPERS ON IN SITU RETORTING
PRESENTED AT 13TH OIL-SHALE SYMPOSIUM
APRIL 16-18, 1980

"GEOHYDROLOGY AND SURFACE WATER HYDROLOGY PROGRAMS OF THE EQUITY/DOE BX IN SITU OIL SHALE PROJECT"

P.M. Dougan, Equity Oil Co., W.W. Loo, D.E. Markley, and S.D. Munson, VTN

The objectives of the Equity/DOE geohydrologic test were to characterize the in situ hydrologic properties of the leach zone of the Green River formation. A thorough understanding of the anisotropic aquifer properties is needed to minimize environmental impact and to provide proper well field design. This paper presents: (1) a standard in situ geohydrologic testing and analysis program to determine the three-dimensional anisotropic properties of the groundwater system; (2) an interpretation of the analysis of selection of the optimum well field design for maximum production and minimum contamination of the local aquifer; and (3) a summary of the results of the testing.

"WELL FIELD DESIGN IN ANISOTROPIC MEDIA FOR IN SITU OIL SHALE MINING"

W.W. Loo, Consultant

The three-dimensional geohydrologic properties of a reservoir are vertical and horizontal permeabilities, leakage, storage coefficient, and vertical and horizontal boundary conditions. These geohydrologic properties can be tested in a single field test program. These properties will provide overall mass balance and fluid flow control parameters of the in situ oil shale mining operation. The sweep efficiency of a well field pattern is a key design parameter. For isotropic condition, a standard 5-spot pattern is preferred. For anisotropic condition, direct line drive, staggered line drive, and marching line drive patterns are preferred.

"DETERMINATION OF PROCESS YIELD FOR OIL SHALE RETORTING BY OIL ANALYSIS"

A.K. Burnham, Lawrence Livermore Laboratory

A method is described to determine the oil yield from a retorting process from the oil composition only. The heating rate and temperature of retorting and the resulting yield loss by oil coking is determined from the 1-alkene/n-alkane ratio. The severity of cracking is determined from the naphthalene/methyl naphthalene ratio. The amount of combustion and associated cracking is determined from the naphthalene content. The utility of this method is demonstrated using oil samples from several large-scale retorting operations. The possibility of using the oil mist from an in situ retort for an on-line determination of the current performance is discussed.

"BLAST DESIGN PRINCIPLES DEVELOPED FOR THE GEOKINETICS IN SITU PROCESS"

K. Britton, BlastMasters, Inc.

Retorts generally of the Geokinetics type provide space by lifting of an overburden and permeability by fragmentation of underlying rock with redistribution of the space provided. For very shallow and thin seams, fragmentation and lifting can be combined, and comparatively conventional blast designs suffice. As scale increases, lifting and fragmentation become increasingly separable and novel techniques must be employed for both. Timing is of critical importance for both, and the final condition of the retort bed is also greatly affected by explosive distribution and sequencing. Intrinsic properties of explosive and oil shale render important factors not significant in normal blasting. The above are discussed in the context of the Geokinetics process and experience, but are of significance to other in situ processes.

"OCCIDENTAL'S RETORT 6 RUBBLIZING AND ROCK FRAGMENTATION PROGRAM"

T. E. Ricketts, Occidental Oil Shale, Inc.

(No published abstract)

"LABORATORY MODELING OF IN SITU RETORTING OF OIL SHALE FROM THE LEACHED ZONE OF THE PARACHUTE CREEK FORMATION BY SUPERHEATED STEAM INJECTION"

H.R. Jacobs, M.S. Marzinelli, and K.S. Udell, University of Utah, and P.M. Dougan, Equity Oil Company

A series of experiments using a 6-inch diameter, 16-foot-long retort to process oil shale from the leached zone of the Parachute Creek Formation are described and related to the field tests being conducted by Equity Oil Company on their holdings.

Oil and gas production are characterized as functions of the time-temperature history and the residence time of the oil vapors within the retort. The average oil produced showed a C/H weight ratio of 6.80 as compared to 7.48 for that produced by Marathon Oil and 6.95 produced by IITRI using RF heating.

"INVESTIGATION OF CRITICAL PARAMETERS IN MODIFIED IN SITU RETORTING"

J.H. Campbell, J.H. Raley, F.J. Ackerman and W.A. Sandholtz, Lawrence Livermore Laboratory

Recent results from operation of a 6,000 kg simulated, modified in situ retort shown that high (up to 3 m/day) retorting rates can be achieved with high (85%) oil yield and acceptable (< 1000°C) maximum temperatures. These results were obtained with a bed of Colorado shale of broad (-30 + 0.001 cm) size range containing a stepped grade change from 75 to 150 ℓ /tonne. Process control by steam and air injection rates, as stipulated by pre-run model calculations, was demonstrated.

Continuous estimation of retorting rate and oil yield from off-gas composition was also demonstrated during the operation.

"SWEEP EFFICIENCY MODELING OF MODIFIED IN SITU RETORTS"

M.L. Gregg and J.H. Campbell, Lawrence Livermore Laboratory

A simple two-dimensional flow model is used to illustrate the effects of porosity and permeability distributions and retort geometries on sweep efficiency during modified in situ oil shale retorting. Results of two case studies emphasizing different retort geometries and porosity distributions are presented along with a study of nonuniform flow around a single, large block.

A simulation of the flow field and resulting retort front movement for Occidental Petroleum Company Retort 5 using a porosity/permeability distribution based on reported tracer data is presented. The results of the model calculation indicate a sweep efficiency of about 65%. From this data an estimate can be made of the amount of oil degradation due to burning, cracking, and coking.

"HEAT AND MASS TRANSFER CHARACTERISTICS OF COMBUSTION OIL SHALE RETORTING"

K.S. Udell, University of Utah

Heat and mass transfer characteristics of combustion oil shale retorting were studied both numerically and experimentally in order to describe the interactions between the thermal and chemical processes particular to modified in situ retorting. A sophisticated heat and mass transfer model of the heating and oxidation of a cylindrical oil shale sample was developed and compared to experimental temperature and heat transfer data.

The model was also applied to the prediction of intraparticle temperature and chemical profiles resulting from the combustion retorting of various diameter samples in a large-scale retort. A numerical parametric study was conducted which establishes retort operation guidelines so that oil yield and residual carbon use would be optimized.

"SOME RELATIONSHIPS OF THERMAL EFFECTS TO RUBBLE BED STRUCTURE AND GAS FLOW PATTERNS IN OIL SHALE RETORTS"

W.A. Sandholtz, Lawrence Livermore Laboratory

Conventional tracer measurements in packed beds rely on detection of specific molecular species to characterize bed structure and measure fluid dispersion under varied flow conditions. The work reported here demonstrates the use of temperature sensors such as thermocouples to develop similar kinds of information from thermal data.

In packed beds, such as batch oil shale retorts in which the process is driven by heat transfer from a flowing medium to the rubble, much can be inferred about bed and void structure and flow patterns from the time/temperature relationship among thermocouple arrays placed in the bed. The use of temperature data as a bed diagnostic tool in oil shale retorting experiments is shown. The close relationships in combustion retorting between the steam front and the retorting front are illustrated. This thermal logging technique has proven useful in understanding laboratory retorting experiments and predicting retort performance.

"LABORATORY SIMULATION OF TRUE IN SITU COMBUSTION RETORTING OF OIL SHALE"

J.J. Duvall, Laramie Energy Technology Center

An experiment simulating true in situ retorting of oil shale by igniting the common surfaces of two blocks of oil shale placed one on the other is described. The resulting combustion zone moved downstream in the fracture at approximately 2.5 inches/hour and retorted approximately 12% of the shale. Of the oil produced, about one-third was recovered and this amounted to 4% of the total oil possible. Heating rates in the shale varied from $34 \pm 6^\circ\text{F}/\text{hr}$ 1 inch from the fracture to $15 \pm 6^\circ\text{F}/\text{hr}$ 4 and 5 inches from the fracture. It is suggested that a slower moving combustion zone is necessary to retort more of the shale.

"HYDRAULIC CEMENT PREPARATION FROM LURGI SPENT SHALE"

P.K. Mehta, University of California, (Berkeley) and P. Persoff, Lawrence Berkeley Laboratory

The production of a hydraulic cement from Lurgi spent shale has been investigated. This cement may be used for on-site construction, sold outside of the oil shale region as a building material, or it may be used to backfill and seal abandoned retorts to mitigate in situ leaching and subsidence. The strength of the cement may be adequate to permit retorting of supporting pillars if abandoned retorts are grouted.

A true hydraulic cement has been produced by adding finely ground limestone to the Lurgi spent shale to increase the CaO-SiO_2 ratio and heating. A 1:1 mixture of spent shale and limestone produces a cement with a 28-day strength of 3,150 psi. Addition of 5% gypsum after heating further increases this to 3,750 psi.

COMMENTS ON ENVIRONMENTAL ASPECTS

by J. Clardy

Since published proceedings will be available, only a brief summary of environmental concerns is given here. The possibly limiting role of environmental controls was stressed in the introductory talk at the conference by T. A. Sladek who said "environmental problems could delay the projects and increase their costs". He pointed out that there are 300 species, some endangered, in the Piceance Creek Basin and that the air and water quality are generally excellent.

One major problem that was emphasized by M. Stanwood and T. Thoem is the status of spent shale under the regulations for the Resource Conservation and Recycling Act (RCRA). If it is considered a hazardous waste, a "cradle-to-grave" monitoring system using "best engineering judgment" will be needed. Revised regulations will be published in the near future; a detailed solid-waste disposal and management system is estimated to add \$2/bbl to the cost of shale oil. The disposition and behavior of spent shale was the major concern of K. Markey (Friends of the Earth, Denver). There was an optimistic report from the Paraho group on spent shale management. R. Heistand (Paraho) stated that Paraho's re-torted shale "could be disposed of properly with no dusting, self-ignition or attack by water". The impression was that the environmental activists were not adequately reassured by these observations.

Thoem posed ten environmental problems that summarized his areas of concern:

1. How much ground water will be used?
2. What is the quality of the discharge water?
3. How can the quality of water be protected?
4. How can spent shale be disposed of?
5. Can the mined area be revegetated?
6. How much SO₂ will there be in the off-gas streams?
7. What will be the visibility impact?
8. What are the levels and pathways of trace elements?
9. Is known pollution control technology applicable and effective?
10. How can population growth be managed?

FERWG-III SITE VISITS TO
PARAHO DEVELOPMENT CORP., ANVIL POINTS FACILITY;
UNION OIL COMPANY OPERATIONS NEAR DE BEQUE, COLORADO;
OCCIDENTAL PETROLEUM CORP., LOGAN WASH SITE;
Discussions of Regulatory Aspects with
P. Rutledge, Department of the Interior
(May 5, 1980)

FERWG-III DISCUSSIONS AT
THE UNIVERSITY OF COLORADO AT DENVER,
CENTER FOR ENVIRONMENTAL SCIENCES,
THE OIL SHALE TASK FORCE, with
T. Thoem, Environmental Protection Agency
A. Vickery, Colorado Mountain Club
P. Phillips, Environmental Defense Fund
K. Markey, Friends of the Earth
E. Redente, Colorado State University
W. Chappell, The Oil Shale Task Force
W. Hecox and D. Shelton,
Colorado Department of Natural Resources
J. Hutchins, Energy Development Consultants, Inc.
J. Knepper, Rio Blanco Oil Shale Company
(May 6, 1980)

Submitted by: S. S. Penner (5-28-80)

The following FERWG-III members and ex-officio members participated at all of the site visits and discussions: J. Clardy, A. E. Kelley, R. R. Lessard, S. S. Penner, W. S. Reveal (for S. B. Alpert, EPRI), J. Ross, R. P. Sieg, J. R. Thomas, M. A. Weiss; A. E. Lewis, J. Powers. In addition, A. G. Oblad and P. B. Weisz took part in the site visits on May 5.

The site visits and discussions were arranged by Arnold E. Harak (DOE, Laramie E.T.C.) and W. Chappell and K. Petersen (The Oil Shale Task Force). The composite schedule represented an exceptionally well-organized opportunity for FERWG to view the

complex problems that must be resolved before a major oil-shale development program can be implemented in the U.S. Although we shall discuss especially technical issues that require resolution, it is apparent that the principal impediments to early commercialization of shale-oil recovery relate to political, institutional, and socio-economic factors, all of which appear to be resolvable over the near term for a development schedule leading to moderate production goals (e.g., about 400,000 barrels per day production by 1990). Substantially larger production will require a national commitment by responsible officials in the Administration and support by the Congress, together with appropriate incentives to facilitate rapid private-sector entries.

1. The Paraho Program

A detailed review of the Paraho Program was presented by H. Pforzheimer, Jr. (President and Chief Executive Officer, Paraho Development Corporation, 300 Enterprise Building, Grand Junction, Colorado 81501) and by John B. Jones, Jr. (President, Paraho Corporation).

The Paraho Corporation is a closely held company, the principal subsidiary of which is the Paraho Development Corporation. The program at Anvil Points began with a lease in 1972 and retorting since 1974. A subsidy of $\$10 \times 10^6$ was received from 17 oil companies for a 3-year program, with industry funding ending in 1976. Support from the U.S. Navy allowed program continuation

until September 1978. Since September 1978, only foreign shale-evaluation programs (dealing with Israeli 15 GPT and Moroccan shales) have been actively pursued. The present Paraho lease expires in 1982. Under the Navy program, up to 100,000 barrels of shale oil were to be delivered to Sohio for refining but, because of insufficient funding, only 88,000 barrels were actually refined and shipped.

With retorting lasting up to 100 days while processing up to 200 BPD (= barrels per day), Paraho has successfully demonstrated intermediate-scale shale-oil recovery on a substantially larger scale than any other organization in recent years.*

A. Operational Aspects

Paraho management is currently searching for support of a 10,900 BPD retort with gas sufficient to produce 9.0 M_W_e for sale (this unit will cost \$500 to 600 x 10⁶, including mining and disposal) from an industry consortium or government. Scale-up (by a factor of ~50) is not viewed as a major problem because there were no identifiable operational problems (including materials problems) noted at the 200 BPD scale. Workers at Paraho have mined over 300,000 tons of shale. The shale is ground to manageable dimensions before use. About 5% of the material is said to

*For comparison, the Lurgi process that has recently operated at Essen, F.R.G., involved the processing of 300 kg of shale per hour, corresponding to 7.9 BPD for 42 GPT (= gallons per ton) shale with 100% Fischer assay recovery.

appear as fines that must be removed upstream of the retort; this material could perhaps be salvaged by pelletizing or briquetting or by conversion in a fluidized-bed reactor. The residence time for shale in the retort was about 6 hours in the 25-ft-long retort used, while the operating pressure drop was 0.7 to 1.0 inch/foot of bed. Typical rock dimensions were 3 inches and the supporting grate had 0.5 inch grids. The gravity-fed reactor was scaled up from a 2.5-ft lime kiln to 8.5 ft. The commercial unit (~10,000 BPD) will presumably also be 25 ft in height; additional bed height of 15 ft is available but has not been used. The retort uses a rotating spreader made of carbon steel. During operation, the only moving components in the retort are the spreader and a moving grate. The shale grade has an important influence in the mist-formation zone, where a mist separator is employed. Generally, about 2% of carbon remains on the shale with the currently used retorting technique. The flow-down retort, of which only about one third is utilized, is believed to be uniform. Thermocouples were inserted into the retort and presumably measured gas temperatures, which were then used to calculate rock temperatures. About one quarter of the total residence time of 6 hours is believed to be spent in the retorting zone. There are about 22,000 ft³ of gas per ton of rock and 500 lbs of rock per hour per ft² in the existing retort, which operates at a bed porosity near 40%.

Detailed, quantitative diagnostic measurements were apparently not performed in conjunction with the development of a numerical model for the retort.

The off-gas is low-Btu gas (~140 Btu/SCF) containing C_5^+ compounds, H_2S and NH_3 . It is claimed that the removal of these three components will reduce the energy contents of the gas to ~110 Btu/SCF.

B. Environmental Studies

The major environmental work done by the Paraho Corporation involves treatment of the spent shale. It is claimed that Paraho spent shale after water treatment and compaction is impervious to water. Thus, one may envision a scheme of spent-shale disposal in which a liner of treated and compacted shale is filled with spent shale and topped with oil shale (as a capillary barrier) and soil. Workers at Paraho have been successful in revegetating such areas and were unable to detect water permeability with simulated two-inch rainfalls.

Little work has been done on air pollution, which is not viewed as a major problem. Emissions were not visible from an operating plant.

2. Union Oil Company Operations

The FERWG visit was restricted to discussions of Union's program on the revegetation of spent shale. It has been shown that the success of revegetation of spent shale depends on the retort technology employed. If the spent shale has unconsumed carbon, it functions well in revegetation studies, i.e., it functions about as well as the native soil. The addition of fertilizer helped in all cases. When extensively decarbonized shale (undergoing carbonate reactions) is used, there is a problem resulting from the formation of a concrete-like, impervious layer. No criteria pollutants were found in the runoff water but it was alkaline and salty. There was also a capillary rise of salt and the long-term (several years) effects of this phenomenon are not yet clearly defined.

3. The Occidental MIS Program at the Logan Wash Site

A two-hour visit to the Logan Wash site was divided roughly equally between a trip through the mine and a conference room presentation about Oxy's operations. Seeing the site was of value for first-time visitors because it provided a sense of the size and nature of in situ shale operations. The information communicated was familiar to people who have been following Oxy's work and was presented at a level appropriate for technically literate but in-expert (in oil-shale matters) visitors.

A. Operational Aspects

Some data were shown on results obtained from Retort 6. About 47,000 barrels of oil were obtained (35% recovery) from the 133,000 barrels contained in 362,000 tons of rubbed shale (15 GPT average). Significant additional oil, perhaps 7-9,000 barrels, was said to have been lost as a mist with the retort off-gases whose volume and composition were not specified. The retort was prepared by removing 125,000 tons of rock and blasting with 386,000 pounds of explosives. While the site visit provided only modest specific information, extensive details on Retorts 5 and 6 were made available by A. E. Harak of LETC (the DOE technical project officer) through a copy of the 2-volume, 1335-page report "Occidental Vertical Modified In Situ Process for the Recovery of Oil from Oil Shale, Phase I, Final Report for the Period November 1, 1976 through April 30, 1979". Air injection in Retort 6 continued until July 17, 1979; all of the data for the run are included despite the nominal cut-off date given in the report title.

There was brief mention of Retorts 7 and 8, which are now being prepared. These retorts are identical to each other but differ somewhat from Retort 6 in both mining and blasting designs.

B. Environmental Studies

Workers at Occidental have been monitoring air and water quality at the Logan Wash site since 1974. They feel that the quantity of water consumed is not a problem. They are also

sanguine about the effects of MIS retorting on water quality. The relatively high retorting temperature and length of time of MIS recovery lead to extensive conversion of carbonates to insoluble silicates. Leachates from this spent shale have a pH comparable to that of groundwater in the Colorado Basin. It is expected that proper environmental management will reduce the solid particulates in the air to acceptable levels and that standard control technology will handle SO_2 emissions. Land use and abandonment of MIS retorts were not discussed.

4. Regulatory Aspects

It was stated (by P. Rutledge of the Department of Interior) that to date no regulatory requirement or permit had caused a delay in any planned operations on lease tracts under the Federal Prototype Oil Shale Program due, at least in part, to the high level of effort by the lessees and Government agencies involved. Lists of required permits, notifications, and regulatory actions required for development of oil shale plants set out a bewildering array of about 100 actions, some of which require multiple filings. It should be kept in mind though, that only a limited number (less than 10) of key permits, requiring complex submissions, is necessary prior to commencing operations. These permits are in the areas of overall development plan approvals, mined land reclamation, County special land use, air and water quality.

5. Discussions at the University of Colorado at Denver

The discussions at Denver covered a very wide spectrum of topics, most of which dealt with environmental issues. We shall

not attempt to review here the multiplicity of views and opinions presented but confine ourselves instead to brief comments dealing with special problem areas, where we believe that programmatic changes are required.

A. Air-Quality Modeling

The current EPA program, as described by T. Thoem, is very modest in scope and appears to be designed to provide answers on developments that are consistent with an implementation schedule leading to 400,000 BPD production by 1990. Thoem repeated his statement from the 1980 Oil Shale Symposium at Golden, Colorado, that SO_2 emissions will control the size of an oil-shale industry. Using crude models, this limit is in the 200,000-400,000 BPD range. The lack of a realistic model for air circulation over rough terrain and data to put into this model were extensively discussed. We believed that issues concerning air-quality and impact assessments can and should be resolved on a much shorter time scale, even allowing for the need to develop an improved regional computer model that includes orographic winds and special land contours in the Piceance Basin and other regions that are rich in shale oil. According to Thoem, a three-year field-measurement and modeling program costing $\$5$ to 6×10^6 should be sufficient to provide needed quantitative information concerning the relations between air quality and shale-oil recovery; this level of funding represents about a 100-fold increase above currently planned funding levels.

We concur with the view expressed by Thoem that the specifications for an acceptable regional model are properly a governmental responsibility, while industrial developers supply site-specific data that relate to their own development programs.

FERWG will examine the availability and suitability of regional air-quality models in greater detail at subsequent meetings.

Spent shale should not be considered a hazardous waste under RCRA but Colorado regulations will make spent-shale disposal a substantial problem. Mutagenicity tests might lead to the classification of spent shale as a hazardous waste. EPA has not been able to reproduce the Paraho results. There seems to be a difference in protocols and EPA finds troublesome residues in the runoff produced by the initial leach (albeit, with 40 inches of rainfall!).

B. Concerns of Environmentalists

A. Vickery (Colorado Mountain Club) gave a list of concerns. She pointed out that environmental regulations were not put up as constraints but in response to past abuses. She wanted an oil-shale industry to start out small so that its effects could be carefully monitored. The exacerbation of air pollution in Denver and the problem of acid rain were also mentioned. She was quite candid that her organization felt a lack of technical expertise in a variety of areas.

P. Phillips (Environmental Defense Fund) also listed her concerns. She claimed that there was already an acid rain problem on the front range. The major focus of her concern was the influx of people.

K. Markey (Friends of the Earth) spoke at length. His major concern was public access to environmental data from the private tracts. He felt that current laws were inadequate to assure access to these data.

All three environmentalists shared the view that an oil-shale industry should start small and should be monitored very closely.

There is a clear and as yet unmet responsibility by federal planners to address the issues raised in believable and quantitative terms. The regional air-quality model, to which we referred in Section A, is a part of the answer. Other problem areas deal with water supplies, water distribution and contamination, and with the broad spectrum of issues addressed under the WELMM (water, energy, land, manpower, management) model developed at the International Institute for Applied Systems Analysis.

We intend to provide detailed research recommendations dealing with environmental studies and public education on these topics in our final report.

C. Solid-Waste Research Needs

E. Redente (Colorado State University) emphasized the importance of toxicological studies relating to the concentration of toxic trace elements in selective plants and possibly also in microbes and animals. This particular issue was emphasized, some years ago, in deliberations of the Environment and Health Panel

of the Congressional Office of Technology Assessment. We recommend the prompt initiation of an adequate program to minimize the likelihood that developing shale-oil industries will lead to unexpected contamination through processes of this type.

In general, there appears to be considerable room for programmatic developments at the interfaces between shale-oil retorting, spent-shale disposal, regeneration of plants (not necessarily native varieties), discovery of microbial cultures that are compatible or adapted to the physico-chemical environments created in spent shale, etc.

D. The Oil Shale Task Force

W. Chappell, Director of the Oil Shale Task Force, discussed the overall program of his group, which includes a wide spectrum of activities (e.g., construction of regional trace-element maps, coordination with health-effect studies at Los Alamos, etc.).

E. Concerns of the State of Colorado

A 400,000-BPD industry is expected to increase the population of Colorado by about 75,000 people. There appears to be considerable concern with the socio-economic impacts of this influx of population, a problem which we have not yet properly examined. Water supplies are generally considered to be adequate for an industry processing up to 1×10^6 BPD and are thus not expected to be limiting over the near term, provided an efficient management system is developed.

F. The Rio Blanco Program (Tract C-a)

The Rio Blanco Program of Gulf Oil and Standard Oil of Indiana appears to be a well-conceived effort to perform critical studies before commitment to commercialization.

This MIS program has the following sequence: Retort 0 [$(30 \times 30) \text{ft}^2 \times 200 \text{ ft}$], to be ignited in August 1980; Retort 1 [$(60 \times 60) \text{ft}^2 \times 400 \text{ ft}$], to be ignited by January 1981 and to be provided with adequate instrumentation; Retort 2 [$(120 \times 120) \text{ft}^2 \times 400 \text{ ft}$], to be ignited after dewatering problems have been resolved. The total program cost is estimated to be $\$250 \times 10^6$.

A 4,000-TPD (= ton per day) surface retort, using Lurgi technology, is under design. After the initial pass through the retort bed, this retort will be fueled by the burn-up of carbon residues remaining on the shale. This plant design will profit from a 700 kg/hour plant that will go on-line by mid-1982 near Hamburg, F.R.G. It is expected that 100% of Fischer assay will be recovered. Perhaps fines removal may pose problems with the Lurgi technique.

FERWG DISCUSSIONS OF WATER REQUIREMENTS
FOR SHALE-OIL RECOVERY
(May 10, 1980)

Submitted by: S. S. Penner (May 28, 1980)

FERWG members S. S. Penner and M. A. Weiss met with Professors R. F. Probstein and J. P. Longwell consecutively on the M.I.T. campus for discussions of water requirements and availability for shale-oil recovery.

R. F. Probstein has been actively assessing water requirements in an expanding synthetic fuels industry. Important parts of these studies have been performed by Water Purification Associates (238 Main Street, Cambridge, Mass. 02142), which was founded by Probstein. Studies performed by Probstein and his associates have been widely published. Of particular interest to us are studies dealing with wastewater treatment and management at oil shale plants. Probstein does not view water availability or management as critical bottlenecks in foreseeable regional development plans. Some of these studies are described in the book and other publications listed under the references to this brief report.

J. P. Longwell provided the following useful summary of water requirements, for various planned shale-oil recovery processes, on the basis of Probstein's work:

1. Paraho (99,170 B/D): 1.13 B of H_2O/B of oil.
2. Union Process B (55,555 B/D): 2.0 B of H_2O/B of oil.
3. TOSCO II (47,000 B/D of syncrude and 4,300 B/D of LPG): 3.5 B of H_2O/B of oil.
4. A combined MIS-Oxy plant with a Lurgi surface retort: 0.92 B of H_2O/B of oil.
5. Rio Blanco Project using Lurgi retorts: 1.39 B of H_2O/B of oil.

It is apparent from Probstein's data that process selection may increase recoverable shale oil by as much as a factor of four when the least water-demanding technology is used in place of the technology with heaviest water demands. Significant efforts to reduce water consumption even further may well yield still more favorable estimates. A table showing water use in shale-oil recovery, prepared by J. P. Longwell, is attached.

The combined pressures of minimizing regional socio-economic impacts and reducing consumptive water requirements as much as possible may suggest that technological implementation of these R&D goals should receive emphasis in the final FERWG report.

According to John Shaw (Civil Engineering) of M.I.T., who joined the discussions with J. P. Longwell, water consumption in cooling systems is a major problem. He believes that water storage units should be built and that the customarily used cost estimate of \$1,000/acre-foot may prove to be too high. Improved management of water run-off during springtime may yield significant returns.

Fluidized-bed retorting, using optimally selected amounts of CaCO_3 and temperatures of $\sim 1100^{\circ}\text{F}$ for sulfur removal, were briefly discussed.

Following studies in Sweden, a froth flotation process has been considered for shale beneficiation with brominated hydrocarbons. Large separation factors should be obtainable for finely ground shale. Brief mention was made of the possibility of employing microbial conversions on beneficiated shales.

Water Use in Shale-Oil Production,

compiled by J. P. Longwell

| Use | B Water/B Oil | | Comments |
|-------------------------------------|---------------|---------|---|
| | Minimum | Maximum | |
| mining | 0.1 | | For surface mining. |
| | | 0.25 | For underground mining. For dust control; low-grade water may be used and the amount reduced by the use of CaCl_2 . |
| preparation and handling | 0.1 | 0.1 | |
| retorting | (0.3) | (0.3) | This is water production from shale condensate (Fischer assay for $\text{H}_2\text{O} \approx 1.4\%$ of the stone treated). |
| spent stone disposal & revegetation | 0.7 | | Paraho plan involving mostly revegetation; a cement-lined dump is used for dry stone. |
| | | 2.8 | Tosco plan; all of the stone is wetted with 15% H_2O to make cement. |
| domestic use | 0.4 | 0.4 | Much of this water could be recycled. |
| Total | 1.0 | 3.2 | |
| refining | 0.2 | 0.2 | Water use can be reduced by recycling blowdown water; wet cooling is not included. |
| wet cooling (power & refining) | 1.4 | 1.4 | Water use may be reduced by dry cooling. |
| Total | 1.6 | 1.6 | |
| Grand total | 2.6 | 4.8 | |

Selected References

1. R. F. Probstein and H. Gold, Water in Synthetic Fuel Production - The Technology and Alternatives, M.I.T. Press, Cambridge, Mass., 1978.
2. R. F. Probstein, "Water for a Synthetic Fuels Industry," Technology Review 81, 3-9 (1979).
3. R. E. Hicks, R. F. Probstein, I. Wei, D. S. Farrier, J. Lotwala, and T. E. Phillips, "Wastewater Treatment and Management at Oil Shale Plants," paper presented at the 13th Oil Shale Symposium, Golden, Colorado, April 16-18, 1980.
4. "Upper Missouri River Basin Water Availability Assessment for Coal Technology Requirements Conducted for the U.S. Water Resources Council," Missouri River Basin Commission, Suite 403, 10050 Regency Circle, Omaha, Nebraska 68114, December 1978.
5. "The Availability of Water for Oil Shale and Coal Gasification Development in the Upper Colorado River Basin, Summary Report," Executive Director, Colorado Department of Natural Resources, Denver, CO, October 1979.
6. H. Gold and D. J. Goldstein, "Water-related Environmental Effects in Fuel Conversion: Volume I. Summary," Industrial Environmental Research Laboratory, Office of Energy, Minerals, and Industry, Research Triangle Park, NC 27711, EPA-600/7-78-197a, October 1978.

PLANNING CONFERENCE ON SYNTHETIC FUELS

Forum on Processes and Impacts *

Impacts of Water Use in Synfuel Production

by

Ronald F. Probstein

M.I.T.

The impacts of water use in synfuel production fall into three principal categories: (1) Supply, (2) disposal of treatment wastes and (3) process/site effects.

The past six years of study have shown that there are specific environmental and other impacts in the categories cited, but this same body of work gives no evidence for delaying the construction of large-scale synthetic fuel plants until still further studies are completed. This is particularly true in relation to the often-quoted problem of water supply in the arid western areas of the country, where much of the easily-mined coal and almost all of the high-grade oil shale are found. All indications are that the production of synthetic fuels from coal and oil shale is not limited by inadequate water supply and that available surface water could support a large-scale synfuels industry. In some cases, such as in oil-shale mines, brackish ground water may be an unwanted product which then will have to be used as the water source.

The principal impacts concerning supply relate to defining technically, economically, environmentally and otherwise the alternative choices among local surface and groundwater usage, the transport of water from distant sources, and the use of desalinated brackish groundwater. The principal unanswered questions concerning the impact of disposal of water treatment

* Reproduced with the author's permission.

wastes center on the local ecosystem effects, and in particular the effects of disposing of large quantities of salts from treating millions of gallons of medium- or low-quality waters to the high quality needed for the synfuel plants steam boilers. Both field and laboratory studies should be undertaken to determine the optimum disposal procedures. The water-related environmental impacts of siting different coal-conversion processes at different sites can be expected to be somewhat different since each of the different areas have different ecological problems. This question has not been considered in detail but should be in connection with the siting of demonstration plants.

More detailed statements of the problems and impacts in the three areas are as follows:

1. Supply -

The desalting of large quantities of surface water and brackish ground water is required for synthetic fuel plants, because these plants need large quantities of boiler water makeup to produce the high-quality water consumed in producing hydrogen. For example, a Lurgi coal-gasification plant producing 250×10^6 SCF/day of pipeline gas requires about 3000 gal/min of very high quality boiler feed water, or about 15 times that used in a steam electric power plant producing 1000 MW of electricity. Large quantities of brackish ground water are available for use in synthetic fuel plants in the western United States. In some cases, such as in oil-shale mines, brackish ground water may be an unwanted product which then will have to be used as the water source. Because even good-quality surface water must be treated it may be more appropriate to desalt brackish ground water for plant use

rather than transporting fresh water from a distant source and then desalting it, though to a lesser degree than groundwater. Water transport economics should be examined in relation to desalting costs. In addition, laboratory and field desalting tests should be carried out, along with parallel studies on the desalting of briny blowdowns and treatment wastes produced in the plants.

2. Disposal of Treatment Wastes

Both fundamental and applied studies should be undertaken on the ecosystem effects, particularly in the East, which could result from the disposal of large quantities of salt. The salt disposal problem arises from treating large quantities of medium-quality river water to high-quality boiler feed. A synfuel plant could produce from 20 to 50 tons/day of salts concentrated from the original source water. How this disposal is to be carried out is an open question. Included among the possibilities are return to the source, deep well injection and landfill. Other disposal ideas which should be investigated include the slurring of the coal or other fossil fuel into high-temperature gasifiers with the saline waters so that the salts then become solidified with the gasifier slag. Other possibilities including encapsulation should also be studied. In the West where open landfill disposal will more likely be employed, ecosystem studies on long-term leaching effects from evaporation pond beds should also be investigated.

3. Process/Site Effects

In each of the coal-bearing regions, the environmental impacts of coal type, water availability, land and water ecology should be ranked in order of their importance. For the desired fuel products

and various generic conversion processes a rational ranking of the process characteristics and their environmental impacts should be undertaken in relation to the siting of demonstration plants and synfuel complexes. For example, for a given process consideration should be given to the environmental impacts of cooling-water requirements, by-product oils, by-product vapors, and the quantity and content of the solid waste products. The commercial processes should then be suitably matched to sites to determine their environmental impacts.

FERWG SITE VISITS TO THE
LARAMIE ENERGY TECHNOLOGY CENTER
(June 3, 1980)
and
LAWRENCE LIVERMORE LABORATORY
(June 4, 1980)

Submitted by: S. S. Penner (June 6, 1980)

The following FERWG members visited the Laramie Energy Technology Center on June 3 and the Lawrence Livermore Laboratory on June 4: W. S. Bergen, J. Clardy, A. E. Lewis, M. A. Weiss, S. S. Penner, and R. P. Sieg; FERWG members J. M. Hopkins, A. E. Kelley, and J. R. Thomas participated on June 3, while S. B. Alpert and J. Ross joined the discussions and site visits on June 4.

At Laramie, J. H. Weber served as host. J. H. Weber, B. Sudduth (manager, engineering) and S. Dorrance (manager, physical sciences) presented overviews of past and ongoing programs. FERWG members also inspected the 10- and 150-ton retorts. In addition, the following special topics were briefly discussed:

1. The role of university research in the shale-oil recovery programs. Examples of possible university-based studies were considered (e.g., pyrolysis of oil shale in evacuated chambers, rock properties, thermophysical properties of heated shales under dynamic loading, adsorption and desorption kinetics of H_2S on shale, reactions of shales at elevated temperatures, development of improved instrumentation for diagnostic measurements,

etc.). Several of the participants expressed the view that university-based programs could profitably utilize 5-10% of the total DOE and industry budgets on the developments of new shale-oil recovery technologies.

2. The desirability of developing a centralized library of shale properties (including physico-chemical parameters, materials properties, etc.) that would be programmed for direct access by many users and might ultimately be applied in relating measured shale properties to shale behavior in retorts and the definition of optimal product yields. It was noted that this properly integrated data-acquisition activity would be analogous to Neavel's proposed coal-characterization program. Several of the participants suggested, however, that this type of programmatic development might be less useful for shale than for coal.

The discussions at the Lawrence Livermore Laboratory dealt primarily with the impressive progress that has been made in quantifying the kinetics and fluid mechanics of retorting that has led to useful predictions of both underground and surface retorting processes. Also discussed were recent work on application of RF heating to shale-oil recovery and implementation of large-scale developments of shale-oil recovery according to the proposal of A. E. Lewis. The following Lawrence Livermore Laboratory staff members made presentations: A. E. Lewis (introduction and overview), Albert J. Rothman (program definition and future plans), John H. Campbell (retorting), Alan K. Burnham (kinetics,

chemistry), Richard Mellon (RF heating), Richard Heckman (large-scale shale-oil recovery), Robert L. Braun (modeling).

COMMENTS ON SITE VISITS TO LETC AND LLL

by J. Clardy

1. LETC

LETC is the lead DOE laboratory for oil shale and a review of the existing industry/government projects was given by J. H. Weber. Much of the LETC work is devoted to resource characterization. There is an extensive collection of core samples for regional shale characterizations, as well as current interest in characterizations at the molecular level. A useful technique is solid state ^1H NMR for the determination of aliphatic/aromatic ratios of native oil-shale samples. These ratios appear to be critical process variables. There is concern at LETC about the poor state of knowledge of the inorganic phases of oil shale. Available characterization techniques are deemed inadequate. This deficiency is of concern since there is evidence that the inorganic constituents control much of the process chemistry.

David Sheesley at LETC is in charge of environmental work and interacts closely with EPA. Special areas of concern are the quality of process water, the applicability of existing control technology to oil-shale problems and biological effects of oil-shale residues and products. The carcinogenicity of shale oils

is uncertain, with rather different assessments coming from Los Alamos and Dupont. There was agreement that the problem is diminished on hydrotreating.

The problem of nitrogen compounds in shale oils was discussed. Nitrogen compounds are responsible for instability and incompatibility problems. Their removal involves substantial hydrotreating.

While LETC is not actively involved in the study of problems of land reclamation, this issue was discussed. Experience in foreign countries with land reclamation is extensive but information on these efforts is poorly organized. A direct visual display of land-reclamation projects would be useful.

Support for really innovative university research relating to synfuels processing seems to have disappeared, both at NSF and at DOE. The damaging effects of this lack of funding on the next generation of processes and scientists were emphasized.

There was brief discussion of a process using CO, H_2O and kerogen to produce oil. Presumably CO and H_2O form H_2 , which then reacts with the kerogen. Hydrogen generated by the shift reaction appears to be more reactive than added molecular hydrogen. Yields in excess of Fischer assay are obtained in a one hour, $450^{\circ}C$ batch process.

2. LLL

The LLL has been involved in oil-shale work since the early 70s. The current budget is \$3.4M, with most of the effort concentrated on modified in situ (MIS) retorting. Some of the MIS effort is also applicable to surface retorting. The program is highly interactive at LLL, with excellent interplay between laboratory experiments, retort modeling, and pilot-scale retorting. There is considerable interaction with industry; the Oxy #5 retort has been modeled and operating conditions for the upcoming Rio Blanco Retort-0 have been selected by using the LLL model. Modeling results are generally in good agreement with experiments but it is premature to conclude that the available models have all salient aspects properly included.

There is an effort in progress to determine composition ratios in the retort off-gas or retort oil. These ratios may serve as guides for the selection of burn temperature and degrees of coking and cracking in an uninstrumented MIS retort. Some useful ratios, such as ethene/ethane, 1-alkene/alkane and aromatic/alkylaromatic have been categorized, although the fundamental basis for their utility is not well understood.

An effort to define the sulfur chemistry in retorting processes is just starting and should prove to be useful.

A crude economic analysis of retorting with RF energy has been done. This idea merits further study.

COMMENTS ON THE SITE VISIT TO LLL

by M. A. Weiss

The \$3.4M 1980 oil-shale budget at LLL is devoted chiefly to experimental and modeling work on in situ retorting with field applications to large-scale tests by Laramie, Occidental, and Geokinetics. Some surface retorting research is just beginning with the rationale that (a) in situ processing may not yet be successful commercially, (b) in situ processing generally uses some surface retorting, and (c) surface retorting is of great commercial interest at this time. Furthermore, basic in situ data and theory are often applicable to surface processing.

The presentations covered three general areas: (a) pilot retorting, (b) laboratory research, and (c) modeling. Most of the work reported has been recently published or presented at oil-shale meetings (see the attached list for details). The latest large-scale retorting tests have involved examinations of the effects of retorting rates and grade change on recovery. High recovery (80+) can be obtained with proper retort gas control. Interpretation of the data is based on the notion that recovery equals the product of sweep efficiency (SE) and oil yield (OY); SE is the fraction of total shale contacted by the retorting front and is high in the pilot retorts but proved to be low in a detailed analysis of the flow in the Occidental Retort No. 5;

OY is the fraction of oil remaining after losses by combustion, cracking, and coking. Losses due to the latter two effects may be inferred from the respective ethylene/ethane and naphthalene/methyl-naphthalene ratios in the products. Rate data for the oil-loss reactions, carbonate decomposition, kerogen pyrolysis, char gasification, etc. are combined with the heat and mass transfer equations to produce a computer model for one-dimensional retorting, which agrees satisfactorily with most of the experimental results.

Two additional reports of studies of non-traditional oil-shale topics were presented. One report covered in situ oil recovery by radio-frequency heating. The surprising conclusion of the analysis was that a barrel of raw shale oil could be produced for \$8.5 (early 1980 dollars, 15% equity capital of \$6400 per daily barrel of capacity, 20-year life, no taxes, no credit for gas produced) plus the total cost of 390 kilowatt-hours of electrical energy; a debate over the "true" total cost of power (off-peak vs. dedicated, nuclear vs. coal, etc.) did not lead to definitive conclusions but, if the numbers are correct, RF heating cannot be rejected out of hand. The second report covered legal devices which might be applicable in planning and coordinating a large-scale shale-oil industry. This study led to the conclusion that an interstate compact (e.g., the Delaware River compact) is the most promising means for delegating state and federal oil-shale interests to a single agency.

The facilities for the LLL retorts (6-ton, 20'H x 6'D; 1/8-ton, 5'H x 1'D) were visited.

UCRL 82457 J. H. Raley, "Monitoring Oil Shale Retorts By Off-Gas Alkene/Alkane Ratios," for submission to FUEL, March 1979.

UCRL 82482 R. G. Carbonell, "Dispersion in Oil Shale Retorts: Effect of Particle Size Distribution and Flow Non-Uniformities," presented at the 14th Intersociety Energy Conversion Engineering Conference, Boston, Mass., August 5-10, 1979. October 1979.

UCRL 82512 D. W. Gentry, R. H. Carpenter, G. L. Krum, "Oil Shale Resource Assessment for In Situ Retorting: Piceance Creek Basin, Colorado," for submission to Energy, May 1977.

UCRL 83236 A. E. Lewis, "Oil from Shale: The Potential, the Problems, and a Plan for Development," for submission to Energy, September 1979.

UCRL 83261 H. Y. Sohn and S. M. Shih (consultants from Univ. of Utah), "An Approximate Solution for the Retorting of a Large Block of Oil Shale with an Interval Temperature Gradient," for submission to FUEL, September 1979.

UCRL 83265 M. L. Gregg, J. H. Campbell and J. Taylor, "Laboratory and Modeling Investigation of Oil Shale Block Retorting to 900°C," for submission to FUEL, September 1979.

UCRL 83348 T. R. Galloway and W. A. Sandholtz, "In Situ Oil Shale Retorts: Coupling of Heat and Mass Transfer," for submission to the American Institute of Chemical Engineers Meeting, San Francisco, November 25-29, 1979. September 1979.

UCRL 83531 R. G. Carbonell, "Effect of Particle Size Distribution and Flow Non-Uniformities on Dispersion in Porous Media: Application to Oil Shale Retorts," presented at the 2nd Multiphase Flow and Heat Transfer Symposium, Miami, Florida, March 16-18, 1979. October 1979.

UCRL 83568 A.K. Burnham, "Studies of Oil-Shale Reaction Chemistry at LLL," for presentation at the IGT Symposium, Atlanta, Georgia, December 3-6, 1979. November 1979.

UCRL 83569 Rothman, A.J., "Recent Experimental Developments in Retorting Oil Shale at the Lawrence Livermore Laboratory," for presentation at the IGT Symposium, Atlanta, Georgia, December 3-6, 1979. November 1979.

UCRL 83612 Carley, J.F., "Spontaneous Ignition in Preheated Beds of Spent Oil Shale," for submission to In Situ, November 1979.

UCRL-83738 A. E. Lewis, "Oil Shale: A Framework for Development," submitted for presentation at the 13th Oil Shale Symposium, Golden, Colorado, April 16-18, 1980. December 1979.

UCRL-83739 J. H. Campbell, J. H. Raley, F. J. Ackerman, W. A. Sandholtz, and S. B. Libicki, "Investigation of Critical Parameters in Modified In-Situ Retorting," submitted for presentation at the 13th Oil Shale Symposium, Golden, Colorado, April 16-18, 1980. December 1979.

UCRL-83740 W. A. Sandholtz, "Some Relationships of Thermal Effects to Rubble Bed Structure and Gas Flow Patterns in Oil Shale Retorts," submitted for presentation at the 13th Oil Shale Symposium, Golden, CO, April 16-18, 1980. December 1979.

UCRL 83741 J. H. Campbell, M. L. Gregg, "Sweep Efficiency Modeling of Modified In Situ Retorts," for presentation at the 13th Oil Symposium, Golden, CO, April 16-18, 1980. February 1980.

UCRL-83742 A. K. Burnham and others, "Determination of Process Yield for Oil-Shale Retorting by Oil Analysis," submitted for presentation at the 13th Oil Shale Symposium, Golden, Colorado, April 16-18, 1980. December 1979.

