OIL SHALE RESEARCH RELATED TO PROPOSED NUCLEAR PROJECTS

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ABSTRACT

The Bureau of Mines is conducting research to develop data pertinent to in situ retorting of oil shale fractured by a nuclear explosion or other means. Maximum utilization of the Green River oil shale found in Colorado, Utah, and Wyoming, at depths ranging from outcrops to several thousand feet, requires development of several methods of processing. Early research was devoted to developing processes for application to oil shale occurring at depths suitable for mining. In present research, the emphasis is on in situ retorting and recovery processes that would be more satisfactory for oil shales occurring at greater depths.

Development of an in situ process depends upon finding or establishing sufficient permeability in the oil shale beds for the passage of fluids which serve as a heat carrier in bringing the oil shale to retorting temperature. Use of a nuclear explosive seems to offer the best chance for successfully fracturing the thicker and more deeply buried portions of the deposit to give the required permeability. Processing the very large quantity of broken and fractured oil shale that would be produced presents many problems which require new background data for their solution. This paper describes research the Bureau of Mines is conducting to develop pertinent data. Primarily this research involves laboratory determination of properties of oil shale, pilot scale investigation of retorting characteristics of ungraded broken shale, and underground combustion of shale fractured by pressure and chemical explosives. Application of the research results should aid in designing the oil recovery phase and provide an estimate of the quantity of oil that may be obtained in a nuclear experiment in oil shale.

INTRODUCTION

Oil shale in the Green River Formation in Colorado, Utah, and Wyoming represents a tremendous energy resource and contains associated minerals that may be valuable. Research on methods for utilizing this resource has been conducted for many years, but has not yet resulted in commercial processing. Because the formation extends over a large area, approximately 16,500 square miles, in which the thickness and grade of shale as well as the amount of overburden vary greatly, many different combinations of mining and processing techniques will be required to fully utilize the deposit. The technique with which this paper deals is the utilization of an underground nuclear explosion to produce a chimney containing broken oil shale and a fractured zone around the chimney, and the subsequent processing of this oil shale in place to recover oil and possibly other minerals from it.

The possibility of using a nuclear explosive in oil shale has been actively considered for over 10 years, and numerous papers concerning it have been published (1-2)[1/]. In these publications it has frequently been necessary to base much of the discussion on assumptions, as this is a new concept for which background data are not available. This is particularly true for underground processing because practically all of the extensive oil shale research in the past has been devoted to mining and aboveground retorting. Only in recent years has research designed to provide some of the background data required to evaluate the potential of the nuclear approach been undertaken. In this paper we will discuss the present research program of the Bureau of Mines to obtain this type of data, the results so far achieved, and the significance of these results to the nuclear approach for utilizing oil shale.

RESEARCH PROGRAM RELATED TO NUCLEAR EXPERIMENTS IN OIL SHALE

Two types of research are being conducted relating to the use of a nuclear explosive in oil shale. These are (1) resource evaluation to determine location, thickness and grade, physical properties, and chemical composition; and (2) engineering studies related to recovering shale oil from the deposit after it has been fractured by a nuclear explosive.

Resource Evaluation

Location

The Green River oil shale formation covers about 16,500 square miles in Colorado, Wyoming, and Utah, as shown in Figure 1. The thickness of the shale and the amount of overburden vary widely throughout this area. Until a few years ago, most of the information about the deposit had been obtained from coreholes drilled where the deposit would be amenable to mining or from cuttings from wells that passed through the formation, for example, during drilling of oil and gas wells. The results did not give adequate information about the thick, deep shales that might be suitable for fracturing by a nuclear explosive; therefore, during the last several years, the Bureau of Mines and the Atomic Energy Commission drilled three holes to obtain such information in the north-central portion of the Piceance Creek Basin in Colorado. These are shown on Figure 1 as Colorado Coreholes 1, 2, and 3. The conditions in the vicinity of Corehole 3 seem to be suitable for the use of a nuclear explosive. These have been discussed previously (1-3).

