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AEROSOL SAMPLING AND CHARACTERIZATION IN THE DEVELOPING U. S. OIL SHALE INDUSTRY*

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ABSTRACT

Aerosol sampling and characterization studies of workplace air were conducted at four demonstration-scale oil shale facilities located in northwestern Colorado and northeastern Utah. These facilities consisted of an underground mining/aboveground retorting facility, two modified _in situ_ retorting facilities with associated underground mining, and a true _in situ_ retorting facility. Emphasis was placed on study of the retorting phase of operation at these facilities.

Aerosol samples were collected on filter media by high volume air samplers, low volume portable sampling pumps with or without cyclone pre-separators, and cascade impactors. Samples were analyzed to determine total and respirable dust concentrations, particle size distributions, free silica content, total benzene or cyclohexane extractables, and selected polynuclear aromatic hydrocarbons. Total and respirable dust were observed to range from very low to very high concentrations, with significant free silica content. Measurable levels of polynuclear aromatic hydrocarbons were also observed at each of the facilities.

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INTRODUCTION

The United States contains extensive oil shale deposits. The known high-grade resources of the Green River Formation of Colorado, Utah and Wyoming are estimated to contain some 500 billion barrels of crude oil equivalence [Yen (1976)]. Other lower-grade deposits cover wide areas of the eastern United States. As much as 400 billion barrels of shale oil could be recovered economically with existing technology [Office of Technology Assessment (1980)]. At current rates of consumption, these resources alone could potentially meet the crude oil needs of the United States for more than 50 years.

Oil shale contains an organic material known as kerogen which yields combustible gases and shale oil when heated (retorted) to some 500°C. A solid waste residue, known as spent or retorted shale, remains from this process which accounts for 85 to 90 percent by weight of the original material. Although there is currently no commercial shale oil industry in the United States, various oil shale retorting technologies are being developed. Current developments support the expectation that several commercial-scale facilities (employing thousands of workers) will begin operation in the western U. S. within the next five years. By 1995, the Green River Formation is projected to yield some 300,000 barrels per day of shale oil [Department of Energy (1980)].

Processes being developed to retort oil shale may be classified as 1) aboveground retorts, in which the oil shale is mined and transported to metal retorting vessels located on the ground surface, and 2) _in situ_ retorts, in which the oil shale is blasted by explosives to form retorts in the ground. _In situ_ retorts being developed include both true _in situ_ retorts in which no mining occurs prior to creation of a retort, and modified _in situ_ retorts in which 20 to 40 percent of the oil shale is mined prior to creation of a retort. Five types of aboveground retorting technologies appear likely to reach commercial status within the next ten years. These consist of the Paraho, TOSCO II, Union B, Lurgi Ruhrgas and Superior retorting technologies. Two companies are actively developing modified in situ retorting methods, and one company is developing a true in situ retorting method.

Because of the limited experience with the oil shale recovery processes and the materials processed and produced, little is known of the health and environmental consequences of oil shale development. Experience in Scotland and the U. S. S. R. suggest the potential for cancer (particularly skin cancer) and pneumoconiosis as primary health concerns [Weaver and Gibson (1979)]. A number of studies are being conducted to evaluate health hazards associated with the shale oil extraction processes being developed in the U.S. These studies include characterization of potential releases to the environment, toxicological testing of materials associated with the production of shale oil, and medical examinations of workers at oil shale facilities [Petersen (1980), Rom and Archer (1980), Weaver and Gibson (1979)].

This paper describes aerosol sampling and characterization studies of workplace air at four demonstration-scale oil shale facilities located in northwestern Colorado and northeastern Utah. The primary objectives of the studies were to 1) characterize potential inhalation exposures associated with shale oil extraction processes for use in the design of toxicological studies on oil shale materials and to determine if unique potential hazards exist, and 2) obtain bulk samples of oil shale materials for toxicological studies. Emphasis has been placed on the study of the retorting phase of oil shale processing because retorting appears most likely to produce hazards which may be unique relative to industrial processes already in commercial use. In particular, the modified in situ processes may present unique exposure problems due to the proximity of miners preparing retorts underground while previously-prepared retorts are burning.

DESCRIPTION OF FACILITIES

Facilities studied to date have consisted of an aboveground retorting facility, two modified *in situ* (MIS) retorting facilities, and a true *in situ* retorting facility. All of these facilities process oil shale from the Green River Formation of Colorado and Utah. The aboveground retorting facility, developed by the Paraho Development Corporation, is located at the U. S. Department of Energy Anvil Points Oil Shale Mine and Retorting Facility near the town of Rifle, Colorado. The true *in situ* retorting facility, operated by Geokinetics, Inc., is located near Vernal, Utah. The MIS retorting facilities, operated by Occidental Oil Shale, Inc. and the Rio Blanco Oil Shale Company, are located near DeBeque and Rangely, Colorado, respectively.