UCRL-83788 A. E. Lewis and R. L. Braun, "Retorting and Combustion Processes in Surface Oil-Shale Retorts," prepared for presentation at the 15th Intersociety Energy Conversion Conference, Seattle, WA, August 18-22, 1980. May 1980.

UCRL-84048 A. K. Burnham and R. L. Ward, "A Possible Mechanism of Alkene/Alkane Production in Oil Shale Retorting," for presentation at the ACS Meeting, San Francisco, CA, August 25-29, 1980.

UCRL-84098 R. G. Mallon, "Economics of Shale Oil Production by Radio Frequency Heating," for presentation at the Society of Petroleum Engineers Meeting, Dallas, TX, September 1980. May 1980.

COMMENTS ON THE SITE VISIT TO LLL

by John Ross

FERWG-III spent a full day at Livermore and received a comprehensive review of the research and development program on retorting for both above-ground and modified in situ oil-shale recovery. The program at Livermore, currently funded at \$3.4 million, is primarily concerned with retorting.

The overall efficiency of the retort depends on two factors: the sweep efficiency and the oil yield. The sweep efficiency measures the fraction of shale in the retort which is swept by the flame front and the oil yield is a measure of the distribution of the oil used for combustion, coking and cracking. The laboratory retorts have a 100% sweep efficiency and therefore the measurements are solely concerned with oil yield. The retorts are adiabatic vessels and both energy and mass balances are performed. Measurements are made of temperature and gas combustion. Extensive modelling of retort operations has been accomplished and the predictions of the models are in good agreement with measurements. Furthermore, operating conditions of retorts can be changed and the results predicted by using the models.

The chemical reactions occurring in the retorting of shales are extremely complex. A beginning has been made for quantitative modeling by postulating the most probable overall reactions

and including these in the kinetic schemes that are used in the modelling calculation. It is recognized that a great deal more fundamental research on the essential chemical reactions, free radical species present, and reaction mechanisms will be necessary for understanding and control of retorting procedures.

A report was presented on estimates for the economics of dielectric heating of oil shale, which has the advantage of uniform heating and no requirement for expensive rubblization. Although the energy ratio for radio-frequency (dielectric) heating is not as favorable as for retorting, the economic assessment is favorable and the water requirements are considerably lower for dielectric heating.

We were impressed by the quality of the research and development work.

SHALE OIL DEVELOPMENT AND COST ESTIMATES,
UNIVERSITY OF CALIFORNIA/SAN DIEGO,
LA JOLLA, CALIFORNIA 92093
(July 8, 1980)

Submitted by: S. S. Penner

1. Introduction

Discussions were held at La Jolla on shale-oil costing on July 8, 1980, under the chairmanship of FERWG member John R. Thomas. A complete listing of attendees is given in Table 1. Prior to the meeting, the invited participants had been asked to summarize their economic assumptions according to the format shown in Table 2. It was our hope that the discussions would serve to clarify the origin of the large differences that exist in recently published cost estimates for shale-oil production, viz. ~\$15/B [A. E. Lewis, "Oil from Shale: The Potential, the Problem, and a Plan for Development," Energy 5, 373-387 (1980)], ~\$12/B [N. R. Ericson and P. Morgan, "The Economic Feasibility of Shale Oil: An Activity Analysis," The Bell Journal of Economics 9, 457-487 (1978)], \$48-62/B [T. A. Sladek, P. L. Poulton, W. E. Davis, and P. A. Robinson, "A Technology Assessment of Oil Shale Development," paper presented at the 13th Oil Shale Symposium, Golden, Colorado, April 16, 1980; "An Assessment of Oil Shale Technologies," Office of Technology Assessment, Washington, DC 20510, June 1980].

Table 1

List of participants attending the FERWG meeting on retorting techniques and associated costs on July 8, 1980 at the University of California, San Diego.

Dr. Seymour B. Alpert
Technical Director
Advanced Power Systems Division
Electric Power Research Institute
P.O. Box 10412
Palo Alto, California 94303

Dr. Arthur A. Boni
Science Applications, Inc.
1200 Prospect Street
La Jolla, California 92037

Dr. Jon Clardy
Department of Chemistry
Baker Laboratories
Cornell University
Ithaca, New York 14853

Dr. Brian Harney, M/SD-107
Office of Oil Shale
U.S. Department of Energy
Washington, D.C. 20545

Dr. Walter Hecox, Room 723
Executive Directors Office
Colorado Department of Natural
Resources
1313 Sherman Street
Denver, Colorado 80203

Mr. Arnold E. Kelley
Vice President
Engineering and Development
Union Science and Technology Division
Union Oil Company of California
P.O. Box 76
Brea, California 92621

Dr. John H. Knight
Division Manager
Oil Shale Division
The Superior Oil Company
2750 So. Shoshone
Englewood, Colorado 80110

Dr. Richard R. Lessard, Director
Coal Research Laboratory
Baytown Research & Development
Division
Exxon Research & Engineering Co.
P.O. Box 4255
Baytown, Texas 77520

Dr. Arthur E. Lewis, L-207
Oil Shale Project Manager
Lawrence Livermore Laboratory
University of California
P.O. Box 808
Livermore, California 94550

Mr. Dan Murphy
Rio Blanco Oil Shale Company
9725 East Hampton
Denver, Colorado 80212

Dr. Alex G. Oblad
Department of Mining & Engineering
University of Utah
Salt Lake City, Utah 84112

Dr. S. S. Penner, Director
Energy Center and
Chairman, FERWG
University of California, San Diego
La Jolla, California 92093

Table 1 (continued)

Mr. Ted Pollaert
Lurgi Corporation
445 South San Antonio Road
Los Altos, California 94022

Dr. John R. Powers
Acting Director for Research and
Technical Assessment
U.S. Department of Energy
Mail Stop J-309, GTN
Washington, D.C. 20545

Dr. John Ross
Department of Chemistry
Stanford University
Stanford, California 94305

Dr. John R. Thomas, President
Chevron Research Company
P.O. Box 1627
Richmond, California 94802

Dr. Malcolm A. Weiss
Deputy Director
MIT Energy Laboratory, E19-439
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

Dr. Joseph Yerushalmi
Electric Power Research Institute
P.O. Box 10412
Palo Alto, California 94303

Table 2

SUMMARY OF ECONOMIC ASSUMPTION

| | |
|-----------------------------|------|
| Actuarial Rate of Return, % | 15 |
| Equity Investment, % | 100 |
| Construction Period, Yr | 4 |
| Production Life, Yr | 20 |
| Income Tax, % | 48 |
| Investment Tax Credit, % | 10 |
| Tax Life | |
| Mine Equipment, Yr | 8 |
| Retorting Equipment, Yr | 13 |
| Operating Factor, % | 90 |
| Project Date, \$ | 1980 |
| Area Factor | 1.25 |

Operating costs include by-product credits as follows:

| | |
|----------------------------|------|
| Export Fuel Gas, \$/EFO B | 15 |
| Export Power, \$/kwh | 0.02 |
| Sulfur, \$/Ton | 20 |
| Ammonia, \$/Ton | 200. |
| (Process Water), \$/M Gal. | 0.40 |
| (Cooling Water), \$/M Gal. | 0.03 |

Retorts are assumed to be energy self-sufficient.

No resource value.

Project scale optional (50,000 B/D preferred).

2. Summary of Presentations

S. B. Alpert (EPRI) commented on the use of shale oil in the electric power industry, noting that high-nitrogen shale oil from Paraho had been used successfully in staged combustion at the Southern California Edison Company. He recommended continuing studies to assess the feasibility of using unrefined and refined shale oils, with or without staged combustion, in utility boilers while meeting applicable environmental control legislation.

A. E. Kelley (Union Oil) described the Union Oil experience on retorting. A detailed description of this work is contained in Appendix I.

Union is designing a prototype rock pump retort to work on 35 gallons per ton shale yielding 10,000 BPD of oil. The retort is about 75 ft. high, 35 ft. at the top, and 10 ft. at the bottom. The 10-ft piston is the biggest that can be made commercially now. The geometry of the sloping walled retort is of critical importance but workers at Union understand the system and uniform flow of rock upward through the retort is obtained. Union's retort needs strong shale. At 40 gallons per ton, they experience a 12% compression under a ΔP of 1 psig. With this compression, the gas flow is reduced. Union's mining plan keeps changing. Management is now considering mining of the whole mahogany layer to obtain an average of about $34\frac{1}{2}$ gallons per ton. The product oil contains 2000-5000 ppm of solids.

The way the streams flow, the solids are unretorted shale fines.

Advantages of the Union retort are stated to be the following:

(a) short residence time at high temperature; (b) minimum agglomeration, which allows handling of rich shale; (c) high mass velocities; (d) low solids contents in the oil. A solid adsorbent step is used to remove the arsenic. This procedure will be satisfactory for the demonstration retort but may not be commercially viable. The preferred incentive is a loan or price guarantee.

Currently planned scale-up to commercial operation will involve about a ten-fold increase in throughput above the operational experience of 1955-58 (~1200 TPD), which had, in turn, been scaled up from about 350 TPD operation. The shale feed size will be about 5/8 inch. The Union Oil combustion retort had a thermal efficiency of 83-85%, an oil yield of ~75%, and produced low-Btu gas at ~125 Btu/SCF. Shale oil at \$3.25/B appeared feasible for production in 50,000 BPD plants during the late fifties. Materials handling was not regarded as a critical problem area. As the oil yield in the shale decreases, the carbon content rises. Retorting of shale occurs at the upper levels of the Union Oil retort. Since the oil is effectively filtered, the contents of shale fines are low. Stearns-Rogers has completed an engineering design for a 50,000 BPD retort, which is expected to be operational by 1988. The following research areas were identified: disposal of spent shale (which may have an energy content of ~3,000

Btu/lb and thus be comparable with some low-grade coals); clean-up of mixtures of solids, liquids and gases and efficient separation of these multiphase systems; improvements in retorting efficiency.

J. M. Hopkins (Union Oil) presented the interesting divisions for cost distributions shown in Table 3 for the Union Oil process, with initial capital costs of \$35,000-40,000/BPD production (i.e., comparable costs with those given in 1979 dollars for coal liquefaction). The product syncrude will have a 36° API gravity and will cost \$37-45/B at a 15% rate of return.

A. G. Oblad (University of Utah) noted that engineering costs for major projects typically range from 5 to 10% of total capital costs and require from 5×10^4 to 1×10^5 man-hours per project. Contingencies for new technologies must be high (~35%) to assure successful commercialization.

T. Pollaert (Lurgi) discussed the Lurgi programs for shale-oil recovery, noting that 1977 cost estimates were about one-quarter of those current in 1980. Lurgi technology involves adaptation of a process that was originally developed for the devolatilization of coal. Material problems are well in hand. A pilot plant has been used to test various materials, including shale. A 10-TPD plant, owned by Bergbauforschung in the Ruhr Valley, has been operated continuously. A new pilot plant (25 TPD) was

Table 3 Cost distributions for the Union Oil process
(J. M. Hopkins).

| Activity | Capital costs plus operations and maintenance | Capital costs of products with 100% equity financing and 15% DCF ROR $\sim \frac{1}{2}$ |
|----------------------|---|--|
| Mining (underground) | $\sim \frac{1}{3}$ | |
| Retorting | $\sim \frac{1}{3}$ | Operation and maintenance costs $\sim \frac{1}{2}$ |
| Upgrading | $\sim \frac{1}{3}$ | |

started up near Frankfurt early during 1980; a 150 TPD pilot plant is under construction for Getty Oil in Kern County, south of Bakersfield, California, for the recovery of oil from diatomides. Operations with diatomaceous earth have yielded many fines. Dedusting has been a major problem with diatomaceous earths but is probably easier for oil-shale recovery. By carefully controlling the condensation process, virtually all of the dust is concentrated in a heavy fraction of the oil and one-half to two-thirds of the oil comes out clean.

A cooperative design is being developed with Rio Blanco (4,400 TPD). A demonstration plant on Rundle shale, jointly with Exxon Corp., will process 5,000 TPD in a single module (the larger throughput in this module, compared with the Rio Blanco design, is the result of higher pressure operation near sea level in Australia). Costs are ~\$30/man-hour for engineering with a total of 1×10^5 man-hours required for completion of the design. The people who build the pilot plant will monitor performance details, including analyses of spent shale, shale liquids, other liquids, air emissions, etc. Handling of the spent shale may involve calcining to cement-like consistency. Calcining may also be preferred for underground recovery to minimize post set-up leaching. The temperature difference between entry and exit in the Lurgi screwmixer is about 50° while the residence time for the solids is 1 to 2 sec. There is a trade-off between temperature and required lengths for the recirculation time. Only a

limited amount of modeling work has been done on the Lurgi process. The capital cost estimate of \$35,000/BPD production is considered to be "at the bottom of the cost scale". Off-site costs are likely to be large. Scale-up factors for screw and lift dimensions, involved in the Rio Blanco and Rundle operations, are factors of 1.3 to 1.4. Unstable operation is expected to occur in the lift pipe at diameters greater than 6 ft. Important R&D areas include the removal of solids from viscous liquids. Pilot-plant operations cannot generally be preempted or replaced by analyses because "the bankers insist on seeing the results of pilot-plant tests" before providing capital. Costs are roughly $\frac{1}{2}$ for capital and $\frac{1}{2}$ for all other contingencies.

The Lurgi-Ruhrgas (L-R) process for shale oil extraction is described in Appendix II.

J. H. Knight (Superior Oil) discussed the advantages of using multimineral processing in shale-oil recovery. About 2000 ft of overburden are involved in the Superior Oil holdings. Electromechanical separation may be used for nahcolite. An adiabatic unit is employed for shale-oil processing. About 40% of the total shale is removed, as compared with ~10% for kerogen recovery only. Hence, spent shale disposal is greatly facilitated. The liquid-phase organic compounds are the most valuable products formed (50-60% of total value); about 20-25% of product value is associated with alumina and nahcolite each. However, full commercialization of shale-oil recovery may lead to

nahcolite production that greatly exceeds market needs. The cost breakdown is roughly as follows: ~1/3 capital, ~1/3 resources, ~1/3 all other factors.

The present commercial design calls for 7000 square feet of circle grate which could approximate 25,000 TPD of shale. The retort is designed for soft ores. Fines less than a quarter of an inch in size are screened out because of plugging difficulties in the gas-to-solid heat transfer in the crossflow of operation. Caution is required in considering the effect of elevation on the crossflow gas-to-solids heat transfer. The oil product contains only about 100 ppm of fines.

Knight cautioned that the operating factor was very important in estimating realistic economics. He guessed that for 50,000 BPD of oil from 30 gallons per ton shale, the capital costs would run \$1-2 billion. About one-third of the costs are offsite charges, one-third processing and one-third mining.

A detailed description of the Superior program is contained in Appendix III.

D. Murphy (Rio Blanco) noted that commercial scale (50,000 BPD) engineering will soon begin on open pit mining and surface retorting in this cooperative program of the Gulf Oil Corporation and Standard Oil of Indiana. The partnership began with the 1974 lease of Tract C-a. About $\$15 \times 10^6$ were spent on baseline engineering studies during 1974-75. In 1977, the MIS method with sub-level caving was adopted. Mining experience involving H_2S , CH_4 and groundwater in the mine workings during 1978 showed that costs would be much higher at the center of

the Piceance Basin than at the rim. During 1978, a random-free-fall and high-void (~33%) method of rubblization was developed. During 1979, the Lurgi retort was selected for surface processing. Comparative economic studies showed that surface retorting and open pit mining could be commercialized over the near term with a reasonable chance of success. RBOSC feels more must be learned about MIS retorting before Rio Blanco could proceed with commercial scale engineering on MIS at Tract C-a at this time. Normal shale variability makes uniform porosity in rubblized shale an unattainable goal and compounds the problems involved in successful MIS development. The planned height for a commercial retort is 700 ft. Rio Blanco could produce well over 50,000 BPD with its presently allocated water rights.

The Rio Blanco MIS activities involve drilling of long blastholes and charge utilization to produce a succession of rubblized slices. MIS retort efficiency has not been determined but a goal of 55 to 60% oil recovery may well prove to be optimistic. Effective utilization of low-Btu gas needs to be defined and constitutes an important R&D area for study; at RBOSC, about one quarter of the total estimated MIS investment is allocated to cleaning and utilizing low-Btu gas.

Rio Blanco is optimistic about the future of open pit mining with surface retorting. A rather long discussion ensued about the large negative cash flow during the period in which the big open pit mines are being opened up and developed before the whole operation is operating at capacity. Safety requirements for miners in the bottom of the pit necessitate careful control of the slopes of the pit walls and result in very large pits. In a later discussion, the Exxon representative talked about a proposed schedule in which open pits could move across

the basin with backfill, as is done in the brown coal area in Germany. When viewed in this context, large production of shale oil could be anticipated for many years with only a small percentage of the basin being disfigured by operating pits at any one time. The Rio Blanco and Exxon representatives were both optimistic about quite large-scale operations in the basin. Exxon has given considerable thought to all aspects of an industry producing at the rate of 8 million barrels per day (see Appendix IV for details).

Costs were not detailed and will not really be known until after engineering studies have been completed. Details of the Rio Blanco operation are summarized in Appendix IV.

The following R&D areas are considered to be important: (a) adequate definition of Piceance Basin regional hydrology to allow believable environmental impact assessments; (b) materials handling on a large scale, which will be required because 3 tons of material must be handled per ton of oil; (c) development of adequate procedures for the disposal of very large amounts of spent shale; (d) low-Btu gas utilization.

J. R. Thomas (Chevron) described a number of tests performed in small-scale pilot plants. In the Chevron A retort, hot and unspent shale were mixed. The Chevron B retort used a turbulent, fluidized bed reactor. Bench-scale tests at a scale of 350 TPD are planned with start-up in 1982. The slides used for the Chevron presentation are reproduced in Appendix VI.

Costing by Morrison-Knudsen of Chevron technology has indicated capital charges of about $\$1 \times 10^9$ for 10^5 BPD production, plus costs for hydrotreating and refining.

APPENDIX I
THE UNION OIL RETORTING PROCESS

by Arnold Kelley*

Union Oil Company is a pioneer in research on shale oil production. In 1920, we started geological field work and began acquiring properties in the Parachute Creek area of Garfield County, Colorado.

The nearly 20,000 acres of oil shale lands Union owns in fee contain some 2 billion barrels of recoverable oil in the high-yield Mahogany Zone. These reserves are large enough to produce 150,000 barrels per day of shale oil for at least 25 years. In addition, there are approximately 2 billion more barrels of reserves in contiguous lower quality zones. We also have 20,000 acres of oil shale reserves in non-patented lands.

Fully aware of the potential energy value of these holdings, Union's research scientists and engineers have conducted a wide variety of laboratory and field studies for more than 30 years. They have sought technically, environmentally and economically feasible methods for producing usable oils from shale.

I will next review Union's retorting technology and the background for design of the 10,000- B per day experimental retort.

Retort "A"

Retort "A", as shown in Figure 1, was developed in the 1940's and used in Union's demonstration plant in the 1950's. In this process, shale is pumped upward through an expanding cone and heated by a once-through stream of flue gas. Heat is supplied by burning the carbonaceous deposit on the retorted shale in the upper part of the retort. The hot fuel gases heat the raw shale to temperatures necessary for retorting. As the gases

*Presented at FERWG Meeting in La Jolla (7/8/80).

cool, the oil condenses and is withdrawn from the cold disengaging section of the retort as a liquid. Non-condensable gases are sent to further processing for heavy ends and hydrogen sulfide removal.

We carried the Retort "A" concept through 2-ton per day and 50-ton per day pilot operations and then through the demonstration plant in Colorado that processed up to 1200 tons per day of shale, producing as much as 800 barrels of shale oil daily. The demonstration plant at our Colorado site is shown in Figure 2. The retort had a 5-1/2 foot diameter feed piston and an upper cone diameter of 17 feet. The process was easy to operate and reliable because agglomeration of retorted shale caused by plastic flow or by refluxing and coking of liquid product could not cause solid flow stoppage.

Because once-through air flow through the retort was used, peak temperatures in the burning zone reached 2000-2200°F and resulted in low liquid yields of about 75% of Fischer assay. The heating value of the product gas was only 120 Btu/scf because of dilution with nitrogen from the air, carbon dioxide from combustion and decomposition of mineral carbonates.

In 1960, at the conclusion of the semi-works retorting program in Colorado, Union attempted to move shale oil into commercial reality by proposing a long-term contract to a Southern California power-generating company for low-sulfur fuel oil made from oil shale at approximately \$3 per barrel which equated to about 50 cents per million Btus. At the time, the power company was buying natural gas for about 33 cents per MM Btu and low-cost (\$1.50/barrel) Middle East oil was becoming available so the contract for shale oil was not consummated.

In the first commercial-scale refining of Colorado shale oil, more than 13,000 barrels of shale oil were successfully refined into gasoline and other products at a Colorado refinery.

Before the 1973 oil embargo and the following rapid rise in the price of foreign crude oil, Union reactivated research and development on oil from shale. The Retort B process and another called the SRG process resulted from this renewed activity.

Retort "B"

As shown in Figure 3, Retort "B" is an indirect retorting process using recycle gas heated in a fired heater to 950-1000°F to provide the energy for retorting. This process produces high liquid yields, essentially Fischer assay values, and a high Btu gas product, about 800 Btu/scf. Liquid product quality from the low temperature, low residence time and oxygen-free retorting is excellent.

Retort "B" yields for processing 36-gallon per ton Colorado shale are shown in Figure 4. These yields were obtained in our pilot unit operations at Brea, California. The pilot unit is a continuous moving bed retort with a nominal capacity of 3 tons per day.

Retort "B" product oil properties are given in Figures 5 and 6. Upflow retorting combined with an oxygen-free retort recycle gas gives a product oil with a moderately low pour point and a low Conradson carbon residue. This oil can be sold as boiler fuel or can be hydrogenated directly to produce a high-quality syncrude. Sulfur, nitrogen and oxygen values are typical of Colorado shale oils. Arsenic is present as a major trace element in Colorado shale oil. In this regard, as a fuel, crude shale oil is closer to coal than petroleum.

Gas produced during the retorting process has a gross heating value of 980 Btu/scf. Its composition is given in Figure 7. After removal of acid gases and C₄-plus hydrocarbons, the gas heating value is about 800 Btu/scf. The heating value of the dry gas can be raised above 1000 Btu/scf by methanation.

Commercial Size Retort

Retort "B" when designed for commercial use would utilize the same concept tested in our pilot operation, but of a much larger size.

As shown in Figure 8, crushed and screened oil shale from the feed bin flows through a feed chute to a piston solids pump. Shale oil product acts as a hydraulic seal to maintain the retort pressure and prevent escape of product gas from the shale feed chutes.

The solids pump is mounted on a movable carriage and is completely enclosed within the feeder housing and immersed in product shale oil. The pump consists of a 10-foot diameter piston and cylinder assembly which alternately feeds shale to the retort and then moves over to take on a charge of raw shale. When charging is completed, the pump carriage is moved horizontally until the cylinder comes under the center line of the retort. The cylinder then charges its shale into the retort. The carriage is then moved back into its original position and the cycle repeated. One complete cycle of the solids pump requires about 1.5-2.0 minutes. A seal plate outboard of the cylinder closes off the feed chute to prevent discharge of shale into the feeder housing. The carriage and solids pump are hydraulically operated.

Experience with pumping oil shale showed us that the cost of the equipment required is justified by the very considerable process advantages of downward liquid/gas flow and positive upward flow of solids within a shale retort. Union has complete confidence in the reliability of the concept based upon months of actual operation of the 5-1/2 foot diameter piston feeder in the demonstration plant. We are convinced that the solids pump will be a dependable, low operating cost component of the oil shale complex.

The shale is retorted as it rises through the retort cone by the countercurrent flow of hot recycle gas. The retort cone contains no internals. As the retorted shale rises above the upper cone lip, it forms a freestanding pile, the slope of which is governed by the angle of repose of the solids. A rake rotates just above the surface of the freestanding pile. Its purpose is to break up any agglomerates that may form and assist their movement down the surface of the pile. The agglomeration tendency of Colorado shale is shown on Figure 9.

The space above the upper cone is enclosed by a dome. The retorted shale slides down chutes and through the cone wall to the retorted shale outlets.

Hot recycle gas is introduced into the space between the free-standing retorted shale pile and the dome. It flows downward into the rising shale to provide the heat required for the retorting process. The oil shale kerogen decomposes into liquid and gaseous organic products which escape from the shale particles. The liquid product trickles down through the cool incoming shale and the balance in the form of a mist is carried from the retort by the cold gases.

The gas and liquid are separated from the shale in the lower slotted wall section of the retort cone. In the disengaging section surrounding the lower cone, the liquid level is controlled by withdrawing the oil product. Recycle and make gas are removed from the space above the liquid level.

The shale particles which fall through the slots into the disengaging section are recycled by screw conveyors into the feed chutes. Very fine shale particles collecting at the bottom of the feeder case are pumped in an oil slurry back to the retort by way of the disengaging section.

The retorted shale is conveyed in chutes to one of the two retorted shale cooling vessels. A water seal is maintained in these vessels through which the downward moving bed of retorted shale is discharged from the retort. The 950°F bed of retorted shale first contacts superheated steam above the water level which strips off any remaining hydrocarbons in the shale before it enters the water. Generated steam is condensed and the oil removed before it is returned to the cooling vessel. A drag chain carries the retorted shale up through a sealing leg to disposal. The retorted shale is about 200°F and surface dry as it enters the disposal area.

Upflow retorting with indirect heating of a circulating gas stream has several important advantages which can be summarized as follows:

- Residence time of oil at high temperature minimized resulting in less polymerization, condensation and coking of the oil.
- Retorting occurs near the top of the shale bed where contact pressure between particles is at a minimum and thus solids agglomeration and pressure drop are avoided even when processing very rich shales.
- Operation at exceptionally high mass velocities is feasible because of the positive solids flow and the high gas/solids heat transfer rates.
- Capital and operating costs for external oil condensing equipment are greatly reduced because of the very effective action of the retort as a heat exchanger.
- Rundown oil has a low particulate content because of the filtering action of the retort shale bed.

Continuing with the process flow, gases from the disengaging sections are scrubbed and cooled in a Venturi scrubber. Agglomerated mist plus light ends and water produced by cooling are sent to an oil/water

separator. The oil is recycled to the retort at the oil shale feed chutes and the water is sent to the water seal after stripping to remove ammonia. The scrubbed gas is divided into a make stream and a recycle stream. The recycle stream is compressed and heated prior to injection into the top of the retort.

The make gas stream would go through a sulfur removal step after which it will be used as fuel for the recycle heater and to generate steam for the large drivers. There is sufficient make gas to supply the energy for the plant except for a small amount of presently available power which will be used for small drivers and lighting.

Experimental Retort Program

Union's experimental shale plant would be located on its wholly owned 20,000-acre block of oil shale lands north of Grand Valley, Colorado. The plant will be situated on the north face of the East Fork Canyon of Parachute Creek on a 5-acre bench site located 1000 feet above the valley.

A mine portal will open onto the bench and provide access to a conventional underground room-and-pillar mine on Union's Long Ridge shale lands. The mine production will be trucked to an underground two-stage crushing-screening plant where shale ore of minus 2 inches to plus 1/8-inch size is prepared for the retort feed.

As shown in this artist's sketch Figure 10, the retort and its auxiliaries will be located on the bench site just outside the mine entrance.

The project would be based on construction of a single Union B-type retort capable of processing 12,500 tons per day of 34 gallons per ton oil shale and extracting approximately 10,000 barrels per day of raw shale oil.

The retorted shale will be moved to the East Fork valley floor deposit area where it then will be spread, compacted, contoured and vegetated with native plants to blend into the surrounding landscape. The pile will be constructed to ensure that no pile drainage flows into the underground aquifers or into surface waters.

Union has carried out extensive studies on revegetation of Retort "B" retorted shale at our Research Center at Brea, California, and in Parachute Creek.

Water required in the experimental project's operations will be taken from wells on Union's property and will be recycled to minimize water requirements. Project design includes detailed plans to prevent contamination of local streams and underground aquifers. There will be no waste water discharge from the plant.

The large experimental project is the next logical step in the development of Union's oil shale process, and Union is confident that it will accomplish the following objectives:

- Establish the operating limits of a full-size retorting module.
- Develop process improvements which can only be accomplished in a large experimental facility.
- Secure economic data needed for any future commercial development.
- Develop techniques to secure the best attainable control of environmental impacts.

RETORT A

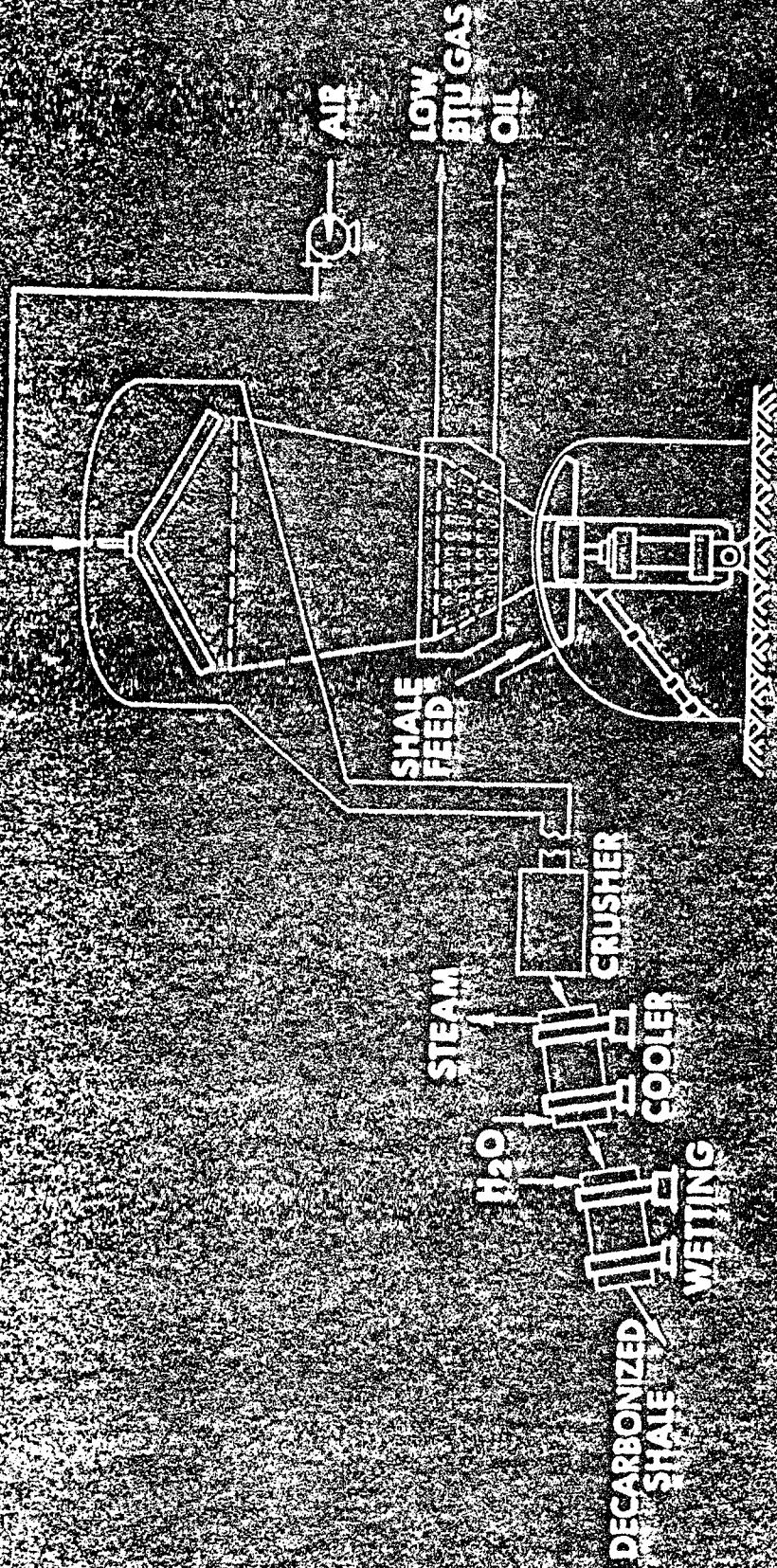


Figure 1

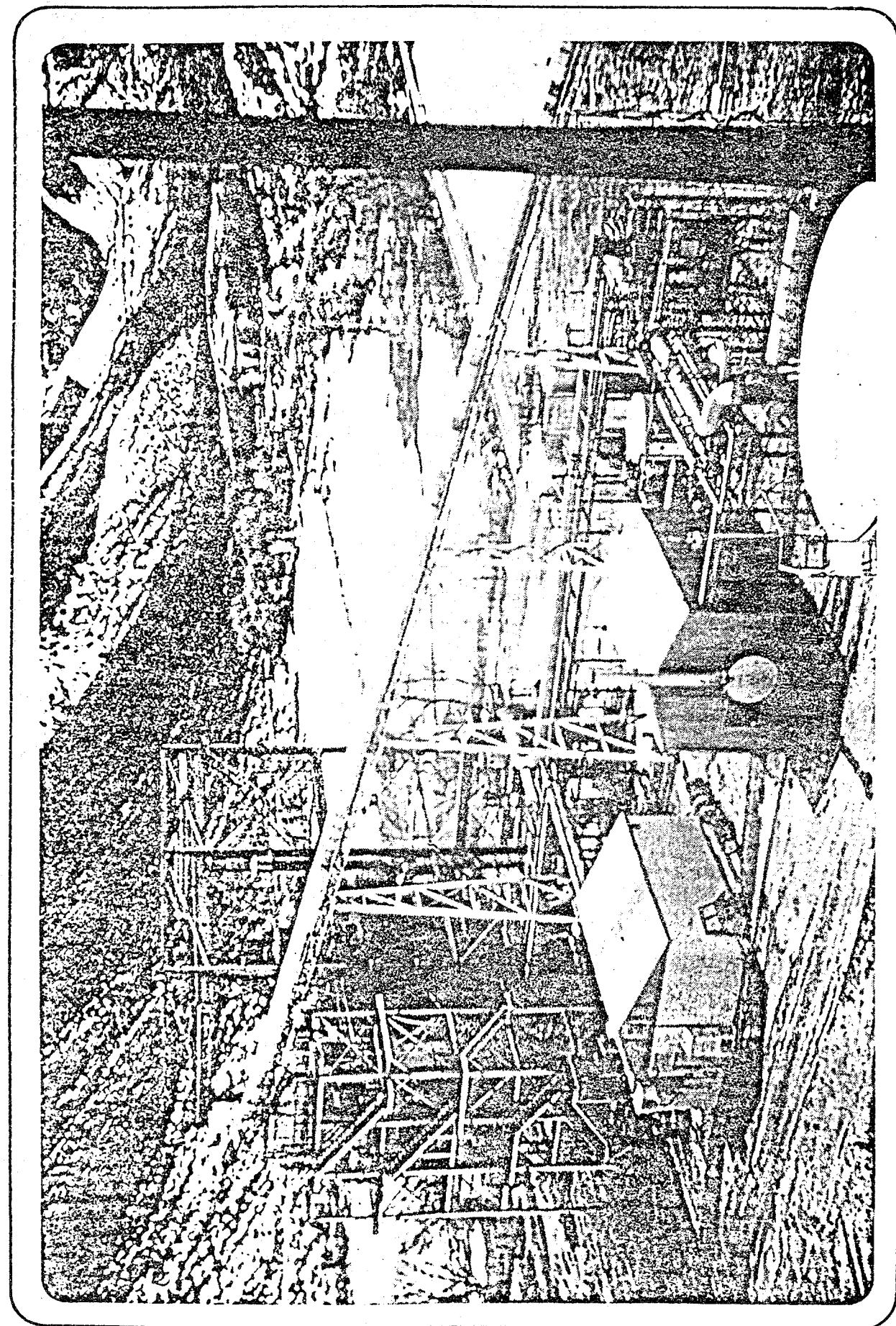


Figure 2

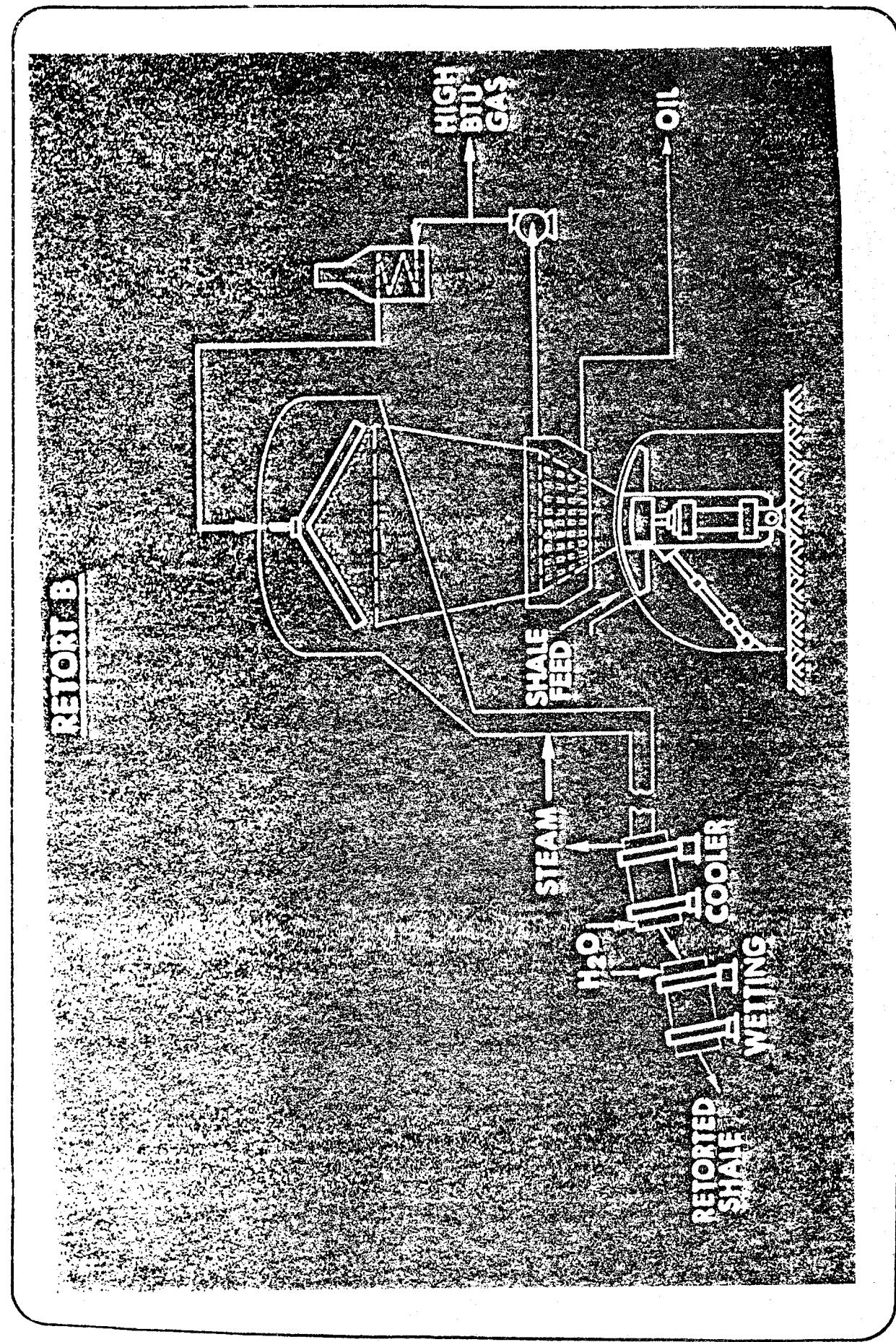


Figure 3

RETORT BYIELDS

36 CAL/TON SHALE

RETORT MAKE GAS (DRY BASIS), SCF/TON

RUNDOWN OIL, GALL/TON

% FISCHER ASSAY

C4 - PLUS OIL, GALL/TON

% FISCHER ASSAY

RETORTED SHALE LB/TON

750

35.1

97.5

37.1

103.0

1660

REPORT B

RUNDOWN OIL PROPERTIES

GRAVITY, °API

22.2

ASTM, D-1160 DISTILLATION, °F

IBP

10

30

50

70

90

MAX

150

390

620

770

875

1010

1095

Figure 5

REPORT B
RUNDOWN OIL PROPERTIES

| | |
|--------------------------------|-----|
| SULFUR, WT % | 0.8 |
| NITROGEN, WT % | 1.8 |
| OXYGEN, WT % | 0.9 |
| FISCHER WATER, WT % | 0.2 |
| POUR POINT, °F | 60 |
| ARSENIC, PPM | 17 |
| CONRADSON CARBON RESIDUE, WT % | 2.1 |
| HEATING VALUE, GROSS, MBTU/GAL | 142 |

| COMPONENT | MASS % | COMPONENT | MASS % |
|----------------|--------|----------------------|--------|
| H ₂ | 25 | C ₅ | 2 |
| C ₁ | 24 | C ₆ -PLUS | 1 |
| C ₂ | 10 | CO | 5 |
| C ₃ | 8 | CO ₂ | 16 |
| C ₄ | 5 | H ₂ S | 4 |