In addition to the coreholes in the Piceance Creek Basin, the Bureau of Mines has, during 1968-69, drilled Coreholes 1 and 1A in the Washakie Basin of southern Wyoming to see whether the deeper shales in this basin might be suitable for in situ recovery, using either nuclear or other fracturing techniques. Long sections of relatively low-grade oil shale were encountered. In general, the oil shales average only 10 to 15 gallons per ton. A selected 650-foot section has an assay averaging 11 gallons per ton. The leanness of the shales makes this site less attractive for initial development than other areas where the shales are richer.

Some support has also been given to an exploratory operation of the CER-Geonuclear Corporation and The Western Oil Shale Corporation in Utah. As a part of a feasibility study for the use of nuclear fracturing, these companies have drilled Utah EX-1 Corehole in the Uinta Basin. The Bureau's Laramie Petroleum Research Center cooperated by performing the assay work on the core. The data obtained are still being evaluated.

1/ Underlined numbers in parentheses refer to items in the list of references at the end of this report.

Physical Properties

Oil shale, as it occurs in nature, is a strong rock, having a compressive strength of about 10,000 psi. This is many times that required to withstand the stresses present in the column of rubble in a nuclear chimney. However, much of this strength, particularly in richer shales, comes from the organic material in the shale which will be altered or removed during the retorting process. Little is known regarding the structural response of oil shale as it is heated under compressive stress.

Research is being conducted, utilizing small cores and fragments, to evaluate the stress-strain-time-temperature relationships of oil shale under compressive stresses such as would exist in a nuclear chimney, and to study the effects of deformation on permeability (4). At present, the research has been on samples of richer-than-average material (35 to 64 gallons per ton), because it was thought that this type of material would be most troublesome in regard to structural changes. The results show that in these rich shales the organic matter is the predominant contributor to the oil shales' mechanical properties and structural response to heat and stress. For example, the compressive strength decreases from about 10,000 psi at ambient temperature to a few hundred psi at 725°F; samples can be sliced readily with a knife at 725°F, either perpendicular or parallel to the bedding plane; and the samples show extensive structural breakdown on heating in a stress-free environment. Although structural response of large masses of rubble cannot be predicted quantitatively from results on small specimens, these preliminary results do indicate that heat produces major structural responses in rich oil shales. The possible effects of these should be considered in designing underground processing experiments, both for a nuclear chimney and for the fractured area surrounding it.

Composition

Green River oil shale is an organically rich, dolomitic limestone that was deposited in the beds of Eocene lakes. Much research has been conducted on the composition of the organic material in the shale, and most past efforts have been directed toward utilizing the resource by obtaining oil from it. Recently it has been found that several minerals occur in quantity in certain areas of the Piceance Creek Basin in the deeper-lying shales that might be suitable for exploitation using nuclear fracturing. At the present time, nahcolite (sodium bicarbonate) and dawsonite (sodium aluminum dihydroxy carbonate) appear to be the most significant of these minerals, and the possibility of recovering them needs to be considered in evaluating the nuclear approach. Pertinent research is still in the early stages since the occurrence of dawsonite in quantity was not reported until 1966 (5). The preliminary nature of such research is illustrated further by the fact that there has been a reliable method for quantitatively determining nahcolite and dawsonite only since publication of a paper by Smith and Young in August 1969 (6).

Engineering Studies

Oil Production

Production of oil from oil shale requires application of heat to raise the shale to retorting temperature, generally about 900°F, and to supply the heat of retorting (7). When heated to retorting temperatures, the organic materials in the oil shale are converted to about 65 percent liquid products, about 10 percent gas, and about 25 percent carbonaceous residue which remains behind on the inorganic portion of the shale. Combustion of the carbonaceous residue generally can provide adequate energy for the retorting process.

During the last 25 years, the Bureau of Mines has conducted numerous investigations that gave results which can be directly related to retorting oil shale fractured by nuclear methods. The research includes the following studies which are of particular interest: (1) Aboveground retorting operations using the N-T-U retort at the Anvil Points, Colo., facility in the late 1940's and the current operation of the 10- and 150-ton retorts at the Laramie Petroleum Research Center; and (2) the present in situ field recovery experiments at Rock Springs, Wyo.