Aboveground retorting. Process unit operations at the aboveground retorting facility consisted of mining, transportation of the oil shale to the retorting facility, crushing and sizing of the oil shale, retorting, and spent shale disposal. Underground mining of the oil shale was conducted using room-and pillar mining with conventional mining techniques. A working face was drilled, loaded with a mixture of prilled ammonium nitrate and fuel oil, and blasted. The broken shale was then scooped up with a front-end loader, placed into a haul truck for removal from the mine, and trucked to the retorting area located at the base of the mountain. Extraction of shale oil was accomplished by first crushing the rock through primary, secondary and tertiary crusher stages to obtain material of 1.3 to 7.6 cm size range which was placed into storage bins (material finer than 1.3 cm was discharged to a waste pile). From the storage bins, the sized oil shale was conveyed to either a pilot-scale retort or a larger semiworks retort. Both retorts utilized the Paraho process.

The Paraho retort, shown in Figure 1, consists of a refractory-lined vertical kiln in which crushed shale moves downward by gravity with the shale feed rate controlled by moving grates at the bottom of the kiln. Gases and vapors are pulled upward during retorting, countercurrent to the flow of the oil shale. The retort may be operated in either an indirect heating mode (in which gases are heated before injection into the retort) or a direct heating mode (in which residual carbon on the oil shale is burned in the retort to provide hot gases). Only the direct combustion mode was used during this study. In this mode, hot gases pass from the combustion zone into the retorting zone, pyrolyzing the kerogen within the shale and producing gases and vapors. As these gases and vapors ascend through the decending oil shale. the shale is preheated and vapors are condensed into oil mist droplets which are carried out of the retort and collected. A portion of the retort offgases are mixed witn air and reinjected into the retort to help cool the spent shale and support additional combustion. The amount of air injected is carefully controlled to maintain the desired temperature profile within the retort. Excess retort gas is burned in a thermal incinerator.

True in situ retorting. In the Geokinetics horizontal in situ process, a pattern of holes are drilled from the ground surface through the overburden and into a bed of oil shale. The drill holes are loaded with explosives which are detonated by a very carefully timed and placed blast pattern. A portion of the overburden and ground surface are uplifted to provide void space necessary for breaking the shale into the desired size and making the shale permeable to gas flow. The retort is also formed with a sloped bottom to allow shale oil and water produced during retorting to flow to sumps. Wells are drilled for injection of air at one end of the retort, and wells for removal of air are drilled at the middle and at the other end of the retort. Wells for production of shale oil and water are also drilled into the sumps created by blasting. Surface facilities installed consist of blowers and piping for injection and removal of air and offgases, pumps for removal of retort products, demisters, storage tanks and a thermal incinerator. A diagram of a Geokinetics true in situ retort is shown in Figure 2.

The oil shale in the in situ retort is ignited at the inlet air wells with burning charcoal, and a flame front is established which moves horizontally across the bed of oil shale towards the air outlet wells. Oil shale is retorted ahead of the flame front by the hot combustion gases as they flow through the retort. Vapors condense as they contact cooler shale, and retort products flow to the sumps and are pumped to the surface.

Modified in situ retorting. Because of the necessity to uplift the ground surface to provide void space within the retort, the Geokinetics true in situ process is limited to relatively shallow oil shale deposits. Much of the high-grade oil shale in the Green River Formation is overlain with several hundred feet or more of overburden. The modified in situ processing of oil shale uses underground retorts in which extractive mining is employed to provide the desired void space. Explosives are then used to form the retort and break the oil shale into the desired particle size and permeability. The MIS process being developed by Occidental Oil Shale, Inc. is based upon mining out some 20 percent of the shale prior to the creation of a retort, while that of the Rio Blanco Oil Shale Company is based on mining out some 40 percent prior to blasting of the retort. Once a retort is formed, air blowers and pumps are connected to the retort for circulation of gases to control combustion and remove retort offgases. Both of these MIS processes utilize vertical retorts which are burned from top to bottom with the gas flow in the sump, and is pumped to the surface. A diagram of a modified in situ retort is shown in Figure 3.

AEROSOL SAMPLING AND ANALYSIS

Several types of aerosol samples were collected at each of the facilities described above. Samples were collected on various filter media by high volume air samplers, low volume portable sampling pumps with or without cyclone pre-separators, and cascade impactors. Most samples were "area samples" taken around process units or areas rather that "personal samples" obtained on employees, and results do not reflect exposures of employees at these facilities. Because of the demonstration nature of the facilities, employees tended to rotate jobs or work assignments, and process operations were in some cases also intermittent or sequential in nature. An attempt was made to sample areas of expected maximum concentrations in order to characterize potential exposures near process units or process areas where employees in a commercial operation might be exposed for extended periods of a workshift. Emphasis was placed upon study of the retorting operation because retorting appears most likely to produce hazards which may be unique relative to industrial processes currently in use.