HEATING VALUE- GROSS BTU/SCF 980

Figure 7

UNION UPFLOW RETORT

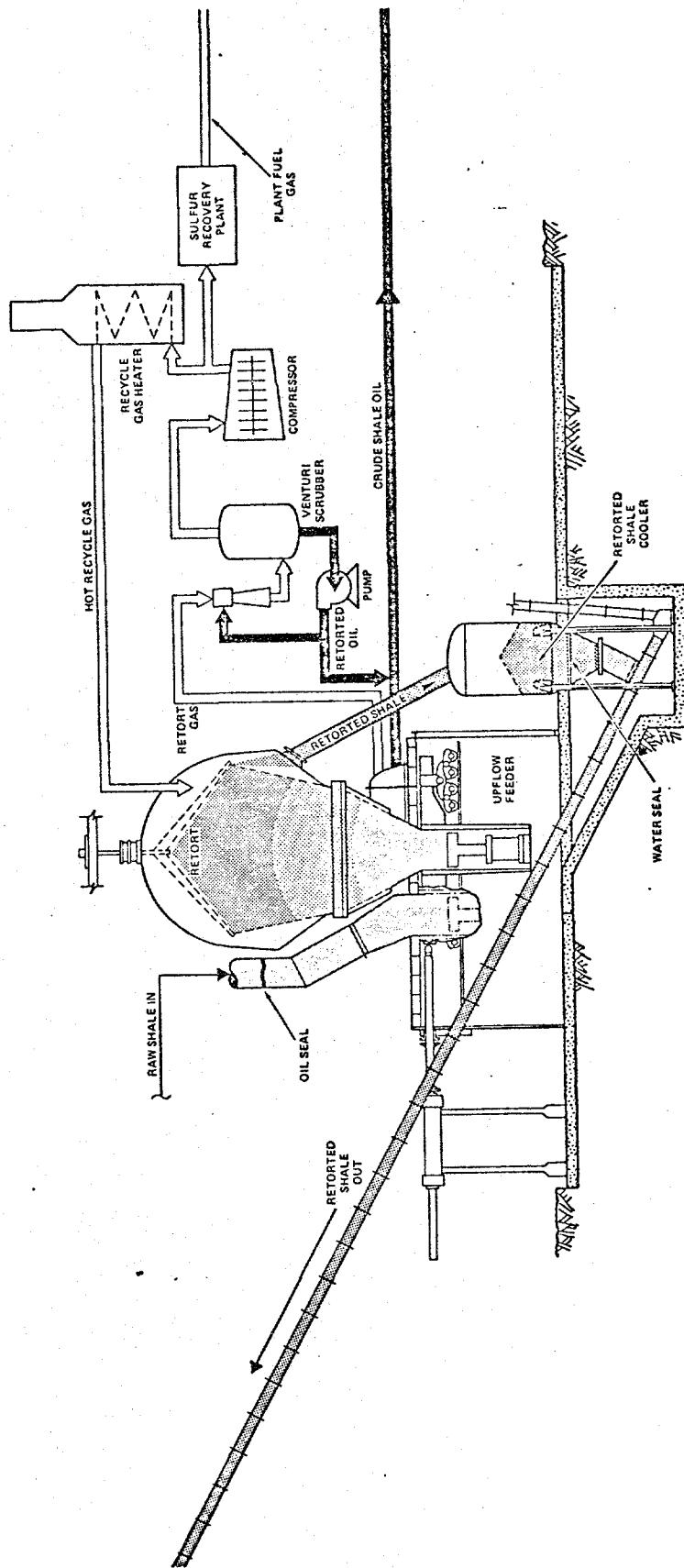


Figure 8

EFFECT OF ASSAY ON ROCK
PRESSURE FOR 12% COMPACTION

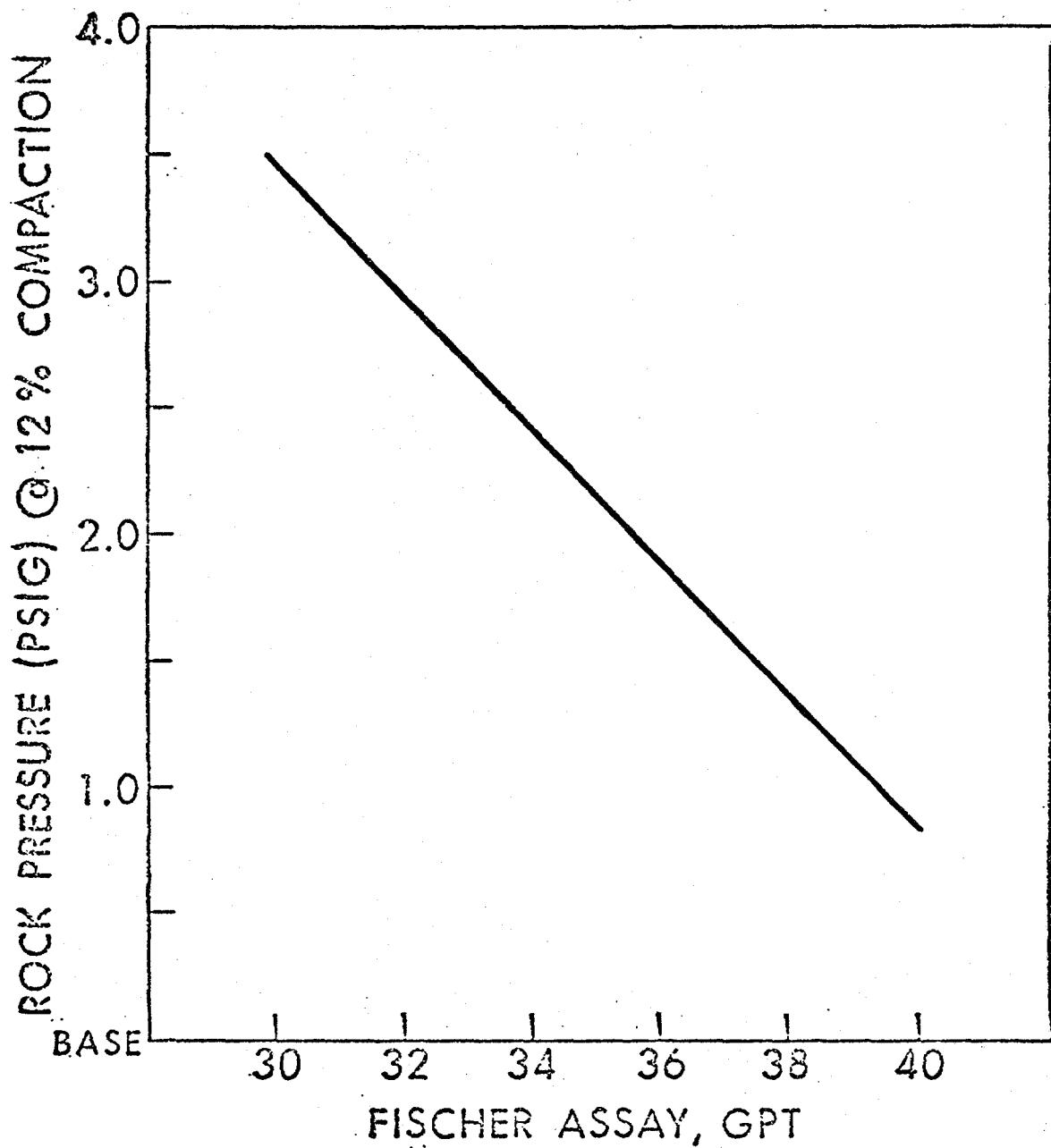
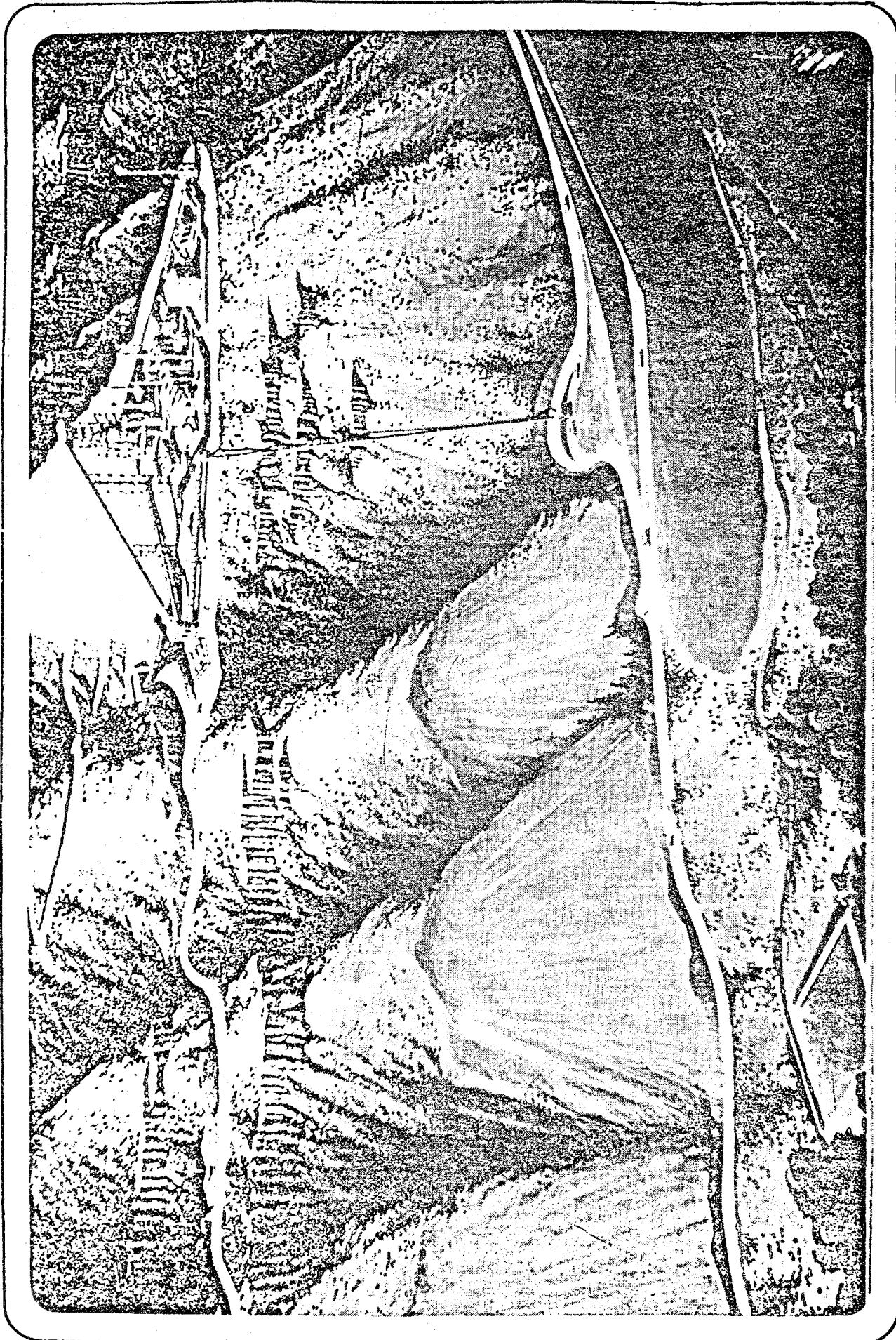


Figure 9



AB-74

Figure 10

AB-5

APPENDIX II

THE LURGI-RUHRGAS (L-R) PROCESS
SHALE OIL EXTRACTION *

January 1980

*Transmitted by T. Pollaert

HISTORY AND DEVELOPMENT OF THE LURGI RUHRGAS PROCESS:

During the late forties, it became evident in Germany that motor fuel and gas demand would grow faster than the demand for electrical energy. Since the North Sea oil and gas and Middle Eastern oil reserves were not known at that time, it was obvious that at least the gas demand would have to be covered by the gasification of coal. This led to the development of the Lurgi Pressure Gasification Process. In parallel there was a development jointly supported by Lurgi and Ruhrgas to recover the gas and oil contained in coal before it is fired in a utility boiler by low temperature pyrolysis.

The first pilot plant contacted finely ground coal with hot ceramic balls. The ceramic balls were reheated after contacting the coal and recirculated. It was found that the smaller the balls, the better the heat transfer. The logical conclusion was to let the devolatilized char act as the heat carrier. This also allowed pneumatic lifting and conveying of the circulating material, eliminating bothersome bucket elevators and simplified reheating of the circulating material by combustion of some of the char with the lifting air.

A new pilot plant was constructed in Herten, West Germany (LR I) with a capacity of 0.2 tons per hour of coal throughput. Devolatilization products consist of medium BTU gas and coal tar. The split between the two could be varied by varying the operating temperature.

It was found that by using sand as the circulating medium, the process could be used to crack crude oil or naphtha to ethylene. This was investigated at length in a larger pilot plant (LR II) operated by Bayer.

LR I, meanwhile, was operated on a large variety of feed materials including tarsand and oil shale and showed itself very suitable for the extraction of oil from these materials.

The original concept (predevolatilization of boiler feed coal) was tested in a semi-commercial plant (LR III) with a coal feed of 10 tons per hour. This plant was closely coupled to a utility boiler at a power plant in Dorsten. The tests in Dorsten were stopped in 1960 because by then the coming availability of North Sea gas and Middle Eastern oil made the devolatilization of coal economically unattractive.

In the same year, the first two commercial units for the production of ethylene were started up in Leuna, East Germany. From 1961 until 1964, three more commercial plants were built in Chiba, Japan; Rosario, Argentina; and Lanchow, Mainland China. The units in Rosario and Lanchow are still in operation. After that, the LR Process had to leave this field to the tubular steam cracking furnaces.

Low-temperature pyrolysis of coal remained of interest however. In 1963, units with a total feed of 1600 tons per day of pre-dried lignite were started up in Lukavac, Yugoslavia. The lignite

char was used as a leaning coal in the Lukavac coke plant.

The process received a new lease on life with the development of the Formeoke Process. Here a caking coal and a coal char are combined and formed into a briquette which is used as blast furnace coke. Since the process is continuous, it is expected that the process will eliminate the pollution problems associated with conventional coke ovens, will require less capital and will be able to operate on coals otherwise unsuitable for coking.

The coal char needed for the process is obtained by devolatilizing either a part of the feed coal or some inferior coal in the LR Process.

A pilot plant for this process, including the LR unit, exists at Bergbauforschung (a research company set up and maintained jointly by the West German coal mining industry).

A semiworks with an LR feed of 350 tons per day of coal was started up in Prosper (Ruhr area) in 1974.

A demonstration plant with an LR feed of 900 tons per day of coal has been operated in England. However, this unit, along with the complete steel plant facility, has been shut down as a result of the recent austerity program.

Over the past decade, interest in the recovery of oil from tarsand and shale and even in low-temperature pyrolysis of coal has increased again. Numerous tests have been run in the Bergbau-forschung pilot plant as a courtesy on the part of Bergbauforschung. Since these were becoming a burden to the client and also because a somewhat larger pilot plant would present results which can be used for scale-up more readily, Lurgi decided to build another pilot plant (LR IV) with a capacity of one ton per hour of feed material in its Frankfurt laboratory. This plant is currently in start-up and will begin pilot program operations by January 1980.

L-R PROCESS DESCRIPTION - SHALE

The L-R Process consists of a circulating system which includes:

- the lift pipe to convey and heat the circulating fine-grained heat carrier
- the collection bin to separate the combustion gas from the hot heat carrier
- the screw mixer which mixes the hot heat carrier and raw shale feed to induce retorting
- a surge hopper which provides surge capacity and time to complete retorting.

On the product gas side of the circulating system are the cooling and condensation facilities for the oil vapors. The waste heat recovery system includes heat exchangers for preheating combustion air and generating steam and facilities for removing particulates from the offgas.

Circulating System

Raw oil shale, crushed to approximately $\frac{1}{4}$ ", is fed to the screw mixer where it is mixed with six to eight times as much hot spent shale from the collection bin. The raw shale feed is thereby heated to about 850 - 1100°F within the screw mixer where retorting occurs. The shale mixture leaving the screw mixer passes to the surge hopper where retorting is completed and then passes to the lower section of the lift pipe. Combustion air, preheated to about 750°F, is introduced at the bottom of the lift pipe. The air simultaneously conveys the shale to the top of the lift pipe while it burns residual carbon from the spent shale. The combustion gas and heated shale residue are

separated at about 1100 - 1300°F in the collection bin. The heated, spent shale is returned to the screw mixer, thereby closing the cycle.

Product Gas Section

The volatile products from the retorting operation are freed of entrained dust in cyclones and are then sent to a battery of scrubbing and condensing coolers. The oil and aqueous condensates from these scrubbers are cooled against air and cooling water. The cooled vapor stream can be further treated in a light oil scrubber for the recovery of naphtha. LPG may also be recovered if the product gas is compressed and cooled.

Flue Gas Section

Combustion gases leaving the collection bin are dedusted in the primary cyclone. Entrained dust separated in this cyclone may be returned to the retort system if necessary. The gases are then routed through a waste heat boiler, feedwater preheater, secondary cyclone, humidifier and finally an electrostatic precipitator before being discharged to the atmosphere. Dust withdrawn from the retort system and collected in the primary cyclone passes through a heat exchanger where it preheats combustion air for the lift pipe. This dust, together with particulates from the humidifier and electrostatic precipitator, are then rejected to the spent shale processing area for final disposal.

ADVANTAGES OF L-R PROCESS:

The L-R Process:

- produces an undiluted vapor product
- maximizes oil yield
- maximizes combustion of residual carbon
- utilizes 100% of mined shale
- minimizes SO₂ and NO_x emissions
- produces a pumpable oil product
- produces an inherently more stable processes shale (when moistened)
- water requirements are low
- uses commercially demonstrated process equipment

The fact that the retort product gas is not diluted with combustion gases results in smaller diameter condensation vessels. In addition, the product gas is a high BTU fuel gas which can be used as process fuel or exported for industry use.

Rapid distillation of the oil, at optimum temperatures ranging from 850 - 1100°F and the short residence time of the oil vapors exposed to these temperatures minimize cracking and insure a high yield of liquid hydrocarbons. For Colorado oil shale, the yield may approach 110 weight percent of the Fischer assay. Furthermore, the heat required for the retorting process is obtained by burning the residual carbon on spent shale. Therefore, none of the product oil or gas is required to supply retorting heat in the L-R Process.

At lift pipe temperatures approaching 1250°F, decomposition of calcium carbonate in the spent shale will occur. The resulting calcium oxide is expected to chemically react with the SO₂ produced by the burning of sulfur compounds contained in shale residue. Consequently, most of the SO₂ is chemically bound on the spent shale which is collected in the flue gas dedusting facilities. Based on pilot plant demonstration, residual SO₂ levels in the combustion gas leaving the collection bin can be reduced to about 20 ppmv. Moreover, with the lift pipe temperatures usually no higher than 1250°F, minimum formation of nitrogen oxides is expected in the L-R Process.

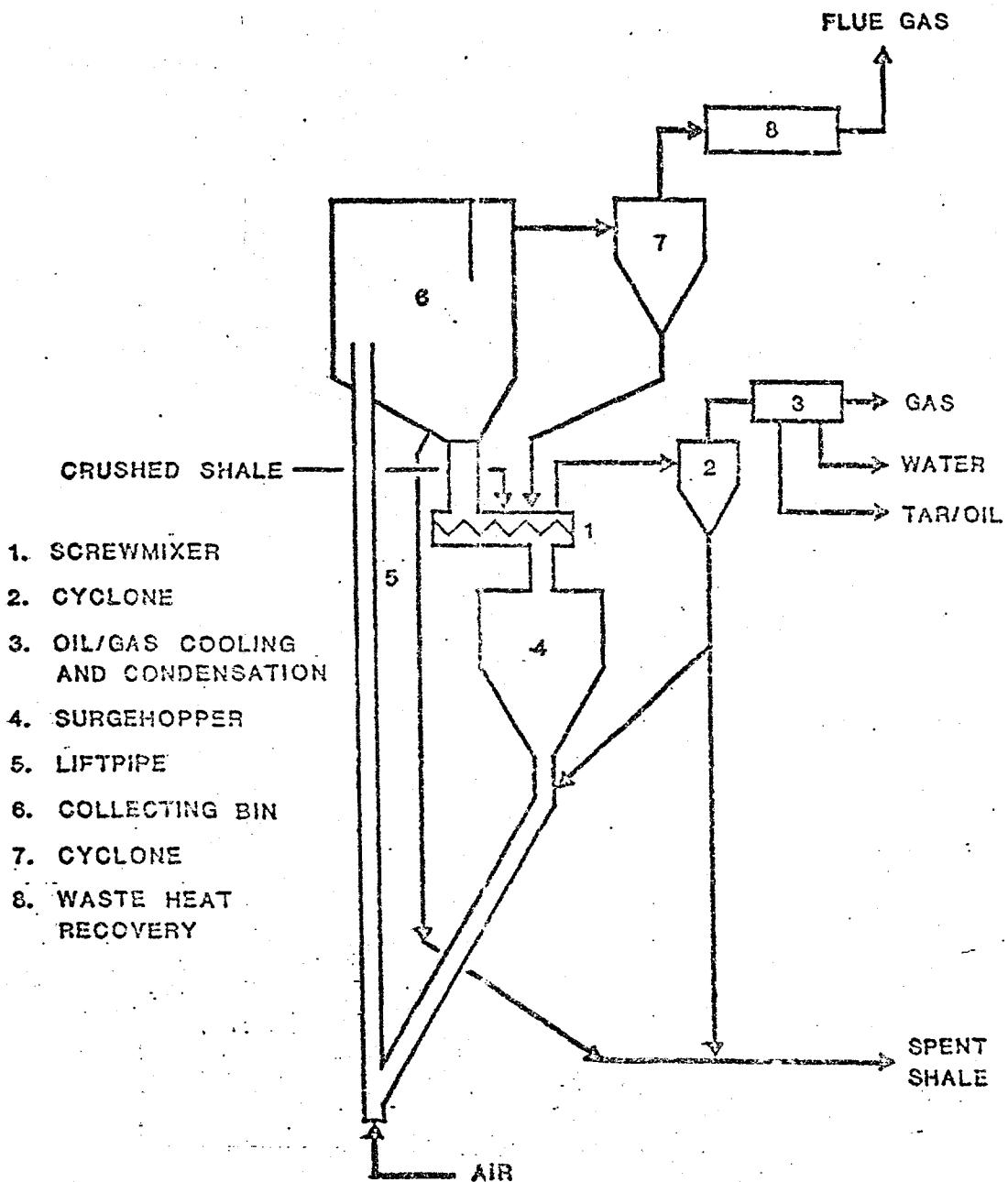
Work carried out by the Denver Research Institute indicates that a fine grained Colorado spent shale, with a majority of its carbon residue burned, will exhibit good cohesive strengths when moistened due to a reaction which is similar to cement formation. The temperature range of the carbon burning through which the cementation reaction will be pronounced is approximately 1100 to 1550°F. The lift pipe in the L-R Process operates within this range.

Since the product vapors are not diluted with combustion gases, a relatively small amount of heat has to be removed to condense the oil vapors and to cool the product gases. This can mainly be accomplished in air coolers thereby essentially eliminating cooling water usage. Makeup water is only required to humidify the combustion offgas and to moisturize the processes shale residue.

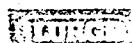
An independent evaluation by a major U.S. oil company shows an economic advantage for the L-R system over other retorting technology of \$2.00 - \$3.50 per barrel of product.

* * * *

SHALE OIL RECOVERY



LURGI RUHRGAS PROCESS



SUMMARY OF LURGI SYNFUELS RETORT EXPERIENCE

| YEAR | RETORT TYPE | CHARACTERISTICS | RETORTS BUILT |
|---------------|----------------------------------|---|---|
| 1938- 1942 | Tunnel Kiln | Used for oil rich shales, 20-30%. High capital & operating costs. Undiluted gas, residue carbon not used. 95% oil yield. Capacity-400 tpd. | 2, Germany 4, Estonia |
| 1935- 1958 | Vertical Kiln (Spuelgas Kiln) | Built originally for low temp. carbonization of lumpy sub bituminous & lignitic coals. Low oil yields, 80-90%; diluted vapor; can't use fines. Capacity - 400 tpd. | 1, Congo 100, Germany (Coal fed) |
| 1942- 1949 | Schweitzer | Batch process for high ash-low oil shales. Low oil yields, 80-90%; diluted vapor. Lower capital & operating costs. Capacity-35 tpd. | 28, Germany |
| 1944- 1954 | Oscillating Grate (Hubofen) | Simple design, diluted vapors, oil yields, 90%. Capacity - 500 tpd. | 2, Germany (60 tpd each) |
| 1951- 1952 | Lurgi-Ruhrgas Initial | Devised for devolatilization of coal fines. Ceramic ball heat carriers, external ball heater & ball transport were major operational problems. | Pilot Plant |
| 1952 | Lurgi-Ruhrgas Current | Replaced ceramic balls with fine grained retort residue. Useful on a wide range of feeds; shale, coal, oil sand liquid hydrocarbons. High oil yield, approaching 110%. Undiluted vapor. Current capacity - 4,000 tpd. | <u>Coal</u> 4, Yugoslavia, Germany, England <u>Liquid</u> <u>Hydrocarbons</u> 5, Germany, Argentina, Japan, China |

SUMMARY OF LURGI RUHRGAS PLANTS

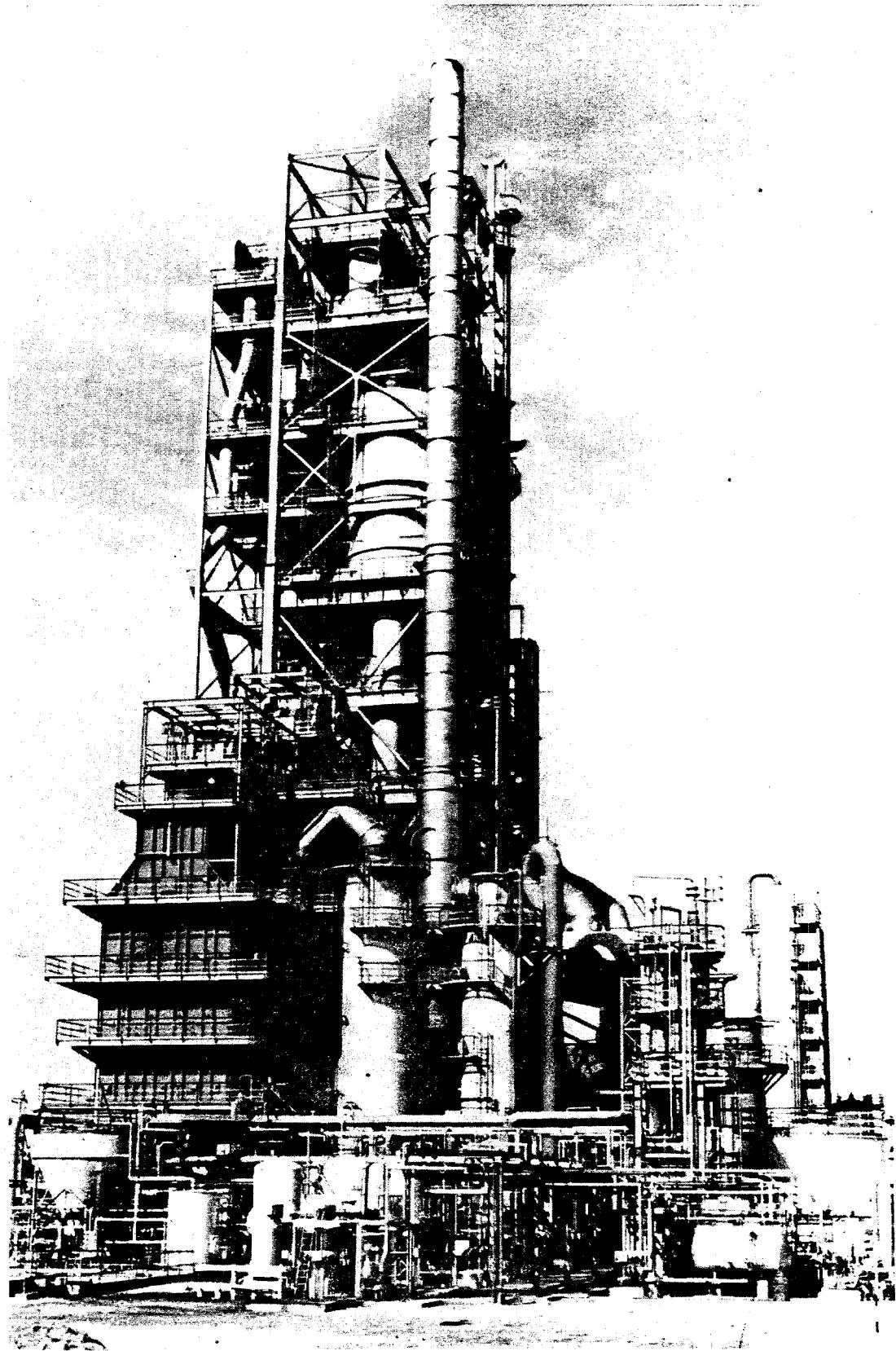
| | |
|--------------------------|--|
| Client: | Lurgi-Ruhrgas (LR I) |
| Location: | Herten, West Germany |
| Product: | N. A. (Pilot Plant) |
| Circulating Material: | Initially ceramic balls/later sand or char |
| Capacity: (feed) | 0.5 tons per hour |
| Operating Period: | 1951 - 1968 |
| Client: | Bayer (LR II) |
| Location: | Leverkusen, West Germany |
| Product: | N. A. (Pilot Plant) |
| Circulating Material: | Sand |
| Capacity: (feed) | 1 ton per hour crude oil |
| Operating Period: | 1955 - 1957 |
| Client: | Erdoelchemie |
| Location: | Dormagen, West Germany |
| Product: | Ethylene (from benzene) |
| Circulating Material: | Sand |
| Capacity: (ethylene) | 50 tons per day |
| Operating Period: | 1958 - 1969 |
| Client: | German Democratic Republic |
| Location | Leuna, East Germany |
| Product: | Ethylene (from naphtha) |
| Circulating Material: | Sand |
| Capacity: (ethylene) | 100 tons per day |
| Operating Period: | 1965 - present |
| Client: | Maruzen |
| Location: | Chiba, Japan |
| Product: | Ethylene (from naphtha) |
| Circulating Material: | Sand |
| Capacity: (ethylene) | 120 tons per day |
| Operating Period: | 1964 - 1971 |

SUMMARY OF LURGI RUHRGAS PLANTS - Cont'd...

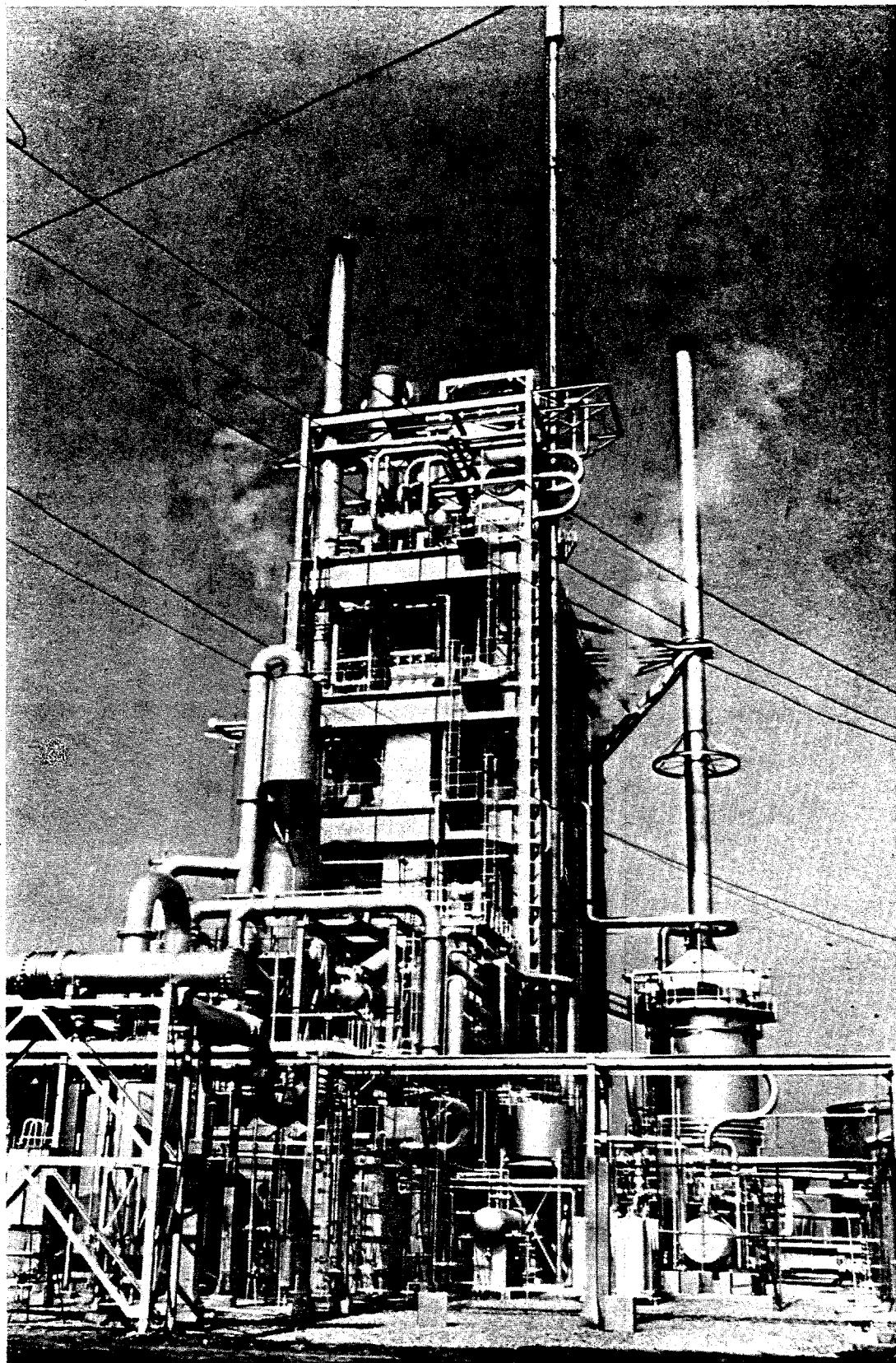
| | |
|--------------------------|------------------------------|
| Client: | Rosario, Argentina |
| Location: | Ethylene (from naphtha) |
| Product: | |
| Circulating Material: | Sand |
| Capacity: (ethylene) | 70 tons per day |
| Operating Period: | 1964 - present |
| Client: | Peoples Republic of China |
| Location: | Lanchow, China |
| Product: | Ethylene (from crude oil) |
| Circulating Material: | Sand |
| Capacity: (ethylene) | 125 tons per day |
| Operating Period: | 1968 - present |
| Client: | Lurgi Ruhrgas (LR III) |
| Location: | Dorsten, West Germany |
| Product: | Gas |
| Circulating Material: | Char |
| Capacity: (feed) | 10 tons per hour |
| Operating Period: | 1957 - 1960 |
| Client: | Kokerei Lukavac |
| Location: | Lukavac, Yugoslavia |
| Product: | Cokeoven feed (from lignite) |
| Circulating Material: | Char |
| Capacity: (feed) | 1750 tons per day |
| Operating Period: | 1963 - 1968 |
| Client: | Ruhrkohle AG |
| Location: | Bottrop, West Germany |
| Product: | Char (for form coke) |
| Circulating Material: | Char |
| Capacity: (feed) | 350 tons per day |
| Operating Period: | 1975 - 1978 |

SUMMARY OF LURGI RUHRGAS PLANTS - Cont'd ...

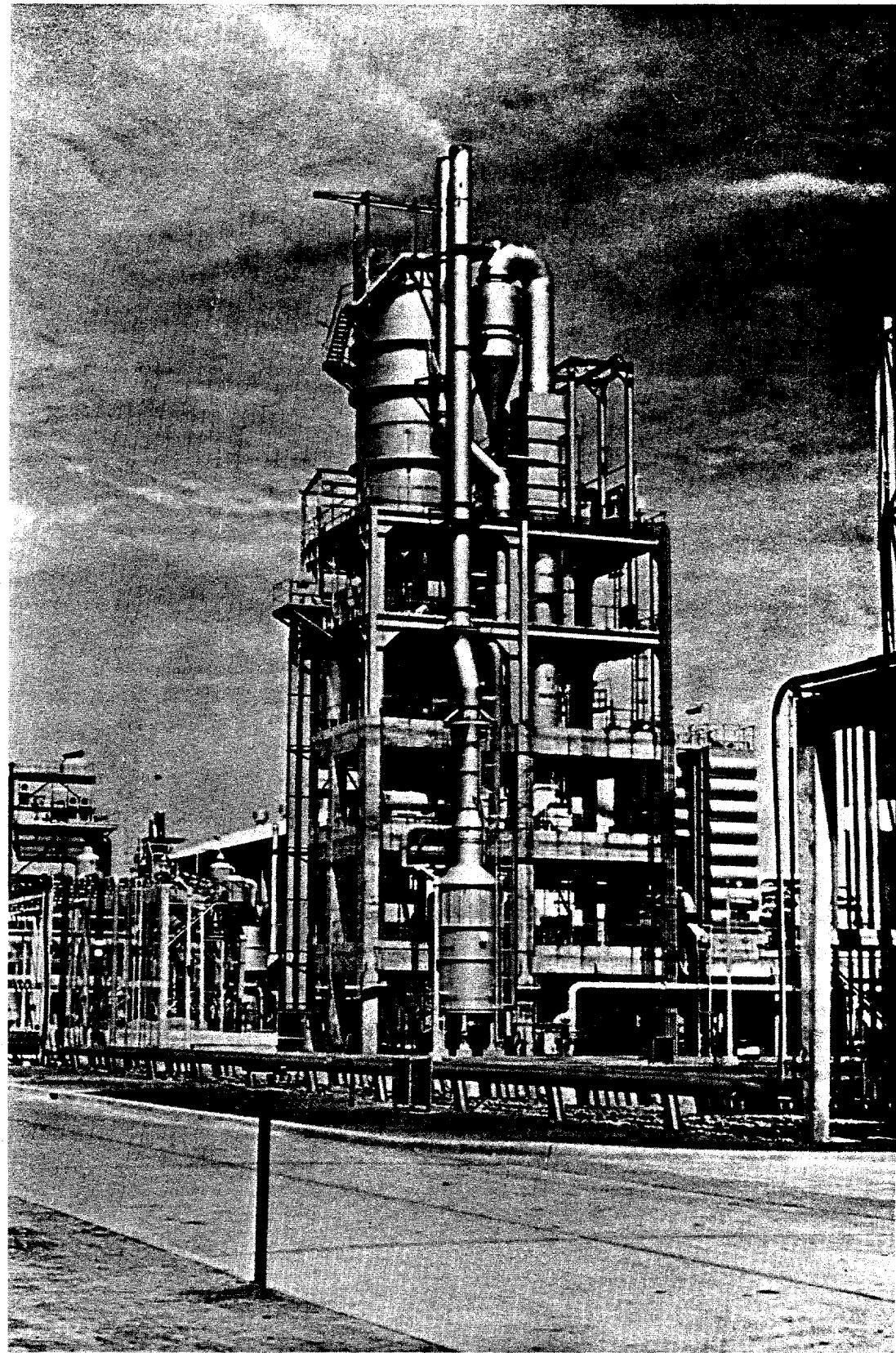
| | |
|--------------------------|--|
| Client: | British Steel Corp. |
| Location: | Scunthorpe, Lincolnshire, England |
| Product: | Char (for form coke) |
| Circulating Material: | Char |
| Capacity: (feed) | 880 tons per day |
| Operating Period: | 1978 - late 1979 (shut-down of complete steel facility due to austerity program) |
| Client: | Lurgi |
| Location: | Frankfurt, West Germany |
| Product: | N.A. - Test Plant |
| Circulating Material: | Various |
| Capacity: (feed) | 1 ton per hour |
| Operating Period: | 1979 start-up |



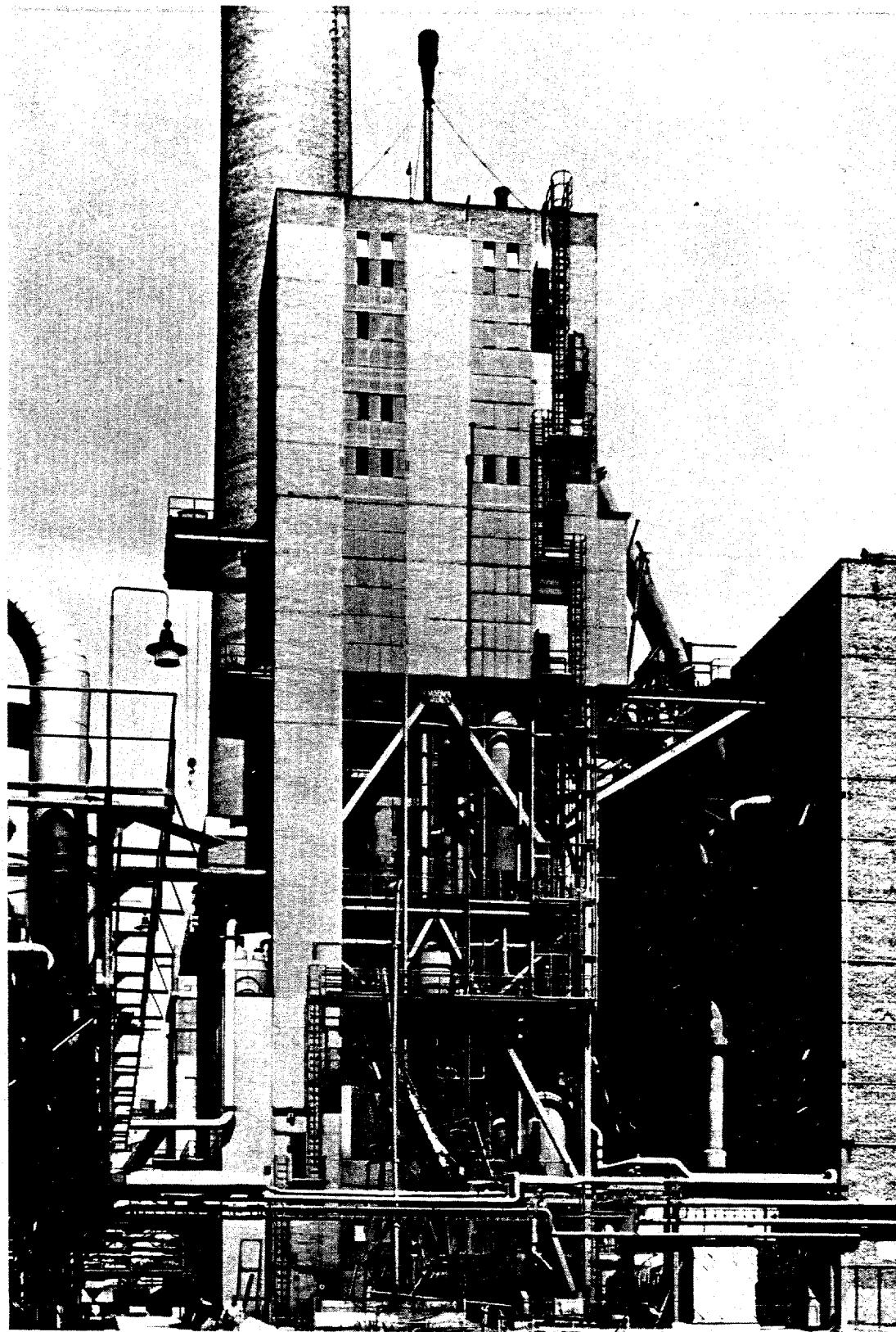
BRITISH STEEL CORPORATION
SCUNTHORPE, GR. BRITAIN



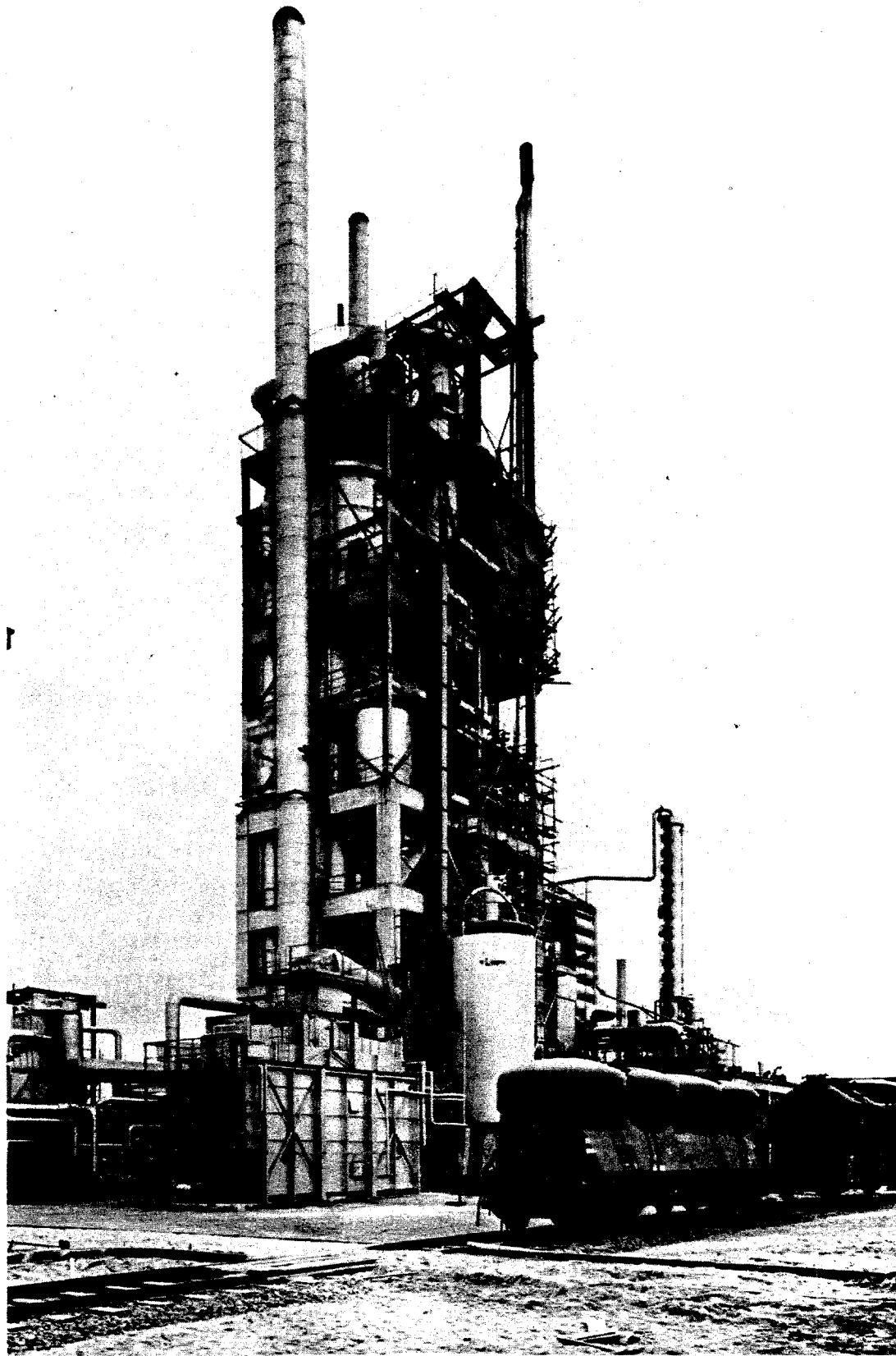
MARUZEN
CHIBA, JAPAN



LR ETHYLENE PLANT
ROSARIO, ARGENTINA



LR - SEMIWORKS
DORSTEN, WEST GERMANY



ERDOEL CHEMIE
DORMAGEN, WEST GERMANY

AB-5

APPENDIX III

AB-95

SUPERIOR OIL

July 18, 1980

Dr. S. S. Penner
Chairman, FERWG
UNIVERSITY OF CALIFORNIA
Energy Center
Mail Code B-010
La Jolla, California 92093

Dear Dr. Penner:

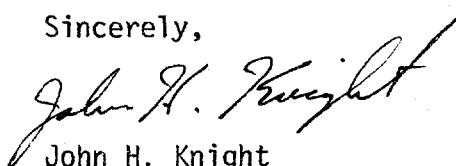
Per your request, attached are documents summarizing the Superior Oil Company's multimineral oil shale process and retorting process.

Several advantages, not immediately apparent unless the details are analyzed, are engineering thermodynamic interfacing that uses low-quality (200°F) energy from the retort in the alumina-soda ash recovery unit. Also, salt aquifer leach water currently discharging into the Colorado River drainage basin is used in the alumina-soda ash unit. This is attractive from both an engineering and environmental viewpoint since much of this water is recovered as salt-free condensate with the dissolved salt adding slightly to the product outputs. Superior's multimineral oil shale also has approximately 40% wt. as product vs. oil only of approximately 10% wt. which allows for spent shale return to mine. The typical volume expansion of ore upon blasting and crushing is 35% increase over in-place whole rock.

Cost of a nominal 50,000 BBL/day oil shale complex will be in the one billion dollar range depending on site specific data such as type of mining method, plant elevation, off-site costs, etc. Cost of producing a barrel of oil is approximately 35% annual operating and 65% annual cost of capital. The cost-per-barrel in OTA's report appears high by a factor of approximately two (2).

In a general comparison, it appears to us that multimineral shale would have a slight economic advantage over 30 gal/ton oil shale only grade and be approximately equivalent to 35 to 40 gal/ton shale only processing economics.

Sincerely,



John H. Knight
Division Manager
Oil Shale Division

Attachments:

SUPERIOR'S CIRCULAR GRATE OIL SHALE RETORTING PROCESS

J. H. Knight

Manager Oil Shale Division

The Superior Oil Company

2750 S. Shoshone

Englewood, Colorado 80110

ABSTRACT

Both circular and straight grates have long been in commercial use for iron ore pellet sintering, cooling, and other kiln applications. Superior's process development effort focuses on adaptation of the circular grate process for oil shale retorting. This effort included construction and operation of an adiabatic fixed-bed retort designed to simulate the conditions encountered by a section of solids as it travels through the separate processing zones in the circular grate. The adiabatic retort tests identified the significant process variables and their effect(s) on cost responses such as throughput rate, thermal efficiency, product yield, etc. Cost sensitivity analyses established optimum ranges in which to design and operate the circular grate oil shale pilot retort which was later constructed.