Aboveground Retorting

N-T-U Retort. The N-T-U retorts designed and constructed by the Bureau in 1947 (8) were used to investigate such retorting process variables as air rate, recycle gas rate, shale particle size, and shale grade. The retorts were cylindrical steel vessels with tapered, firebrick linings. The internal diameter decreased from 10 feet 4 inches at the bottom to 8 feet 8 inches at the top. Average cross-sectional area was 70.7 square feet. Height from the grate to the dome was approximately 16 feet. These retorts normally were charged with about 40 tons of shale.

Because of extreme pressure drops, gas channeling, and lower oil yield when using a wide particle size range of shale, charges to the N-T-U retorts were generally screened to provide minus 3 inch to plus 1/2 inch material. The charge was ignited at the top, the combustion zone passed downward through the shale bed, and all gaseous and liquid products were removed from the bottom of the retort. High air rates increased the retorting rate (pounds of shale processed per hour per square foot of retort cross section), but an optimum air rate somewhat lower than 5 $scfm/ft^2$ of cross-sectional area was required to produce the maximum quantity of oil per ton of shale. Use of recycle gas in the process was not found to be beneficial. Oil yield was also shown to be a function of the grade of shale processed; that is, the percentage of oil recovered, based on assay values, increased with increasing shale grade.

Because of the rather closely sized charge of the N-T-U retorts, the results of this early research do not give all the information necessary for designing a recovery experiment in rubble produced by a nuclear explosive because the rubble will have a large particle-size range. Hence, a project to study the retorting characteristics of this type of material was started in 1965. Subsequently, retorts large enough to contain 10 tons and 150 tons of shale, respectively, have been constructed at the Laramie Petroleum Research Center.

10-Ton Retort. The 10-ton retort (Figure 2) is a small batch unit, similar in principle to an N-T-U retort, consisting of a cylindrical steel shell 6 feet in diameter by 12 feet tall. This shell surrounds a tapered refractory lining 6 inches thick at the bottom and 9 inches thick at the top. The retort has been operated on shale charges made up of mine-run material containing pieces as large as 20 inches in two dimensions with the third dimension generally being between 12 and 18 inches, but occasionally being as large as 36 inches. The oil content of the shale charges ranged from 21 to 48 gallons per ton. Properties of three charges covering the range indicated above are shown in Table 1. Air rates used in these experiments ranged from 0.5 to about 4 $scfm/ft^2$ of retort cross section. Recycle gas-to-air ratios ranged from 0:1 to 1:1. The 10-ton retort has been operated for a total of 30 experiments. Oil yields from these experiments varied widely and ranged up to a maximum of about 80 percent of Fischer assay.

Least squares methods were used to derive linear models relating operating variables to shale oil recovery (9). Multiple regression analysis showed

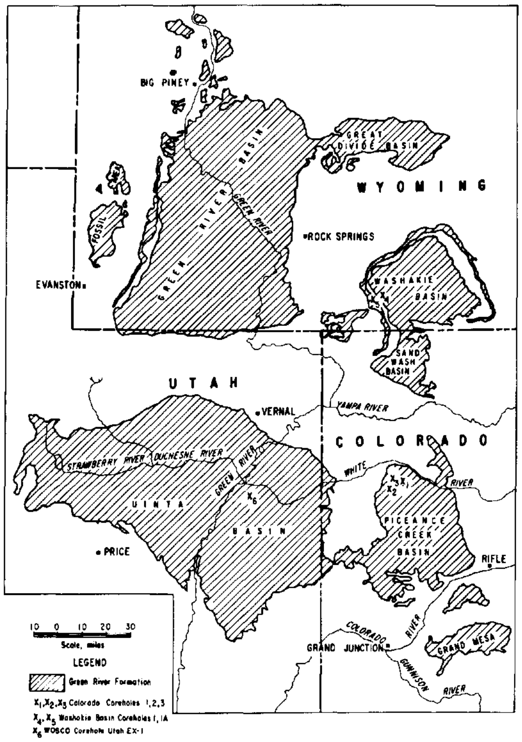

FIGURE 1. - Coreholes in the Green River Formation investigated for nuclear fracturing.