Total dust concentrations were determined using open-face filters followed by gravimetric analysis. Respirable dust concentrations were determined using the Bureau of Mines respirable dust sampler which consists of a 10 mm nylon cyclone pre-separator followed by a 37 mm filter for collection of the respirable mass. This unit was operated at a flowrate of 1.7 Lpm to match the American Conference of Governmental Industrial Hygienists (ACGIH) criteria for respirable dust [ACGIH (1981)]. Particle size was determined by Andersen eight-stage cascade impactor (Andersen Samplers, Inc., Atlanta, Georgia) with impaction surfaces covered by membrane filters, and gravimetric analysis of the mass collected on each stage.

Free silica content was determined on selected total and respirable dust samples collected on PVC filters. Those from the aboveground retorting facility were analyzed by the infrared spectrometric method [Freedman et al (1974)], while those from the other three facilities were analyzed by x-ray diffraction [NIOSH (1977a)] at a private laboratory accredited for free silica analysis by the American Industrial Hygiene Association.

Selected samples were extracted by benzene or cyclohexane via sonic agitation, with subsequent evaporation and gravimetric analysis of an aliquot of the extract to obtain total benzene or cyclohexane extractables. Selected cyclohexane extracts of filters or membrane impaction surfaces from two facilities were analyzed for 7 or 8 specific polynuclear aromatic hydrocarbons by high performance liquid chromatography (HPLC). Extracts from samples from the two other facilities were analyzed by gas chromatography/mass spectrometry (GC/MS) for 16 specific polynuclear aromatic hydrocarbons (PAH) and 5 specific polynuclear heterocyclic nitrogen compounds (N-PAH). The specific PAH and N-PAH analyzed by each method are listed in Table 1.

One set of membrane impaction surfaces from an impactor sample collected at the aboveground retorting facility was subjected to direct-current arc-excited emission spectrographic elemental analysis to evaluate segregation of elements by particle size. Certain filter samples from the true <u>in situ</u> facility were also sent to a laboratory specializing in elemental analysis by the proton induced x-ray emission (PIXE) technique.

More detailed information regarding sampling and analytical techniques, as well as more detailed information regarding the facilities, sampling locations, etc. is available in specific reports on each of the facilities [Garcia et al (1981), Gonzales et al (In press), Hargis et al (In preparation), Oil Shale Task Force (1980)]. These reports also contain information regarding sampling for a number of inorganic and organic gases and vapors at the facilities.

RESULTS AND DISCUSSION

Underground mining/aboveground retorting. Results from dust sampling and analysis at the Anvil Points underground mining/aboveground retorting facility are presented in Table 2. Both total and respirable dust concentrations were high in areas associated with mining, crushing, crushed-shale storage, retorting and spent shale disposal. Total and respirable dust concentrations should not be directly compared because they were not taken simultaneously or even at the same locations. In some cases, the respirable dust concentrations exceed the total dust concentrations in the same general area because concentrations vary considerably in time and space. Free silica content of the dusts was observed to range from 5 to 9 percent in ten air samples taken near the crusher and retort, and 4 percent in the single mine air sample analyzed. Particle size varied at the different operations, with smaller average particle sizes in the mine, tertiary crushing area, shale storage bins, and retort inlet than observed in primary and secondary crushing areas, retort outlet and spent-shale disposal areas. Emission spectrographic analysis of a cascade impactor sample taken in the crusher area showed no evidence of any segregation of elements on any particular particle size range.

The working faces within the Anvil Points mine at the time of the study were some distance from the outlet of the ventilation system and were not effectively ventilated. The mine is relatively dry which may also have contributed to the dust problem. The crusher was not originally designed for crushing of oil shale, and (although equipped with water sprays) was not enclosed as might be expected in a commercial operation. Much of the auxiliary equipment utilized at this facility was salvaged from earlier operations at the site, and blowers and seals were not gas tight. All of these factors contributed to the fugitive emissions.

Respirable dust sampling was also previously performed in the Anvil Points facility by the U. S. Bureau of Mines [Volkwein and Flink (1977)]. Volkwein reported average quartz percentages of operations in the mine at 1.5-5.25 percent, while those in the crushing, screening and bin storage areas ranged from 13 to 22.5 percent. The lower average percentage in the mine was attributed to dilution of the mineral dust by diesel exhaust particulates.