The pilot circular grate retort operations defined design and scale-up information for the oil removal system which had never been tested in prior circular grate applications. Pilot plant operations also confirmed the mechanical reliability of solids flow on four types of shale. The primary results of this process development effort have been:

- Attainment of thermal efficiency for the cross-flow circular grate which approaches those achieved in countercurrent flow devices.
- Product oil yields of over 98 percent of Fischer Assay.
- Development of a proved oil recovery system.
- Optimized throughput and gas rates per ton of oil shale processed.

These successful process development results can now be combined with the proven mechanical reliability of commercial-size circular grate heating-cooling equipment for oil-shale retorting.

INTRODUCTION

The modern efficient oil refinery was developed to present capacities only after years of operational experience. The 100,000-barrel-per-day refineries of today had their beginnings as commercial 1,000-barrel-per-day units. This growth resulted in improvements in materials of construction, lubrication, transportation, and engineering of auxiliary items which have continued to improve the economic efficiency of the refineries. Most types of engineered equipment and processes evolve to larger and more (economically) efficient systems once they are part of the industrial economy. The environmental impact per unit of production in the larger systems also is reduced many fold over the smaller units. The principles of many engineered systems are developed in the laboratory or in feasibility studies prior to commercial application, however, the major economic advantages of size and efficiency improvements are most pronounced after commercial application experience.

Synthetic crude oil production from oil shale is essentially in the laboratory pilot-plant and feasibility-study stage and has been for the past 100 years. The economics has also remained at generally the same marginal level throughout this period. Until commercial units are operated, the numerous operational and equipment improvements which greatly affect economics will not develop.

The production of alternate mineral resources and synthetic fuels will continue to be required by modern society. The alternative is crisis management, leading to a decline in the standards of living and economic strengths of those countries affected.

SUPERIOR'S DEVELOPMENT PROGRAM

Superior recognized the need for synthetic fuels production and started a multi-mineral shale development effort in the early 1970's. Pilot plant quantities of nahcolite, shale oil, alumina, and sodium compounds have been produced from Superior multi-mineral shale holdings. One stage of multi-mineral shale processing is shale oil production or "retorting". Superior's program for the selection and development of a retorting process was divided into the following four steps:

1. Evaluation of equipment and processes to determine inherent advantages and disadvantages.
2. Implementation of laboratory and adiabatic fixed-bed pilot retort test programs.
3. Testing of a circular grate pilot plant retort.
4. Engineering, design, and cost estimation for a commercial size circular grate retort.

STEP 1: Evaluation of Existing Processes

During the evaluation of various heating and cooling processes, Superior placed strong emphasis on methods which had a long history of development and commercial application. Both the circular grate and straight grate had long, successful operational histories at large throughput rates. Other advantages of the grate systems were that temperature and gas flow rates could be controlled independently, thus allowing for control of energy delivery in each processing zone. Therefore, the close control of temperature and residence time, both important factors affecting spent shale leaching and mineral recovery processing, can be achieved. Existing installations had been designed to handle pellets with low green strength with little or no attrition to the solids. This equipment allowed for the introduction of solids and layering of the bed with different rock size fractions. In these processes, the solids do not move relative to the grate or grate walls, as the solids move in a horizontal plane through each of the processing zones. Therefore, the amount of dust carryover with the oil mist is minimized.

The circular grate equipment had been designed with water seals between the top stationary hoods and bottom stationary windboxes at the inner and outer walls to seal in hydrocarbon process gas and seal out air. These water seals also allowed for unrestrained thermal expansion of structural members. Thus, leaks from cracks caused by thermal expansion stress can be avoided. The materials of construction for refractories and the grate itself have been operated at 2400°F, which is a considerably

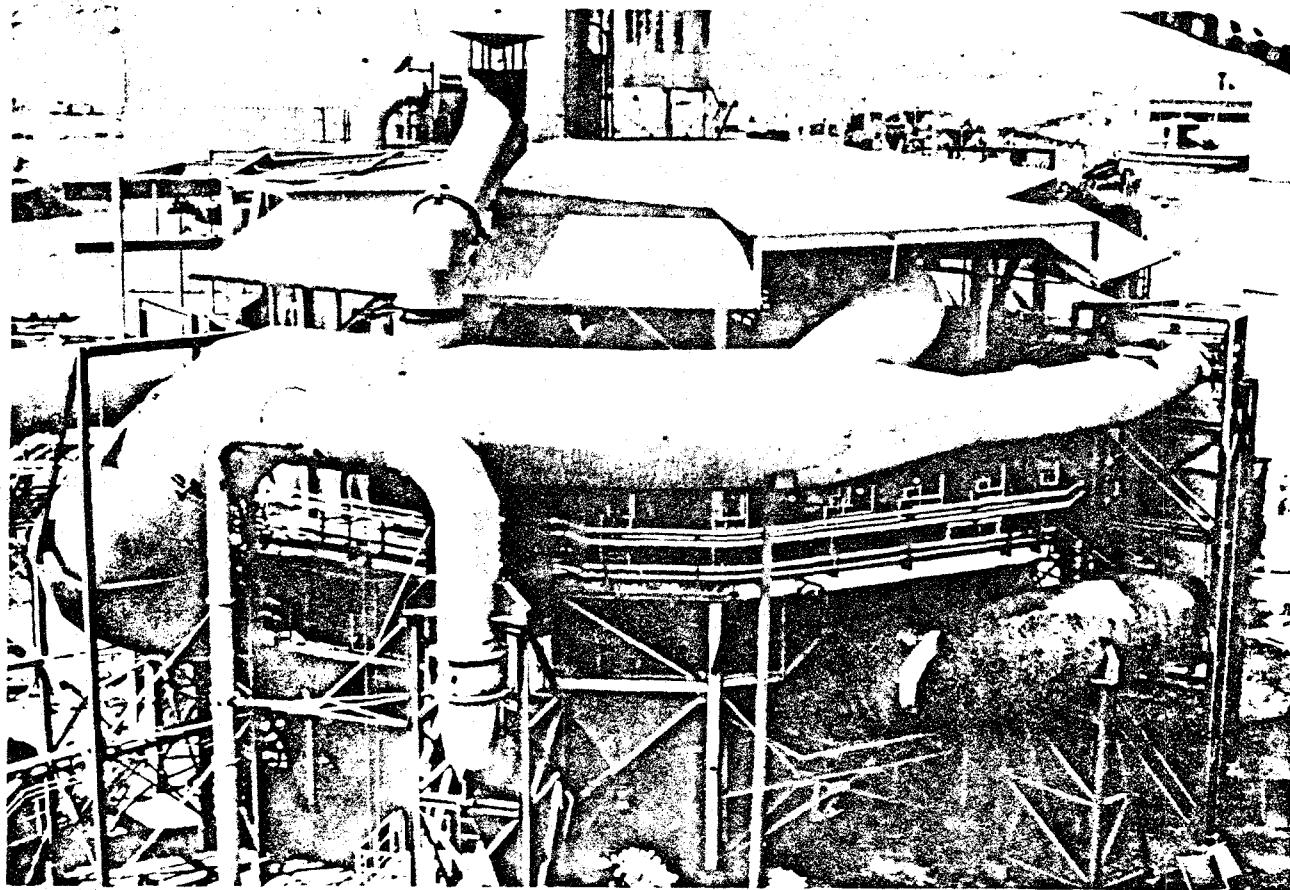


Figure 1. Commercial Circular Grate in La Perla, Mexico

more severe operating condition than the 900°F to 1000°F required for shale retorting. A good example of a commercial water-sealed circular grate constructed by Arthur G. McKee is in La Perla, Mexico. This unit is currently used to sinter iron ore pellets at grate temperatures in the 2400°F range. This circular grate, water trough-sealed system is the most advanced state of the art in equipment development. A photograph of the unit is shown in Figure 1. For the above reasons, the water-sealed circular grate system was selected by Superior for further development and testing of oil shale.

Prior to development by Superior, the circular grate process had a number of shortcomings which required improvement and testing to make the process applicable for oil shale retorting. Thermal efficiency, throughput rate per square foot of active grate area, and circulation of heating media required improvement. An oil removal system was also required in the circulating gas stream and this system required optimization for retorting oil shale.

STEP 2: Adiabatic Fixed-Bed Retort Testing and Laboratory Testing

Over the years, a large quantity of retorting data has been generated and collected by the U.S. Bureau of Mines, U.S. Geological Survey, and others. The data available was primarily for Mahogany Zone shales of the Green River formation, which do not contain significant quantities of nahcolite or dawsonite as does the deposit owned by Superior. Therefore, laboratory analyses and adiabatic retort tests were conducted on raw and spent shale, oil product, gas phase product, retort water, and residual carbon.

The adiabatic fixed-bed retort simulates a section of the solids on the moving grate as it travels through the various processing zones in the circular grate retort. This is shown in Figures 2 and 3. Figure 4 is a simplified flow diagram of the adiabatic fixed-

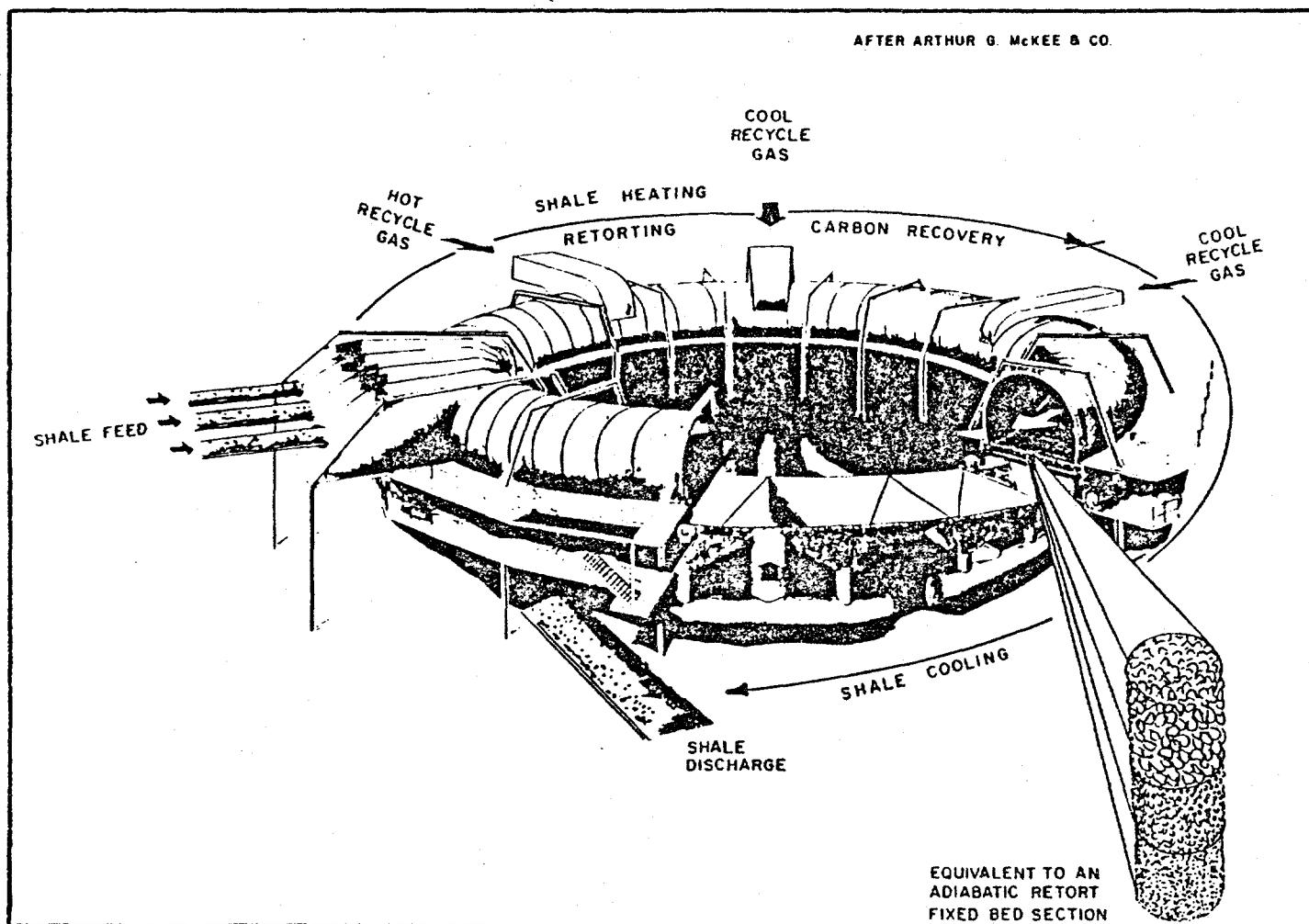


Figure 2. Conceptual View of Circular Grate Retort

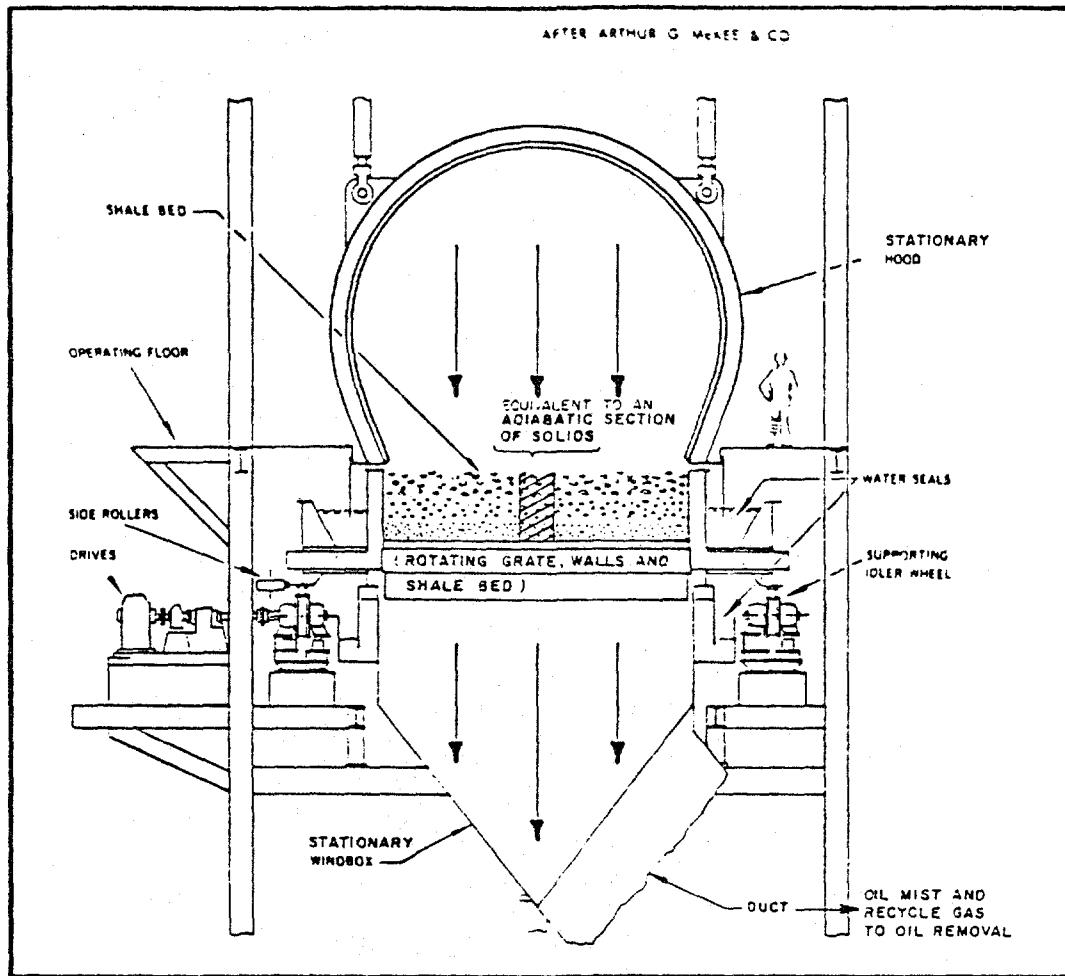


Figure 3. Cross Sectional View of Circular Grate Retort

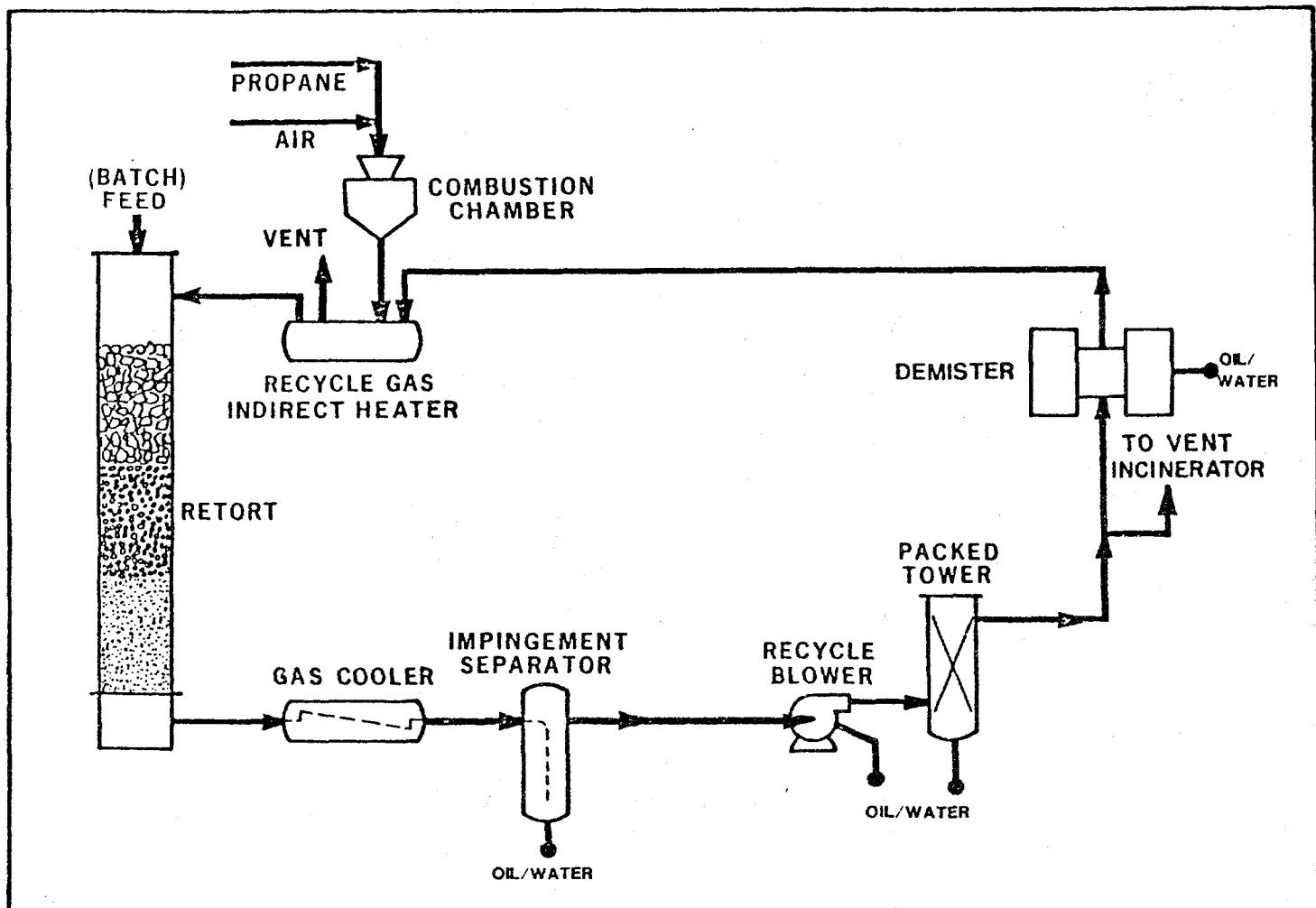


Figure 4. Simplified Flow Diagram of Adiabatic Retort

bed retort facilities. Time in the fixed-bed retort is equivalent to a length of travel of the solids section in the circular grate retort. The adiabatic fixed-bed retort was used to establish significant process variables and their effects on retorting cost responses in the same manner that smaller fixed-bed devices are used to obtain sizing data for straight and circular grates in other kiln applications.

Preliminary variable and cost sensitivity analyses were conducted prior to conducting the adiabatic retort tests. This was a comprehensive study of the effect of energy transfer variables on process economics. This included determining the cost sensitivity effect which changes in process variables have on cost responses such as throughput rate, thermal efficiency, product quality, product yield, etc. Insignificant variables and

cost responses were eliminated. A test program was developed and over 100 tests based on a statistical experimental design were conducted on the adiabatic retort to determine optimum ranges of variables (Ref. 3). The primary cost responses in a cross-flow, gas-to-solid heating device were determined to be:

1. Throughput (expense) — This is defined as the total annual cost per ton for facilities to heat and cool oil shale. This element includes cost of money, depreciation, taxes, and maintenance and labor costs for a given size retort. Throughput is related to the residence time required to load heat, cool, and unload the shale. Required residence time is a function of various heat transfer variables and the ability to use the entire active grate area effectively (Ref. 1).
2. Feed (expense) — This is the cost of providing and preparing oil shale feed for the retort. Most of this cost is for mining and is therefore constant, having no effect on the retort economics. The variable costs are for crushing and screening the shale to the required size. Crushing cost increases as particle size decreases.
3. Utilities (expense) — This is essentially the power cost (both electric power and/or steam for turbines) required to circulate the retort gases through the system loop, including the shale bed. This expense is a function of variables affecting pressure drop in the bed and the amount of recycle heating media gas required per ton of shale processed. Other utility expenses were determined to be relatively constant or insignificant.
4. Thermal Efficiency (expense) — This item is related to the cost of fuel required to supply the energy needed for retorting. The circular grate retort, with its cross-flow type heat exchange mechanism, has an inherently poor heat transfer efficiency, however, substantial progress has been made to improve this efficiency (Ref. 1). For multi-mineral shale processing, some waste heat from the retort is used in the alumina and soda recovery processes. Thermal efficiency expense is the cost of net energy required to retort a unit weight of shale and the cost penalty for unused waste heat

removal. The effectiveness of recovering the sensible heat from the shale and use of the residual carbon heating value are the dominant variables affecting thermal efficiency.

5. Yield (credit) — This is defined as the total recovery of the three organic phases (solid, liquid, and gas). The yield is the percent of organic heating value recovered from the solid phase (in the form of residual carbon), liquid phase (as oil), and gas phase (as process fuel gas). The value of each is based on its fuel value, expressed in terms of dollars per million BTU.
6. Quality of Organic Products (credit) — This is evaluated for various retorting conditions which improve the value of the organic products. The method used to heat the recycle heating media gas affects the composition of the produced gas phase. The use of air or oxygen in the carbon recovery zone also affects gas phase composition.
7. Spent Shale (credit) — This is defined as the total value of recoverable alumina, soda ash, and energy (as sensible heat) contained in the spent shale. Retorting conditions, temperature and time in particular, have the most significant effect on spent shale value for product recovery.

Referring again to Cost Response 1, we may cite one example of a preliminary variable and cost sensitivity analysis which results in defining the dominant heat transfer variables affecting throughput expense.

Two modes of heat transfer are present in the shale bed. The first is the rate at which heat is transferred through the bed of solids, and the second is the rate at which energy is transferred from the surface of the solid to its center. In order to pyrolyze the kerogen in the raw shale feed and use the maximum amount of the retorting zone, the final temperature at the center of the large rock in the top layer must match the final temperature of the center of the smaller rock in the bottom layer. Dominant variables are:

- o Energy delivery rate to the solids, which is primarily a function of gas flow rate and temperature.
- o Particle size and shape.
- o Bed height.

Variables which are inherently constant for a specific ore are thermal conductivity of the solids, recycle gas composition, specific heat, etc.

STEP 3. Pilot Plant Circular Grate Testing

In addition to determining the optimum ranges for variables, process improvements were also tested on the adiabatic retort and were included in modifications to the pilot circular grate retort. Proper oil removal operation and equipment scale-up data were determined from continuous steady state operation of the pilot circular grate retort. A simplified flow sheet of the pilot circular grate retort is shown in Figure 5. A

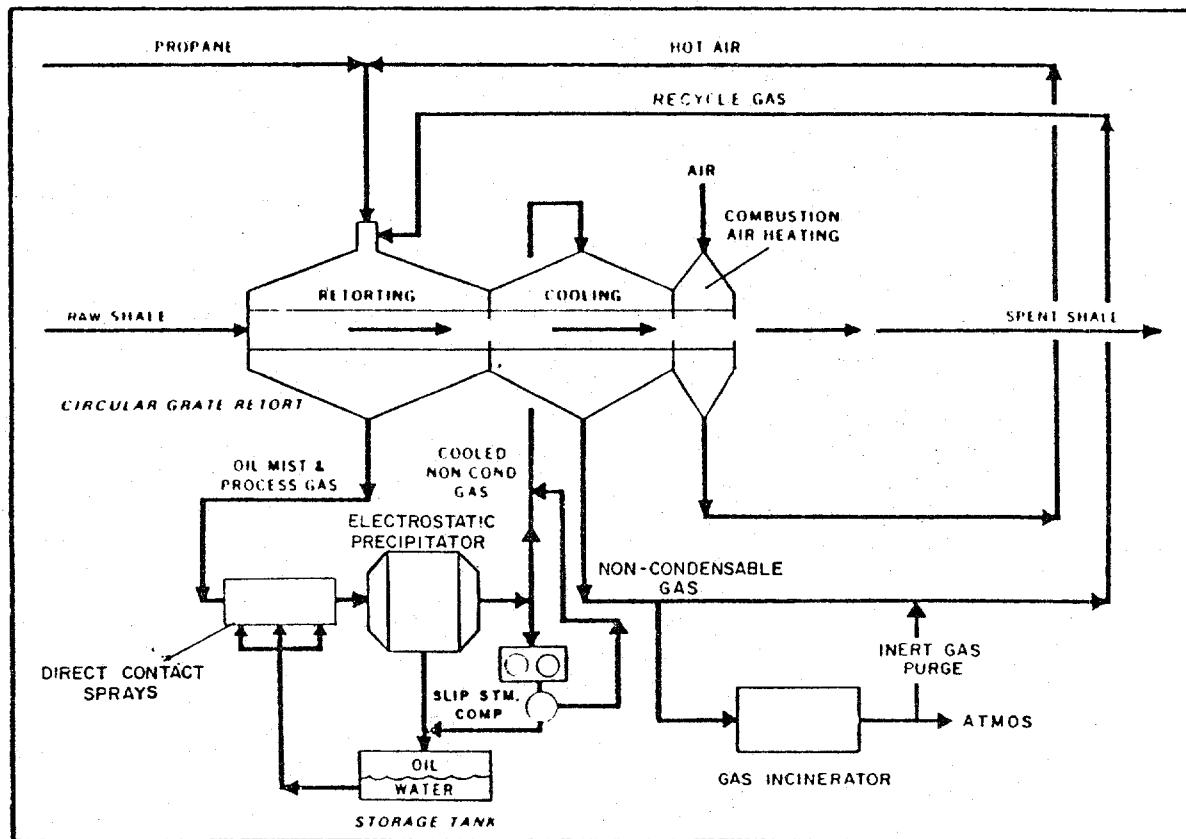


Figure 5. Pilot Circular Grate Oil Recovery Unit

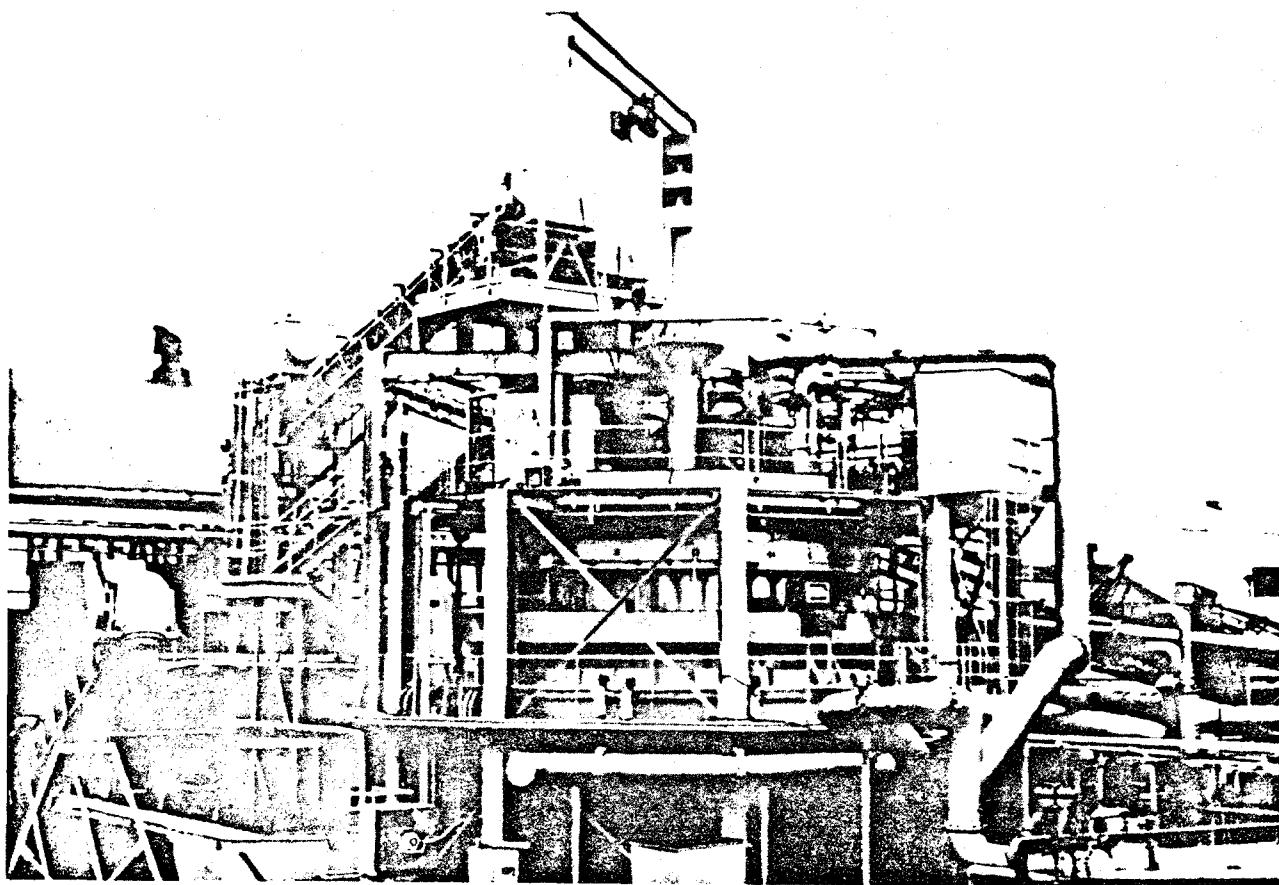


Figure 6. Pilot Circular Grate Retort

photograph of the plant is shown in Figure 6. This 250-ton-per-day pilot plant defined scale-up information for the oil removal system which had not been tested on prior circular grate applications. This system is a combination of a direct contact spray scrubber and an electrostatic precipitator.

As a result of the data generated from the statistical adiabatic test program investigating significant cost responses and variables, optimum process design curves for commercial-size retorts were generated. These optimum design curves were verified in subsequent pilot retort testing.

One key process improvement tested in the adiabatic retort and confirmed by the pilot circular grate retort tests was the enhancement of throughput by overlapping zones, thus increasing thermal efficiency by eliminating interzone leakage, and optimizing residual carbon recovery (Ref. 1). This effect is graphically shown in Figure 7. When oil

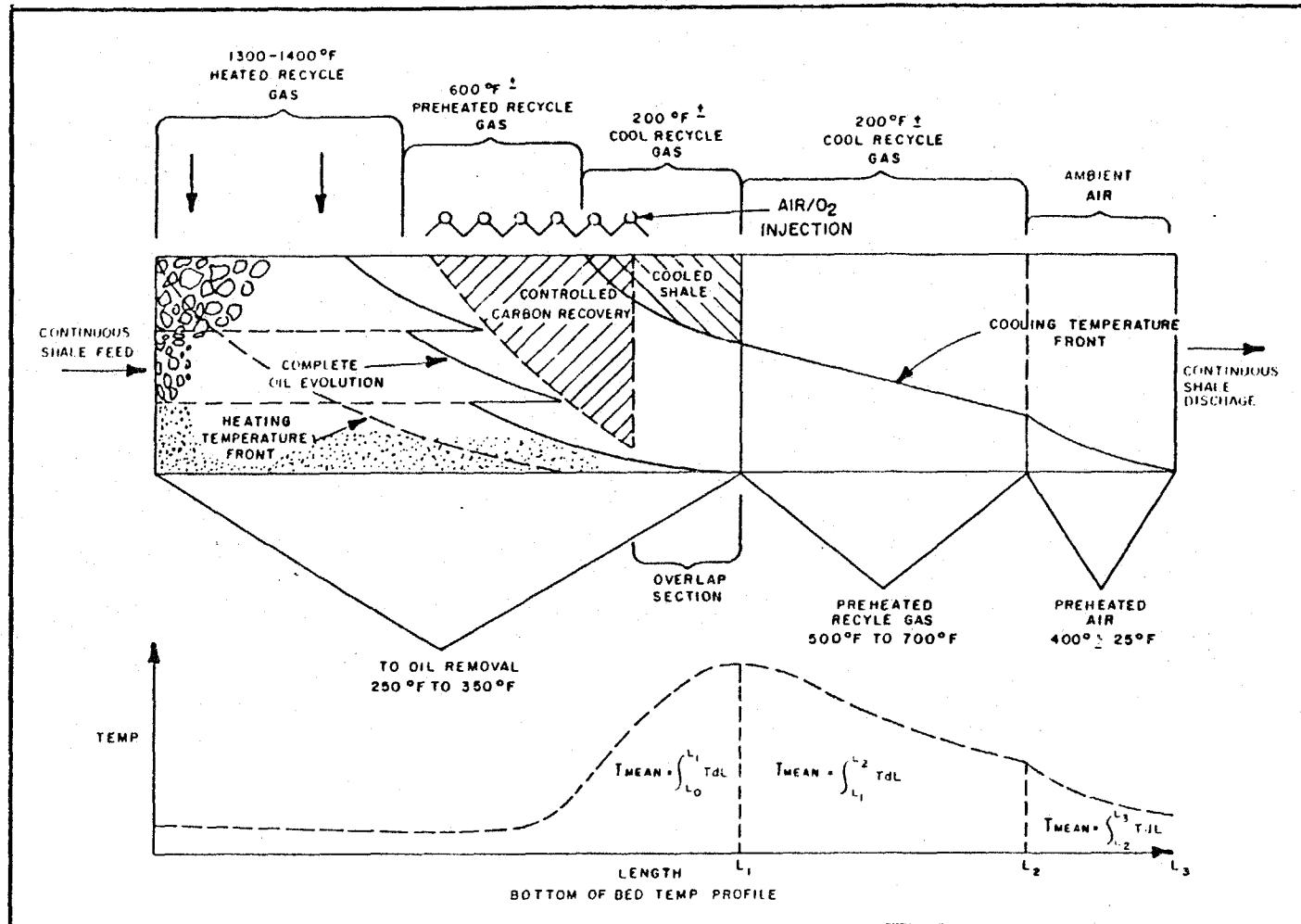


Figure 7. Circular Grate Retort Bed Profiles

evolution from the large rock at the very top of the bed is complete (this rock is exposed to the hottest gases at the very beginning), controlled oxidation (Ref. 2) of the residual carbon is begun and the energy from the carbon-oxygen reaction replaces external energy requirements. The retorting temperature front then continues down through the bed. Recycle gas temperature and oxygen concentration is progressively changed to control bed temperature during carbon oxidation. The cool gas also begins to cool the solids in the upper portion of the bed. Sensible heat from the top of the bed and the carbon-oxygen reaction furnish the energy necessary to complete the retorting of the bottom of the bed. Thus, cooling and retorting operations are overlapped, using the same grate area. By this method, significantly increased shale tonnage rates for a specific residence time and equipment size are achieved.

Depending on the type of shale used and several other variables, the gas temperature at the bottom of the retort in the oil evolution zone ranges between 230°F and 340°F, with approximately 80 percent of the oil in liquid mist form. Upon leaving the retort, the stream of oil mist and process gas is contacted with water sprays. The functions of these direct contact sprays are:

- To cool the gas and water vapor mixture to the steady-state saturation temperature (180°F ± 20°F).
- To condition the oil mist for subsequent recovery in the electrostatic precipitator.
- To scrub sulfur compounds from the gas phase.
- To stabilize the electrostatic precipitator ionizing electrode and grounding plates.

Both wet and dry pilot electrostatic precipitators were tested. The two units used were both flat plate units which were also used to scale equipment for other commercial oil mist electrostatic precipitation applications.

In addition to defining oil removal scale-up information, the solids handling characteristics of shale from four different sources were tested in the pilot unit. Oil-shale grade varied between 19 gallons and 40 gallons per ton and sodium content varied between .5 and 9 weight percent sodium carbonate equivalent. The original process configuration

of the pilot plant was acquired with the contract for the equipment construction. This configuration had a maximum throughput rate of 60 tons per calendar day with 39 percent of Fischer Assay oil recovery obtained in January, 1976. Superior Oil then implemented process improvements defined predominately by U.S. Patent No. 4,058,905 and by over 100 adiabatic retort tests. With heating and cooling gas ducts connected to two thirds of the active grate area, these improvements resulted in a throughput rate of 250 tons per calendar day and over 99 percent of Fischer Assay oil recovery.

STEP 4. Commercial Designs

Commercial design configurations have been completed for both direct-heated and indirect-heated modes of operation. Figure 8 shows the direct-heated mode, wherein

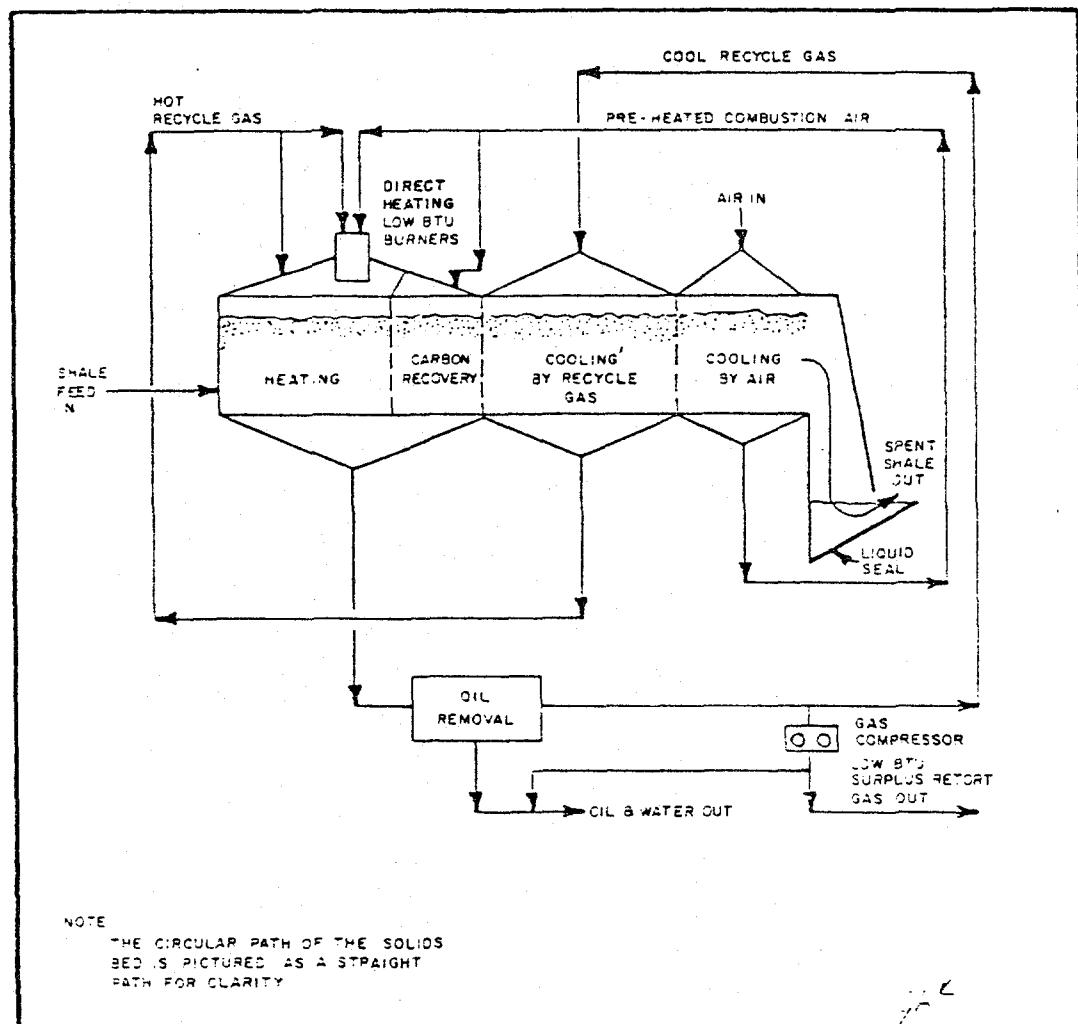


Figure 8. Circular Grate Retort — Direct-Heated Mode

part of the retort gas phase is burned and the flue gas produced is mixed with preheated recycle gas from the shale cooling zone. The resulting combination of gases produces retort zone hood inlet temperatures as desired between 1100° and 1500°F. This heating mode produces surplus retort gas with a heating value of 90 to 150 BTU per standard cubic foot, depending on shale grade.

The second mode of operation is indirect heating, as shown in Figure 9. In this mode, part of the retort gas phase is burned with preheated air in a tubular furnace to heat recycle gas to the desired temperature for introduction to the retort zone hoods. Carbon recovery is achieved by controlled oxidation with either preheated air or oxygen. Oxygen is used when higher heating value gas is desired since dilution by nitrogen is avoided. The gas produced by an indirect-heated retort has a higher heating value but a lower total energy content than that produced by a direct-heated retort. This is the result of the stack losses in the indirect heater and the dilution effect of the flue gas on the gas evolved from the shale in the direct-heated mode.

Superior has completed both direct- and indirect-heated process designs and corresponding capital and operating costs for 10,000 and 20,000 ton per calendar day units. The optimized process, demonstrated process improvements, and successful pilot plant operation, combined with an existing history of commercial operations for the circular grate equipment, make this method a viable surface retorting system. In addition to development on multi-mineral shale, Superior has tested and provided the process design for the Rundle shale deposit in Australia for Southern Pacific Petroleum. Terms are available for the detailed design, cost estimates, and processing conditions to those interested in comparing this method with other systems being considered for commercial development of oil shale deposits.

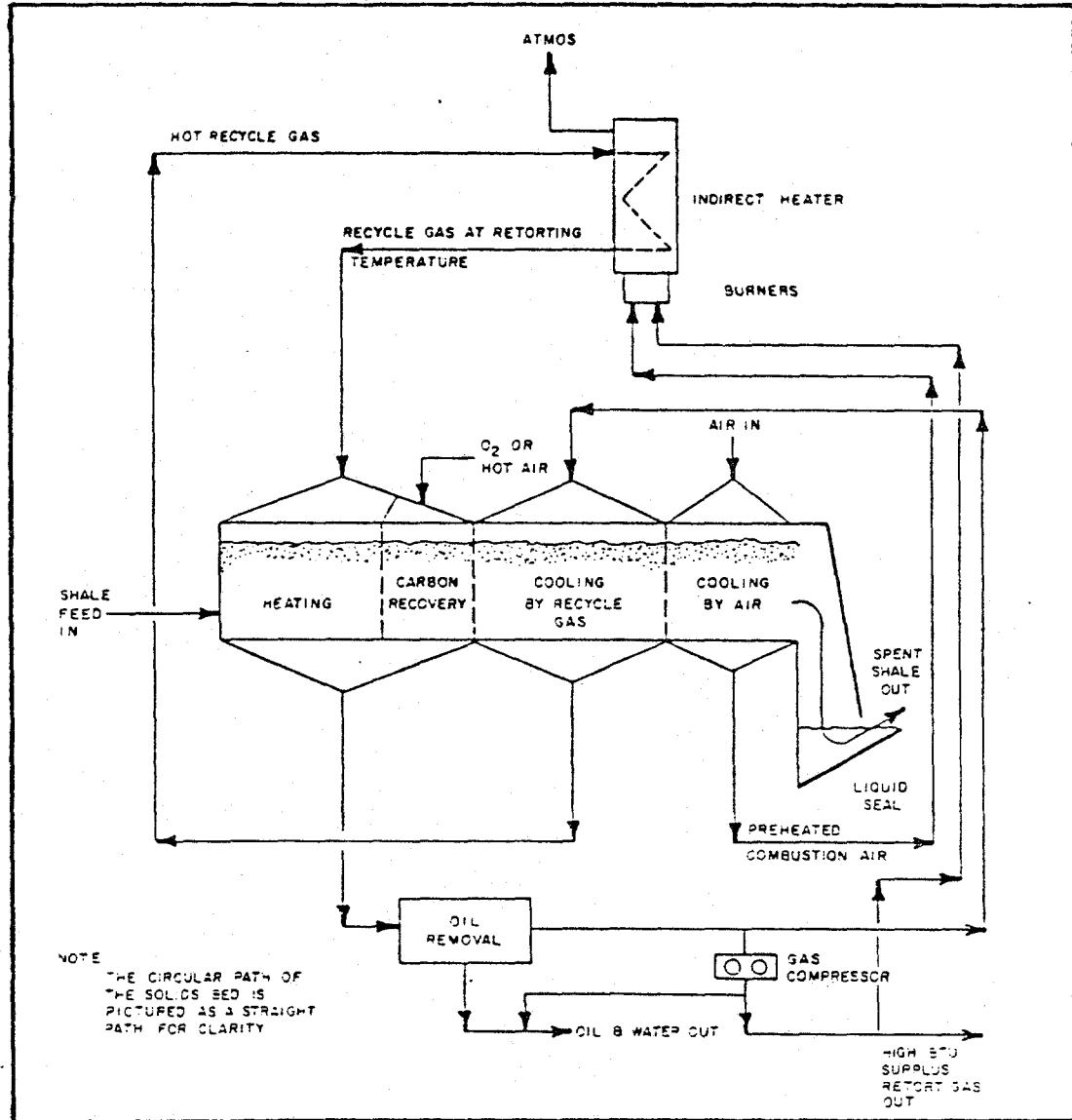


Figure 9. Circular Grate Retort — Indirect-Heated Mode

References:

1. U.S. Patent No. 4,058,905 (Knight), "Method for Reducing Residence Time and Eliminating Gas Leakage Between Zones in a Cross Flow Device for Heating and Cooling Solids".
2. U.S. Patent No. 4,082,645 (Knight, St. Cyr, Wilson), "Recovery of Energy Values by Controlled Oxidation of Oil Shale Residues".
3. N.D. Shah, "Process Development Report from Adiabatic Retort Testing", The Superior Oil Company's Internal Report.
4. J. W. Fishback, "Oil Mist Scrubber and Electrostatic Precipitation Sizing Report", The Superior Oil Company's Internal Report.
5. Arthur G. McKee & Company, "Circular Grate Retort for Shale Oil Recovery - Capital Investment and Operating Costs", April, 1978, The Superior Oil Company's Internal Contracted Report.