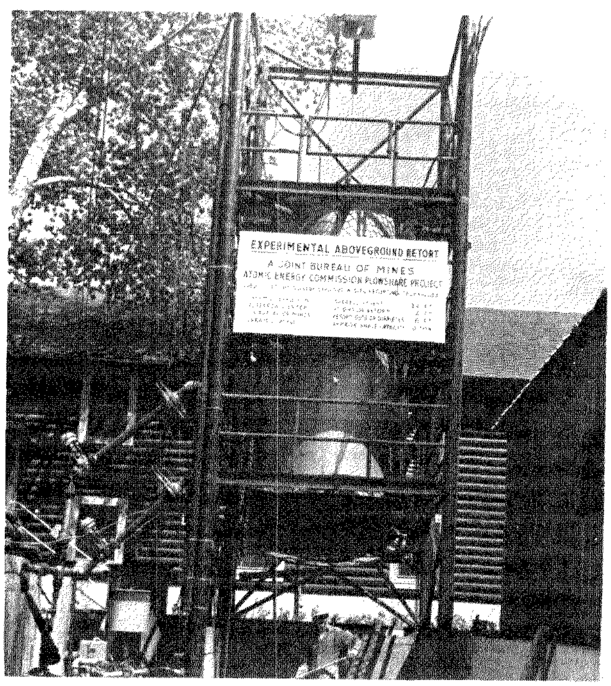

FIGURE 2. - 10-Ton retort.

Table I. - Properties of oil shale charges to 10-ton retort

	Charge number		
	1	2	3
Oil yield by Fischer assay, gal/ton	21.7	30.8	48.0
Water from Fischer assay, gal/ton	3.4	1.8	4.6
Organic ultimate analysis, wt pct			
Carbon	80.27	80.55	81.07
Hydrogen	12.86	11.79	11.30
Nitrogen	2.74	2.53	2.70
Sulfur	4.12	5.12	4.93
Shale particle size, wt pct			
+ 20 inches	-	29	17
12 to 20 inches	5	18	21
6 to 12 inches	22	16	10
$<$6 inches	73	37	52

that, over the ranges investigated, the most significant variables in the study were retorting temperature, recycle gas rate, and assay of the oil shale charge. Retorting temperature is not an independent variable, but depends on the primary variables as well as on heat lost to the surroundings. Further studies are planned to define these relationships.

150-Ton Retort. Because operation of the 10-ton retort on ungraded shale with a maximum size of approximately 20 inches gave recoveries approximately equivalent to those obtained on the N-T-U retort using closely graded shale, it was deemed advisable to determine the effect of scaling up the operation. To do this, a 150-ton retort (Figure 3) was constructed to operate on charges of ungraded material containing pieces up to a maximum of 4 feet on a side. The 150-ton retort is simply a larger version of the 10-ton retort and operates in the same manner with the combustion zone traveling downward through the shale bed. It has a cylindrical steel shell 12 feet in diameter by 45 feet tall, with a refractory lining consisting of 4 inches of insulating castable refractory next to the shell and 6 inches of high-density firebrick next to the charge.

One shakedown run has been made on the retort in which the charge consisted of mine-run, 25-gallon-per-ton shale, containing pieces as large as 3 feet on a side and weighing approximately 2 tons. In addition, the charge contained one 3-foot by 4-foot by 6-foot block of shale weighing 7500 pounds. Six thermocouples were imbedded in this block to permit comparing its heating rate with that of the surrounding bed. Retorting was completed after about $3\frac{1}{2}$ weeks of operation, and the bed was cooled with recycle gas prior to discharge. No operating difficulties were encountered, and temperature histories show that the retorting and combustion fronts advanced uniformly through the bed with little or no channeling or fingering. Because the run was made primarily for shakedown purposes to determine the operability of the unit, operating conditions were varied widely without any attempt at optimization. Oil yield amounted to more than 60 percent of Fischer assay, a most encouraging figure because optimization can be expected to result in substantial improvement in oil yield.