Assuming a quartz content of 10 percent, the present threshold limit value, or TLV, for total dust is 2.5 mg/m^3 and 0.8 mg/m^3 for respirable dust [ACGIH (1981)]. The majority of the dust samples reported in Table 2 exceed these levels. Although quartz levels observed in the mine were lower, most of the mine samples would exceed the TLV for dusts containing only 5 percent quartz of 3.8 mg/m^3 for total dust and 1.4 mg/m^3 for respirable dust. This does not necessarily mean that employees were being overexposed because the TLV is based on an 8-hour time-weighted average, and employees did not remain for 8 hours where most of the samples were taken. Because of the developmental nature of the Paraho retort, mining activities were sequential in nature and miners did not spend full shifts at one task. Operators of the crusher, retort and spent-shale coveyors worked inside enclosures and were not exposed to the higher dust concentrations. The data on dust concentrations and free silica content do indicate that dust control and/or respiratory protection will be required at commercial facilities where workers remain underground or near process operations for major portions of a work shift.

The cyclohexane extracts (assumed to constitute "total hydrocarbon content", or THC) of raw shale and spent shale samples and several filter samples from the Anvil Points mine, crusher, retort and spent shale disposal areas were analyzed by GC/MS for 16 specific PAH and 5 specific polynuclear heterocyclic nitrogen compounds as listed in Table 1. Tentative observations on the results of these few samples are: 1) the THC content of the sample of the mine atmosphere was high relative to bulk raw shale and crusher samples, indicating that the air sample probably contained organic components from diesel exhaust; 2) the spent shale was lower in THC than the raw shale, but the PAH content of the THC from the spent shale was higher than from the raw shale; and 3) there appeared to be little difference in the ratio of non-nitrogen to nitrogen PAH between raw and spent shale. Similar analyses on impactor samples taken in the crusher, retort and spent shale pile indicate that: 1) the amount of THC per unit weight of sample increased as the particle size decreased (which may be partially due to increased effectiveness of extraction for small particles); and 2) that the fraction of PAH in the THC increased with smaller particle size for samples composed principally of spent shale.

Several high-volume sampler filters and bulk raw and spent shale samples were extracted by benzene. Benzene is the solvent traditionally used for extraction of organic material, but cylohexane is now recommended by NIOSH due to a finding that benzene causes leukemia [NIOSH (1977b)]. The amount of THC measured by benzene extraction indicates that benzene may be more effective in extraction of such samples than cyclohexane. The results of analysis of the benzene extracts for PAH also confirm that while THC was lower in the spent shale than the raw shale, the PAH fraction in the THC from spent shale was higher than in the raw shale.

The composition of airborne organic materials in the operations associated with aboveground oil shale retorting has not been well defined or characterized. The organic content is extremely complex with several hundred compounds indicated by gas chromatography. The results of analyses for PAH and heterocyclic nitrogen compounds indicate that the materials contain compounds considered to be carcinogenic and compounds which may be carcinogenic. No standards or TLVs exist for most of these compounds at this time because litle is known of the effects of the pure compounds or the combinations of such compounds in complex mixtures. A great deal of work in the characterization and toxicology of these materials is required.

True in situ retorting. The results of aerosol sampling at the Geokinetics horizontal in situ retorting facility are presented in Table 3. Very low concentrations of dust were observed in the retort area. This was expected as no dust generation sources were present during retort operation. The retort area was open to the atmosphere, and most dust was likely generated by traffic on unpaved roads which surrounded the retort and from windblown dust. Somewhat higher (but still quite low) concentrations were observed in the area around a demister and exhaust fan which carried retort offgases. These process units experienced some leakage of retort offgases and oil mists.

The few dust samples taken in the area of drilling of blastholes for another retort indicated high concentrations of total dust in the immediate vicinity of the drilling operation. Personal sampling indicated that employee exposures were less than 1 mg/m^3 because the employees usually worked within an enclosure or stayed outside the area of the highest dust levels.

Free silica content of the dusts at this facility was observed to range from 2 to 7 percent. Average particle size of the dusts observed during retorting was relatively small, with approximately 50 percent by mass of the dust considered respirable by the ACGIH criteria [Moss and Ettinger (1970)]. Dust levels, however, were very low. No cascade impactor samples were collected in the area of the drilling operation.

Fugitive organic emissions (with possible condensation of organic material on particles) were a potential concern as the retort was sealed only by overburden which had been severely cracked during blasting. Cyclohexane extracts of a number of samples from various areas of the retort and auxiliary equipment were analyzed by HPLC for eight specific PAH, as listed in Table 1. The sum of the eight PAH analyzed was observed to be up to 55 $\mu g/m^3$ in the area of the leaking demister and fan carrying retort offgases, although not detectable in 10 of 12 samples from the area above the retort. Levels of PAH observed at the true _in situ_ retorting facility were considerably higher than at the other three oil shale facilities.

Several high volume sampler filters from this facility were divided into sections with extraction of the sections by either benzene or cyclohexane. Total extractable content or THC was observed to be slightly higher with benzene than cyclohexane, consistent with our results on the Anvil Points samples. However, the PAH content (sum of the 8 PAH analyzed) was no higher within the THC extracted by benzene than within the THC extracted by cyclohexane.