SUPERIOR OIL'S MULTIMINERAL PROCESS

and sodium compounds. Over the past five years, we have constructed and operated pilot plants on all steps in the processing and determined the technical viability and economics involved. However, during this time we have not been able to consummate a 1973 land exchange application to block our lands into an economical mining configuration. Our resource lays in a long narrow L shape that requires prohibitive ventilation, haulage, and access cost.

How: Nahcolite Recovery

Nahcolite is separated from the mine run material by a selective crushing and photo-sorting technique. The nahcolite occurs in nodules in the base shale, and being more friable can be selectively crushed and released from the shale. Commercial size photosorting equipment has been used to separate commercial grade nahcolite from the shale (Figure 4).

Nahcolite has been used in pilot tests as a scrubbing agent to reduce SO_2 , NO_x , and particulates from coal-burning electric generating facilities in Colorado and other states. These successful pilot tests hold the promise of reducing emissions in many generating facilities as well as use in various chemical and refinery clean-up operations.

Oil Recovery

Both circular and straight grates have long been in commercial use for iron ore pellet sintering, cooling, and other kiln applications. Superior's process development effort focuses on adaptation of the circular grate process for oil shale retorting. This effort included construction and operation of an adiabatic fixed-bed retort designed to simulate the conditions encountered by a section of solids as it travels through the separate processing zones in the circular grate. The adiabatic retort tests identified the significant process variables and their effect(s) on cost responses such as through-put rate, thermal efficiency, product yield, etc. Cost sensitivity analyses established optimum ranges in which to design and operate the circular grate oil shale pilot retort, which was later constructed (Figure 5).

The pilot circular grate retort operations defined design and scale-up information for the oil removal system, which had never been tested in prior circular grate applications.

SUPERIOR OIL CO., JOHN KNIGHT,
ASSISTANT DIVISION MANAGER

Where

Northwestern Colorado on the northern edge of the Piceance Basin about twenty-two miles west of Meeker and thirty-five miles east of Rangley (Figure 1, Figure 2).

What

Multi-mineral process for recovering oil, alumina, nahcolite and soda ash from oil shale (Figure 3).

When

As an historical introduction, Superior's multi-mineral oil shale program entails surface processing for producing nahcolite, oil, alumina,

Pilot plant operations also confirmed the mechanical reliability of solids flow on four types of shale. The primary results of this process development effort have been:

1. Attainment of thermal efficiency for the crossflow circular grate that approaches those achieved in countercurrent flow devices
2. Product oil yields of over 98% of Fischer Assay
3. Development of a proved oil recovery system
4. Optimized throughput and gas rates per ton of oil shale processed

These successful process development results can now be combined with the proven mechanical reliability of commercial-size circular grate heating-cooling equipment for oil shale retorting.

Alumina and Soda Ash Recovery

We plan to meet our plant and processing needs for water requirements from the deeper salt content groundwater aquifers. These saltwater requirements total approximately 7 ft³/sec gross production. They are predominately for the alumina and soda ash recovery processes (Figure 6).

The salt water is used for leaching and washing the retorted shale of mineral content. A mineral rich pregnant mother liquor is produced. Multi-effect evaporators and crystallizers generate water condensate from the pregnant mother liquor in production of alumina and soda ash products. The resulting water condensate is used for the major plant freshwater needs. Minor plant freshwater needs, such as construction drinking water, etc.; totaling approximately 0.177 ft³/sec, will be met from our surface water rights either through irrigation or conditional decreed surface rights. Actual replacement, storage, or exchange for our surface water is in the process of refinement and are not defined at this time.

Environmental

Key environmental aspects of Superior's multi-mineral shale processing are:

1. Use of low quality energy in the mineral winning processes; alumina-soda ash for an overall very thermal efficient interfaced processing complex
2. Return of leached spent shale to the mine (Figure 6-A)
3. Use of salt water from the Leach Zone vs. fresher surface water, thus

decreasing salt content in the White, Green, and Colorado rivers

4. No water discharge from Superior's project

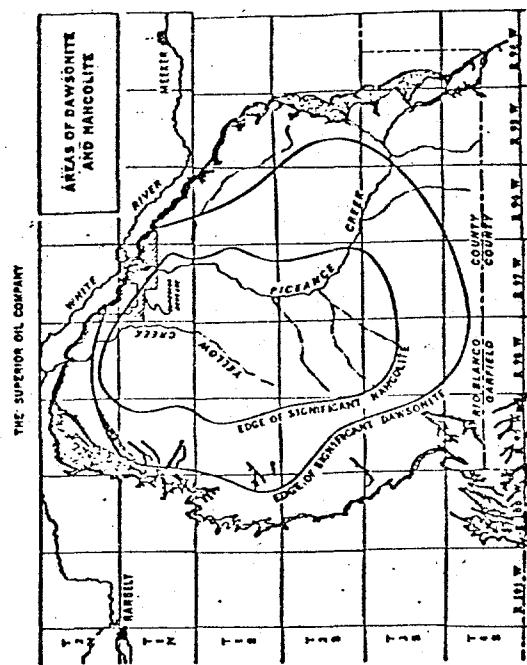


Figure 1. Areas of Dawsonite and Nahcolite

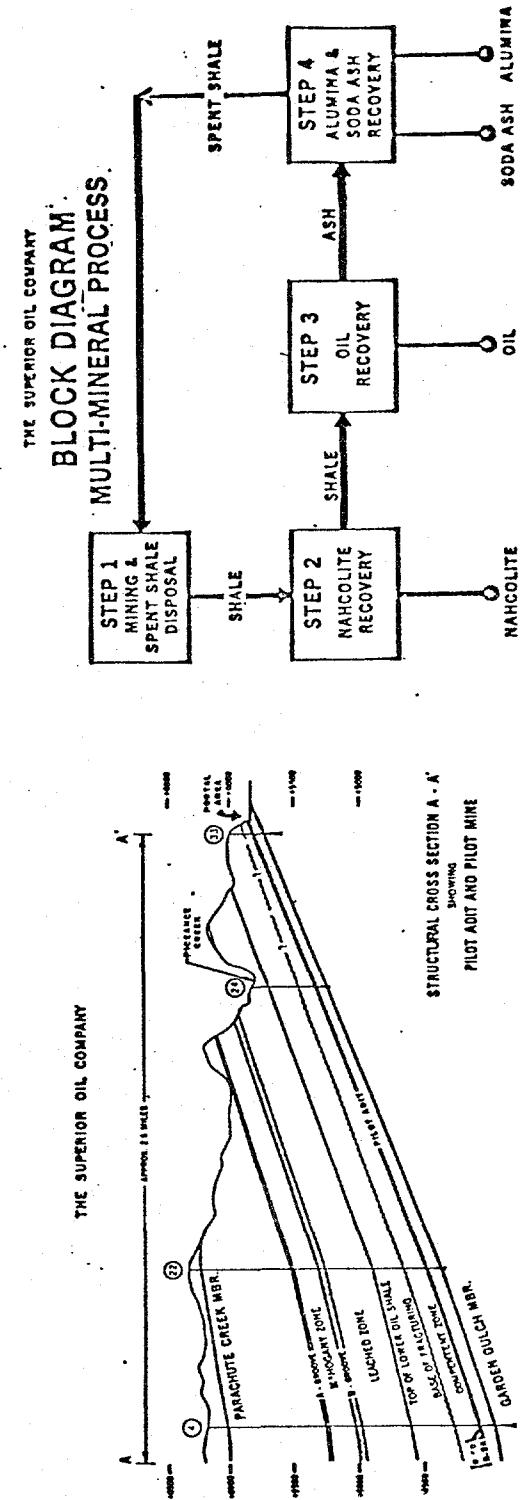


Figure 3. Block Diagram Multi-Mineral Process

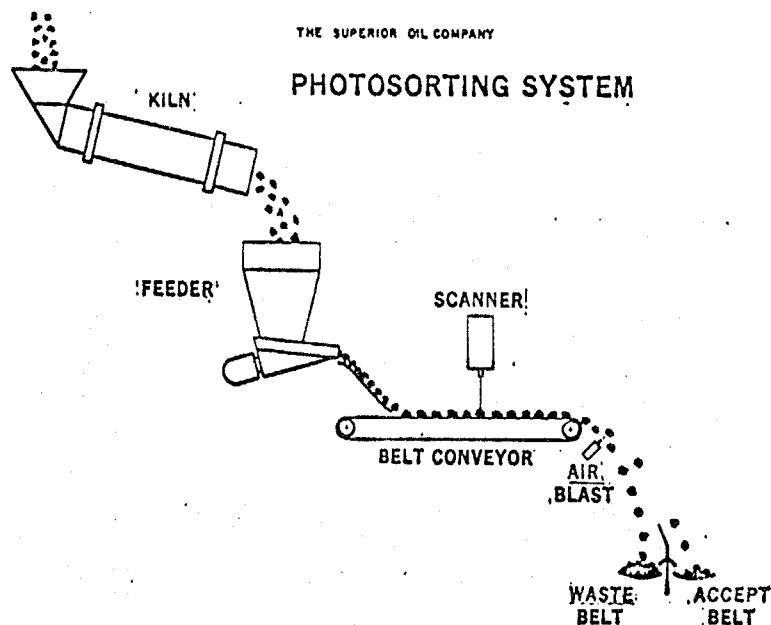


Figure 4. Photosorting System

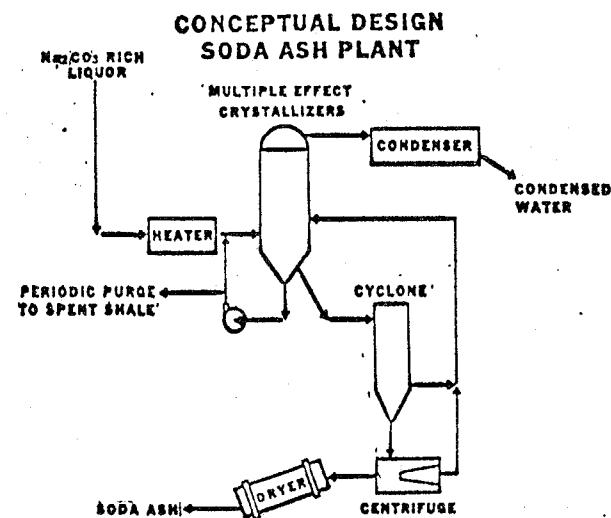
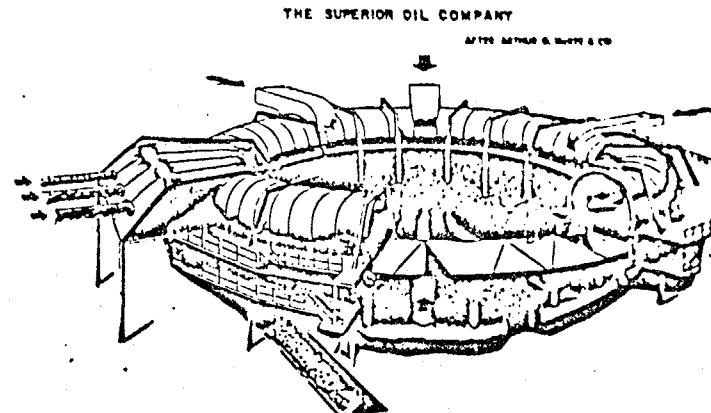


Figure 6. Conceptual Design Soda Ash Plant



Conceptual View of Circular Grate Retort

Figure 5. Conceptual View of Circular Grate Retort

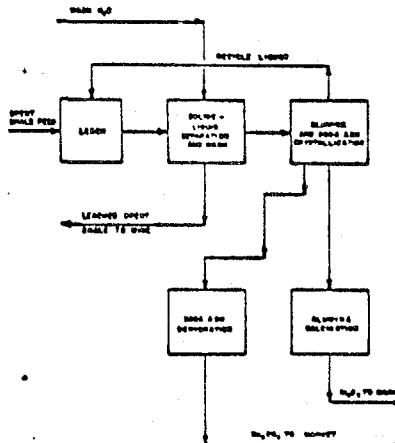
THE SUPERIOR OIL COMPANY
ALUMINA AND SODA ASH RECOVERY PROCESS

Figure 6-A. Alumina and Soda Ash Recovery Process

EXXON COMPANY, U.S.A.

POST OFFICE BOX 2180 • HOUSTON, TEXAS 77001

AN EXXON PLAN FOR COMMERCIALIZING
SYNTHETIC FUELS DEPARTMENT
SYNTHETIC FUELS

July 25, 1980

Dr. S. S. Penner
Energy Center, B-010
University of California San Diego
La Jolla, California 92093

Dear Dr. Penner:

Attached is a copy of the slide material I presented to your FERWG group on July 10, 1980 in San Diego. I have not attached the corresponding text, but have included a copy of the testimony presented by Mr. W. T. Slick, Jr. to Senator Hart's Budget Committee Hearing in Denver on July 17. I think you will find this testimony of interest.

I have asked our technical group to respond to FERWG through Dr. Lessard on the two questions raised during my presentation; namely, room and pillar mining resource recovery efficiency and costs per barrel of oil shale produced.

Sincerely,



Larry Kronenberger

LK: jcw
Attachments
cc: Mr. T. M. Campbell, w/o attach.
Mr. J. P. Racz, w/o attach.
FERWG-III Members, w/ attachments

Types Of Synfuels And Relative Costs

| Synfuel | Process | Products | Cost |
|-----------------------------|--------------------------------------|---|------------------|
| Shale Oil | Heating Of Oil Shale | Most Similar To Crude Oil | Base |
| Intermediate Btu Gas (IBG) | Gasification Of Coal | Gas, Largely CO And H ₂ For Industrial Fuels Or Chemical Feedstock | Base |
| Synthetic Natural Gas (SNG) | Gasification Of Coal And Methanation | Gas, Largely Methane For Distribution With Natural Gas | 15 to 25% Higher |
| Methanol From Coal | Gasification And Synthesis | Fuel Grade Methanol And SNG (50/50) | 20 to 30% Higher |
| Other Liquids From Coal | Indirect And Direct Routes | Gasoline, Distillates, Heavy Fuel Oil And Up To 50% SNG | 40 to 60% Higher |

Potential Utilization U.S. Oil Shale and Coal

Chart 2

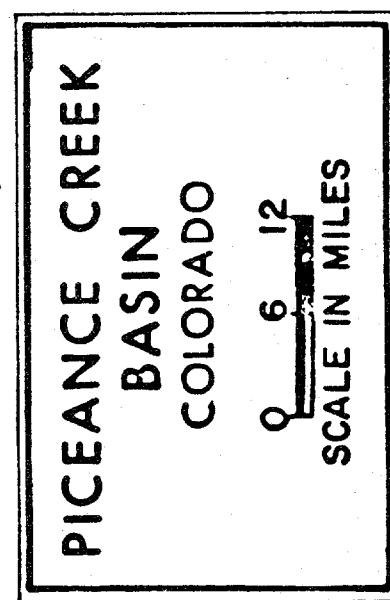
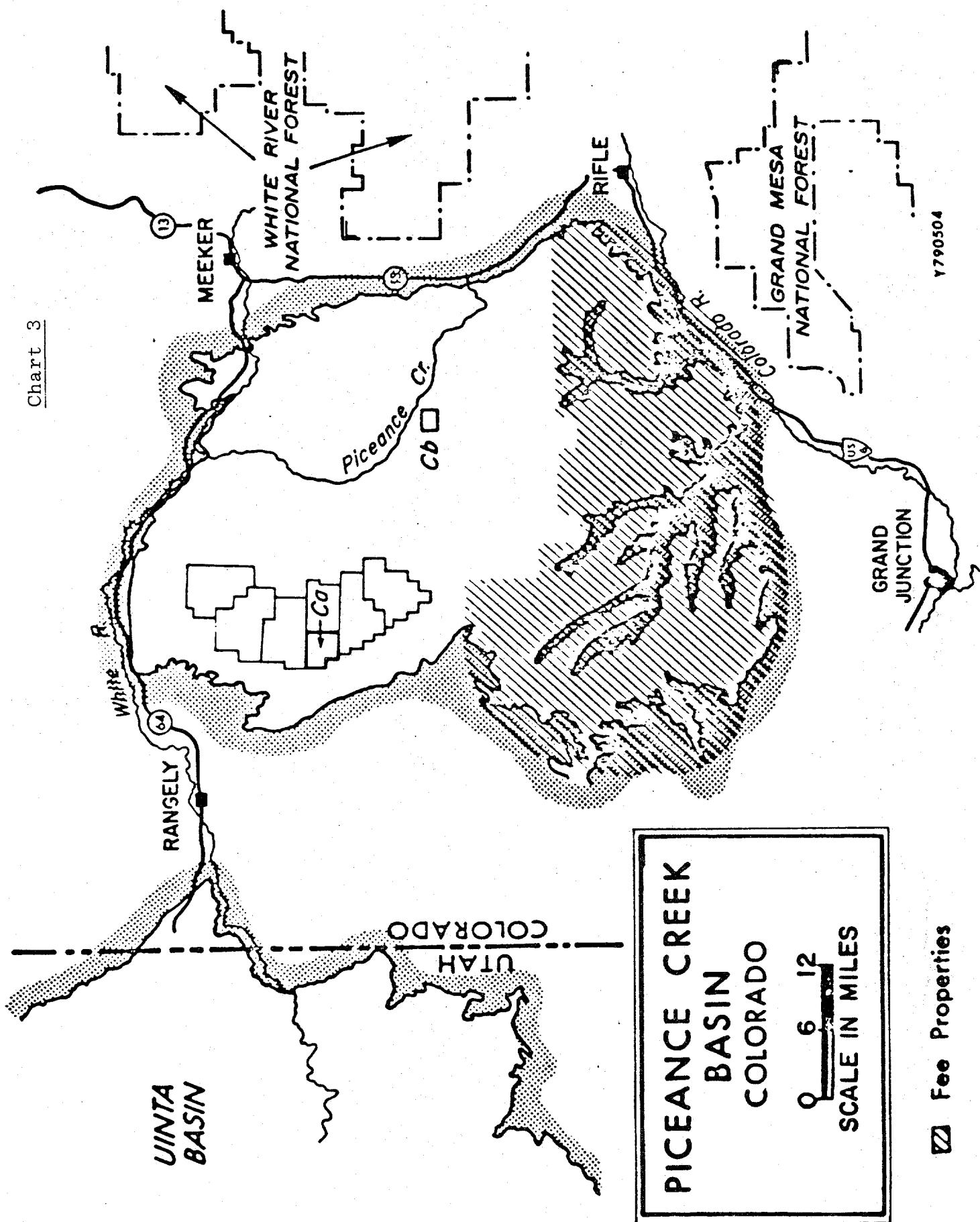
| Oil Equivalent, Billion Barrels | | | | Net Synthetics Production |
|---------------------------------|-------------------------|-----------------------|-----|---------------------------------|
| Resource In-Place | Recoverable As Mined | Demand Ex Synfuels | | |
| Oil Shale | | | | |
| 670 | 1400 | 60 | 0 | 50 |
| 730 | 580 | | 0 | 500 |
| Underground Mined | | | | |
| Surface Mined | | | | |
| 2000 | 1360 | 570 | 430 | |
| 3400 | 2000 | 570 | 980 | |
| Coal | | | | |

✓

Equivalent to 15 million BPD for 175 years:

- 8 million BPD shale-based
- 7 million BPD coal-based

Chart 3



Fee Properties

SKETCH OF SURFACE OIL SHALE MINING OPERATION

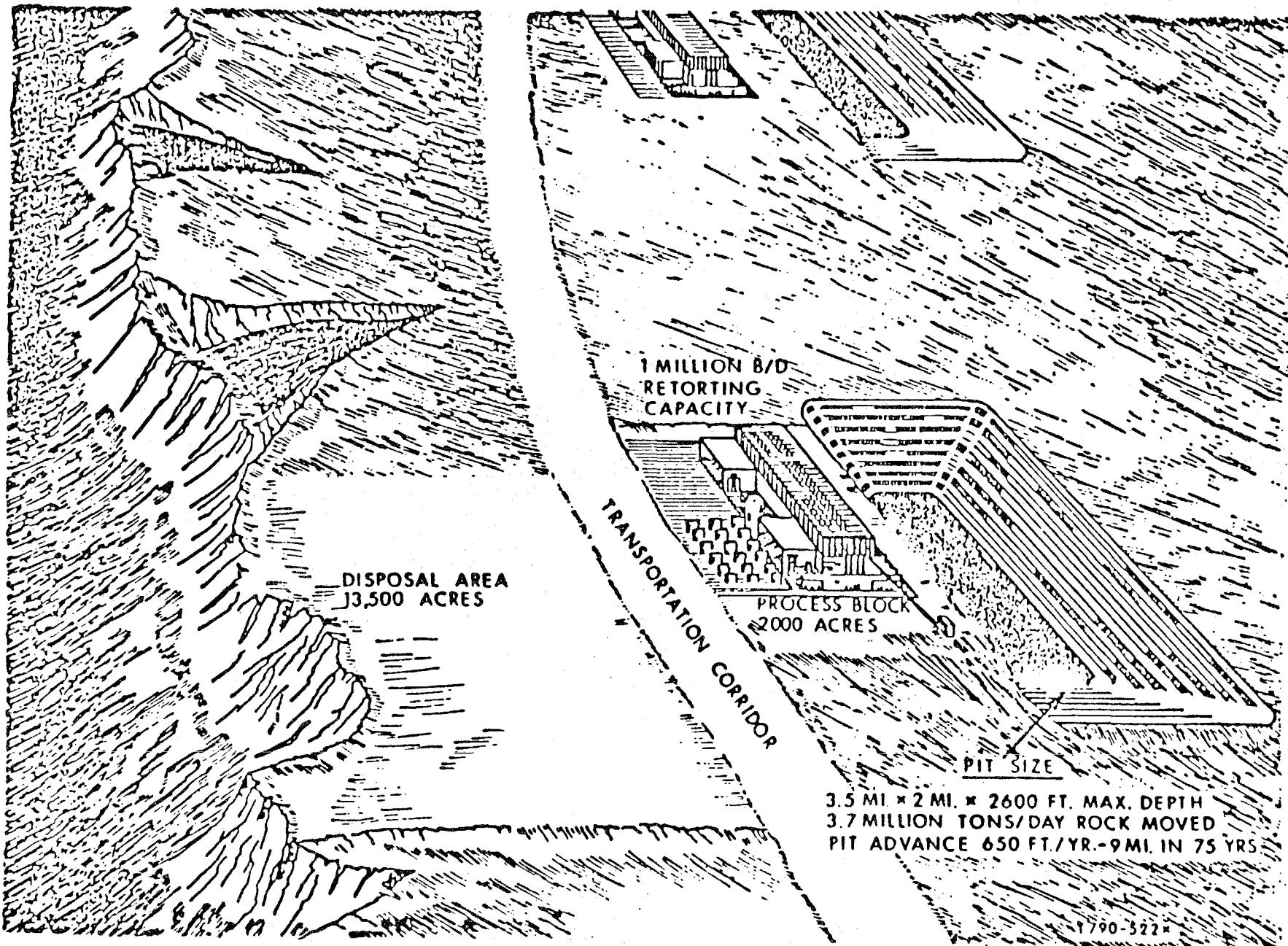


Chart 5

Assumed Distribution Of Synthetics Industry (Million BPD Oil Equivalent)

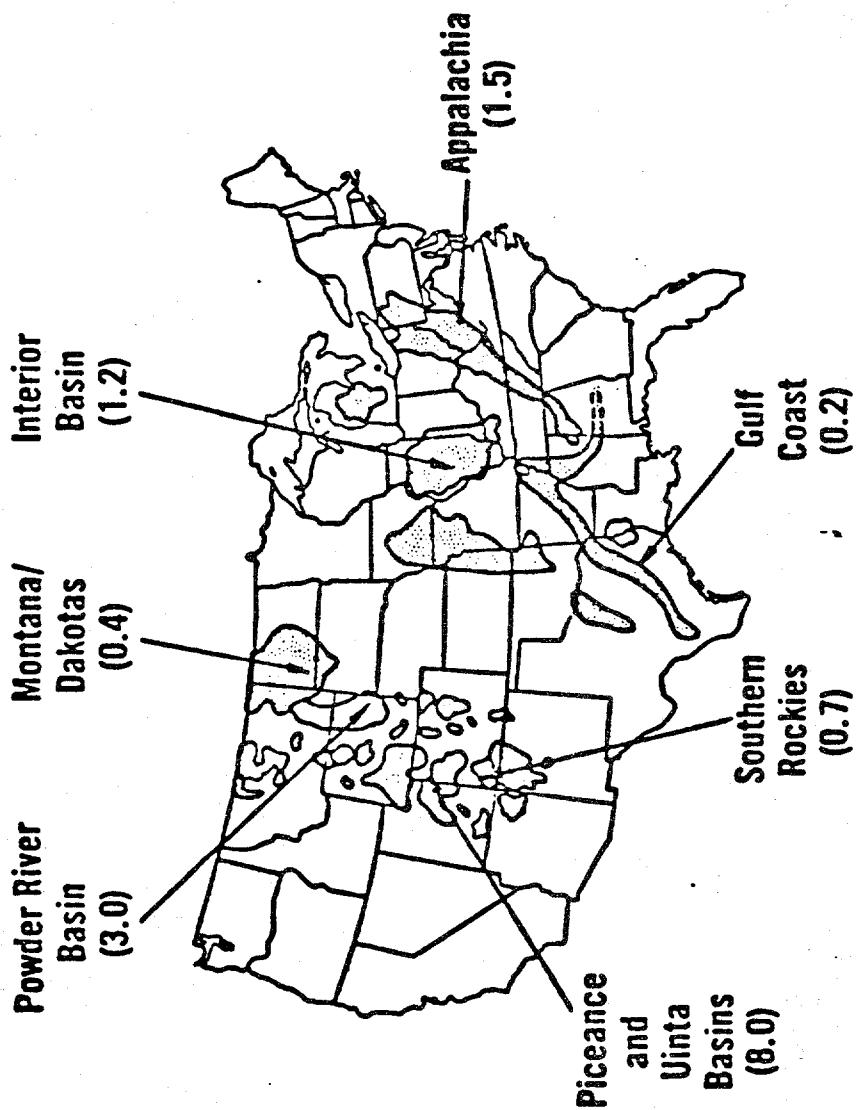


Chart 6

**Synthetics Development Requirements
For 15 Million BPD Production In 30 Years**

| | <u>Shale Oil</u> | <u>Coal</u> | <u>Total</u> |
|---|------------------|-------------|--------------|
| Volume, Million B/DOE | 8 | 7 | 15 |
| Investment, Billion 1979 \$ | 330 | 380 | 710 |
| Percent of GNP | 0.4 | 0.5 | 0.9 |
| Interbasin Water, Million Acre-Feet/Year | 1.1 | 0.6 | 1.7 |
| Employees, Thousands | 310 | 560 | 870 |
| Population Impact In Affected Areas, Thousands | 1620 | 2600 | 4220 |

Chart 7

Direct People Effects

| Category | Peak Requirement | % Over Present | %/Yr. Current Growth | %/Yr. Increase Required |
|--------------|------------------|----------------|----------------------|-------------------------|
| Engineering | 8,400 | 36 | 5 | 0.9 |
| Construction | 250,000 | 15 | 2 | 0.4 |
| Plants | 389,000 | 57 | 0.6 | 1.3 |
| Mines | 482,000 | 60 | 5 | 0.5 |

Total Population Growth

| Location | Initial Population | Population At End of Period | Increase %/Year |
|-------------------|--------------------|-----------------------------|-----------------|
| Piceance Basin | 100,000 | 1,750,000 | 10.0 |
| Powder River | 90,000 | 1,250,000 | 9.2 |
| San Jose (1) | 100,000 | 600,000 | 6.2 |
| Orange County (2) | 130,000 | 1,800,000 | 6.8 |

(1) 1950-1979

(2) 1940-1979

Summary And Conclusions

- Realistically looking at the development and use patterns of all energy sources, including the effect of conservation, we conclude that the United States must develop a synthetics industry.
 - Liquids and gas will be needed for many decades to meet specific end uses which cannot be supplied by electricity.
 - Synthetics can reduce import dependence significantly in the 1990s and cover the shortfall of oil and gas expected in the next century.
 - Synthetics will need to be a large industry, with much of it centered in the West.
 - The private sector has the financial, managerial, and technical resources to develop the synthetics industry.
 - Plans are being made to construct the first synthetics plants.
 - Must begin now to plan for continued development of synthetics beyond 1990 goals.
- Political and management challenge is for government, industry, and other interested parties to work cooperatively in developing synthetics.
 - Synthetics development will have significant impacts in specific geographic areas.
 - Cooperation must begin with initial planning in order to balance and accommodate national energy needs and regional, state, and local interests.

SYNTHETIC FUELS

TESTIMONY OF
W. T. SLICK, JR.
EXXON COMPANY, U.S.A.

BEFORE THE
SENATE BUDGET COMMITTEE

DENVER, COLORADO
JULY 17, 1980

MY NAME IS WILLIAM T. SLICK, JR., SENIOR VICE PRESIDENT OF EXXON COMPANY, USA. I APPRECIATE THE OPPORTUNITY TO EXPRESS EXXON'S VIEWS ON THE SUBJECT OF SYNTHETIC FUELS.

AS AN INTEGRAL PART OF OUR BUSINESS PLANNING EFFORT, EXXON PREPARES ANNUALLY AN ENERGY OUTLOOK WHICH, FOR MANY YEARS, WE HAVE MADE PUBLIC. LAST YEAR, FOR THE FIRST TIME, WE EXTENDED THE OUTLOOK TO THE YEAR 2000. THIS LATEST OUTLOOK, REFLECTING THE CHANGING ENERGY SITUATION, POLITICS AND ECONOMICS OF THE WORLD, SHOWED A SIGNIFICANT ROLE FOR SYNTHETICS IN AMERICA'S FUTURE. TO BETTER UNDERSTAND THAT ROLE AND TO TEST ITS LONG-TERM VIABILITY, WE EXTENDED OUR ASSESSMENT TO THE YEAR 2050.

WE HAVE SINCE PUBLISHED THAT WORK AND HAVE BEGUN THE PROCESS OF DISCUSSING IT WITH THOUGHTLEADERS IN BOTH THE PUBLIC AND PRIVATE SECTOR. I HAVE SUBMITTED A COPY OF THESE STUDIES FOR THE RECORD. I WILL MAKE A FEW SUMMARY COMMENTS ON THEIR SUBSTANCE AFTER WHICH I WILL SUGGEST SOME MAJOR AREAS OF EFFORT NEEDED IF THIS COUNTRY IS TO REALIZE ITS FULL SYNTHETIC FUELS POTENTIAL.

BEFORE DOING SO, I FEEL COMPELLED TO SET THE RECORD STRAIGHT REGARDING THESE STUDIES. WE ARE PLEASED THAT THEY HAVE STIMULATED THE PROCESS OF PUBLIC DEBATE. UNFORTUNATELY SOME HAVE MISUNDERSTOOD BOTH THEIR PURPOSE AND THEIR MESSAGE.

THEY DO NOT CONSTITUTE "EXXON'S PLAN," AS SOME HAVE CHARACTERIZED THEM, FOR SOLVING THE COUNTRY'S ENERGY PROBLEM. NOR DO THEY OUTLINE A MAJOR PROJECT UPON WHICH EXXON IS EMBARKED. THEY ARE, QUITE SIMPLY, OUR ASSESSMENT OF THE EXTENT OF THIS COUNTRY'S FUTURE ENERGY NEEDS AND WHAT WE BELIEVE IS POSSIBLE SHOULD THE COUNTRY CHOOSE TO TAKE ADVANTAGE OF ITS TREMENDOUS POTENTIAL FOR SYNTHETIC FUELS.

THE ENERGY TRANSITION

THE UNITED STATES AND THE WORLD ARE IN THE EARLY STAGES OF AN INEVITABLE ENERGY TRANSITION FROM A PRIMARILY PETROLEUM-DEPENDENT ECONOMY TO AN ENERGY-DIVERSIFIED ONE WHICH WILL EVENTUALLY BE MORE RELIANT ON NONDEPLETING FUEL SOURCES.

ALTHOUGH THERE ARE MANY UNKNOWNS ABOUT HOW THIS ENERGY TRANSITION IS GOING TO UNFOLD, THERE ARE SOME IMPORTANT THINGS WE DO KNOW.

- WE KNOW THAT THE TRANSITION FOR OUR COUNTRY ACTUALLY BEGAN SEVERAL YEARS AGO WHEN THE UNITED STATES STARTED TO EXTRACT DOMESTIC PETROLEUM RESERVES FASTER THAN THEY WERE BEING DISCOVERED.
- WE KNOW THAT EVEN THE MAJOR OIL-EXPORTING NATIONS OF THE MIDDLE EAST, WHICH HAVE THE GREATEST KNOWN PETROLEUM RESERVES, WILL BEGIN TO HAVE THEIR OWN PRODUCTION DECLINES WITHIN THE NEXT TWO-THREE DECADES.

AND WE KNOW THAT SOMETIME IN THE NEXT CENTURY, THE WORLD WILL HAVE TO RELY SUBSTANTIALLY ON NONDEPLETING OR RENEWABLE ENERGY SOURCES.

HOWEVER, THE MOST IMPORTANT THINGS ARE THE ONES WE DON'T KNOW. AMONG THE UNKNOWNNS IS WHETHER, OR WHEN, WE AS A NATION WILL DEVELOP A CLEAR COMMITMENT TO IMPROVE OUR ENERGY SITUATION. THE 1973-74 ARAB EMBARGO AND THE RECENT IRANIAN SITUATION PROVIDED SHARP AND PAINFUL WARNING SIGNALS. NONETHELESS, OUR COUNTRY CONTINUES TO "MUDDLE ALONG" WITHOUT AGREED OBJECTIVES OR EFFECTIVE ACTIONS TO DEAL WITH OUR ENERGY PROBLEMS. THIS "MUDDLING ALONG" CANNOT CONTINUE WITHOUT SEVERE RISKS TO BOTH OUR ECONOMY AND NATIONAL SECURITY. THERE IS GREAT PUBLIC CONFUSION OVER WHAT THE SOLUTIONS TO THE ENERGY PROBLEMS REALLY ARE. EACH INTEREST GROUP HAS A DIFFERENT FAVORITE--SOLAR POWER, CONSERVATION, COAL, NUCLEAR, MORE CONVENTIONAL OIL AND GAS, SYNTHETICS, OR A COMBINATION OF SEVERAL OR ALL OF THESE.

HEREIN LIES THE BASIC PARADOX IN THE U.S. ENERGY DEBATE. THE FACT THAT THIS NATION DOES POSSESS A VARIETY OF POTENTIALLY LARGE ENERGY SOURCES ACTUALLY HAS THE EFFECT OF CONFUSING THE SITUATION AND MAKING IT DIFFICULT TO SETTLE ON A COURSE OF ACTION.

IN CONSIDERING WHAT ACTIONS WE SHOULD TAKE, IT IS IMPERATIVE THAT WE MAKE THE DISTINCTION BETWEEN ENERGY SOURCES WHICH CAN HELP US NOW, THOSE THAT CAN HELP IN THE DECADES IMMEDIATELY AHEAD, AND THOSE SOURCES WHICH HAVE PROMISE IN THE MORE DISTANT FUTURE.

IN THAT CONTEXT I'D LIKE TO SUMMARIZE SOME OF OUR FINDINGS THAT PROVIDE THE BASIS FOR OUR CONCLUSION ON THE NEED FOR SYNTHETIC FUELS.

U.S. ENERGY OUTLOOK

WE PROJECT THAT EVEN WITH SIGNIFICANT CONSERVATION, THE NATION'S TOTAL DEMAND FOR ENERGY WILL GROW FROM TODAY'S LEVEL OF ABOUT 39 MMB/DOE TO ABOUT 50 MMB/DOE IN 2000. IN THE 1980S AND 1990S, ALL OF THE GROWTH IN DEMAND FOR ENERGY WILL BE SATISFIED BY COAL AND NUCLEAR. IN THE 21ST CENTURY, THE DEMAND FOR ENERGY WILL CONTINUE TO GROW SLOWLY. NONDEPLETING ENERGY SOURCES, SUCH AS SOLAR AND NUCLEAR FUSION, WILL MAKE INCREASINGLY LARGE CONTRIBUTIONS TO THE ENERGY PICTURE AS MORE AND MORE ENERGY IS CONSUMED AS ELECTRICITY. THERE WILL, HOWEVER, BE LARGE SEGMENTS OF DEMAND--PRIMARILY IN THE TRANSPORTATION AND PETROCHEMICAL AREAS--WHICH CAN ONLY BE MET BY LIQUID AND GASEOUS FUELS. MEETING THE DEMAND FOR ENERGY IN THESE FORMS WILL BE OF CRITICAL NATIONAL IMPORTANCE.

WE EXPECT THAT THE DEMAND FOR OIL AND GAS WILL GRADUALLY DECLINE; HOWEVER, THE ABILITY OF THE U.S., AND EVENTUALLY THE WORLD, TO PRODUCE OIL AND GAS FROM CONVENTIONAL SOURCES WILL ALSO DECLINE. TODAY, THE NATION'S DEMAND FOR OIL AND GAS TAKEN TOGETHER IS ABOUT 28 MMB/DOE, OF WHICH ABOUT 20 MMB/DOE IS FROM DOMESTIC PRODUCTION WHILE 8 MMB/DOE IS SUPPLIED BY IMPORTS. BY THE YEAR 2000, WE ESTIMATE DEMAND FOR OIL AND GAS WILL BE ABOUT 25 MMB/DOE, BUT

DOMESTIC PRODUCTION WILL BE ONLY ABOUT 12 MMB/DOE, LEAVING A DIFFERENCE OF 13 MMB/DOE. THIS DIFFERENCE WOULD HAVE TO BE COVERED BY IMPORTS OR BY SYNTHETICS. EARLY IN THE NEXT CENTURY, THE DIFFERENCE BETWEEN THE DEMAND FOR OIL AND GAS AND CONVENTIONAL DOMESTIC SUPPLIES OF PETROLEUM COULD BE ABOUT 15 MMB/DOE AND COULD CONTINUE AT ABOUT THAT LEVEL UNTIL THE MIDDLE OF THE CENTURY. CLEARLY, THESE PROJECTIONS ARE SUBJECT TO VARIATION. THE ESSENTIAL POINT IS THAT FOR MANY DECADES TO COME, THERE WILL BE A LARGE DEMAND FOR ENERGY IN LIQUID AND GASEOUS FORMS WHICH CANNOT BE SATISFIED BY DOMESTIC PRODUCTION OF CONVENTIONAL OIL AND GAS. THIS ADDRESSES THE IMPORTANT POLICY QUESTION OF WHETHER THE VERY LARGE COMMITMENT OF RESOURCES NECESSARY TO DEVELOP A MAJOR SYNFUELS INDUSTRY WOULD BE WORTH IT. CLEARLY WE BELIEVE IT IS.

SYNTHETICS INDUSTRY

HAVING THUS ESTABLISHED A LONG-TERM NEED FOR SYNTHETIC FUELS, WE NEXT ASKED OURSELVES HOW LARGE AN INDUSTRY COULD BE DEVELOPED AND WHAT WOULD BE REQUIRED. TO ADDRESS THAT PROBLEM ONE HAS TO EXAMINE SEVERAL KEY QUESTIONS. FIRST IS THE QUESTION OF RESOURCES. WITHOUT GOING INTO DETAIL, SUFFICE IT TO SAY THE U.S. IS BLESSED WITH ENOUGH COAL AND OIL SHALE TO PRODUCE 15 MMB/DOE OF SYNFUELS FOR 175 YEARS-- 8 MMB/DOE OF OIL SHALE AND 7 MMB/DOE OF COAL SYNTHETICS.

SECOND, WE EXAMINED SYNTHETIC FUELS TECHNOLOGY. WE FOUND THAT A NUMBER OF PROCESSES ARE NOW READY FOR COMMERCIAL APPLICATION WHILE OTHERS ARE STILL IN THE RESEARCH AND DEVELOPMENT STAGE. SPECIFICALLY WITH REGARD TO OIL SHALE, SEVERAL SURFACE RETORTING PROCESSES HAVE OPERATED SUCCESSFULLY IN LARGE PILOT PLANTS, AND THE TECHNOLOGY NOW IS READY FOR SCALING UP TO COMMERCIAL SIZE. FOLLOWING THE FIRST PIONEER COMMERCIAL SIZE PLANTS, WE CAN EXPECT IMPROVEMENTS IN OPERATING EFFICIENCY AND INVESTMENT ECONOMICS AS THE TECHNOLOGY MATURES. BUT EXPERIENCE IN PETROLEUM REFINING HAS SHOWN THAT THE FIRST GENERATION PLANTS DO NOT BECOME OBSOLETE AS TECHNOLOGY EVOLVES. THUS, GIVEN THE COUNTRY'S OBVIOUS NEED FOR SYNTHETIC FUELS PRODUCTION, WE ANTICIPATE THAT SECOND GENERATION PLANTS WOULD BE IN DESIGN AND EVEN CONSTRUCTION AS THE FIRST ROUND OF PLANTS COMES ONSTREAM. WE SEE LITTLE TO BE GAINED AND MUCH TO BE LOST BY ARBITRARILY DELAYING THAT PROCESS.

THIRD, WE EXAMINED WHETHER ENOUGH CAPITAL COULD BE RAISED TO BUILD A LARGE SYNTHETIC FUELS INDUSTRY. COMMERCIAL SIZE SYNTHETIC FUELS PLANTS WILL BE EXPENSIVE. WE ESTIMATE THAT A TYPICAL 50,000 BARRELS OF OIL PER DAY PLANT WOULD COST \$3 TO \$4 BILLION "AS SPENT" DOLLARS. THE INVESTMENT REQUIRED TO ATTAIN A PRODUCTION LEVEL OF 15 MMB/DOE IS IMMENSE--OVER \$3 TRILLION "AS SPENT" DOLLARS. DESPITE THE MAGNITUDE OF THE INVESTMENTS REQUIRED, WE BELIEVE THEY ARE MANAGEABLE SINCE THEY WOULD BE SPREAD OVER A 30-YEAR PERIOD OR MORE. THE CAPITAL MARKETS HAVE DEMONSTRATED TIME AND AGAIN THAT GIVEN

SOUND INVESTMENT OPPORTUNITIES, THE NECESSARY CAPITAL IS FORTHCOMING. THE ANNUAL INVESTMENT IN SYNTHETICS DURING THE PEAK YEARS OF CONSTRUCTION WOULD REPRESENT ONLY ABOUT ONE PERCENT OF GNP. OR PUT IN ANOTHER WAY, THIS INVESTMENT REPRESENTS A SUM ABOUT EQUAL TO THE PETROLEUM INDUSTRY'S TYPICAL ANNUAL EXPENDITURES ON EXPLORATION AND PRODUCTION OF CONVENTIONAL OIL AND GAS.

IT IS IMPORTANT TO RECOGNIZE THE TIME SCALE FOR THE DEVELOPMENT OF A SYNTHETIC FUELS INDUSTRY. THE FIRST PLANTS WILL NOT COME ONSTREAM UNTIL THE MID-1980s. SEVERAL STUDIES ESTIMATE THAT THE LEVEL OF SYNTHETIC FUELS PRODUCTION IN 1990 WILL BE ABOUT 1.0 MMB/DOE. THESE ESTIMATES SEEM CONSISTENT WITH REACHING OR COMING CLOSE TO THE NATIONAL GOAL OF 2 MMB/DOE OF SYNTHETIC FUEL PRODUCTION IN 1992 AS EMBODIED IN THE RECENTLY PASSED ENERGY SECURITY ACT.

LOOKING SPECIFICALLY AT SHALE OIL, OUR SCENERIO PROJECTS A BUILD-UP OF PRODUCTION TO .4 MMB/DOE IN 1990, 1.5 MMB/DOE IN 1995, ABOUT 3.0 MMB/DOE IN 2000, AND ULTIMATELY TO 8 MMB/DOE. OUR ESTIMATE FOR 1990 IS NOT TOO DIFFERENT FROM NUMBERS DISCUSSED BY OTHERS. TO OUR KNOWLEDGE, FEW, IF ANY, HAVE REALLY TRIED TO TAKE THE PROBLEM BEYOND THE 1990 TIME FRAME. ADMITTEDLY, THERE ARE MANY UNKNOWNS ABOUT THE ULTIMATE LEVELS OF SHALE OIL AND OTHER SYNFUELS PRODUCTION THAT CAN BE ACHIEVED. WE BELIEVE IT IS IMPORTANT, HOWEVER, THAT AS THE NATION PLANS FOR SYNTHETIC FUELS DEVELOPMENT, WE DO SO IN A WAY THAT DOES NOT PRECLUDE ACHIEVING OUR FULL POTENTIAL, WHATEVER IT MAY BE.