In Situ Processing

The rubble-filled chimney resulting from a nuclear explosion will be surrounded by a relatively large fractured area capable of yielding larger quantities of oil than the chimney. Development of successful methods to process this fractured area will greatly enhance the possibility of successfully applying nuclear explosives to recovery of oil from oil shale. For several years the Bureau of Mines has been conducting in situ experiments near Rock Springs, Wyo., the primary purpose of which is to determine whether oil can be economically recovered from shale fractured by less drastic means than a nuclear explosion. The Rock Springs project was undertaken primarily to investigate non-nuclear approaches to in situ retorting of deposits that are too sparsely covered or too thin to be amenable to the nuclear approach; however the processing problems are closely related to those that can be expected in processing the fractured area surrounding a nuclear chimney.

Fracturing. In an effort to create sufficient permeability in a shale interval to allow ignition and support of a combustion zone, three techniques, used individually and in various combinations, were employed. These were (1) electrolinking, which is fracturing and/or weakening the formation with high-voltage electricity (10); (2) hydraulic fracturing with and without sand propping; and (3) fracturing with liquid and/or solid chemical explosives. Because these techniques in themselves are not of interest from the nuclear application standpoint, they are not discussed in detail in this paper.

Although no definitive method for evaluating the results of these fracturing treatments has been devised, flow testing with compressed air did give some information. It showed that electrolinking resulted in no substantial increase in permeability, but consecutive applications of hydraulic fracturing, sand propping, and explosive fracturing did. By injecting air into one of the wells fractured during this experiment, the following increases in permeability were observed:

Stage of experiment	Injection pressure required to give flow rate of 700 mcfd
After hydraulic fracturing	100.0 psig
After hydraulic fracturing and sand propping	34.8 psig
After explosive treatment	2.2 psig

Underground Retorting. An in situ retorting experiment was performed at the Rock Springs site in the Tipton member of the Green River oil shale formation in a 20-foot-thick section from 68 through 87 feet below the surface. Potential oil yield from this shale section was determined by coring and performing Fischer assays on 1-foot intervals of the core. The 20-foot section, which averages about 22 gallons per ton, was fractured by a combination of the techniques mentioned in the preceding section (10-11). The pattern of the wells utilized for the experiment is shown in Figure 4.

The oil shale formation was ignited in Well No. 5 by means of a propane burner. Air was injected into the well to supply oxygen for combustion of the propane and for combustion of the carbonaceous residue remaining on the retorted shale. After 2 weeks, the burner was shut off and combustion in the formation became self-sustaining, the organic material in the oil shale burning with air supplied from the surface. Combustion was then continued for an additional 4-week period. During the course of this retorting experiment, about 190 barrels of oil were recovered.

From this experiment it was concluded that (1) a combustion zone can be established in the fractured oil shale by use of air injection and a downhole burner; (2) this zone can be maintained and moved through the shale by injection of air; and (3) loss of permeability was not a major problem during this experiment at shallow depths and with the amount of permeability that had been created.