Modified in situ retorting. Results of aerosol sampling at the Occidental Oil Shale, Inc. modified _in situ_ retorting facility are presented in Table 4. These samples were collected within the mine during the burn of an underground retort. Samples were collected in the lower level of the mine in ventilation and transport drifts, near the control room, and close to a separation tank. Relatively low levels of total and respirable dust were observed. Because the principal interest was in evaluating potential occupational exposures in the vicinity of the burning retort, samples were not collected near areas of active mining where the highest dust concentrations might be expected to occur. Results of cascade impactor samples indicate a relatively small average particle size, with 50-60 percent by mass of the dust considered respirable by the ACGIH criteria [Moss and Ettinger (1970)]. Analysis of respirable dust samples for free silica content indicated less than 10 percent free silica by mass, but insufficient material was collected on the filters for precise analysis. Assuming that the free silica content was 10 percent, only one of the samples would be above the TLV. This sample was not collected at a work station, but was taken on the wall of a drift and was probably influenced by dust generated by mine vehicles.

One potential concern with the MIS retorting of oil shale is the possible release of fugitive organic emissions from a burning retort and subsequent condensation of organic materials onto particle surfaces. Cyclohexane extraction of several high volume filter samples from the Occidental mine indicated total extractable content similar to that expected for raw oil shale. Analysis of the cyclohexane extracts by GC/MS indicated levels of PAH equivalent to those observed at the aboveground retorting facility (where the same analytical method was employed).

Results of aerosol sampling within the mine at the Rio Blanco Oil Shale Company MIS retorting facility are presented in Table 5. Levels of total and respirable dust were relatively low. A few samples were taken nearer mining activities such as shale crushing and dumping to close up an opening to build a bulkhead or shortly after blasting and mucking operations on another mine level. Samples identified as "pre-burn" were taken prior to the ignition of the underground retort, while those identified as "during burn" were taken after ignition of the retort. This mine is very wet with several inches of water standing in many areas of the mine. Classification of the mine as a "gassy" mine due to the presence of methane gas (this was not related to operation of the retort) resulted in restrictions on the location of some types of sampling equipment. Impactor samples taken prior to ignition of the retort were closer to ongoing mining activity, and this factor probably accounts for the observed difference in particle size.

Free silica content of the dusts within the Rio Blanco mine were observed to range from 1 to 4 percent. All of the samples were well below the TLV for total and respirable dust, assuming a free silica content of 5 percent.

A number of filters and impactor surfaces were extracted by cyclohexane and analyzed for seven specific PAH (fluorene was not analyzed) by HPLC. The presence of PAH did not appear to be related to particle size. There did, however, appear to be an increase in average PAH concentration in samples collected during the burn relative to those collected prior to the burn.

SUMMARY AND CONCLUSIONS

Workplace aerosol sampling and characterization studies were conducted at four demonstration-scale oil shale retorting facilities. Observed dust concentrations were highly variable, with a substantial respirable fraction. Free silica content ranged up to 9 percent. Considering the free silica content of the dusts, levels of both total and respirable dust in the area of a number of operations could exceed extablished threshold limit values if workers remained in the area for extended periods of a workshift. Similar operations in commercial facilities will require dust controls and/or respiratory protection for workers.

The organic material extracted from aerosols collected at oil shale facilities consists of a very complex mixture of components which are not well characterized. Measurable levels of polynuclear aromatic hydrocarbons, which are of concern as carcinogens, were observed at each of the four facilities studied. No standards or TLVs exist for these organic compounds at this time, and the health significance of such levels of PAH or of the total mixture of organic and mineral components is not known. Additional work in characterization and toxicology of airborne materials at oil shale facilities is required.