IN OUR STUDIES, WE HAVE LOOKED AT MANY PARAMETERS THAT WILL INFLUENCE THE ULTIMATE SHAPE AND SIZE OF A U.S. SYNFUELS INDUSTRY. WE BELIEVE THE ONES I HAVE ALREADY MENTIONED WILL NOT BE LIMITING--TECHNOLOGY, THE BASIC RESOURCES, AND CAPITAL AVAILABILITY. I MUST HASTEN TO ADD, HOWEVER, THAT IN THE CASE OF THE LATTER TWO, GOVERNMENT POLICY COULD ACT AS A LIMITATION.

FOR OTHER PARAMETERS, WE BELIEVE THAT REALIZING TIMELY DEVELOPMENT OF OUR FULL SYNFUELS POTENTIAL REQUIRES A COORDINATED EFFORT OF THE PRIVATE SECTOR AND GOVERNMENT AT THE LOCAL, STATE, AND NATIONAL LEVELS. IT IS NOT AN OVERSTATEMENT TO SAY THAT IT WILL, IN FACT, REQUIRE A COMMITMENT OF A MAGNITUDE NEVER ACHIEVED IN PEACETIME IN THE HISTORY OF OUR COUNTRY. FORTUNATELY, IF WE GET ON WITH IT, THERE IS STILL TIME.

FOUR EXAMPLES INVOLVING OIL SHALE--BUT WHICH HAVE COUNTERPARTS FOR WESTERN COAL-BASED SYNFUELS AS WELL--WILL SERVE TO ILLUSTRATE MY POINT.

O FIRST, THE NEED FOR WATER. SEVERAL STUDIES, INCLUDING OUR OWN, SUGGEST THAT WATER FROM LOCAL SOURCES WOULD PERMIT CONTINUOUS DEVELOPMENT OF A SHALE OIL INDUSTRY THROUGH THE LATE 1990'S UP TO A LEVEL OF 1.5-2.0 MM/BD. BEYOND THAT LEVEL, INTERBASIN WATER TRANSFERS WOULD BE REQUIRED. THESE APPEAR TO BE PHYSICALLY FEASIBLE. THE BASE LOAD COST OF INTERBASIN WATER TRANSFER WOULD REPRESENT A VERY SMALL PERCENT OF THE

COST OF SYNFUELS AND COULD BE BORNE BY THE SYNTHETICS INDUSTRY. THIS WOULD, IN FACT, MAKE IT POSSIBLE TO SIZE THE FACILITIES TO BRING IN INCREMENTAL WATER FOR AGRICULTURAL, MUNICIPAL, AND OTHER USES ON ATTRACTIVE TERMS.

FEW SUBJECTS ARE OF GREATER CONCERN IN THE WEST THAN WATER. INTERBASIN TRANSFERS ARE NOT NEW BUT HAVE ALWAYS COME ONLY AFTER LONG DEBATE AND EFFORT. TO DEVELOP SUCH A PROJECT FOR SYNTHETIC FUELS WILL REQUIRE THE INVOLVEMENT AND ACTIVE PARTICIPATION OF ALL THE AFFECTED STATES IN THE REGION AS WELL AS THE FEDERAL GOVERNMENT. THE LATE 90'S TIME HORIZON OF NEED MAKES THIS SEEM DOABLE IF WE START NOW. THE CHALLENGE AT THIS TIME IS TO CREATE THE ACTIVE GROUPS TO DEVELOP PLANS, NOT FURTHER STUDIES TO DEFINE CONSTRAINTS.

O SECOND ARE THE ISSUES OF INFRASTRUCTURE AND SOCIAL IMPACT. WE APPLAUD THE SENATOR'S EFFORT ON COMMUNITY IMPACT ASSISTANCE LEGISLATION. WE WOULD BE PLEASED TO WORK WITH YOU TO OBTAIN THE NEEDED LEGISLATION. I MUST HASTEN TO ADD, HOWEVER, THAT IN LIGHT OF THE POTENTIALLY LARGE GROWTH OF THE INDUSTRY OVER THE COMING DECADES, EVEN MORE ASSISTANCE FOR THE AFFECTED COMMUNITIES WILL BE NEEDED THAN IS PROPOSED IN YOUR LEGISLATION OR IS CONTAINED IN OTHER EXISTING PROGRAMS.

I BELIEVE MANY COMPANIES INVOLVED IN SYNFUELS ARE SENSITIVE TO AND RECOGNIZE A REPONSIBILITY TO HELP MITIGATE THESE SOCIO-ECONOMIC IMPACTS. CERTAINLY, EXXON DOES. PLANNING FOR THESE IMPACTS AND THE CREATION OF THE REQUIRED INFRASTRUCTURE MUST INVOLVE MANY CONSTITUENCIES: THE PRODUCING COMPANIES, PEOPLE AT THE LOCAL LEVEL DIRECTLY AFFECTED, EXISTING BUSINESS AND CIVIC GROUPS, GOVERNMENTS AT LOCAL AND STATE LEVELS, ACADEMIC AND OTHER INSTITUTIONS. IT LIKELY WILL BE NECESSARY TO CREATE SOME NEW ENTITIES TO COALESCE THESE INTEREST GROUPS INTO A RESULTS-ORIENTED EFFORT IF WE ARE TO EFFECTIVELY DEAL WITH THE MANY ASPECTS OF THE PROBLEM. NOT THE LEAST OF THESE PROBLEMS IS ADEQUATE FRONT-END FUNDING.

- 0 THIRD, THE ENVIRONMENTAL ISSUES MUST BE ADDRESSED IN FURTHER DETAIL. ALTHOUGH WE HAVE DONE SOME WORK, WE HAVE NOT UNDERTAKEN FULLY DETAILED STUDIES NEEDED TO ASSESS THE IMPACTS OF A LARGE-SCALE INDUSTRY. BASELINE STUDIES AND RELATED ENVIRONMENTAL IMPACT WORK SHOULD BEGIN NOW FOR A LARGE OIL SHALE INDUSTRY. IF, IN FACT, A MULTI-MILLION BARREL OIL SHALE INDUSTRY IS TO DEVELOP, THE ENVIRONMENTAL EFFECTS CANNOT LOGICALLY BE ASSESSED BY EXTRAPOLATING MODELS CREATED TO STUDY THE FIRST ONE OR TWO PLANTS TO EVALUATE THE IMPACT OF A MATURE INDUSTRY DEVELOPED OVER THIRTY YEARS. AS HAS HAPPENED IN OTHER INDUSTRIES, ONE WOULD LOGICALLY EXPECT CONTROL TECHNOLOGY FOR OIL SHALE TO MATURE WITH THE INDUSTRY.

SOME MODIFICATIONS MAY BE NECESSARY IN THE CLEAN AIR ACT. BUT WE BELIEVE THAT A SIZABLE INDUSTRY CAN BE DEVELOPED WHICH WOULD NOT VIOLATE FUNDAMENTAL HEALTH AND SAFETY STANDARDS AND WHICH WOULD MEET THE EXPECTATIONS OF REASONABLE PEOPLE.

0 FINALLY, THE FEDERAL LEASING PROGRAM FOR THE PICEANCE BASIN MUST BE GEARED TO WHATEVER LONG-TERM EXPECTATIONS THE NATION FINALLY SETS FOR AN OIL SHALE INDUSTRY. A PIECemeal APPROACH WILL NOT SUFFICE. ALONG THIS LINE, WE COMMEND THE DEPARTMENT OF THE INTERIOR FOR THEIR RECENT INITIATIVE TO EXPAND THE PROTOTYPE OIL SHALE LEASING PROGRAM AND TO STRUCTURE A PERMANENT LEASING SYSTEM. FOR THE OIL SHALE INDUSTRY TO DEVELOP CONSISTENT WITH THE SCENARIO I HAVE PRESENTED, THE PERMANENT LEASING PROGRAM MUST BE PUT IN PLACE WITHIN THE NEXT TWO OR THREE YEARS AND MUST INCLUDE LEASES IN THE APPROPRIATE AREAS OF THE BASIN TO ACCOMMODATE LARGE-SCALE SURFACE MINING. WE SUPPORT THE DEPARTMENT OF THE INTERIOR'S INITIATIVE TO REMOVE THE MAXIMUM FEDERAL LEASE HOLDING LIMITATION OF 5,120 ACRES BY ONE COMPANY, AND TO ALLOW OFF-LEASE DISPOSAL OF SPENT SHALE AND OFF-LEASE SITING OF PROCESSING FACILITIES.

IN CONCLUSION, THE U.S. CLEARLY HAS THE POTENTIAL FOR A MAJOR SYNFUELS INDUSTRY. THE DEGREE TO WHICH WE REALIZE THAT POTENTIAL WILL DEPEND ON MANY DECISIONS BY MANY PEOPLE--IN AND OUT OF GOVERNMENT--AND IN AND OUT OF COLORADO.

THE COUNTRY'S POTENTIAL CAN BE ACHIEVED, WE BELIEVE, IN WAYS THAT ARE SOCIALLY, ENVIRONMENTALLY, AND POLITICALLY ACCEPTABLE. THE FIRST STEP IN THE PROCESS IS TO EXPAND THE PUBLIC DISCUSSION--INVOLVING THOSE WHO WILL BE DIRECTLY AFFECTED--BE THEY CITIZENS IN THE AREAS OF POTENTIAL SYNFUELS PRODUCTION OR THAT BROADER GROUP OF CITIZENS WHO ARE AFFECTED BY THE IMPACT OF THE DRAIN ON OUR ECONOMY OF EXCESSIVE FOREIGN OIL IMPORTS OR WOULD BE AFFECTED SHOULD THOSE FOREIGN IMPORTS BE CUT OFF.

WE VIEW THESE HEARINGS AS A PART OF THAT PROCESS AND COMMEND YOU FOR HAVING THEM AND PARTICULARLY FOR HAVING THEM IN COLORADO, WHICH IS DESTINED TO PLAY SUCH A KEY ROLE IN THE NATION'S ENERGY FUTURE.

I WOULD NOW BE HAPPY TO ANSWER ANY QUESTIONS YOU MIGHT HAVE.

7/16/80
PL47/A2-13/SP

AB-139

APPENDIX V

THE RIO BLANCO PROGRAMS

RIO BLANCO OIL SHALE COMPANY

DAYTON COMMONS 9725 E. HAMPDEN AVENUE
DENVER, COLORADO 80231 303-751-2030

August 11, 1980

Dr. S. S. Penner
University of California
Mail Code B-010
La Jolla, CA 93093

Dear Dr. Penner:

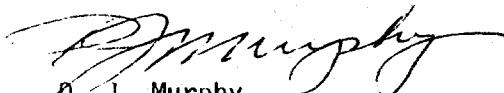
As promised in my letter to you of July 31, we are forwarding to you today by priority mail the attached contribution to your workshop report.

I regret approval could not be secured to provide you with definitive cost data. I'm sure you realize that our cost data have been developed at considerable expense and are considered proprietary and confidential.

As I expressed in my initial letter I would, however, be pleased to discuss in general terms our cost experience in mining MIS retorts in the center of the Piceance Creek basin where we faced excessive ground-water, hydrogen sulfide and methane gas.

Again I enjoyed the opportunity to meet you and the other panel members. Best wishes for continued success with your work.

Sincerely,


D. J. Murphy
Manager, Planning and Economics

DJM/cin
Attachment

D. Murphy (Rio Blanco Oil Shale Company, a general partnership of Gulf Oil Corporation and Standard Oil Company (Indiana) noted that commercial scale (50,000 BPD) engineering will soon begin on an open pit mining and surface retorting approach to Tract C-a development. Rio Blanco, with currently available water rights, could produce well over 50,000 BPD at Tract C-a with open pit mining. Rio Blanco feels that more must be learned about MIS retorting before Rio Blanco could proceed with commercial scale engineering on MIS at Tract C-a at this time. Rio Blanco will continue to test the MIS approach. Test MIS Retort No. 1 will be approximately 400 ft. high x 3,600 sq. ft. in cross-section. A final decision on which alternative to pursue to commercialization, open pit or MIS, will be made at a later date.

The partnership began with the 1974 lease of Tract C-a. About $\$15 \times 10^6$ were spent on baseline environmental and engineering studies during 1974-75. In 1977, the MIS process with sub-level caving for rubblization was adopted. Mining experience involving water, H_2S and CH_4 in the mine workings during 1978 showed that underground mining costs would be much higher at the center of the Piceance Basin than in older oil shale mines developed at the rim of the basin. During 1978, a random-free-fall-high-void (30 to 40% void) method of MIS rubblization was developed. During 1979, the Lurgi retort was selected for surface processing. Comparative economic studies completed in 1979 showed that surface retorting and open pit mining could probably be commercialized at Tract C-a over the near term with a reasonable chance of success. High yields are required from MIS to match open pit/surface retorting economics. MIS rubblization via blasting in contrast to crushing on the surface makes uniform porosity in rubblized shale a very difficult goal to attain and is a significant problem in achieving high MIS yields.

The following R&D areas are considered to be important: (a) adequate definition of Piceance Basin regional hydrology to allow more accurate estimates of groundwater flow and recharge; (b) materials handling on a large scale which will be required for open pit development because approximately four tons of material must be handled per barrel of oil; (c) development of efficient procedures for the disposal of very large amounts of spent shale; (d) development of MIS blasting parameters to produce uniformly distributed porosity in the rubble.



Chevron Research Company
A Standard Oil Company of California Subsidiary
576 Standard Avenue, Richmond, CA 94802

AB-5

APPENDIX VI

THE CHEVRON PROCESS FOR SHALE-OIL RECOVERY*

*Communicated by J. R. Thomas and R. P. Sieg

SMALL PARTICLE RETORTS

Exploratory Research Results

- Small Particles Offer

- Fast Retorting
 - ≥ Fischer Assay Oil Yields
 - Very Fast Char Combustion
 - Manageable Decrepitation

- Carbonate Decomposition Can be Controlled

DEVELOPMENT OF THE CHEVRON OIL SHALE RETORTS

Chevron A Retort Development

Chevron B Retort Development (STB)

- Bench Scale Tests
- Prototype Unit
- One T/D Unit (In Progress)
- Flow Dynamic Studies

- 10-Inch Diameter Model

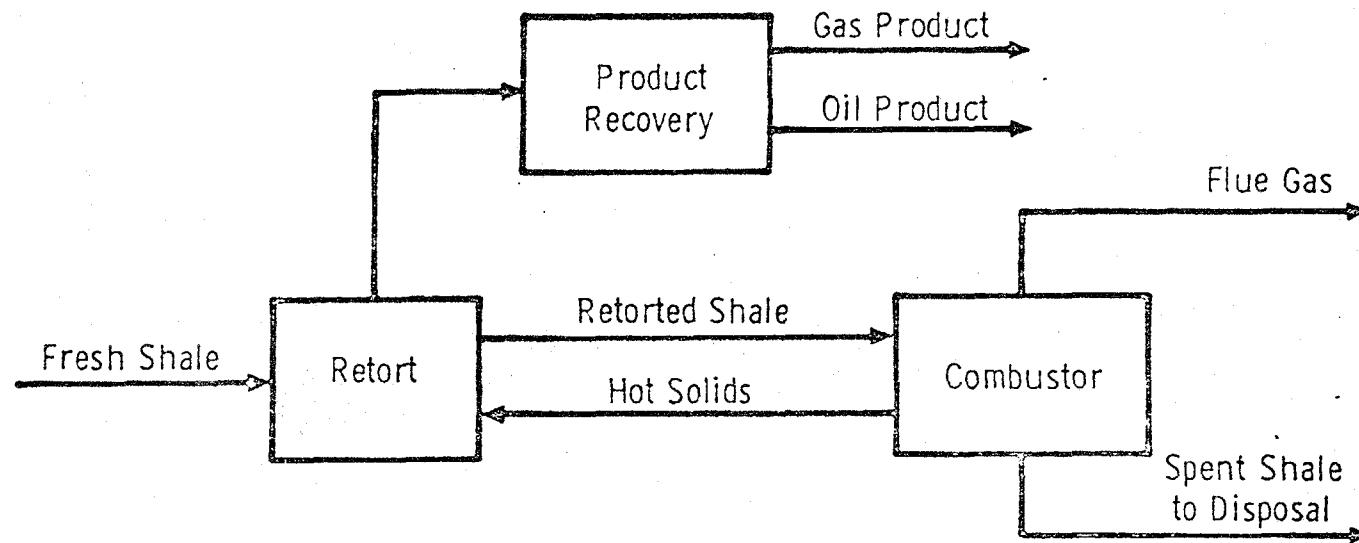
- 3-Foot Diameter Model (In Progress)

- Design of Semiworks (In Progress)

KEY TECHNICAL CONSIDERATIONS

- Retorting Kinetics
- Oil Yields and Qualities
- Recovery of Spent Shale
- Char Combustion/Flue Gas Emissions
- Scale-Up
- Carbonate Decomposition
- Retort-Combustor Heat Balance
- Disposal of Spent Shale
- Recovery of Heat from Spent Shale
- Removal of Solids from Liquid Products

CHEVRON B OIL
SHALE RETORTING PROCESS



TYPICAL PRODUCT YIELDS
CHEVRON B OIL SHALE RETORT
ONE T/D UNIT

| | | | |
|--|----------------------|------|------|
| Shale Grade, Gal./Ton | 14 | 28 | 38 |
| Yields, Wt % Fresh Shale | | | |
| C ₅ ⁺ Oil | 5.4 | 11.1 | 13.8 |
| C ₄ ⁻ Gas ¹ | 0.6 | 1.0 | 1.4 |
| Char | 1.6 | 2.3 | 3.5 |
| Water | 1.3 | 1.3 | 1.3 |
| C ₅ ⁺ Oil, LV % F.A. | ←100 ^{±2} → | | |
| C ₄ ⁺ Oil, LV % F.A. | ←102 ^{±2} → | | |

¹Hydrocarbon Plus H₂ and H₂S

TYPICAL OIL PRODUCT QUALITIES
CHEVRON B OIL SHALE RETORT

| | |
|-------------------------|------|
| Gravity, °API | 20.9 |
| Nitrogen, Wt % | 2.1 |
| Sulfur, Wt % | 0.7 |
| Oxygen, Wt % | 1.2 |
| Arsenic, ppm | 17 |
| Pour Point, °F | +70 |
| Ramsbottom Carbon, Wt % | 4 |

ASTM Distillation, °F

| | |
|---------|---------|
| St/5% | -/330 |
| 10-30% | 380/570 |
| 50% | 725 |
| 70-90% | 862/- |
| EP | 980 |
| Rec., % | 87 |

TYPICAL PRODUCT GAS ANALYSIS

28 gpt Feed

| | <u>Mole %</u> |
|---|---------------|
| Hydrogen | 40 |
| Methane | 13 |
| Ethane | 6 |
| Ethylene | 5 |
| Propane | 2 |
| Propylene | 4 |
| Butanes | 1 |
| Butylenes | 3 |
| CO | 4 |
| CO ₂ | 21* |
| H ₂ S | 1 |
| Gross Heating Value | 750 Btu/SCF |
| Gross Heating Value After Acid Gas Removal | 950 Btu/SCF |

*Calculated from Fischer Assay Analysis

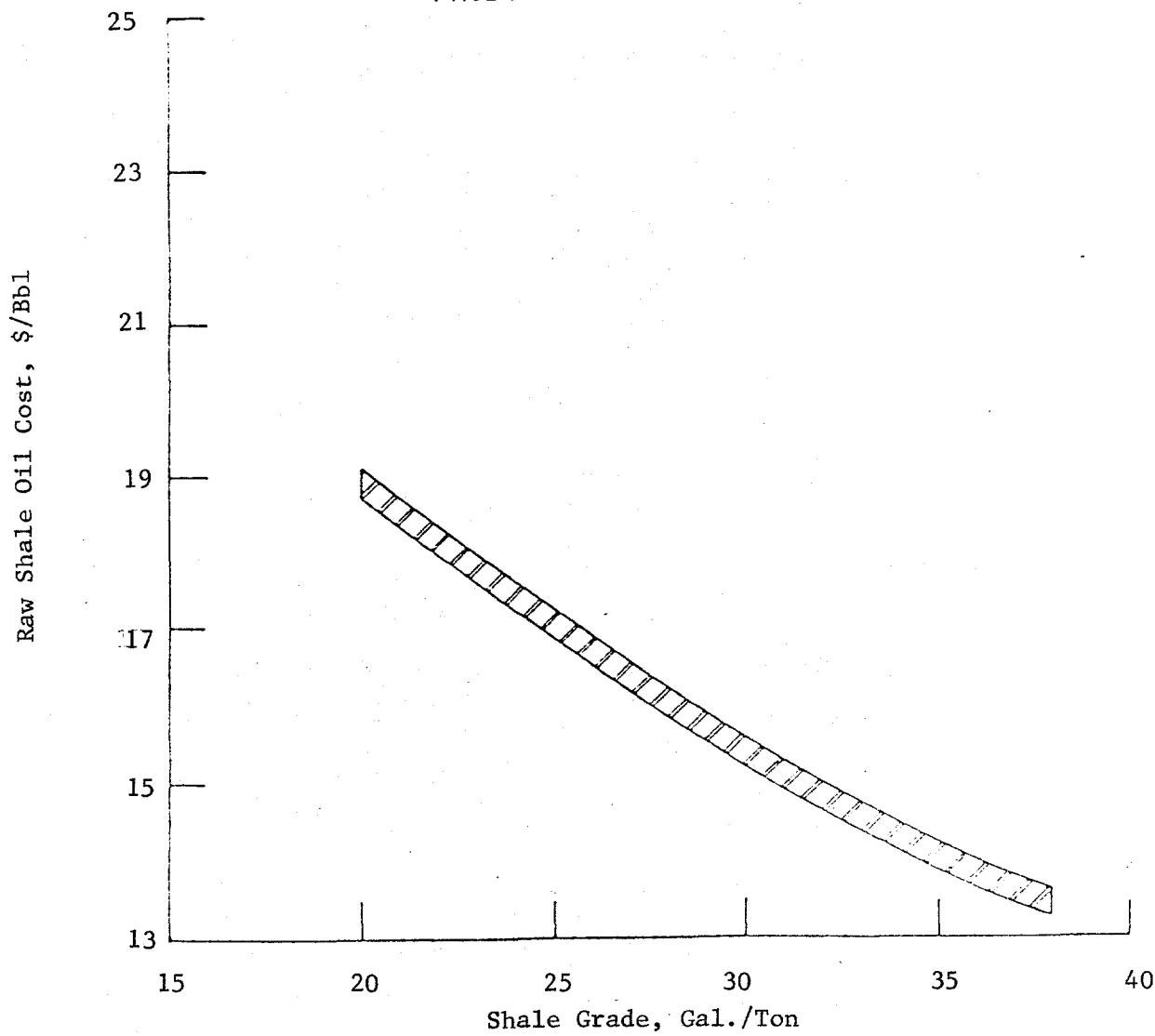
BASIS FOR ECONOMIC ESTIMATES

- Production Rate: 50,000 BPCD of Raw Shale Oil
- Second Quarter 1980 Dollars
- 1.25 "Area Factor" Relative to West Coast
- 20% Contingency
- 15% AROR (100% Equity)
- All Electrical Power and Process Fuel Generated Within the Complex
- Mining and Spend Shale Disposal Cost Based on Morrison-Knudsen Study (8/79)
- No Resource Cost
- No Infrastructure Cost
- Energy Self-Sufficient Retorts

DESIRED RETORT CHARACTERISTICS

- ⦿ High Liquid Yields \geq Fischer Assay
- ⦿ High Btu Product Gas
- ⦿ Minimum Product Degradation
- ⦿ Processes All Shale Mined
- ⦿ Handle Lean as Well as Rich Shales
- ⦿ Thermally Efficient
- ⦿ High Capacity
- ⦿ Tractable Wastes
- ⦿ Scale-Up to Commercial Units

CHEVRON STB PROCESS
OIL SHALE RETORTING, SENSITIVITY OF
PRODUCT COST TO SHALE GRADE



CHEVRON STB PROCESS
RAW SHALE OIL

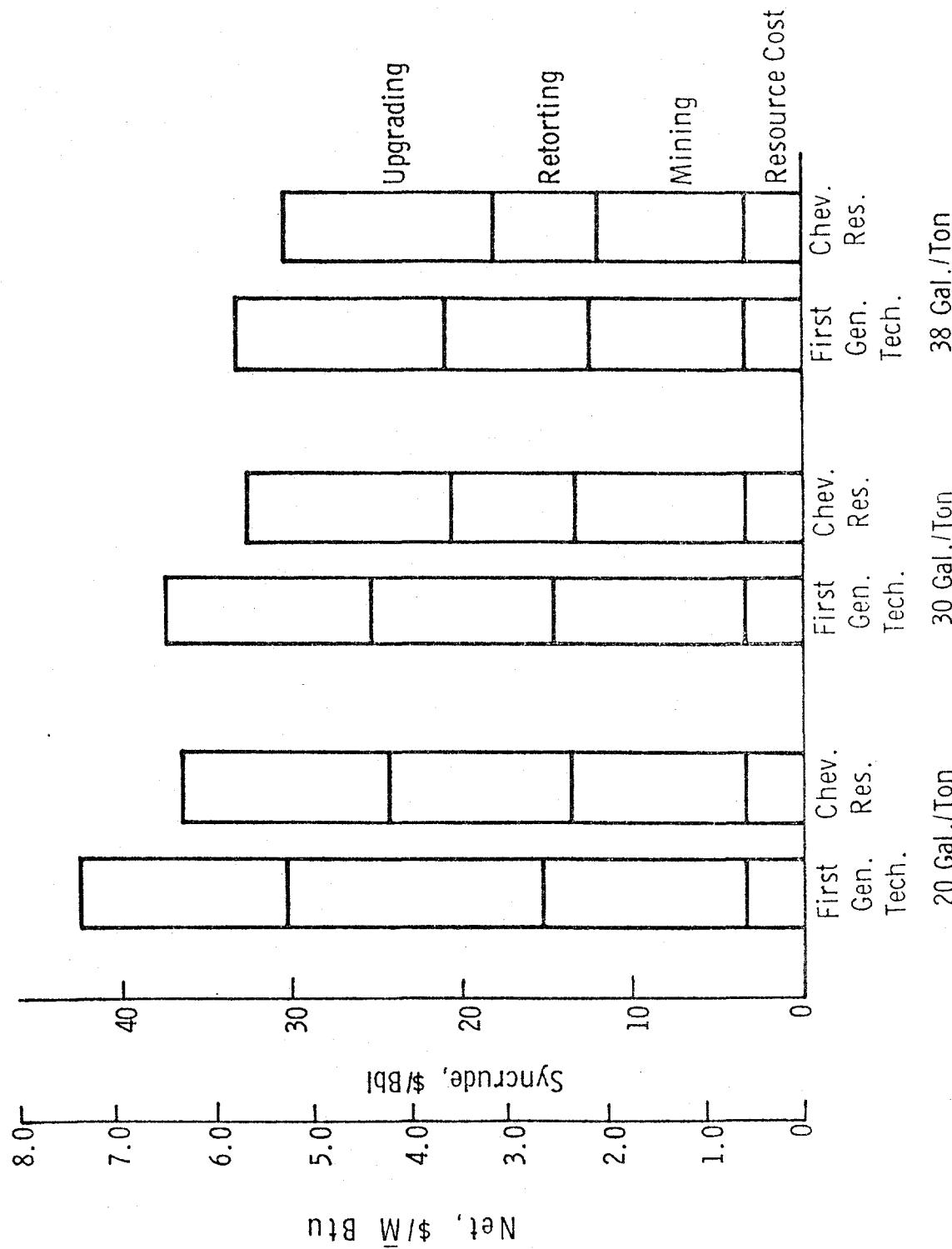
| Shale Grade, Gal./Ton | <u>20</u> | <u>30</u> | <u>38</u> |
|-----------------------------------|-----------|-----------|-----------|
| Investment, \$MM | | | |
| Mining ¹ | 320 | 255 | 215 |
| Retorting | 530 | 410 | 380 |
| Total | 850 | 665 | 595 |
| Product Cost, \$/Bbl ² | | | |
| Operating Cost | | | |
| Mining | 5.50 | 6.00 | 5.00 |
| Retorting ³ | 2.00 | 0.50 | 0.50 |
| Capital Charges | 11.50 | 9.00 | 8.00 |
| Total | 19.00 | 15.50 | 13.50 |

¹20 Gal./Ton Surface Mining, 30 and 38 Gal./Ton Underground Mining

²Rounded to the Nearest 50 Cents

³Includes By-Product Credits

SYNTHETIC CRUDE COSTS FROM OIL SHALE



FERWG ACTIVITIES RELATING TO
ENVIRONMENTAL IMPACT ASSESSMENTS OF SHALE-OIL RECOVERY
(July 1980)

Submitted by: S. S. Penner

1. Meeting of Jon Clardy with Ralph Franklin (DOE-EV),
July 3, 1980)

Ralph Franklin coordinates the DOE's environmental program on oil-shale development. This program has the following objectives:

- a. Development of environmentally acceptable retort-abandonment strategies.
- b. Guidelines to ensure health and safety of workers and the general public.
- c. Development of solid-waste management systems.
- d. Development of water-treatment systems.
- e. Development of an emission-control strategy.
- f. Mitigation of ecological impacts.
- g. Mitigation of social and community economic impacts.
- h. Methods for control and prevention of subsidence.
- i. Development of compliance plans.

It is anticipated that these objectives will be accomplished by a four-part activity embracing development and compliance. All of these topics will be discussed at the Vail conference in August.

If recommendations for research areas that could be profitably expanded were made now, the highest priority items would be the following:

a. The budget for control technology for both air and water emissions would be greatly increased, perhaps by a factor of 10. There is some disagreement about which SO₂ control technology (FGD or Stretford) would be most effective.

b. A major effort should be developed in atmospheric transport and diffusion over complex terrains.

c. The program plan must be extended to deal with other field projects, including those managed by the Synthetic Fuels Corporation.

d. Much better risk-assessment data are needed. Many of the available baseline data are useless because the significance of these data has not been properly verified.

2. Meeting of Jon Clardy with Harold Guthrie (Urban Institute, July 3, 1980)

The Urban Institute has recently issued a report and follow-up study on socioeconomic impacts of pipelines in the State of Washington and may become involved in a similar study for the MX missile program. The people at the Urban Institute are not familiar with oil-shale technology and development but nevertheless appear to be interested in assessing associated socioeconomic problem areas.

3. Environmental Aspects of Oil Shale Production (Urey Room, UCSD, La Jolla, California, July 10, 1980)

Technical presentations were made according to the schedule listed below, with Jon Clardy serving as chairman.

1. Overview of DOE Programs

Mr. David Sheesley, Laramie Energy Technology Center

2. Regional Modeling

Dr. Janusz Kindler, International Institute for
Applied Systems Analysis

3. Socioeconomic Impact

Dr. Erik Stenehjem, Denver Research Institute

Dr. Walter Hecox, Colorado Department of Natural
Resources

Dr. Willard Chappell, University of Colorado, Denver

4. Industrial Overview

Ms. Rosielea Gash, Rio Blanco Oil Shale Company

Dr. Larry Kronenberger, Exxon USA

5. Air Quality

Dr. James Pitts, University of California, Riverside

6. Spent Shale and Land Reclamation

Dr. Dan Rogers, Occidental Oil Shale

Dr. J. P. Fox, Lawrence Berkeley Laboratory

7. Water

Dr. Larry Icerman, New Mexico State University

The complete list of participants is given in Table 1.

Table 1

List of participants attending the FERWG meeting on environmental impact assessments of shale-oil recovery on July 10, 1980, at the University of California, San Diego, La Jolla, California.

Dr. Arthur A. Boni
Science Applications Inc.
1200 Prospect Street
La Jolla, CA 92037

Dr. W. Chappell, Director
Center for Environmental Sciences
University of Colorado at Denver
1100 14th Street, Campus Box 136
Denver, CO 80202

Dr. Jon Clardy
Department of Chemistry
Baker Laboratories
Cornell University
Ithaca, NY 14853

Dr. Phyllis Fox
Lawrence Berkeley Laboratory
University of California, Berkeley
Berkeley, CA 94720

Dr. Rosielea Gash
Director, Environmental Affairs
Rio Blanco Oil Shale Company
9725 East Hampden Avenue
Denver, CO 80231

Dr. Brian Harney
M/SD-107, Office of Oil Shale
U.S. Department of Energy
Washington, DC 20545

Dr. Walter Hecox
Executive Director's Office
Colorado Department of Natural
Resources
1313 Sherman Street, Room 723
Denver, CO 80203

Dr. Larry Icerman
Director, Energy Institute
Box 3EI
New Mexico State University
Las Cruces, NM 88003

Mr. Arnold E. Kelley
Vice President
Engineering and Development
Science and Technology Division
Union Oil Company of California
P. O. Box 76
Brea, CA 92621

Dr. Janusz Kindler
International Institute for
Applied Systems Analysis
A-2361 Schloss Laxenburg
AUSTRIA

Dr. Lawrence Kronenberger
Synthetics Department
Exxon USA
P. O. Box 2180
Houston, TX 77001

Dr. Richard B. Lessard
Director, Coal Research Lab.
Baytown Research and
Development Division
Exxon Research & Engineering Co.
P. O. Box 4255
Baytown, TX 77520

Dr. Arthur E. Lewis
Oil Shale Project Manager, L-207
Lawrence Livermore Laboratory
University of California
P. O. Box 808
Livermore, CA 94550

Dr. John Maziuk
Manager, Synfuels
Mobil Research & Develop. Corp.
P.O. Box 1026
Princeton, NJ 08540

Dr. Alex G. Oblad
Department of Mining and
Engineering
University of Utah
Salt Lake City, UT 84112

Dr. S. S. Penner
Director, Energy Center
Chairman, FERWG
University of California
La Jolla, CA 92093

Table 1, continued

Dr. James Pitts
Department of Chemistry
University of California
Riverside, CA 92521

Dr. John R. Powers
Acting Director for Research
and Technical Assessment
U.S. Department of Energy
Mail Stop J-309, GTN

Dr. Dan Rogers
Occidental Oil Shale, Inc.
P.O. Box 2687
Grand Junction, CO 81501

Mr. David Sheesley
Laramie Energy Technology Center
P.O. Box 3395
Laramie, WY 82071

Dr. Erik Stenehjem
Industrial Economics Division
Denver Research Institute
Industrial Park, CO 80208

Dr. John R. Thomas
President
Chevron Research Company
P. O. Box 1627
Richmond, CA 94802

Dr. Malcolm A. Weiss
Deputy Director
MIT Energy Laboratory, E19-439
Massachusetts Institute of Technology
Cambridge, MA 02139

Some of the material presented by D. Sheesley, J. Kindler, E. Stenehjen, and J. Fox is contained in Appendices I to IV, respectively. A preliminary assessment of these and other studies dealing with environmental issues will be prepared by FERWG members Jon Clardy and Richard Lessard after the August conference on these problems, which will be held in Vail, Colorado. An incomplete commentary on remarks made by workshop participants at La Jolla is given below.

D. Sheesley emphasized the following problems areas: modeling, retort abandonment, worker health and safety, solid-waste management systems, water-treatment systems, emission-control strategies, control or prevention of subsidence, compliance plans, determinations of water balance (USGS), water-containment designs. He noted that about 90% of DOE's effort had been related to in situ studies and required reorientation.

W. Hecox emphasized the importance of monitoring non-criteria pollutants.

R. Gash recommended the concurrent development of multiple technologies and noted that the Rio Blanco holdings include 19 highly variable zones in its resource base. A DOI contract deals with environmental impact monitoring and mitigation when 2000 BPD are produced in 1980, 6 years after program initiation. More than 160 separate permits have been required for the Rio Blanco operation (as compared with ~120 permits specified by Rutledge of DOI and 108 specified by E. Kane of Chevron).

J. Pitts discussed, among other factors, research on possible carcinogenic constituents of shale oil.

J. Fox discussed a wide range of important topics, including initial dewatering of retorts (where water flows of 5-15 ft³/sec have been encountered); the creation of permeable regions through retort construction; leachate transport leading to aquifer and, subsequently, surface-water contamination; adequate description of regional hydro-geology to define probabilities that aquifers will communicate with surface streams; leachability of spent shale remaining in retorts; containment of retorts after use; subsidence after removal of 20-40% of the shale initially present; possible grouting of retorts; intentional leaching of retorts to recover minerals; construction of bypass flows for water; filling of retorts with ion-exchange resins to trap leachates as they are formed. Shale-oil recovery produces 9-12 ft³ of voids per bbl which would cost ~\$20/bbl if filled with Portland cement but which might be made tight at a cost of \$½-1/B if cementitious material present in spent shale is used. Water filling rates at Oxy's Logan Wash facility after retorting have been 1-10 ft/yr with subsequent residence times of ~10 years. For surface retorting, spent-shale disposal must be viewed as the principal problem.

D. Rogers noted that Oxy's in situ process uses about 1 barrel of water per barrel of oil. Waters from the retorts are yellow in color, have a disagreeable odor, and contain organic compounds, trace elements, and dissolved gases (10^3 - 10^4 ppm of NH₃, 10^4 - 10^5 ppm of CO₂, 10^2 ppm of H₂S) at a pH of ~8.7. Upgrading of

water on site has not been successful, primarily because of the difficulty of removing organic compounds.

A micro-biological process for water purification is under development at Rio Blanco but the cost for this procedure may be high ($\geq \$5/B$ of oil). There are severe measurement problems associated with the characterization of water impurities.

Upgrading by using reverse osmosis is presumably (cf. R. F. Probstein) possible at a cost of about \$0.30/B. The treatment of water blends rather than of highly contaminated waters may facilitate purification; this procedure is used at SASOL.

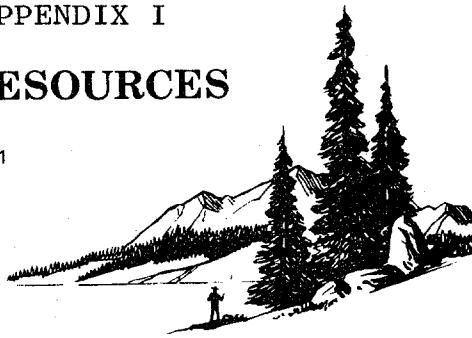
W. Chappell noted that shale oil is somewhat more mutagenic and carcinogenic than petroleum and somewhat less so than coal liquids. Mixtures of diesel exhausts and shale dust will be tested for carcinogeneity. A key issue in MIS is worker safety. Flexibility is needed with regard to the standard analytical methods used, especially when these methods are of doubtful validity.

The ultimate size of a shale-oil industry in Colorado may be limited by any of the following factors: air quality, water quality, problems with shale disposal, reclamation of spent shale piles. Implementation feasibility may be limited by occupational health and safety considerations for workers that have not yet been properly addressed.

Correspondence from D. M. Pascoe (Executive Director, Department of Natural Resources, Colorado) and a memorandum to him from David Shelton dealing with "Oil Shale Research Needs" are attached in Appendix I.

STATE OF COLORADO RICHARD D. LAMM, Governor

DEPARTMENT OF NATURAL RESOURCES

D. MONTE PASCOE, Executive Director
1313 Sherman St., Room 718, Denver, Colorado 80203 839-3311

Board of Land Commissioners
 Division of Administration
 Division of Mines
 Division of Parks & Outdoor Recreation
 Division of Water Resources
 Division of Wildlife
 Geological Survey
 Oil and Gas Conservation Commission
 Soil Conservation Board
 Water Conservation Board
 Mined Land Reclamation

July 22, 1980

Professor S. S. Penner
 Director, Energy Center, B-010
 University of California, San Diego
 La Jolla, California 92093

Dear Professor Penner:

The Colorado Department of Natural Resources has begun the process of identifying specific research concerns in the area of oil shale. The first set of concerns has been developed by the Mined Land Reclamation Program and I am enclosing a copy of these research needs with this letter.

In your Fossil Energy Research Working Group's deliberations, I hope that you can make good use of these focused concerns about oil shale research needs. We in Colorado hope that other similar agendas will be developed in other areas of state responsibility concerning oil shale. As these are developed I will send copies to you.

I welcomed an opportunity to visit with you the other day. Best wishes.

Sincerely,

 D. MONTE PASCOE
 Executive Director

DMP:car
 cc: Mr. David Shelton



STATE OF COLORADO RICHARD D. LAMM, Governor
DEPARTMENT OF NATURAL RESOURCES
Harris D. Sherman, Executive Director

MINED LAND RECLAMATION

723 Centennial Building, 1313 Sherman Street
Denver, Colorado 80203 Tel. (303) 839-3567

Hamlet J. Barry, III,
Director

June 25, 1980

TO: Monte Pascoe
FROM: Dave Shelton *Dave*
RE: Oil Shale Research Needs

When the Mined Land Reclamation Division receives a major oil-shale mining and reclamation application, the difficulties in processing it adequately are substantial. The factors that contribute to this include the large size of the application and project, the limited staff, and the experimental nature of the industry. The last of these facts has resulted in the recognition of many instances where knowledge is lacking to answer the questions which the staff is asking. It is possible that some of the needed information is available and we are unaware of its existence, or that research is currently underway which will answer these questions.

The following list of questions and comments are related specifically to sections of the Colorado Mined Land Reclamation Act of 1976. It is these general performance standards that must be met prior to issuance of a permit to any mining operation in the state. The discussion of each of the performance standards indicates areas of further research which are needed. Many of the performance standards of the law have overlapping areas of concern, and the research mentioned under one standard may well be applicable to other areas. This memo is an evolving document, and will be refined and amended as needed.

* * * * *

34-32-116(1)(b) Grading shall be carried on so as to create a final topography appropriate to the final land use selected in accordance with paragraph (k) of this subsection (1).

Discussion - The choice of final topography is critical to many of the other performance standards below. This particular section of the Law refers specifically to creating a topography which is suitable for the proposed end-use such as wildlife or rangeland. The challenge and question related to this section is "what topography is suitable for wildlife?" For example, on the face of the retorted shale pile, is it more advantageous to the final land use to have steeper slopes with more frequent terraces, or longer gentler slopes with few terraces? Are there significant influences

on wildlife or range animals if one creates topographic features similar to those in the natural environment as opposed to artificial, anomalous landforms? How does the newly created topography (independent of other physical factors) affect the suitability of land for wildlife?

Research Topics

1. The effects of different topography on wildlife as long-term viable habitats.

- a. slope
- b. aspect
- c. surface drainage pattern (stream and ponds, etc.)
- d. topographic variety vs. uniformity

2. Could subsidence significantly alter the topography during or after an operation (room and pillar mining or modified in situ)?

3. What topographic configurations are possible given the character of the waste material?

* * * * *

34-32-116(1)(c) - Earth dams shall be constructed, if necessary to impound water, if the formation of such impoundments will not interfere with mining operations, damage adjoining property, or conflict with water pollution laws, rules or regulations of the federal government, or the state of Colorado, or any local government pollution ordinance.

Discussion - This section of the law is self-explanatory. One problem related to this could be that during an operation a dam may trap contaminated sediment in the pool area which is derived from the retorted shale piles. The problem then becomes one of how to decommission and reclaim the dam area to prevent this sediment from moving downstream and where to dispose of the waste. Dredging the pool area appears to be the most reasonable approach.

Research Topics

1. Viability of leaving a dam in place as part of the reclamation plan.

2. Best method to handle toxic materials collected in the pool area behind a dam.

3. Effect of the ponding of water on the hydrologic balance (sec. 34-32-116 [1][h]) both operational and post mining.

* * * * *

34-32-116(1)(d) Acid-forming or toxin-producing material that has been mined shall be handled in a manner that will protect the drainage system from pollution.

Discussion - This section of our law provides a very broad performance standard which relates very specifically to retorted spent shale. Most of the tests indicate that retorted shale does contain significant amounts of several toxic elements which are capable of mobilization by water. The challenge of this section is "what type of water management will insure that the drainage system is protected from pollution?" Some of the possibilities for control include physical and chemical alteration and stabilization of the waste material itself; the location used for disposal; the topography and contouring of the waste material; the method of construction of the waste pile; the types and thicknesses of cover material; relationship to surface drainage and ground water; and types of plants used for revegetation. In the long term, it appears that it is nearly impossible to prevent the retorted shale from becoming exposed and moving into the stream system due to the fact that most of the areas being considered for disposal of spent shale are in a generally eroding environment. Therefore, part of the challenge is to create as stable a condition as possible so that the erosion is delayed and retarded. The other is to determine what level of erosion and mass wasting of the spent shale would be acceptable, not causing a significant amount of pollution. Once determined, the placement of the waste material must be designed to achieve the acceptable levels.

Research Topics

1. What toxic elements or compounds could potentially be released to the environment by an oil-shale operation (surface or subsurface retort and waste material)?
2. How might changing chemical, physical, and biological conditions influence the release and adverse effects of the toxic elements?
3. What management techniques are available to control the release of toxic substances? What are the best techniques for reducing long-term erosion?
4. What is the most likely long-term scenario for the rate of release and effect on the drainage system (this assumes eventual erosion of retorted shale)?
5. What will the operational and long-term water budget related to the toxic materials be?
 - a. Dependent on what variables.
 - b. Probability of long-term leaching of toxic substances.
 - c. Effect of leaching surface of pile to benefit revegetation.
6. What are the erodability rates and pollution potentials of retorted shale from the various processes?