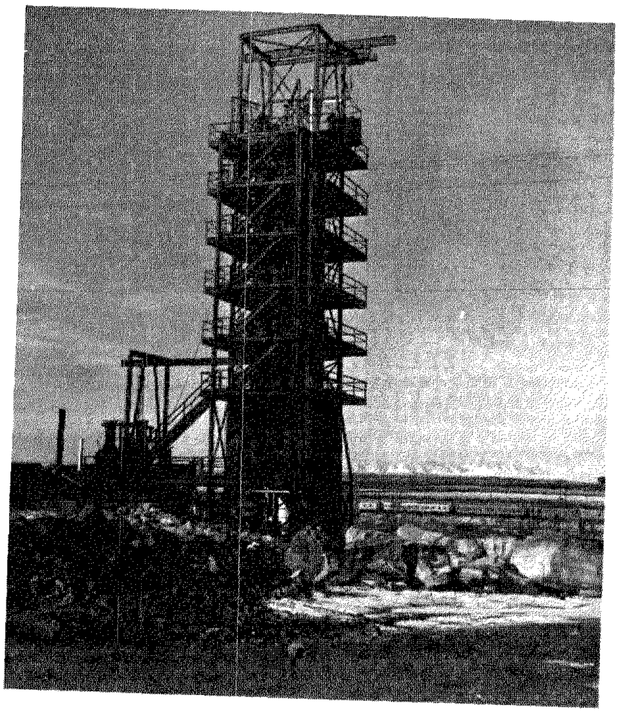

FIGURE 3. - 150-Ton retort.

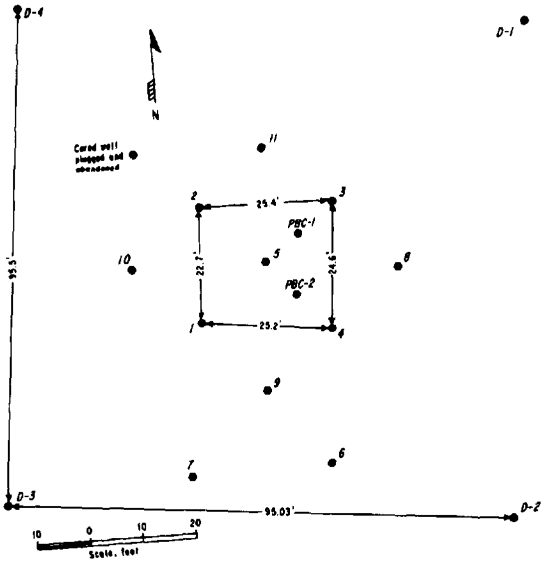

FIGURE 4. - Test well locations, Rock Springs Site 4.

Cores have been taken through the shale section in order to evaluate the areal and volumetric extent of the retorted zone. Examination of the cores is not complete, but preliminary results are given in Table II. These results

TABLE II. - Assays of cores from the in situ experiment

Depth, feet	Original assay, gal/ton	Post-burn assays PBC-1, gal/ton	Post-burn assays PBC-2, gal/ton
68	20.7	22.6	12.3
69	21.1	22.6	21.4
70	16.6	8.8	21.8
71	24.2	3.6	22.2
72	32.2	3.6	20.2
73	28.6	3.6	20.6
74	28.5	13.1	15.8
75	31.7	32.6	14.6
76	32.4	33.2	34.8
77	18.1	20.5	21.0
78	20.2	22.7	22.9
79	15.4	13.8	16.0
80	18.6	19.7	13.9
81	26.6	26.6	28.7
82	21.2	18.9	22.6
83	16.6	11.7	12.2
84	19.8	18.6	17.8
85	24.6	28.3	27.4
86	14.0	18.5	17.7
87	9.2	13.0	10.1

show that a thin but readily discernible retorted zone (70-74 feet) occurs at the location of one of the cores; a similar pattern is not evident at the other location, indicating that retorting did not proceed uniformly from the injection well.

Oil Yields and Properties

Yields and properties of oils obtained from the N-T-U, 10-ton, and in situ processes are given in Table III. The oil from the N-T-U retort has a

TABLE III. - Oil yield and properties

	N-T-U retort	10-ton retort	In situ experiment
Oil yield 1/, vol pct of Fischer assay	79.7	80.4	2/
Selected oil properties:			
Specific gravity, 60°/60°F	0.932	0.915	0.874
Pour point, °F	90	70	20
Viscosity, SUS at 100°F	278	93	45
Nitrogen, wt pct	2.10	1.88	1.35
Sulfur, wt pct	0.79	0.76	0.68
Naphtha, vol pct of crude	2.7	6.7	12.4
Light distillate, vol pct of crude	16.5	18.5	43.4
Heavy distillate, vol pct of crude	31.2	38.2	29.2
Residuum, vol pct of crude	49.6	35.5	12.0

1/ Oil yield from the N-T-U retorts represents yield from a production run. Yield from the 10-ton retort represents approximately the maximum yield obtained.