ACKNOWLEDGEMENTS

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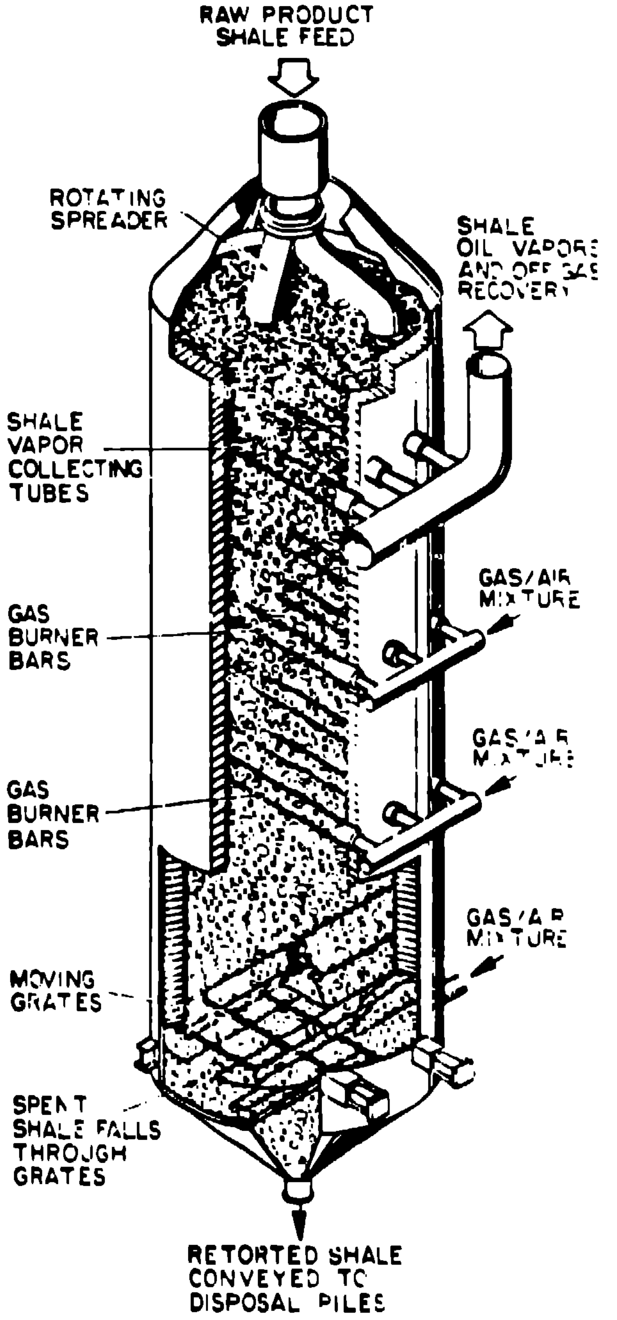

FIGURE 1

THE PARAHO ABOVEGROUND OIL SHALE RETORT
[From Rudnick et al (1980)]