* * * * *

34-32-116(1)(e) All refuse shall be disposed in a manner that will control unsightliness, or deleterious effects from such refuse.

Discussion - If refuse in this section means any waste material, which apparently it does, this section is a very broad charge to control adverse environmental effects from disposal of retorted shale and other waste. Considerations include aesthetics, as well as all other deleterious effects. These other effects are adequately covered in the other sections of this memo.

Research Topics

1. Stability of waste material
 - a. method of construction;
 - b. relationship to hydrology of pile;
 - c. will the characteristics change through time?

* * * * *

34-32-116(1)(f) In those areas where revegetation is part of the reclamation plan, land shall be revegetated in such a way as to establish a diverse, effective, and long-lasting vegetative cover that is capable of self-regeneration and at least equal in extent of cover to the natural vegetation of the surrounding area. Native species should receive first consideration, but introduced species may be used in the revegetation process when found desirable by the Board.

Discussion - Revegetation of retorted oil shale is a problem which has received much attention over the years. The primary concern we have in meeting this standard of the law is that many aspects of the work that has been carried out at this time do not duplicate those conditions which we believe will exist under commercial operation of an oil-shale operation. Examples of this point include the fact that test plots have been constructed with methods other than those which would be used in a full-scale operation. In general, the retorted shale used in the experiments differs in temperature, moisture, thickness, compaction, and other physical and chemical properties from what would be expected in a commercial operation. The size of the plots, the length of slope, and the degree of slope do not correspond to the expected commercial operations. In general, we think it is risky to extrapolate many of the factors which have been analyzed for the small experimental plots to a full-scale operation.

To meet this standard of the law, several purposes for revegetation must be considered. First is the immediate effect that revegetation can have on

reducing erosion and general stabilization of piles. The second is the ability of the vegetation chosen to reproduce and establish an effective, long-lasting cover. Third is whether or not the vegetation will be suitable for the end land-use which most likely will be wildlife habitat and rangeland. The fourth is whether or not the plants will concentrate dangerous levels of toxic elements. We feel that, since much of the area will be proposed for wildlife habitat after reclamation, the effect of toxic uptake on wildlife should be examined. The question of the necessity for leaching the shale to remove salts and the effectiveness of such action for the long-term is still poorly defined. The possibility of use of a capillary break and what materials will be satisfactory for such a capillary break needs further investigation as well.

Research Topics

1. Are leaching or other methods of removing salts from the upper zone of the retorted shale necessary for success?
2. If leached, where do salts go? Under what conditions and how quickly will they return to the surface?
3. Is a capillary break necessary? What materials could be used? How long will it function?
4. What thickness of soil cover is necessary? How should the thickness vary with type of retorted shale and cover material used? Should soil cover depth be uniform or vary with topographic position?
5. How can the uptake of toxic substances be reduced?
6. What species are best under what conditions?
7. What experiments could be initiated early in the life of an operation to identify, quickly and completely, which method of revegetation should be used at the site?
8. Where topsoil is scarce, what possibilities exist for revegetation of retorted shale with no cover material?
9. Is water harvesting a viable practice?
10. How will various management practices and inputs affect diversity persistence, reproduction, cover and productivity of the vegetation over the long term?

* * * * *

34-32-116(1)(g) Where it is necessary to remove overburden in order to mine the mineral, topsoil shall be removed from the affected land and segregated from other spoils. If such topsoil is not replaced on a backfill area within a time short enough to avoid deterioration of the topsoil, vegetative cover or other means shall be employed so that the topsoil is preserved from wind and water erosion, remains free of any contamination by other acid or toxic material, and is in a usable condition for sustaining vegetation when restored during reclamation. If, at the discretion of the Board, such topsoil is of insufficient quantity or of poor quality for sustaining vegetation or if other strata can be shown to be more suitable for vegetation requirements, the operator shall remove, segregate, and preserve in a like manner such other strata which are best able to support vegetation.

Discussion - This part of the law is quite clear in what it requires. All topsoil must be salvaged from the entire area of the mining operation that will be affected, unless it is shown that other materials are more suitable for vegetation requirements. The problem here relates back to items (f) and (d) concerning whether or not the available topsoil is sufficient to establish adequate vegetation and isolate toxin-producing materials. It may be desirable to use non-soil materials in addition to topsoil as a buffer zone and perhaps a capillary break between the retorted waste shale and the topsoil growth medium.

Research Topics

1. What topsoils are suitable and unsuitable for reclamation?
2. Are combinations of topsoil and other materials superior to topsoil alone as a cover material and ultimate medium for plant growth (particularly considering the other functions of the cover material)?
3. What are the best methods for preserving biological activity (e.g. microorganisms essential to nutrient cycling) in stockpiled topsoil or introducing the organisms into sterile subsoil, geologic material or retorted oil shale?
4. What are the best methods for applying soil or substitute materials to the reclaimed area so as to promote slope stability and reduce piping or slumping?

* * * * *

34-32-116(1)(h) Disturbances to the prevailing hydrologic balance of the affected land and of the surrounding area and to the quality and quantity of water in surface and groundwater systems both during and after the mining operation and during reclamation shall be minimized.

Discussion - This section of the law is perhaps the most all-encompassing since water is involved in essentially all biologic and geologic processes. The challenge for an operator is to show in his application that his proposed

plan for mining and reclamation does indeed minimize the disturbances to the prevailing hydrologic balance. The hydrologic balance is defined as the quality and quantity of water in the surface and groundwater systems, both during and after the mining operation. It is difficult to separate this issue from all the others, but some of the major issues related to this performance standard are as follows:

1. Major changes in topography cause changes in runoff characteristics within drainage basins. To minimize the effect of these changes involves looking at stream processes both above and below the area of disturbance, including such things as erosion, deposition and mass wasting.
2. Changes in surface water quality caused by mining operations is probably inevitable. The surface water geochemistry is balanced within certain natural limits which can easily be upset by the mining activity. What ways will it be upset and how significant will the change in the water quality be to the environment?
3. Groundwater quantity may be significantly altered, particularly if subsidence occurs over underground mines, causing fracture of the overlying aquifers. This problem also exists for modified in situ oil-shale operations. Also, local springs and groundwater regimes may be altered by the placement of large fills of spent shale.
4. Groundwater quality may clearly be changed in the same way as the quantity, by underground activities as well as major changes on the surface. The hydrologic balance is a range of hydrologic conditions which exist on a site as a result of natural processes. There are seasonal changes as well as longer-term changes which result from climatic and earth processes. The challenge is to minimize the disturbance to this natural range of conditions. Changes in water quantity and water quality may cause major changes in other physical parameters such as local vegetation, slope stability, wildlife, geochemical processes, etc.

It is difficult to predict the effect of an activity on the hydrologic balance. This area of research certainly could be explored to the benefit of all. Further work should be done on both the operational phase and the reclamation and post-reclamation phases of all aspects of hydrology.

Research Topics

1. What is the complete hydrologic model for an oil-shale operation?
 - a. What is the effect on all surface and subsurface water during an operation?
 - b. What is the effect on all surface and subsurface water after reclamation?

(cont'd)

2. What data are needed to describe the pre-mining, operational, and post-reclamation hydrologic balance?
3. What disturbances to the hydrologic balance would be tolerable and/or intolerable?
4. What are the most likely effects on secondary processes which would be caused by:
 - a. Changes in surface water quantity?
 - b. Changes in surface water quality?
 - c. Changes in sub-surface water quantity?
 - d. Changes in sub-surface water quality?

Such secondary processes which might be affected include: geomorphic, biologic and geochemical.

5. What location of waste disposal will cause the least disturbance to the hydrologic balance? Head of drainage, top of ridge, valley fill, underground in mine, etc.
6. How will leaching, irrigation, water harvesting and use of capillary breaks affect surface and groundwater hydrology?

* * * * *

34-32-116(1)(i) Areas outside of the affected land shall be protected from slides or damage occurring during the mining operation and reclamation.

Discussion - The general nature of this provision relates very directly to the preceding performance standards. This difference is that this provision specifically refers to the areas outside of the permit area. Off-site effects which should be considered in this performance standard include: landslides, erosion, deposition, changes in groundwater and surface water quality and quantity, damage to vegetation and wildlife, and any other possible off-site effects. These effects are, once again, difficult to define. Areas needing further research include a definition of what the potential off-site effects are, and how they can be mitigated.

Research Topics

1. A characterization of the common materials found in the oil-shale region in terms of their susceptibility to landslides.
2. Identify those activities on an oil-shale development site which could affect lands outside of the permit area. (These might include the major blasting, dust, hydrologic changes, etc.)

(cont'd)

34-32-116(1)(j) All surface areas of the affected land, including spoil piles, shall be stabilized and protected so as to effectively control erosion and attendant air and water pollution.

Discussion - This section of the law is incorporated within the previous sections but specifically refers to erosion as an important concern. Air and water pollution are handled by other state agencies in some ways, however, our charge is much broader, insofar as water pollution is not controlled at a point discharge. This provision requires us to control on-site and subsurface pollution potential. Similarly, needless air pollution caused by unprotected affected land must be minimized.

Research Topics

1. *What method of waste management will reduce erosion potential from the affected lands?*
2. *What geomorphic modeling can be developed to predict the long-term erosion potential of the affected lands?*
3. *Does this section of the law require that we go further than the air pollution and water pollution control laws which already exist?*

* * * * *

CONCLUSION

This memo is directed towards underground mining with surface retorting of oil shale since this method appears to be the most likely to be used for commercial operations. Modified in situ operations may also involve surface retorting of material excavated prior to rubbilization. It will thus have many of the same concerns and certainly must comply with the same performance standards. The specific areas of research, however, would have a slightly different emphasis. All research related to our law must recognize the site-specific nature of each operation and the individual characteristics of that operation, particularly the variety of retorted-shale characteristics from each process.

The state of Colorado, in its permitting process, must make decisions now regarding operations which may not conclude for thirty or forty years. When the Mined Land Reclamation Board issues a permit, it is for the life of the

(cont'd)

Monte Pascoe

Oil Shale Research Needs

June 25, 1980

mine. We are forced, then, into making our best judgement on issues for which there are no easy answers. Relevant research carried out over the next few years may greatly reduce the unknowns with which we must deal.

What seems abundantly clear from our work to this date is that we are dealing with an experimental industry for which most answers do not exist. This fact leads us to believe that any operation which we approve must contain an experimental program which will attempt to provide, as quickly as possible, the answers we need for a successful, viable, oil-shale operation. A primary challenge is to determine what the key variables are, and what the shortest path to the best solution is.

FERWG REPORT ON
"OIL SHALE: THE ENVIRONMENTAL CHALLENGES",
VAIL, COLORADO
(August 11-14, 1980)

Submitted by: Jon Clardy and Richard Lessard

The Vail meeting was a joint effort by The Oil Shale Task Force (W. Chappell- Univ. Colorado, Denver) and DOE (Ralph Franklin - DOE, EV). Detailed meeting proceedings with texts of all papers and discussions will be issued shortly so this report summarizes only major points of special interest to FERWG III.

1. Fraser Cook reported on the Scottish Oil Shale industry which existed from 1851-1962. The quality of Scottish shale is quite different from the U.S. Green River formation so the relevance of many of his observations is unknown. His report was quite optimistic and included:

- There were no real health problems with the workers in this industry. The few health problems that existed can be attributed to the primitive technology employed.
- The spent shale piles were easily revegetated with grass. Farms adjacent to such piles benefitted from the runoff of ammonium sulfate. One of the piles is in the process of being declared an historic monument.
- Much of the effluent from the operation was pumped into an abandoned mine 2-3 miles from a river. Careful monitoring of the river has not revealed any adverse or detectable impact.

2. Robert Meglen (UC, Denver) presented an overview of the current state of chemical analysis for inorganic constituents of oil shale. In general this field is not in good shape and there is enormous scatter

in interlaboratory studies. Whether these problems are due to sampling difficulties or technique is not clear. There is a definite need for:

- Reliable and routine methods to analyze for cations.
- The analytical chemistry of anions is in very poor shape. This area has generally been ignored but anions have important effects on mobility, toxicity and treatment.
- There is a strong need for analytical methods that determine the speciation of the elements present.
- Speciation studies on organic and organometallic compounds are also needed.

3. Jonathan Fruchter (Batelle - Pacific Northwest Laboratories) presented a companion report on the characterization of oil-shale retort effluents. He pointed out that the nature of effluents was highly process-dependent, e.g., CO_2 emissions can vary by a factor of ten with surface retorts at the low end and MIS at the high end. Most trace elements, which are higher in oil shale than petroleum, tend to stay with the spent shale. Only C, H, N, S and H_g are redistributed more than 10%. Mutagenic activity (Ames test) seems to reside in the polar organic fractions and, based on limited data, is lower in MIS than surface-retort oils. His final point was that processes should be studied for emissions not only in their steady-state operations but also in start-up and interruption modes.

4. H.J. Ettinger (Los Alamos) spoke on industrial hygiene concerns associated with oil-shale development. The overall tone was quite optimistic and he stated that "current technology can control many, probably all, industrial hygiene concerns". His major points:

- Toxicological testing of materials unique to oil shales should be carried out.

- The industrial hazards of MIS are not now well understood.
- Procedures and models to extrapolate current data to commercial facilities are needed.
- There needs to be a mechanism to transfer data on health effects in the industry.
- There should be a registry of workers.

5. L.M. Holland (Los Alamos) reviewed studies of the biology and toxicology of oil shale materials. He pointed out that crude shale oils are very active in in vivo skin painting tests, worse than crude petroleum by a factor of two. This problem may be process-dependent and appears to go away with hydrotreating. Retort waters have the same health problems but dust does not appear to pose a significant health problem. He felt that most health effects could be minimized by limiting contact and that the real risk was not terribly great.

6. T.E. Hakonson (Los Alamos) reviewed ecological problems. He concluded that most ecological studies are pointless number-gathering and should be redone using good scientific and statistical procedures. Vigorous discussion ensued. A consensus began to emerge that the data being gathered was not being interpreted fully.

7. J.P. Fox discussed issues and research needs in MIS retort abandonment. A copy of her paper was distributed to FERWG III members at our July meeting.

- Better regional and site-specific hydrological models are needed. These should include the regime of unsaturated flow caused by dewatering the sites. USGS claimed to be doing some of this.
- A better understanding of the chemical and physical aspects of leaching is needed. This should include the effect of process variables on leachate.

- More work is needed on grout characteristics and distribution.
- Work should move to field studies (vs. laboratory) and control technology (vs. problem identification).

8. E.F. Redente (Colorado State University) reported on efforts to revegetate spent shales. Efforts to grow native or salt-tolerant plants on spent shales or spent shales with additives have not been successful in his opinion. Short-term experiments with compacted shale, capillary barriers and soil have been successful. All of these studies have noted an adverse effect on microbial populations in the soil. He did not feel that the existing studies were any basis for optimism about the long-term stability and reclamation of spent shale.

9. R.E. Wildung discussed the geochemistry of oil-shale solid-waste disposal. He emphasized the magnitude of the problem; one to two tons of spent shale will be produced per barrel of oil. The detailed hydrology of a spent-shale pile is complicated and poorly understood. As the spent shale ages, the nature of the leachate changes. Some suggestions:

- Development and disposal sites need detailed characterization.
- There should be laboratory and field studies to establish the solubility, form and leaching ability of organic and inorganic residues.
- A model that would predict the movement of material out of a spent-shale pile and its effects is needed.
- This model should be validated by careful monitoring.
- The effectiveness of remedial measures must be demonstrated.

10. J.P. Fox (LBL) gave a second presentation on the issues and research needs for water management. The most vexing problem is "retort" water which is produced at the rate of 0.1 to 1.0 B/B of oil. This water is difficult to characterize and extremely difficult to treat. In the following discussion many industrial representatives claimed that the

problems were somewhat overstated. Cleanup could be accomplished although it would be costly.

11. D. Sheesley (LETC) reviewed air emission control strategy. We heard much of this at LETC and at La Jolla in July. The need for a complex terrain model was emphasized.

COSTING OF SHALE OIL:
COMPARISONS OF O.T.A. AND INDUSTRY ESTIMATES
(August 15, 1980)

Submitted by: S. S. Penner

The following FERWG-III members met with Thomas A. Sladek, who participated as a principal investigator in the oil-shale technology project for the Office of Technology Assessment: W. S. Bergen, A. E. Kelley, A. E. Lewis, A. G. Oblad, S. S. Penner, and R. P. Sieg; P. Petzrick from DOE/Resource Applications also participated at the discussions. The discussions were held in Dr. Oblad's offices at the University of Utah in Salt Lake City.

A. O.T.A. Costing Procedure

Dr. Sladek emphasized that the O.T.A. costing study did not deal with anticipated steady-state costs for a mature industry. Instead, it was the purpose of the O.T.A. cost assessment to define the transient cost maxima that might be encountered if a number of alternate technical developments was initiated concurrently with the expectation of developing a 400,000 B/D industry by 1990, in accord with the President's announced objectives. The assumptions made in the O.T.A. costing study are reproduced as Table I from the 1980 O.T.A. report (An Assessment of Shale Technologies, Office of Technology Assessment, Washington, DC 20510, June 1980). Reference to Table I shows that a number

of unusual assumptions was made.

(a) Project expenditures occur over a four-year period to the 90% level; for unspecified reasons, a one-year shut-down to alleviate unanticipated problem areas will then occur before project completion during the sixth year; finally, build-up to full production occurs during a two-year period.

This eight-year schedule to reach full production is not consistent with normal industry procedure and accounts for about a 20% increase in the per-barrel product cost over the life of the plant.

(b) A 4% real rise in annual operating costs is assumed in order to account for severe competition for scarce personnel and other resources, including heavy machinery, in the region where shale-oil recovery will occur. This real cost rise of 4% per year is charged entirely to the shale-oil development programs, even though it will include socio-economic reprogramming arising because of the stresses produced by rapid immigration into the region.

The 4% per year rise in real operating costs is not consistent with normal industry practices or expectations and accounts for about a 20% increase in the per-barrel product cost during the life of the plant.

We may combine the preceding summary statements to translate a high average industry cost estimate of \$42/B to the upper O.T.A. estimate of \$63/B as follows:

| | | | | | | |
|--------------------------------------|---|------------------------------|---|-------------------------------------|-----------|-------------------|
| \$42/B | x | 1.20 | x | 1.20 | \approx | \$60.5/B |
| (a high cost estimate from industry) | | (for long construction time) | | (for 4%/year real cost rise in O&M) | | (O.T.A. estimate) |

The preceding summary statements of the FERWG discussions are supported by the results of cost analyses appearing in Tables II to IV, which were prepared at Chevron Research. We note from Table II that capital costs for TOSCO technology are about equally divided between mining, retorting and upgrading, which is consistent with the results of FERWG discussions (held on July 10, 1980) and with presentations from the Union Oil Company. Operating costs per barrel of syncrude are roughly equally divided between mining, on the one hand, and retorting and upgrading, on the other hand.

The basis for the O.T.A. costing procedure is detailed again in Table III. Results obtained from the O.T.A. costing procedure are summarized in Table IV and are consistent with the statements made earlier in this report.

B. Comments on the O.T.A. Costing Procedure

As we have already noted, the O.T.A. costing procedure was not designed to make estimates of steady-state costs for a mature technology. Therefore, the results do not apply to anticipated long-term costing of the developed industry.

The long construction time used in the O.T.A. analysis should properly be regarded as a sensitivity study, which illustrates the high cost of maintaining plants with high capital costs under nonoperative conditions. For every year of delay beyond the normal four-year construction time, product costs over the life of the plant will rise by about 5%. This result shows the importance of adequate planning and of insuring plants against retroactive changes once construction has been committed.

We regard the 4%/yr real rise in operating costs assumed in the O.T.A. study as unlikely to occur in the course of normal regional development. As currently planned, small-scale, staged construction will take place, rather than rapid, concurrent commercialization of numerous 50,000 B/D plants. Furthermore, the assumed 4%/yr increase in real operating costs appears to include the entire regional socio-economic charges for settling incremental populations; these charges should have been reduced by the costs of locating the same population elsewhere with equivalent employment opportunities. We conclude that about 20% of the final product cost appearing in the high-cost O.T.A. scenario will be saved by careful regional planning and staged industrial development.

Capital costs for shale-oil production have been discussed in our previous report. They will remain uncertain until full-scale plants have been built and operated successfully. We concur with the O.T.A. estimate that capital costs are likely to

range from \$28,000 to \$40,000 per daily barrel of production.

C. Other Topics Discussed by FERWG Members

A number of additional topics was briefly discussed by the FERWG members who were present at the Utah meeting.

(i) We reviewed the recommendations appearing in the report "R&D Needs for Oil Shale Mining and Health/Safety Technology," final report from Skelley and Loy (U.S. DOE Contract No. DE-AC01-79ET 11268), 2601 North Front Street, Harrisburg, Pennsylvania, August 1980. A copy of this report has been sent to all of the FERWG members. Mining problems will be further evaluated by a number of FERWG members during October.

(ii) Program opportunities and resources of Eastern oil shales were discussed by Alex Oblad, who had obtained data on Eastern shale resources available for processing from C. G. Kirkbride. Alex Oblad is in the process of preparing an overview of Eastern shales for discussions at the December FERWG meeting in La Jolla. According to Paul Petzrick (DOE), a type 3 cost estimate for Eastern shales is being performed by an industry consortium including Bechtel.

(iii) Procedures for estimating the true cost of imported oil for the U.S. were discussed briefly, with reference to a recently published summary (Chemical and Engineering News, pp. 5-6, August 11, 1980).

In order to discuss technologies and R&D needs for processing Eastern shales, it was decided to schedule a FERWG site visit to IGT in the near future.

TABLE I
ASSUMPTIONS AND DATA FOR COMPUTER ANALYSES

| Data item | Value used | Explanation |
|--|---|--|
| Costs | | |
| Capital cost distribution: | | |
| Maximum capital cost | \$2.0 billion | The capital cost data apply to all the capital equipment needed to mine and retort shale and hydro-treat the raw shale oil product; the costs do not include land acquisition or interest charges. Data were based on recent industry cost estimates. |
| Most probable capital cost | \$1.7 billion | |
| Minimum capital cost | \$1.4 billion | |
| Operating and maintenance (O&M) cost distribution: | | |
| Maximum O&M cost | \$17/bbl | Operating costs include hydrotreating costs. Data were based on recent industry cost estimates. |
| Most probable O&M cost | \$12/bbl | |
| Minimum O&M cost | \$ 9/bbl | |
| Operating cost increase | 4 percent/year | Operating costs were assumed to increase 4 percent per year in real terms (i.e., net of inflation) to account for probable increases in labor costs due to expansion of shale industries in sparsely populated areas. Assumption was based on expectations expressed to OTA by industry sources. A 6-year construction period (i.e., a 1-year delay between the fourth and fifth years) decreased expected profits by \$117 million for the no-incentive, 12-percent discount rate case. |
| Construction period | 6 years | |
| Fraction of costs occurring each year during construction: | | |
| Year 1 | .10 | |
| Year 2 | .25 | |
| Year 3 | .30 | |
| Year 4 | .25 | |
| Year 5 | .00 | |
| Year 6 | .10 | |
| Prices | | |
| Initial oil price (1979) | \$35/bbl | |
| Mean annual oil price increase | 3 percent | Based on the price of imported oil, which at the time of the analysis ranged from \$33 to \$37/bbl. The assumed 3-percent real increase in oil prices accounts for increasing scarcity as cheap domestic supplies are exhausted, and is midway in the range (2-4 percent) used by DOE planners. |
| Standard deviation of annual oil price change distribution | 3 percent | Based on historical trends from the American Petroleum Institute, <i>Basic Petroleum Data Book</i> , 1976. |
| Taxes and transfers | | |
| Federal corporate tax | 46 percent | Current Federal corporate income tax rate. |
| State corporate tax | 3 percent | Colorado corporate income tax rate. |
| State severance tax | 4 percent | Colorado severance tax on oil shale reserves. |
| Investment tax credit | 10 percent | Investment tax credit of 10 percent applies to all investments; an existing additional 10-percent credit for energy-related investments was ignored because it is to expire in 1982. |
| Depletion allowance | 15 percent | Depletion allowance computed on oil shale revenues and deducted from taxable income. |
| Royalty | 1 percent | Current royalty is 12.5 cents per ton of mined shale; this is equivalent to a royalty on oil revenues of less than 1 percent. |
| Depreciation lifetime | 12 years | Based on discussions with industry sources. |
| Annual rent | \$2,600 | Based on a 50-cent-per-acre rent on Federal shale leases of 5,200 acres. |
| Depreciation method | Sum-of-years digits with switch-over to straight line | Provides the most rapid tax writeoff. |
| Production | | |
| Maximum output of facility | 50,000 bbl/d | Size of typical commercial facility. |
| Production lifetime | 22 years | Based on production lifetime of 20 to 30 years in industry cost estimates. |
| Annual output | | |
| Year 1 | 15,000 bbl/d | 2-year buildup accounts for probable startup difficulties. |
| Year 2 | 35,000 bbl/d | |
| Years 3 to 22 | 50,000 bbl/d | |

^aAll monetary values in constant 1979 dollars.

SOURCE: Office of Technology Assessment.

TABLE II

COMPARISON OF CHEVRON RESEARCH AND TOSCO ESTIMATES
FOR TOSCO INVESTMENT AND OPERATING COSTS¹

Basis: TOSCO Technology
 50,000 BPOD of Syncrude, 90% Operating Factor
 30 Gal./Ton Shale² (TOSCO)
 2nd Quarter 1980 Dollars

| | | Capital Investment, M\$ | |
|-----------|-------------|--------------------------------------|----------------|
| | | Chevron Research Estimate | TOSCO Estimate |
| Mining | 650 | | Not Available |
| Retorting | 530 | | Not Available |
| Upgrading | <u>535</u> | | Not Available |
| Total | 1,715 | | 1,700 |
| | | Operating Cost, \$/B Syncrude | |
| | | Chevron Research Estimate | OTA Estimate |
| Mining | 6.60 | | Not Available |
| Retorting | 3.30 | | Not Available |
| Upgrading | <u>2.50</u> | | Not Available |
| Total | 12.40 | | 12.70 |
| | | Total Processing Cost, \$/B Syncrude | |
| | | Chevron Research Estimate | OTA Estimate |
| | 37.00 | | 62.00 |

¹ OTA's "Most Probable" case (see Table IV).

² Chevron Research estimate based on 31 gal/ton shale, room and pillar underground mining at Clear Creek, and whole oil hydrotreating.

TABLE III
BASIS FOR OTA SHALE OIL ECONOMICS

| | |
|---|-----------------------|
| Capital Costs, \$ Billion | |
| Most Probable Capital Cost | 1.7 |
| Range | 1.4-2.0 |
| Initial Operating Costs, \$/Bbl Syncrude | |
| Most Probable Operating Cost | 12.70 |
| Range | 9.00-17.00 |
| <u>Economic Assumptions</u> | |
| Construction Period, Including One-Year Delay | 6 |
| Fraction of Costs Occurring Each Year | |
| During Construction: | |
| Year 1 | 0.10 |
| Year 2 | 0.25 |
| Year 3 | 0.30 |
| Year 4 | 0.25 |
| Year 5 | 0.00 (One Year Delay) |
| Year 6 | 0.10 |
| Depreciation Lifetime, Years | 12 |
| Taxes: | |
| Federal Corporate Tax | 46% |
| State Corporate Tax | 3 |
| State Severance Tax | 4 |
| Investment Tax Credit | 10 |
| Depletion Allowance | 15 |
| Royalty | 1 |
| 50,000 BPOD, 90% Operating Factor | |
| 30 Gal./Ton Shale | |
| 15% AROR | |
| 100% Equity Investment | |

CHEVRON RESEARCH
COMPANY
RICHMOND, CALIFORNIA

TABLE IV
 OIL SHALE PROCESSING COSTS¹
 CALCULATED BY AROR

| | Most Probable Cost | Minimum Cost | Maximum Cost |
|---|--------------------|--------------|--------------|
| Capital Investment, M\$ | 1,700 | 1,400 | 2,000 |
| Initial Operating Costs, \$/B (Escalated at 4%/Year) | 12.70 | 9.00 | 17.00 |
| Total Processing Cost, \$/B | 51.00 | 41.00 | 64.00 |

¹Based on OTA's Assumptions (Table III).

AB-185

8-5-80

CHEVRON RESEARCH
COMPANY
RICHMOND, CALIFORNIA

RBS

COMMENTS BY T. A. SLADEK ON
FERWG WORKING DRAFT "COSTING OF
SHALE OIL: COMPARISONS OF OTA AND INDUSTRY
ESTIMATES" (Dated August 15, 1980)*

Page 2, Item a

The 1-year shutdown during construction results from environmental, legal, or political problems and not from technical difficulties per se. Although considering such delays is not consistent with normal industry procedures, they are likely to occur unless an overriding commitment is made to oil shale by the federal and state governments. (Please consider the experience with the federal oil-shale tracts, with the Trans-Alaskan pipeline, with the Foothills water treatment plant in the Denver region, and with nuclear and hydropower projects.) Although present indications are more positive than in the past, I don't think that anyone believes that oil shale's legal and regulatory problems have all been resolved.

Page 2, Item b

I also had some trouble with the 4% escalator that OTA applied to operating costs. I felt that it should have been much higher during construction and for the first few years of operation and then drop to zero after, say, the 10th year. Obviously the region could not sustain that rate of increase for very long because destructive hyperinflation would result. Furthermore, the portion attributable to problems with equipment availability and construction services would also decrease over time as new suppliers responded to the opportunities for profit. How soon the necessary adjustments could be made would depend on how many plants were being built simultaneously and on whether they used similar technologies with similar equipment and staffing requirements. Timing is the critical factor: eight simultaneous projects might not experience the operating cost escalation for very long; 20 projects in the same time frame certainly would, although perhaps not for their full economic lifetime.

*Comments and corrections made by T. A. Sladek, which have not been incorporated into the FERWG reports on oil-shale costing, are reproduced here.

Page 4

The first two paragraphs are excellent, but I have two major problems with the third paragraph. First, small-scale staged construction may occur, and I hope it does. But 95,000 bbl/d from C-b, 76,000 from C-a (or up to 300,000 if Rio Blanco returns to open-pit mining), 75,000 from Union, 46,000 from Colony, 100,000 from U-a/U-b, 50,000 from Sand Wash, and unknown amounts from Chevron, Cities Service, Superior, Multi Mineral, Texaco, Geokinetics, Equity, other new private players, and the new federal lease tracts is not small scale, nor can it be effectively staged or phased if the projects are to be completed by 1990. Second, the costs of relocating the population will be borne by either the developers or the federal government. Although some savings may arise because the populations would not have to be supported unproductively elsewhere, or relocated to another site, I doubt that the developers will experience any such savings. They will only know that they have X jobs to fill and X-Y potential employees available to fill them; ergo, the purchase price for labor will definitely go up. They will also know that productivity is down and absenteeism up because of inadequate housing, health care, schools, recreational opportunities, and other types of social stress. It will matter little that the socioeconomic infrastructures in the cities that previously contained the new people now have excess capacity. Estimating the "net" cost of relocating the people may be of philosophical interest to economists and public-policy analysts. It will be of less interest to the accountants in the oil shale companies and to the communities that will be directly impacted by the population growth.

TECHNOLOGY ASSESSMENT BOARD
MORRIS K. UDALL, ARIZ., CHAIRMAN
TED STEVENS, ALASKA, VICE CHAIRMAN
EDWARD M. KENNEDY, MASS. GEORGE E. BROWN, JR., CALIF.
ERNEST F. HOLLINGS, S.C. JOHN D. DINGELL, MICH.
ADLAI E. STEVENSON, ILL. LARRY WINN, JR., KANS.
ORRIN G. HATCH, UTAH CLARENCE E. MILLER, OHIO
CHARLES MCC. MATHIAS, JR., MD. JOHN W. WYDLER, N.Y.
JOHN H. GIBBONS

Congress of the United States
OFFICE OF TECHNOLOGY ASSESSMENT
WASHINGTON, D.C. 20510

JOHN H. GIBBONS
DIRECTOR
DANIEL DE SIMONE
DEPUTY DIRECTOR

October 1, 1980

Dr. S. S. Penner
Professor of Engineering Physics
and Director, Energy Center
Chairman, FERWG
University of California, San Diego
La Jolla, California 92093

Dear Sol:

We at OTA are encouraged that FERWG (COSTING OF SHALE OIL: COMPARISONS OF OTA AND INDUSTRY ESTIMATES, 8/15/80) has chosen to take the time to carefully review our shale oil cost estimates and place them in the context provided by current industry estimates. Like you, we understand that the magnitude and reliability of capital and operating cost estimates for commercial facilities will be among the critical factors that determine if and when a commercial shale oil industry comes into existence. Examination and evaluation of the available cost estimates and the procedures used to reach them are particularly desirable in view of the wide range of estimates. Reliable estimates are unlikely until actual construction and operating experience is available for commercial facilities, more detailed and final engineering designs have been completed, and therefore less dependence on assumptions is required to bound cost estimates.

Dr. Sladek is quite correct in emphasizing that the OTA costing study did not explicitly deal with anticipated steady-state costs for a mature industry. Instead, it was our intention to define the likely costs for a first generation U.S. commercial oil shale plant utilizing a technology untested at anything like commercial scale. Such plants will be built with uncertain environmental and socio-economic impacts and regulation, and in a sparsely populated area simultaneously with other large capital intensive energy projects. In general, we agree with your description of the differences between the cost procedures and assumptions employed by the OTA and those of much of the industry. However, I must add that we do not entirely share FERWG's optimism that the current industry estimates will, in fact, accurately represent the steady-state costs for a mature industry in the future. A drop in the real cost of constructing and operating an oil shale plant from the first to the second generation of facilities is likely. However, it is far from certain. It is much less certain that the cost reduction will be sufficient to reach the level of current industry estimates. Present industry cost estimates are not based on actual commercial experience, nor are they based on complete engineering designs. Such estimates have been disappointing in the past, and it is still quite possible that they significantly underestimate actual costs. Given the fact that oil shale development will occur at the same time and in the same area as expanded petroleum, natural gas, and coal development, hyper-inflationary increases in construction cost and operating expense are quite

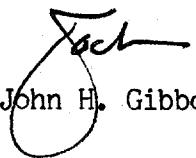
possible in those sectors. Shale oil development will presumably take place within the framework of environmental and health and safety regulations which were enacted during the late 1960s and 1970s. The density of this system of regulation may limit real capital and operating cost reductions more than industry estimates anticipate. Increased costs for socioeconomic mitigation programs and water could well reinforce this tendency.

Although we generally agree with FERWG's description of OTA's costing assumptions, several specific issues require clarification. First, (p. 2c) OTA's model results for the 15 percent rate of return case did not use the $\$2 \times 10^9$ capital charge. The number was definitely $\$1.7 \times 10^9$. Second, the upper OTA estimate is variously listed in the document as being \$64/bbl. It is actually \$62/bbl. It appears that some of the confusion over the size of our capital estimate may be related to this discrepancy.

We would also agree that OTA's analysis is useful to show the sensitivity of costs to delays in construction, but believe it also shows the level to which construction costs could plausibly rise. Obviously, FERWG also agrees since the \$40,000/barrel of installed cost would translate the \$2 billion total cost--\$300 million above the OTA capital cost estimate.

Again, let me say that OTA is pleased that FERWG has taken the trouble to explicitly examine our costing assumptions and procedures. We share your concern that the predictions of cost in this controversial area be based on clearly stated assumptions and be as accurate as possible.

Sincerely,


John H. Gibbons

DISCUSSIONS ON ROCK MECHANICS
WITH EXPERTS FROM
SANDIA/ALBUQUERQUE AND
LOS ALAMOS SCIENTIFIC LABORATORY AT THE
AIRPORT AMFAC HOTEL, ALBUQUERQUE, NEW MEXICO
(September 30, 1980)

Submitted by: S. S. Penner

FERWG members W. S. Bergen, A. E. Lewis, S. S. Penner and R. P. Sieg discussed rock mechanics problems with the following people: T. F. Adams (LASL), R. Boade (Sandia/Albuquerque), B. M. Butcher (Sandia/Albuquerque), K. Cooper (LASL), L. S. Costin (Sandia/Albuquerque), G. F. Dana (DOE/LET), J. Dienes (LASL), J. N. Edl, Jr. (DOE/LET), W. Eichfeld (CMTC), D. Grady (Sandia/Albuquerque), A. Harak (DOE/LET), M. Harper (LASL), D. Johnson (DOE/LET), J. Johnson (LASL), B. Killian (LASL), M. Kipp (Sandia/Albuquerque), L. Margolin (LASL), A. K. Miller (Sandia/Albuquerque), W. Morris (LASL), B. Olinger (LASL), W. A. Olsson (Sandia/Albuquerque), T. G. Priddy (Sandia/Albuquerque), M. Ray (LASL), J. T. Schamaun (Sandia/Albuquerque), A. Stevens (Sandia/Albuquerque), H. M. Stoller (Sandia/Albuquerque), H. E. Thomas (DOE/HQ-GTN), B. Travis (LASL), N. Vanderburgh (LASL), J. Virgona (DOE/LET), B. Wenzel (CMTC), and E. Williams (LASL).

A. Stevens introduced the presentations from Sandia/Albuquerque dealing with laboratory examination of fracture and fragmentation (D. Grady), modeling of fracture and fragmentation with applications to retort preparation (M. Kipp), modeling of geo-kinetics retort blasts (J. Schamaun), structural analysis of MIS

retorts (K. Miller), and quasi-static constitutive behavior of oil shale (L. Costin and W. Olsson).

The LASL presentations were introduced by W. Morris and dealt with the following topics: characterization of commercial explosives (J. Johnson), oil shale rock mechanics (B. Olinger), field experiment results (M. Harper), application of fracture calculations to field engineering (T. Adams), TRACER flow modeling (B. Travis), bedded crack model (L. Margolin), and statistical crack mechanics (J. Dienes).

1. Rock Mechanics

A central problem in shale-oil recovery relates to rock fracturing. This statement applies to all types of recovery techniques, including the Oxy MIS process, the Geokinetics in situ process, as well as procedures using mining and surface retorting.

The Sandia/Albuquerque and LASL programs on rock mechanics have been in progress since about 1973 and utilize outstanding competence for analysis of fracture processes that was developed in connection with underground testing studies of nuclear weapons.

Studies encompass the following topical areas: development of analytical and computational models of static tensile fracturing for shales with variable kerogen contents; investigations of directional dependence of fracture; direct impact fracturing (which requires much higher fracture stresses than static fracturing); dependence of fracture stress on strain rates. Experimental

studies include the use of laser interferometry to measure fracture rates. Measurements relate stress and fragment sizes to strain rates, fracturing of large shale blocks (with ~1m dimensions), fragmentation near free surfaces, and the effects of kerogen contents on fragment dimensions.

Wave propagation codes have been adapted to calculate rock fracture in retorts. These codes are suitable for studying sequentially two-dimensional slices through retorts. Critical problems relate to the initial distribution of flaws and the needed rates of loading for desired fracture responses. Efficient fragmentation requires determination of optimal depths for charge burial, careful design of explosive charge configurations, and proper staging of interacting explosive charges. The observed fragment-size distributions are not yet quantitatively predicted by calculations, although qualitative features of observed damages near free surfaces are quite well accounted for by the use of two-dimensional wave-propagation codes. The computational times are large: a generation 5 computer (e.g., a CDC 7600) is used for several hours for damage calculations.

Three-dimensional, time-dependent codes have been developed at LLL and LASL for applications other than fracture (fluid dynamics). When such codes are developed to predict such effects, they will be limited by computer capacity, especially in attempts to predict the effects of interacting stress waves in multiple, nearly simultaneous explosions.

A. The Geokinetics Program

In the Geokinetics retort, the overburden may be moved up to 15 ft. Blasts produce motion and free surfaces and operational problems relate to definition of the relation between rubblization and structure and weight of the overburden. The timing of explosions is of great importance. Experimental and analytical studies involve measurements of motion of overburden (by using high-speed cinematographic techniques), definitions of distortion of surface layers and of differential motions, as well as studies of the effects of explosive charge locations and detonation timing. Engineering analyses use lumped mass or finite element techniques. Predictions of vertical motions as functions of time, retort length, and location are generally in good accord with observations.

B. MIS Retorts

Work on MIS retorts parallels the studies of surface fracturing and includes modeling of (a) structural aspects for known geometry and materials properties (anisotropy, inhomogeneities, failure characteristics), (b) mechanical and thermal loading, (c) structural anomalies (faults, discrete joints, discrete parting planes), etc. This work has been correlated with observations at Oxy's Logan Wash site. There is an observed area of low horizontal normal stress between pillars. A critical problem relates to the identification of stable walls without separate supports. Usable

data for industry on chamber stability following retorting are urgently needed. In this connection, the constitutive behavior of spent shales requires definition.

C. Explosives

Work on commercial explosives was begun at LASL about 4 years ago and has focused on performance evaluations of inexpensive ammonium-nitrate-based explosives. For given explosives, performance depends on bore-hole diameter and confinement. A model "aquarium test" at LASL allows direct observations of downward explosions of cylindrical charges in columns of water. In order to correlate observations of ANFO (94 wt% ammonium nitrate/4 wt% fuel oil) with BKW code calculations, it must be assumed that only about 55% of the explosive reacts directly at the detonation front for small (4") charge diameters; for diameters ≥ 1 ft, CJ detonations should be observable.

Explosives utilization rates will be about 100-500 tons/day for a 50,000 BPD commercial plant since 1 to 1.75 lbs of explosive are required per ton of rock.

D. Models and Other Comparisons with Field Data

Experiments have been conducted also in the Colony mine, especially on the relation between scaled crater volumes and the scaled depths of burial of explosives charges, for both

single and multiple bore holes. It appears that the special properties of geological anomalies are minimized by the use of multiple bore-hole explosions.

The Yaqui code for explosive fracture of oil shale has been used to simulate 14 out of 19 Colony mine experiments; reasonable agreement was achieved between calculations and observations concerning surface damage, partial rubbling of surfaces, and the nature of the joint system. Critical experiments must answer the following simple question: When does the rock move? The creation of transient free surfaces is of great importance in defining observed rock fractures.

2. Needed Future Studies

Future work is expected to include the following: studies of blast designs and their relation to overburden distortion, lateral motions of rubble, performance of decked charges, explosives behavior.

The quasi-static constitutive behavior of oil shales requires careful measurements and field classification because it determines failure mechanisms, nucleation, and growths of fractures. Generally, shales with higher kerogen contents have lower compressive strengths. Models are needed for the identification of failure surfaces in orthotropic materials.

An important program at LASL on the relation between oil-shale rock mechanics and sound-speed measurements merits continuing support, as do measurements of shale tensile strengths using direct impacts of small pellets on aluminum plates.

Tracer flow modeling in porous, fractured media is an important experimental tool in answering the following types of questions: (a) what permeability was achieved and (b) what is the relation between fracture efficiency and retort performance? Two- and three-dimensional models of multi-component, multi-phase flows are being developed but require more extensive comparisons with field studies. The same observation applies to the use of bedded-crack and statistical-crack models in predicting fracture formations.

3. Recommendations

The talented groups at Sandia/Albuquerque and LASL are currently interacting with industrial field-development programs involving surface fracturing and MIS. A closer tie-in with mining operations and augmented emphasis on field verification may well improve the applicability and utility of these studies. Hence, it is imperative that high-quality field measurements support the code development efforts. For example, existing results suggest that joint patterns and other geologic phenomena influence blasting performance; it will be necessary to include such features into predictive codes. This inclusion demands continuing field experiments. Currently, LASL and Sandia/Albuquerque plan field experiments in code verification at the Anvil Points oil-shale facility. Proper funding levels are required if such field tests are to be reasonable in scope and utility. Current budget levels do not provide adequate support for these field experiments. Funds should be provided since field experiments are centrally important for this entire effort.

AB-10

SITE VISIT TO THE
INSTITUTE OF GAS TECHNOLOGY (3424 SOUTH STATE STREET,
ITT CENTER, CHICAGO, ILLINOIS 60616)
FOR DISCUSSIONS OF EASTERN SHALES
(October 1, 1980)

Submitted by: S. S. Penner

FERWG Members W. S. Bergen, J. Clardy, A. E. Lewis, and S. S. Penner discussed the IGT programs on shale-oil recovery and, especially, the utilization of Eastern U.S. oil shales with the following IGT staff members: P. B. Tarman (Vice President, Process Research), H. L. Feldkirchner (Assistant Director, Oil Shale Research), J. C. Janka (Assistant Director, Process Analysis), R. D. Matthews (Senior Geologist, Process Research), D. V. Punwani (Associate Director, Chemical Process Research), and others.

1. Resources*

A preliminary estimate has been made of "recoverable resources" as defined by the following constraints: (a) the organic carbon contents of the shales are at least 10% by weight; (b) the overburden thickness is less than 200 ft. (59m); (c) the volumetric stripping ratios are less than 2.5 to 1; (d) the stratigraphic thicknesses of the deposits are 10 ft (3m) or more. The

* R. D. Matthews, J. C. Janka and J. M. Dennison, "Devonian Oil Shale of the Eastern United States," IGT paper presented to The American Association of Petroleum Geologists, Evansville, Indiana, October 1-3, 1980.

Eastern Devonian shale resources are estimated to amount to about 423×10^9 B_e with the following distribution: 190×10^9 B_e in Kentucky, 140×10^9 B_e in Ohio, 44×10^9 B_e in Tennessee, 40×10^9 B_e in Indiana, 5×10^9 B_e in Michigan, 4×10^9 B_e in Alabama.

The specified resources are expected to be recoverable at economically competitive prices by using the proprietary IGT Hytort Process.

A program of verification of estimated recoverable resource should include extensive coring, analyses, and more definitive costing of Hytort technology to define the carbon contents of usable shales.