2/ Not determined.

high pour point and viscosity and large contents of nitrogen and residuum. The oil from the 10-ton retort has somewhat lower values for these properties. The oil from the in situ experiment has more desirable properties than those from the other two processes, as the pour point, viscosity, and amounts of nitrogen and residuum are all substantially lower. These changes may be due in part to secondary thermal cracking reactions.

Minerals

In those areas where nahcolite and dawsonite occur, it appears that they are the principal minerals that should be considered in planning a nuclear experiment in oil shale. Nahcolite occurs in crystal masses from microscopic size to several feet in diameter and occasionally occurs in thin beds. Dawsonite, on the other hand, occurs in small crystals disseminated through the oil shale in continuous sections up to 800 feet thick.

Because of the large market for aluminum, the dawsonite, from which alumina has been produced in the laboratory, seems to be potentially the more valuable of the minerals. As discussed in a previous section, interest in dawsonite utilization is relatively new, and methods for economic processing are considered to be within the realm of possibility with further research. The rock in a nuclear chimney will be in fairly large pieces; hence, it will have relatively small surface area, and extraction of alumina before retorting to produce oil does not seem to offer much promise. Therefore, present research of interest from the nuclear application standpoint is directed toward determining what effect exposure to retorting temperatures has on the extractability of alumina and toward developing and evaluating extraction processes to see whether they may have potential economic value.

Waste Materials

All of the problems that will be encountered in disposal of organic and inorganic wastes from shale processing cannot be established until a processing scheme has been developed. For example, they will be quite different depending on whether or not leaching has been used to recover the associated minerals discussed in the preceding section. However, waters produced during retorting will probably be reasonably similar for all processing schemes, so detailed studies of retort waters are being made to determine what compounds are present, to demonstrate whether any of these can be recovered profitably to offset waste disposal costs, and to develop methods of treatment to render the water innocuous. Consideration is being afforded to both (1) the water that will have to be treated and disposed of aboveground, and (2) the water that will be left underground and that must be handled in such a way as to prevent contamination of ground waters. Waters presently being studied have been obtained from the 10- and 150-ton retorts at Laramie and the in situ combustion experiments at Rock Springs.

DISCUSSION AND CONCLUSIONS

Until the possibility of utilizing a nuclear explosive for fracturing oil shale was proposed some 10 years ago, most efforts to evaluate Green River formation oil shales were devoted to the portions that would be amenable to mining and aboveground retorting, as this was thought to be the only practical approach to the recovery of the resource. With the prospect of utilizing nuclear explosives, increased effort has been devoted during the last 10 years to examining the deeper-lying portions of the formation. Results obtained indicate that there is a very large quantity of oil potentially recoverable from portions of the formation that are sufficiently thick, deeply buried, and remote to be suitable for application of the nuclear approach.

Physical property determinations that have been made on the oil shale indicate that a nuclear explosive should produce a rubble-filled chimney and a surrounding fractured zone. The rubble, before retorting, will have sufficient strength to support itself and very high permeability. However, as the shale is heated toward retorting temperatures, it will have a tendency to become plastic, particularly in the case of higher-grade shales. Also, as the organic material is removed, the shale will lose much of its strength. Much additional information needs to be obtained concerning shale properties, as these properties will have to be considered in such contexts as placement of the nuclear device with relation to rich zones and design of the recovery system for the fractured area around the nuclear chimney.

The increased efforts of the last several years to evaluate the deeper-lying shales that would be suitable for a nuclear recovery process have indicated that certain of these shales contain associated minerals that may be recoverable along with the oil normally sought from oil shale. The presence of these minerals should not have any effect on the proposed experiments to determine whether or not nuclear fracturing and subsequent retorting offer promise as a means of recovering oil from oil shale. However, if these experiments indicate that this method has merit for the recovery of oil, economic recovery of the associated minerals, if suitable methods can be developed, could have a definite effect on the commercial application of the overall technique. Research has not yet progressed far enough to indicate how likely this possibility may be.