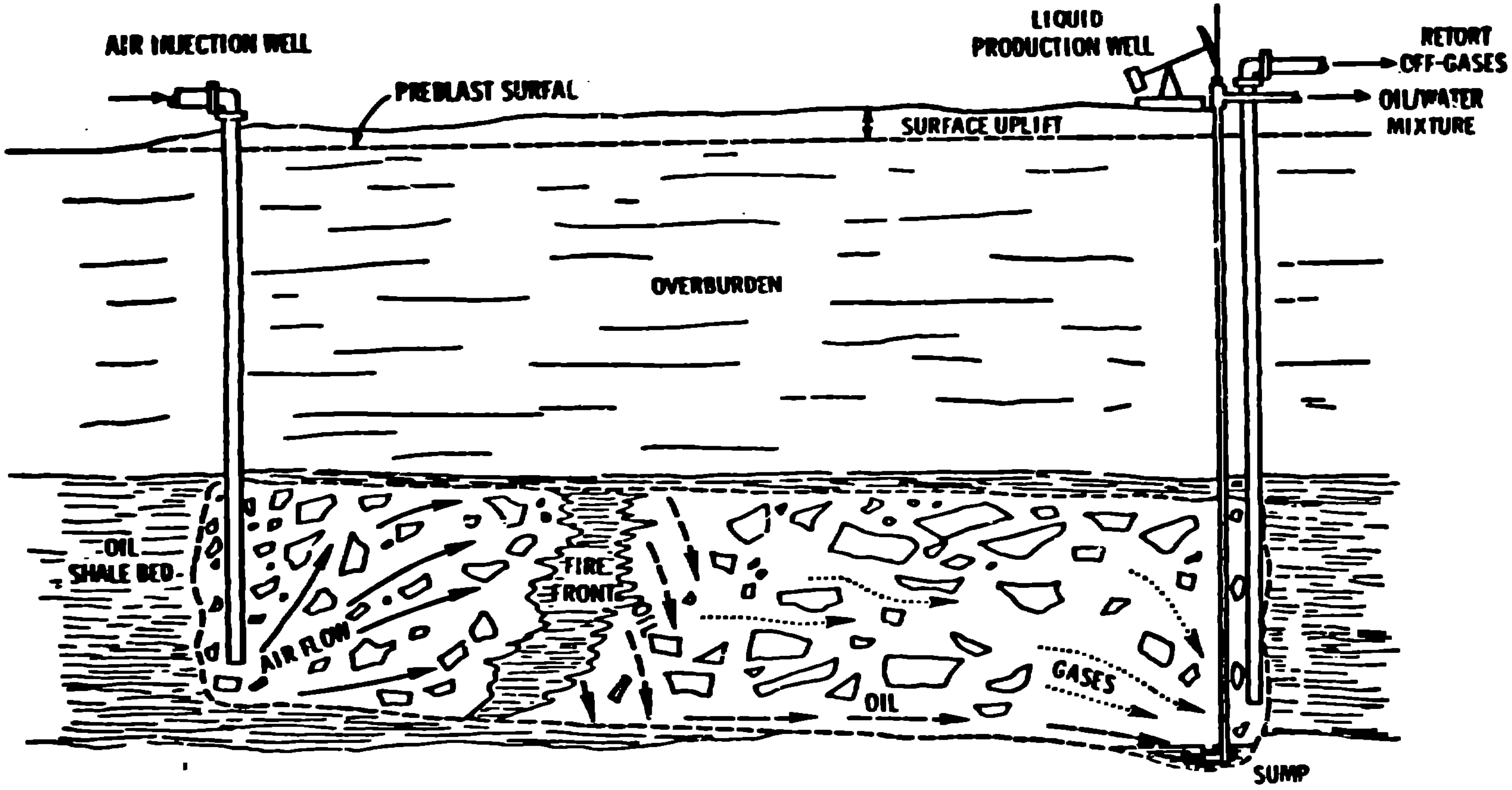

FIGURE 2

THE GEOKINETICS TRUE IN SITU OIL SHALE RETORT
[From Rinaldi et al (1981)]

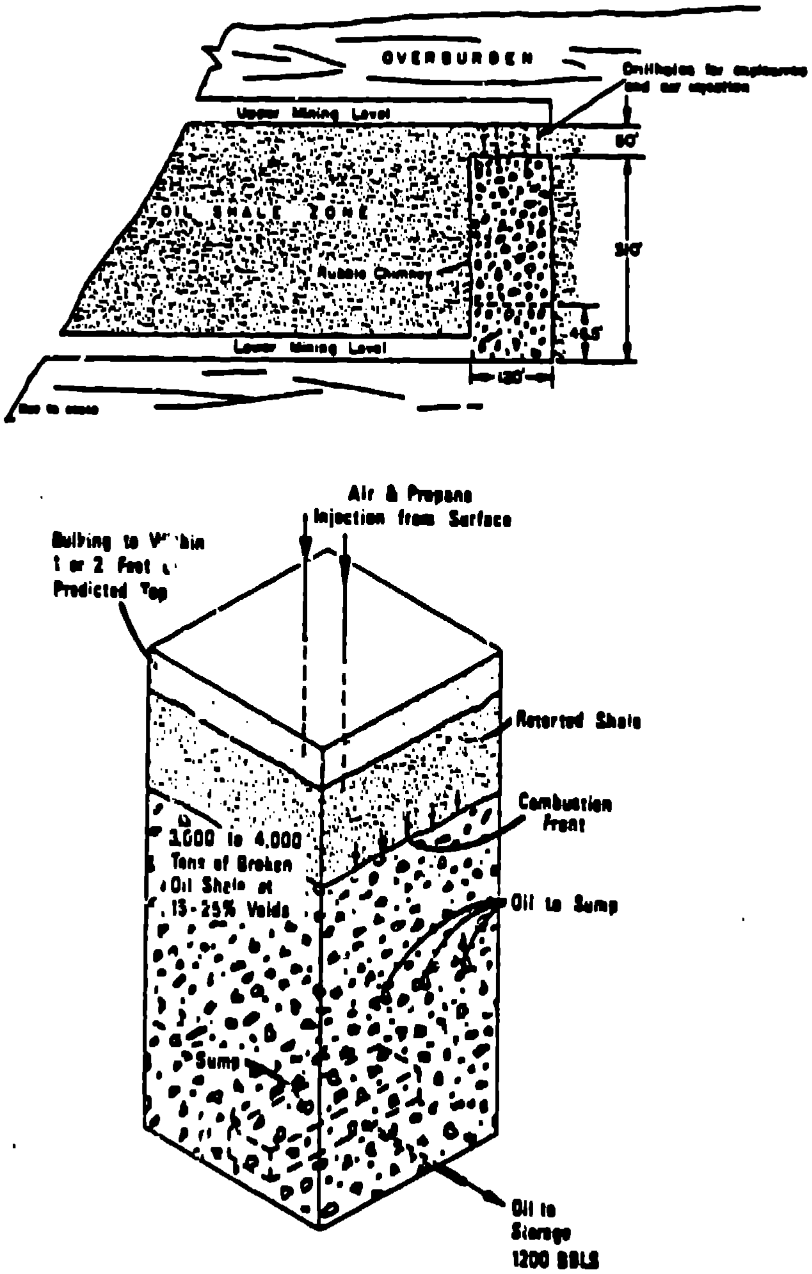

FIGURE 3

OCCIDENTAL MODIFIED IN SITU OIL SHALE RETORT
[From Bates and Thoem (1980)]