2. Cost Estimates

Shale oil cost estimates must allow for capital, mining, operations and maintenance, upgrading, and distribution costs.

A. Mining Costs

Mining costs were estimated for IGT by Dames & Moore Consulting Engineers (Suite 1300, 55 Queen Street East, Toronto, Ontario, M5C 1R6, Canada) during 1977. The results listed in Table 1 were obtained.

Table 1 Mining costs for Devonian shale, estimated by Dames and Moore during 1977.

| | Kentucky | Tennessee | Ohio |
|--|----------|-----------|--------|
| Mine capacity, 10^6 ton/yr | 25.25 | 19.41 | 33.96 |
| Direct operating cost, \$/ton | 1.60 | 1.90 | 1.75 |
| Total plant investment (excluding working capital, interest during construction, and start-up costs), $\$10^6$ | 112.80 | 135.00 | 176.90 |
| Shale price for 12% DCF and 100% equity, \$/ton | 2.73 | 3.65 | 3.06 |

B. Hytort Process Economics

D. V. Punwani summarized briefly the results of a Bechtel National, Inc., costing study (early 1980) for a 47,000 BPD plant (using 93,000 TPD of shale at a 90% stream factor) with raw shale supplied at a cost of \$3.50/ton, including upgrading ($N < 0.2$ weight percent, S removed to meet applicable environmental standards), spent shale disposal to meet environmental constraints. With 15% for operations and maintenance, a 15% contingency, capital costs were estimated to be about \$28,000 per daily barrel of production and product costs of upgraded synfuel between \$26.50 and \$28.60. These costs compare favorably with an independent study for room-and-pillar mining in De Kalb County, Tennessee, which was done by Cleveland-Cliffs Iron Company.

These cost estimates form the basis for a proposal submitted to DOE by Transco Energy Co., in collaboration with Gas Developments

Corporation (a subsidiary of IGT) and Bechtel National, Inc., to build an initial commercial module of the Hytort process (at a cost of \$80 to 100×10^6) with the expectation of constructing a 50,000 BPD plant at a capital cost of $\$1.5$ to 2.0×10^9 .*

3. The Hytort Process

The Hytort process uses direct hydrogenation of shale in an overall, thermally-balanced process; 2.5 to 6.9 B of H_2O are consumed per B of oil produced, with cooling water accounting for a major share of the water losses. The process has been under development at IGT with funding supplied by the Gas Industry since 1972; DOE funding has been obtained since 1979 ($\$2.6 \times 10^6$ for 20 months). A 4-inch bench scale reactor (100 to 200 lbs/hr) was fed continuously from a feed chamber and was electrically heated to achieve desired process temperatures. A 1 TPH thermally-adiabatic PDU with two reaction stages (in the first stage, the shale feed is reacted at about $700-800^{\circ}F$ and in the second stage at $1200-1500^{\circ}F$) has been in use since 1976. Using Eastern Devonian shales, at hydrogen pressures up to about 500 psia, oil yields of 20 to 22 GPT plus 1 to 2×10^6 Btu of HC gases were obtained from New Albany Shale (Ky.) yielding 11.5 GPT by Fischer Assay.

In addition to hydroretorting, the Hytort process supplies a small amount of external process heat, for example by oxidation of

* "Feasibility Study: Synthetic Liquids from Eastern Devonian Oil Shale Using the Hytort™ Process," 1980.

hydrogen (about 2% of the shale heating value is estimated to be used in the retort).

A 47,000 BPD plant will use 37 acre-ft of H_2O /day and 10^3 tons of O_2 per day. The shale blocks will be comminuted to 1 to 2" dimensions, and steam-reformed HC gases (produced within the process) will be employed for the production of H_2 in a balanced plant operation. This commercial unit is expected to contain 5 retorts and 5 hydrogen trains. The commercial plant facility is expected to occupy 100 to 200 acres and will be fed by a 100,000 TPD shale mine. Shale fines may be gasified to make additional H_2 . Only about 10% of the H_2 run through the retort is consumed per pass. For proper operation, the product of heat capacity and flow rate must be roughly equal for the gas and solid phases.

Monitoring equipment on the PDU includes facilities to perform the following measurements: flow rates in and out for solids, liquids and gases; elemental mass balances; pressure and temperature profiles through the retort; gas-compositions using on-line gas chromatographs.

Scaling to commercial size is proposed to proceed from the 24 TPD PDU to an intermediate unit using 4×10^3 TPD of shale (in a 12 to 14 ft diameter retort) to commercial retorts handling 25,000 TPD.

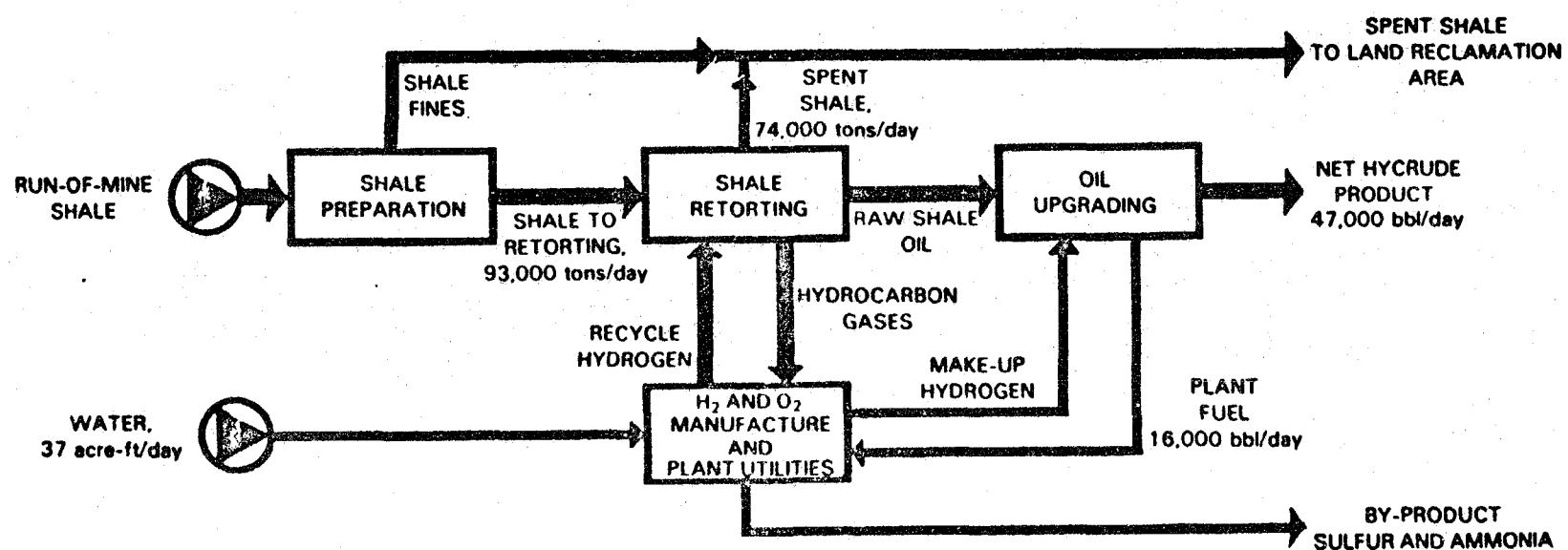
A historical overview of the IGT shale-oil programs is summarized in Table 2. The steps involved in shale conversion are listed in Table 3. The HytortTM process and performance data are summarized in Figs. 1-7. Upgraded Hyocrude is compared with Kuwait crude in Table 4.

Table 2 Historical overview of IGT shale-oil programs.

| Date | Program | Sponsor |
|--------------|--|--|
| 1959 to 1964 | Experimental program directed towards production of SNG from Colorado shale by rapid hydrogenation. | American Gas Association |
| 1964 to 1971 | Fundamental research into kinetics and mechanism of oil-shale/hydrogen reactions. | Institute of Gas Technology |
| 1972 to 1979 | Development of the IGT Hytort TM process. | American Gas Association and Gas Research Institute |
| 1979 to 1981 | Technical and economic verification of the IGT Hytort TM process. | U.S. Department of Energy |
| 1980 to 1981 | Feasibility study: synthetic liquids from Eastern Devonian oil shale using the Hytort TM process. | U.S. Department of Energy and Transco Energy Company |

Table 3 Steps in shale preparation and conversion.

| | |
|----------------------------|---|
| Shale preparation | Run-of-mine shale is crushed and screened. |
| Shale retorting | Shale reacts with hydrogen to form shale oil and hydrocarbon gases. |
| H ₂ manufacture | Cleaned hydrocarbon gases are steam-reformed to produce hydrogen. |
| Oil upgrading | The raw shale oil is upgraded to yield the Hyocrude product. |

THE HYTORTTM PROCESS

Note: Thick lines delineate primary process-streams
Thin lines delineate secondary process-streams

Fig. 1 Schematic diagram of the HytortTM process.

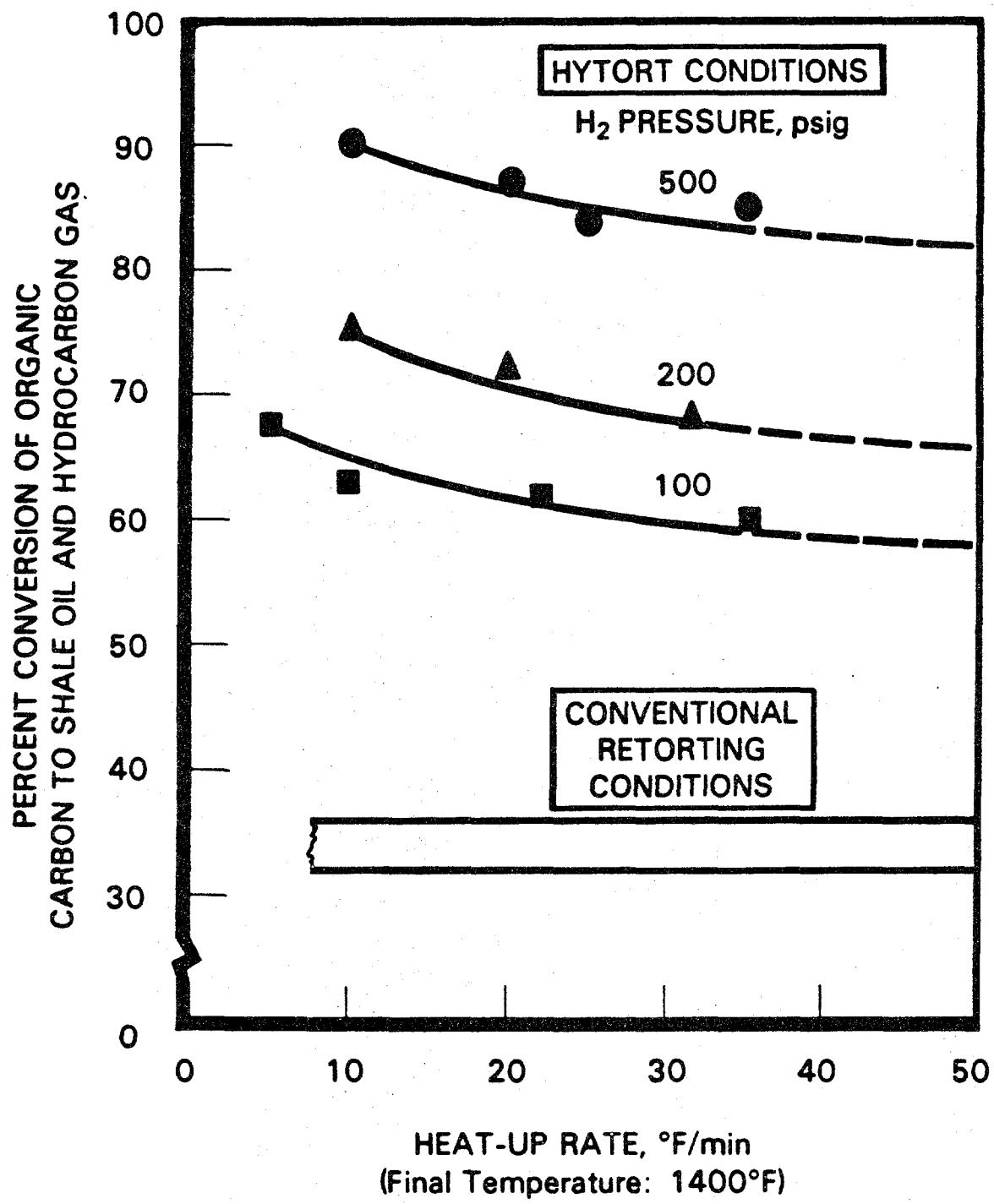


Fig. 2 Percentage conversion as a function of heat-up rate for various H_2 pressures.

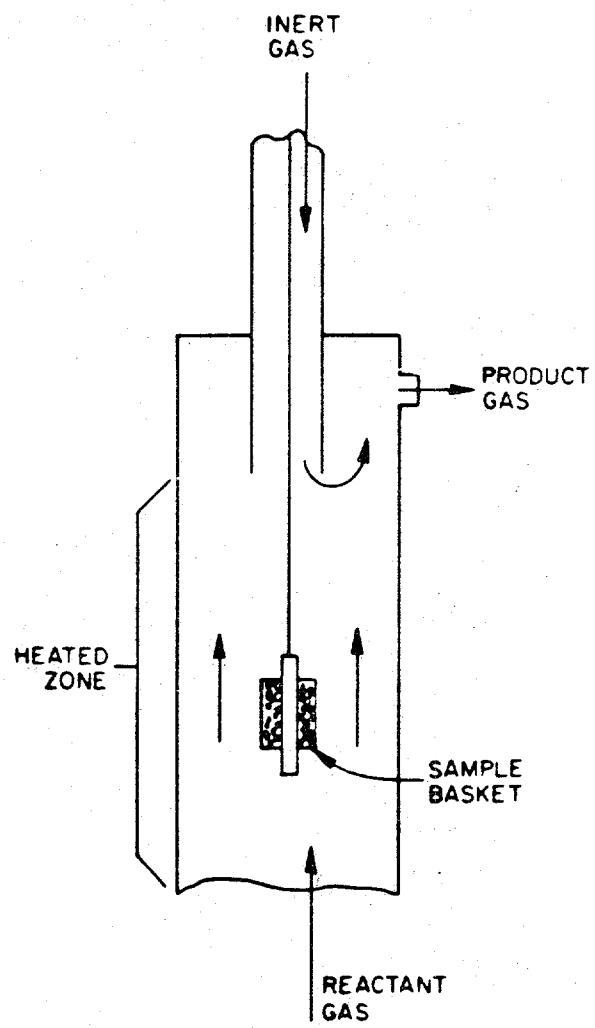


Fig. 3 Thermobalance reactor.

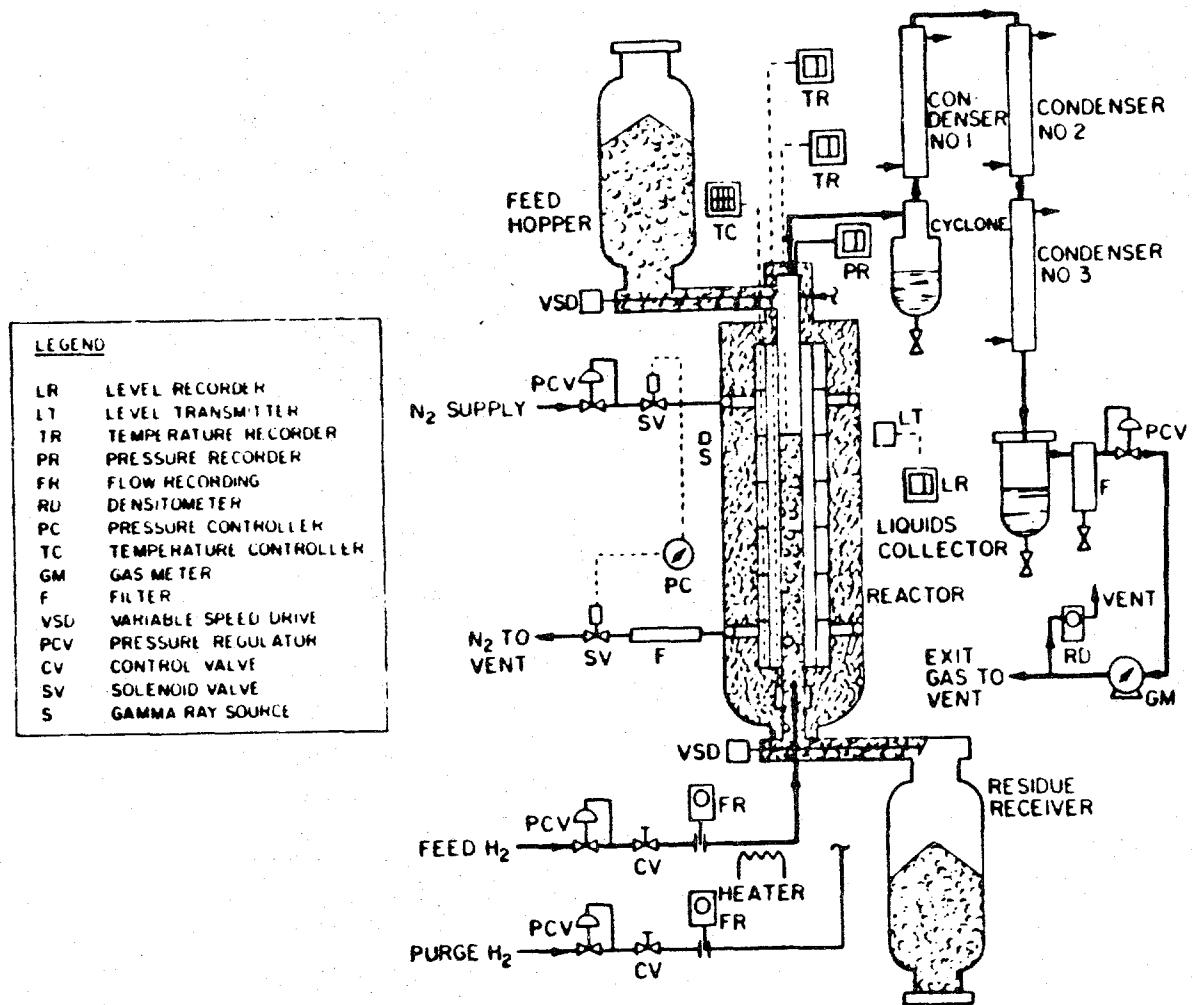


Fig. 4 High-temperature, balanced-pressure bench-scale unit.

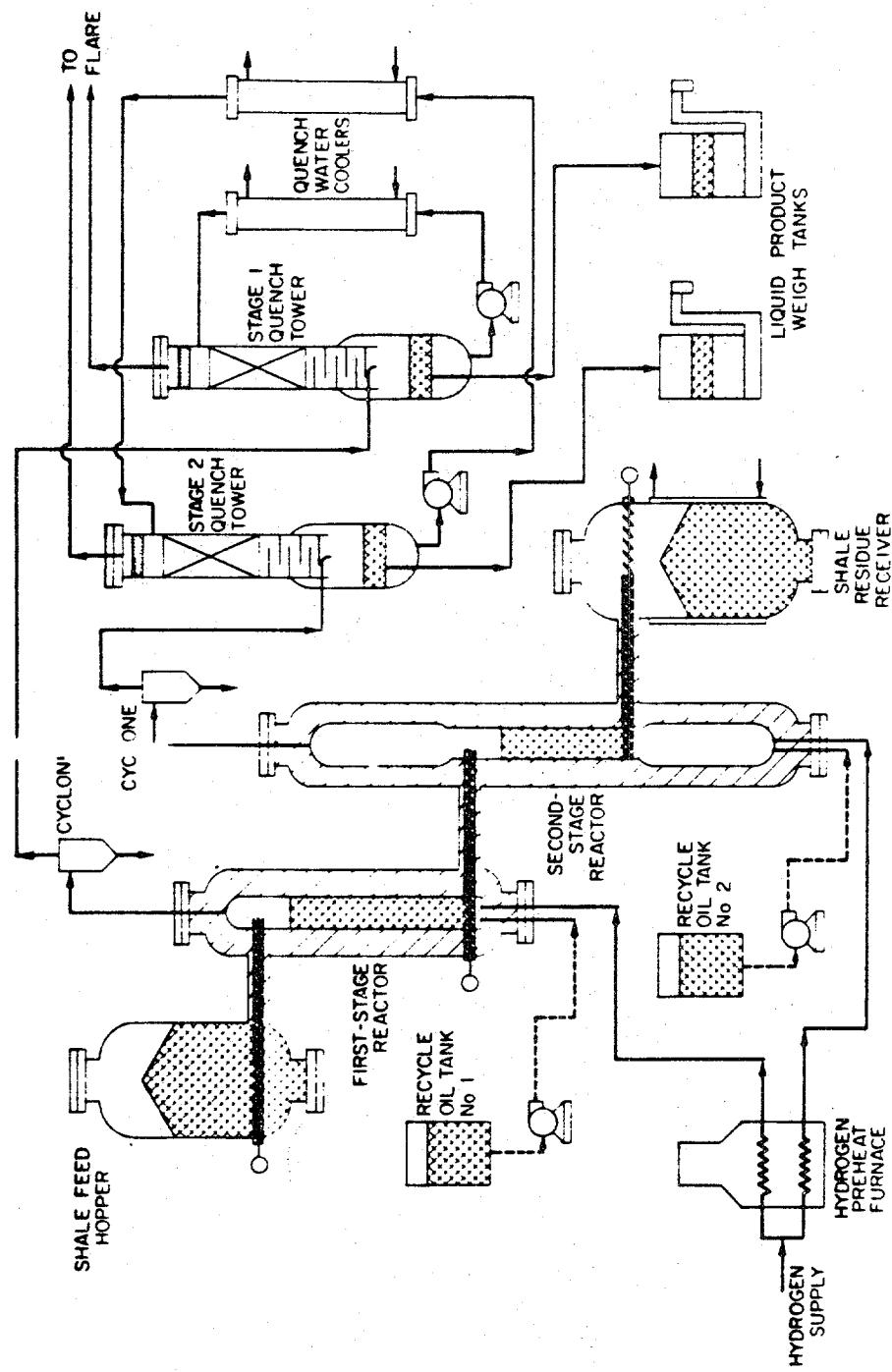


Fig. 5 Schematic diagram showing the process development unit.

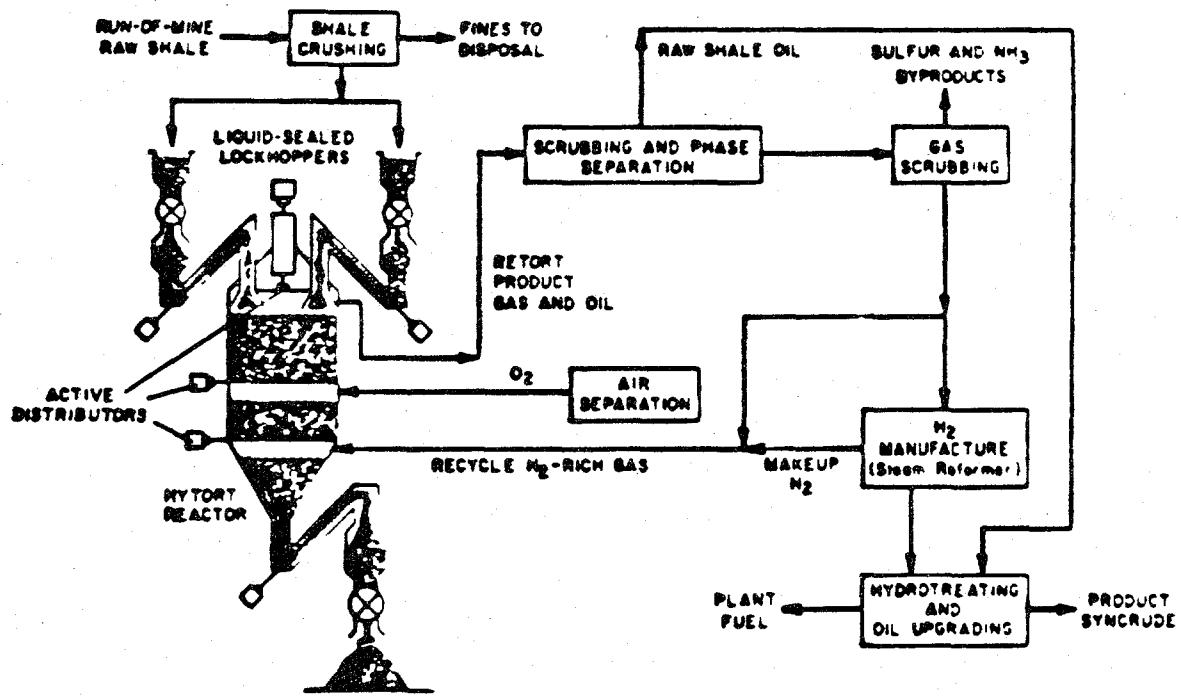


Fig. 6 Conceptual design for a HytortTM commercial plant.

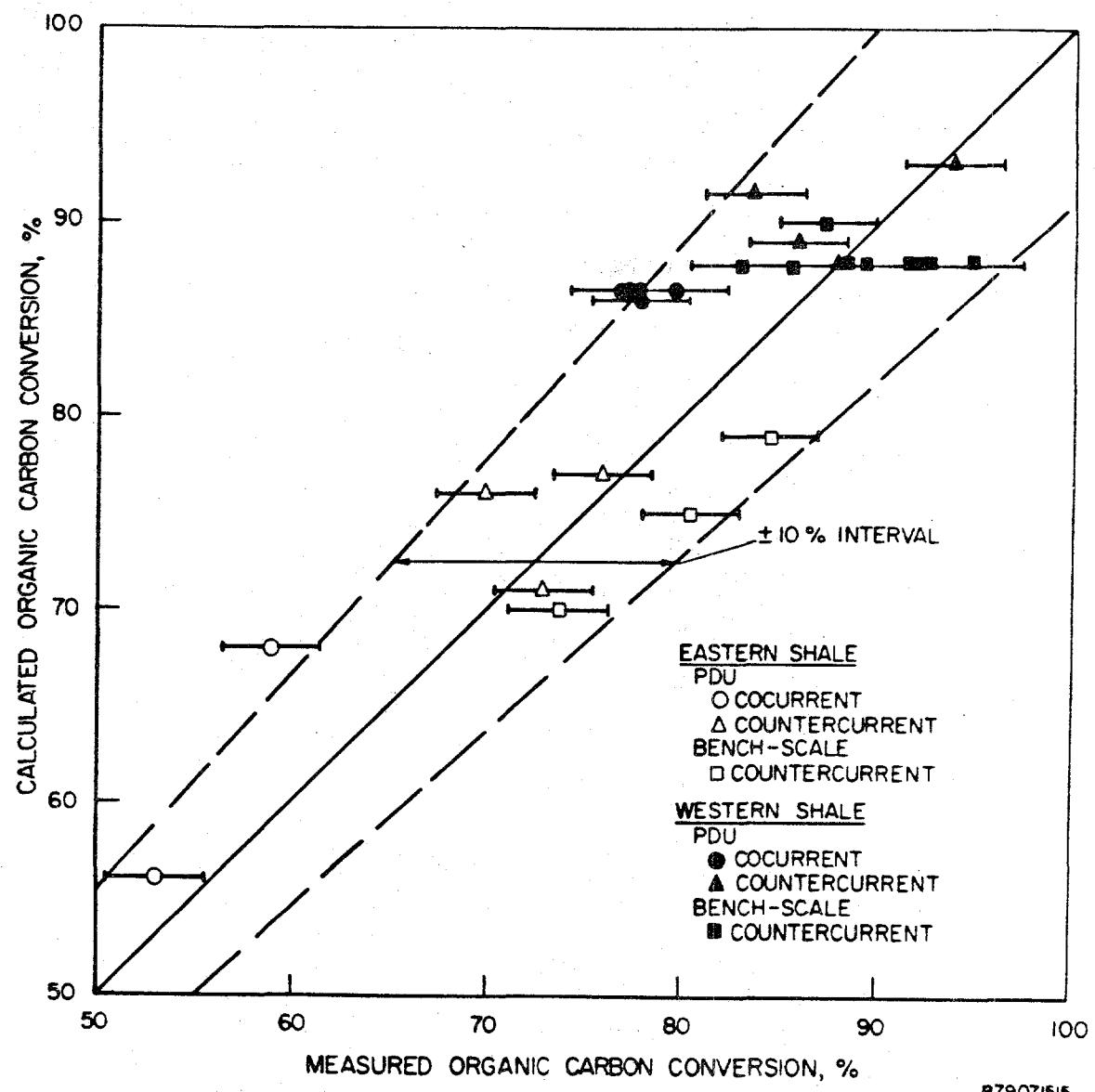


Fig. 7 Comparison of measured and calculated organic carbon conversions.

Table 4 Physical properties of Hyocrude and Kuwait crude.

| | Hyocrude | Kuwait Crude |
|--|----------|--------------|
| Light Naphtha (SR Gasoline) IBP to 230°F | | |
| Yield volume % | 16 | 12 |
| Gravity °API | 53 | 78 |
| Sulfur % | <0.01 | 0.01 |
| Heavy Naphtha 230° to 400°F | | |
| Yield volume % | 26 | 14 |
| Gravity °API | 38 | 53 |
| Sulfur % | <0.01 | 0.09 |
| Diesel Fuel or Distillate Stock 400° to 700°F | | |
| Yield volume % | 53 | 28 |
| Gravity °API | 23 | 36 |
| Sulfur % | 0.03 | 1.00 |
| Residual Cracking Stock 700°F+ | | |
| Yield volume % | 5 | 46 |
| Gravity °API | 0 | 13 |
| Sulfur % | 0.06 | 4.20 |

4. Environmental Studies

The IGT Hytort process will substantially improve the yield of shale oil from Devonian shales. Rough estimates of resource availability and process economics are encouraging for oil-shale production but a new set of environmental concerns must be addressed. In general, the Devonian shales of the East are rather different from the Green River shales. For shales of comparable organic contents, the Eastern shale sulfur contents are much higher and the mineral carbonate contents much lower. Because of these inherent differences and process differences, it is not clear how applicable the Green River experience will be to Devonian shales. Most of the work that has been done refers to small-scale demonstration of the process and evaluation of process variables. Environmental work is still at an early stage of assessment but a rather comprehensive evaluation is planned.

A. Air Quality

The proposed process would produce pollutants in the form of particulates, SO_2 , NO_x , light hydrocarbon vapors, CO, aldehydes, and CO_2 . There are no baseline data for specific sites and, therefore, specific impacts are impossible to judge at this time. A study performed by Dames and Moore suggests that available process and central technology could be used to meet EPA standards. The Hytort process has not been run in the steady state for periods sufficiently long to identify all trace pollutants, although week-long tests are planned for the near future. These tests are expected to yield reliable emission data.

B. Water Quality

Water availability is not a serious problem in the East. Conceptual schemes to clean up process water have been devised but are untested. The application of standard technology has not succeeded well in other projects and this area should be studied as soon as possible.

C. Spent Shale Disposal

Spent shale disposal has received little study to date. Some experiments were done to characterize organic compounds in the leachate by GC/MS. Concentrations were very low and no materials of concern, according to the OSHA list, were identified. Similar studies on trace minerals have not yet been performed. Revegetation studies have not yet been done but they will clearly be needed in the near future.

D. Socioeconomic Considerations

Resolution of problems associated with the development of an industry in the Piceance Creek Basin will provide useful answers also for an Eastern industry. The population in the East is currently underemployed. A Dames and Moore study suggests that industrial development could be done with relative ease and would improve the socio-economic status of the area. State legislatures in the East are cooperating with industrial development.

5. Research Needs

D. V. Punwani presented a summary of research needs (see Table 5). He emphasized that particular attention needs to be paid to the following six operational topics:

- i. long-term continuous Hytort PDU tests;
- ii. the utilization of shale fines and spent shale disposal;
- iii. careful assessment of Eastern shale resources;
- iv. development of effective commercial procedures for shale mining and preparation;
- v. quantitative assessments of environmental and socio-economic impacts;
- vi. shale-oil upgrading techniques.

R&D should be directed to improve hydrogen-production methods, metals recovery, correlation of geology with process requirements for hydro-retorting, conversion kinetics and yield, reaction calorimetry, identification of the lowest grades of shale that can be processed economically, studies of crushing and grinding and also of shale beneficiation, etc.

Although cold-flow model studies of shale flow in the retort were discussed, work of this type is not currently in progress.

Definition and implementation of fundamental supporting research for Hytort appears to be a worthwhile task in view of the magnitude of the contemplated development and commercialization charges.

6. Policy Considerations

The concurrent development of shale-oil recovery technologies for Western and Eastern shales is a desirable national objective. If Hytort performs as hoped, total syncrude recoveries per ton of shale mined will be comparable for these resources. There are obvious advantages in utilizing Eastern shales (e.g., water-supply problems are eliminated, socio-economic dislocations are greatly reduced, product-distribution costs become far smaller, political objections may well be non-existent, etc.). For these reasons alone, Hytort and its associated programs merit careful examination and evaluation.

Table 5 Research needs for an Eastern shale development program (prepared by D. V. Punwani, IGT).

I. Resource Data Bank

A. Geology

1. Detail local stratigraphy of shale outcrop and near-surface deposits
2. Obtain additional subsurface data (via geophysical logs and cores) near outcrop areas and for subsurface deposits
3. Improve geological mapping of outcrop areas
4. Summarize regional stratigraphy of shales
5. Subdivide stratigraphic units on the basis of shale grade and "waste"
6. Map regional distribution of organic matter

B. Resource Estimates

1. Determine amount of commercial-grade shale existing in place at various depths
2. Determine how much shale can be recovered economically using modern mining methods

C. Geochemistry

1. Elemental analysis of shales vs. location and seam for each rock unit.
 - a. organic matter
 - b. mineral matter
2. Correlate type and quantity of organic matter with oil yield
3. Correlate shale grade with
 - a. geophysical logs
 - b. physical properties
 - c. location within rock unit
 - d. vertical position in seam for various rock units
4. Correlate chemical structure of kerogen with rock unit
5. Categorize shales by grades of "richness"
6. Correlate type and quantity of organic matter with oil yield

II. Shale Mining

(Surface outcrops, Near-Surface Deposits and Sub-surface Deposits)

- A. Determine optimum mining method for each location
- B. Determine optimum spent shale disposal method for each location
- C. Determine value of shales in place
- D. Determine "commercial grade level"
- E. Determine how "CGL" is related to and limited by:
 - 1. Shale richness
 - 2. Pay thickness
 - 3. Overburden thickness
 - 4. Land and mineral acquisition cost
 - 5. Legal and environmental constraints

III. Shale Feed Preparation

- A. Determine shale primary crushing methods for each shale type
- B. Determine shale secondary crushing methods for each shale type
- C. Determine shale grinding methods for each shale type
- D. Determine shale screening methods for each shale type
- E. Determine shale fines handling for each shale type
- F. Determine shale beneficiation methods for each shale type

IV. Retort Shale Feeding Techniques

- A. Determine raw shale feeding methods
- B. Develop spent shale withdrawal methods
- C. Evaluate lockhopper systems
 - 1. gas-pressurized
 - 2. liquid-sealed
 - 3. entrained systems (for shale fines)
 - 4. novel methods

V. Shale Processing

- A. Determine product slate for each shale unit
 - 1. With oil or gas as only product marketed
 - 2. Oil plus gas marketed
(hydrogen from coal gasification)

V. Shale Processing (Cont'd.)

3. Determine mineral byproducts for each shale unit
4. Optimize oil/gas ratio for minimum net cost of product

B. Determine optimum process configuration for each shale unit

C. Evaluate shale processing methods for each shale unit and various shale grades

1. Retorting

a. Moving-bed (coarse shale)

1. Hydroretorting
2. Spent shale gasification to produce hydrogen in retort

b. Fluidized-bed (fines)

1. Hydroretorting
2. Gasification to produce hydrogen makeup for process

2. Combustion

- a. raw lean shale
- b. spent shale from retorting
- c. raw shale fines

D. Establish metals byproduct recovery method for each shale unit

VI. Product Upgrading

A. Raw oil treatment

1. Develop water removal methods
2. Develop solids removal methods

B. Dry oil upgrading

1. Evaluate conventional upgrading processes for each type of oil
2. Determine oil properties

- a. metals present
- b. hydrocarbon types present
- c. heteroatoms (esp. N)

1. bonding
2. functionality

3. Evaluate new technology for oil upgrading

VI. Product Upgrading (Cont'd.)

C. Gas purification

1. Sulfur

- a. Removal methods
- b. Recovery methods

2. Ammonia

- a. Removal methods
- b. Recovery methods

3. Carbon Dioxide

- a. Removal methods
- b. Recovery methods

4. Hydrogen Separation Methods

- a. Cryogenic separation
- b. Pressure-swing adsorption
- c. Diffusional (Monsanto)

D. Metals and Mineral Byproducts
(Conversion to final saleable product)

VII. Evaluate Hydrogen Production Methods

A. Catalytic steam reforming

- 1. gaseous hydrocarbons
- 2. light liquid hydrocarbons

B. Partial Oxidation

- 1. Heavy shale oil fractions
- 2. Coal

VIII. Process Economics

A. Mining (see above, section II)

- 1. Surface methods
- 2. room-and-pillar (below ground)

B. Shale Feed Preparation

- 1. Crushing
- 2. Grinding
- 3. Screening
- 4. Beneficiation

VIII. Process Economics (Cont'd.)

C. Retorting

1. Hydroretorting methods
2. Conventional methods

D. Shale feeding and withdrawal (see above, section IV.A & IV.B)

E. Product upgrading

1. Raw oil
2. Dry oil
3. Gas purification
 - a. Sulfur
 - b. Carbon dioxide
 - c. Ammonia
 - d. Hydrogen separation

4. Metals and mineral byproducts

F. Product Marketing

G. Hydrogen production

H. Beneficiation

I. Byproduct recovery

IX. Environmental Factors

A. Mining

1. Surface retorting
2. In-Situ retorting

B. Spent shale disposal

1. Surface retorting
2. In-Situ retorting

C. Process environmental assessment

1. Surface retorting
2. In-Situ retorting

D. Raw shale and spent shale leaching

IX. Environmental Factors (Cont'd.)

E. Health effects

1. Raw shale
2. Spent shale
3. Product oil
4. Process water

F. Water, air and solid waste treatment

G. Socioeconomic factors

X. Plant Siting

- A. Water supply
- B. Shale resource location
- C. Population density
- D. Local and state regulations
- E. Environmental factors

XI. Supporting Data (This information is needed for each major shale type)

A. Thermochemistry

1. Shale
 - a. raw
 - b. spent
2. Oil
 - a. raw
 - b. upgraded
3. reaction calorimetry (for various types of shale, or shale oil.)
 - a. shale hydroretorting
 - b. spent shale gasification
 - c. shale combustion
 1. raw
 2. spent
 - d. raw oil upgrading processes.

XI. Supporting Data (Cont'd.)

B. Chemical structure and composition

1. Oil shale kerogen

- a. aliphatic/aromatic ratios via instrumental methods (e.g. NMR)
- b. dissolution in solvents (e.g. hydrogen donor-solvents)
- c. removal of mineral matrix
- d. nature of heteroatom bonding
 - 1. sulfur
 - 2. nitrogen
 - 3. oxygen
- e. metallic species in organic matrix and metal-organic bonding
- f. nature and molecular weights of primary products of kerogen decomposition.

2. Oil shale mineral matter

- a. definition of inorganic matter elements
- b. identification of minerals present
- c. correlation of mineral matter properties with geologic history

3. Shale oils

C. Chemical Reactivity

1. Kinetics and mechanisms of major types of primary shale reactions

- a. Pyrolysis
- b. Hydrogenolysis
- c. Combustion
- d. Steam gasification

2. Kinetics and mechanisms of shale oil reactions

- a. Pyrolysis
- b. Hydrogenation and hydrogenolysis (catalytic and non-catalytic)
- c. Combustion
 - 1. NO_x formation
 - 2. Soot and smoke formation

3. Effects of process variables on shale reaction rates

- a. shale particle size
- b. shale heatup rate
- c. hydrogen partial pressure
- d. total pressure

XI. Supporting Data (Cont'd.)

4. Effects of shale properties on reactivity

a. physical properties

1. density
2. porosity and pore volume
3. effects of shale weathering

b. chemical properties

1. organic matter
2. mineral matter
3. kerogen structure

c. geological history

5. Modeling of kinetics and mechanisms of reactions

- a. oil shale
- b. shale oil
- c. spent shale

D. Engineering Data

1. Fluid flow

- a. moving-bed retorting
- b. fluidized-bed retorting

2. Heat transfer

- a. moving-bed retorting
- b. fluidized-bed retorting

3. Shale physical properties

- a. for retort design
- b. for mine design
- c. for crushing and grinding

1. hardness index
2. grindability index
3. abrasivity

- d. raw and spent shale thermophysical properties

4. Materials of construction for oil shale processing and utilization

XI. Supporting Data (Cont'd.)

5. Mathematical modeling

a. Retorting

1. moving-bed
2. fluidized-bed

b. Process

1. total plant
2. plant sections

6. Scale model testing

(Moving-bed retorts)

- a. solids flow
- b. gas flow

REPORT OF INSTRUMENTATION PEER REVIEW
OF THE DOE OIL-SHALE PROGRAM AND
SOME REMARKS ON THE INSTRUMENTATION PROGRAM ON OIL SHALE
ALBUQUERQUE, NEW MEXICO
(October 28-30, 1980)

Submitted by: J. Ross

The DOE Oil-Shale Program held an instrumentation peer review on October 28-30 in Albuquerque, N.M.

W. E. Little of the Laramie Energy Technology Center introduced the instrumentation program within the DOE Oil-Shale Program. He stressed the importance of peer review by representatives of industry and academia. The major parts of the instrumentation program supported by the oil-shale program are carried out at Sandia, Los Alamos, and Lawrence Livermore Laboratories.

The total budget of the Oil-Shale R and D Program is about \$36 million, of which approximately \$32 million are allocated to field operations. The budget for all aspects of instrumentation is $\$5 \times 10^6$.

At this point, a discussion began on the definition of instrumentation R and D. In practice, what is meant by instrumentation R and D is a composite of measurements, experiments and instrumentation used in laboratory and field studies. The current budget for instrumentation development is only of the order of \$100,000. Of the $\$5 \times 10^6$ budgeted for all aspects of instrumen-

tation, Sandia receives about $\$4 \times 10^6$, of which $\$2.5 \times 10^6$ goes for the Oxy MIS project. Instrumentation R and D for environmental monitoring and studies is funded through other sources.

The following major topics were discussed at the instrumentation peer review:

1. rubble evaluation, remote methods;
2. rubble evaluation, direct methods;
3. flow/tracer modelling;
4. rubble blasting evaluation;
5. instrumentation for retort stability and integrity.

No attempt will be made here to present a review of all the presentations since there would be some repetition because the work at LETC and LLL has been reviewed by FERWG separately.

Modified in situ oil-shale technology depends on effective rubblization of large volumes of oil-shale deposits. It is important to characterize, measure and control the blasting performance. Important characteristics of the rubblization process include fragment size and distribution, void distribution, and permeability distribution.

L. Warne of Sandia made a presentation of rubble evaluation by remote methods using electromagnetic techniques. Short and long wavelength electromagnetic radiation measurements of attenuation, measurements of velocity changes and of phase shifts are made and then used in a program of computerized tomography. The

computer process is designed to yield by matrix inversion the desired quantities of void fraction, void distribution, and particle-size distribution. The program has many interesting aspects. However, it also seems to have some major problems. I asked when, where and how the results would be used in the field and how the theory behind the measurements can be tested in order to lead to trustworthy predictions. The answers were less than satisfactory. The main problem with this and similar programs is the lack of testing a given procedure such as the use of electromagnetic waves on samples of adequate size with known void and particle fractions and known distributions of voids and particle sizes. Furthermore, the relation of any results received with this and similar methods in the field to the mode of operation of the retort seems to be missing. Here, as well as in a number of similar measurement R and D programs, there is a rush to support the field programs without adequate backing of laboratory and small-scale studies.

J. DuBow of Colorado State University made a presentation on his studies of measurements of material properties. In the last few years, he and his colleagues have developed instrumentation to measure a variety of properties such as thermal diffusivity, thermal conductivity, thermal analysis, dynamic dielectric analysis, mechanical behavior, acoustic impedance, heat-flow calculations, mineral identification, heat requirements for

retorting shale, and transport mechanisms in oil shale. The program seems most ambitious and a large number of measurement results was shown. Aside from a smaller program on dielectric properties of oil shales, this is the only program within the DOE oil-shale program to support thermophysical characterizations of oil shales. We were informed that this research program is to be cut entirely in the next fiscal year. The basic reason given by DOE representatives was that field work takes most of the money and the basic work could slide. Opinions on this attitude were requested.

Other techniques for rubble evaluation include the use of a well-bore tool for obtaining void distributions by reflected gamma radiation from a source lowered into the well bore; the use of radioactive tracers (krypton or helium) for permeability measurements; and use of TV cameras lowered through a well bore into cavities. The tracer experiments appear interesting and may in time lead to useful information. At present, the application of the technique is limited by the difficulty of interpretation of the measurements.

A presentation by J. J. Ronchetto included various intraretort thermal profiling instruments, including ultrasonic temperature probes, sliding thermocouples, and radio bugs-gas canisters.

The DOE-sponsored instrumentation research on oil shale is designed primarily as a support service for field operations.

The program consists in large part of measurements and their development in field operations. Some funds are provided for laboratory-size retort studies and these experiments seem well planned and have led to useful results. Some of the in situ measurement procedures, although necessary in time, seem at present to be lacking predictability because of inadequate calibration studies.