Experiments on the 10- and 150-ton retorts at Laramie are designed to give data which will indicate whether or not there is a reasonable chance of retorting successfully the ungraded rubble in a nuclear chimney. Results from the 10-ton retort showed that recoveries of approximately 80 percent of Fischer assay could be achieved on charges having pieces with maximum dimensions of 20 inches. Because of these encouraging results, the research has been scaled up to the 150-ton retort which has so far had only one shakedown run. However, this run was conducted without difficulty on a charge containing pieces as large as 3 feet by 4 feet by 6 feet, and weighing 7500 pounds, to give a recovery of about 60 percent of Fischer assay. Recoveries from the two retorts were achieved over a reasonably wide range of operating conditions, indicating that the process was not unduly sensitive to operating variables. Pressure drops across the beds in both retorts were less than 0.2 inch of water and did not increase appreciably during retorting, indicating that neither pressure drop nor pressure buildup in a nuclear chimney would be a problem in retorting the rubble column.

Research designed specifically to study problems involved in recovering oil from the fractured area surrounding the nuclear chimney is not in progress. However, in situ combustion experiments on shale fractured by combinations of electrolinking, hydraulic pressure, and chemical explosives are yielding data pertinent to the problems. Results indicate that combustion can be started and maintained in shale that has been fractured with some as-yet-undetermined degree of similarity to the broken material that presumably will surround a nuclear chimney. Although these results are encouraging, the present research is on a narrow shale interval (20 feet) at shallow depths, so results cannot be projected directly to the nuclear experiments. Planned research at depths of several hundred feet should yield more pertinent data.

LITERATURE CITED

1. The Bronco Oil Shale Study. PNE-1400, Clearinghouse for Scientific and Technical Information, Springfield, Va., October 1967, 64 pp.

2. Lombard, D. B., B. G. Bray, and H. W. Sohns. Technical Considerations for Plowshare Applications. Proceedings, Symposium on Engineering with Nuclear Explosives, January 1970, in press.

3. Dana, G. F. Bureau of Mines-Atomic Energy Commission Colorado Corehole No. 3, Rio Blanco County, Colorado. Bureau of Mines Open File Report, Laramie Petroleum Research Center, 1968.

4. Tisot, P. R., and H. W. Sohns. Structural Response of Rich Green River Oil Shales to Heat and Stress and Its Relationship to Induced Permeability. Preprints, Division of Petroleum, American Chemical Society, v. 14, No. 3, 1969, pp. B94-B104.

5. Smith, J. W., and Charles Milton. Dawsonite in the Green River Formation of Colorado. Economic Geology, v. 61, 1966, pp. 1029-42.

6. Smith, J. W., and N. B. Young. Determination of Dawsonite and Nahcolite in Green River Formation Oil Shales. Bureau of Mines Report of Investigations 7286, 1969, 20 pp.

7. Sohns, H. W., L. E. Mitchell, R. J. Cox, and W.I.R. Murphy. Heat Requirements for Retorting Oil Shale. Ind. Eng. Chem., v. 43, No. 1, 1951, pp. 33-36.

8. Ruark, J. R., K. L. Berry, and Boyd Guthrie. Description and Operation of the N-T-U Retort on Colorado Oil Shale. Bureau of Mines Report of Investigations 5279, 1956, 26 pp.

9. Carpenter, H. C., and H. W. Sohns. Application of Aboveground Retorting Variables to In Situ Oil Shale Processing. Colorado School of Mines Quarterly, v. 63, No. 4, October 1968, pp. 71-82.

10. Melton, N. M., and T. S. Cross. Fracturing Oil Shale with Electricity. J. of Petrol. Technol., v. 20, No. 1, January 1968, pp. 37-41.

11. Miller, J. S., and W. D. Howell. Explosive Fracturing Tested in Oil Shale. Colorado School of Mines Quarterly, v. 62, No. 3, July 1967, pp. 63-73.