TABLE 1
POLYNUCLEAR AROMATIC HYDROCARBONS AND POLYNUCLEAR HETEROCYCLIC NITROGEN COMPOUNDS ANALYZED

By High Performance Liquid Chromatography

Acenaphthene
Anthracene
Benzo(a)pyrene
Chrysene
Fluoranthene
Fluorene
Pheneanthrene
Pyrene

By Gas Chromatography/Mass Spectrometry

Acenaphthalene
Anthracene
Benzo(a)pyrene
Benzo(e)pyrene
Benzo(g,h,i)perylene
Chrysene
Dibenz(a,h)Anthracene
7,12-Dimethylbenzanthene
Fluoranthene
Fluorene
3-Methylcolanthrene
Naphthacene
Naphthalene
Perylene
Phenanthrene
Pyrene

Acridine
1-Azapyrene
Benzo(f)quinoline
Benzo(h)quinoline
Carbazole

TABLE 2
DUST SAMPLING AND ANALYSIS
ANVIL POINTS UNDERGROUND MINING/ABOVEGROUND RETORTING FACILITY

PARAMETER AND LOCATION	NO. OF SAMPLES	CONCENTRATION			PARTICLE SIZE		
		Max.	Mean	Unit	No. of Samples	MMAD[a] (µm)	GSD[b] (σ_g)
Total Dust							
Within Mine	14	31.9	12.0	mg/m^3	1	2.2	3.5
Crusher Area	10	47.2	21.1	mg/m^3	3	4.0	4.0
Retort Area	38	90.8	25.6	mg/m^3	9	4.9	3.3
Spent Shale Disposal	8	18.6	8.0	mg/m^3	2	6.3	2.2
Respirable Dust							
Mine Area	5	14.6	5.9	mg/m^3			
Crusher Area	7	20.0	7.3	mg/m^3			
Retort Area	27	15.6	3.3	mg/m^3			
Spent Shale Disposal	9	16.7	6.8	mg/m^3			
Free Silica Content							
Mine Area	1	---	4	Percent			
Crusher/Retort Areas	10	9	7	Percent			
Cyclohexane Extractables							
Mine Area	1	---	0.58	Percent			
Crusher Area	4	0.27	0.22	Percent			
Retort Area	2	0.26	0.17	Percent			
Spent Shale Disposal	1	---	0.08	Percent			
PAH Content[c]							
Mine Area	1	---	995	ng/g			
Crusher Area	4	493	428	ng/g			
Retort Area	2	382	308	ng/g			
Spent Shale Disposal	1	---	166	ng/g			

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[a] MMAD = mass median aerodynamic diameter

[b] GSD = geometric standard deviation

[c] Sum of 16 PAH and 5 N-PAH, analysis by GC/MS.

TABLE 3
DUST SAMPLING AND ANALYSIS
GEOKINETICS TRUE IN SITU RETORTING FACILITY

PARAMETER AND LOCATION	NO. OF SAMPLES	CONCENTRATION Max.	Mean	Unit	PARTICLE SIZE No. of Samples	MMAD[a] (μm)	GSD[b] (σ_g)
Total Dust							
Area Above Retort	30	0.54	0.06	mg/m^3	2	4.0	3.8
Offgas Blower Area	11	0.30	0.12	mg/m^3	1	3.3	4.8
Drilling Operation							
Area Samples	3	85.1	32.2	mg/m^3			
Personal Sample	1	----	0.8	mg/m^3			
Respirable Dust							
Area Above Retort	1	----	0.02	mg/m^3			
Drilling							
Area Sample	1	----	3.4	mg/m^3			
Personal Sample	1	----	0.04	mg/m^3			
Free Silica Content							
Area Above Retort	2	7	5	Percent			
Drilling Area	3	4	3	Percent			
Cyclohexane Extractables							
Area Above Retort	13	37.8	6.1	Percent			
Offgas Blower Area	7	31.4	13.8	Percent			
PAH Content[c]							
Area Above Retort	12	0.31	0.04	10^6 ng/g			
Offgas Blower Area	6	33.1	1.8	10^6 ng/g			

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[a] MMAD = mass median aerodynamic diameter

[b] GSD = geometric standard deviation

[c] Sum of 7 PAH, analysis by HPLC.

TABLE 4
DUST SAMPLING AND ANALYSIS
OCCIDENTAL MODIFIED IN SITU RETORTING FACILITY

PARAMETER AND LOCATION	NO. OF SAMPLES	CONCENTRATION			PARTICLE SIZE		
		Max.	Mean	Unit	No. of Samples	MMAD[a] (μm)	GSD[b] (σ_g)
Total Dust							
Within mine	14	1.0	0.5	mg/m^3	6	2.8	3.6
Respirable Dust Within Mine	7	1.2	0.4	mg/m^3			
Free Silica Content Within Mine	4	---	<10	Percent			
Cyclohexane Extractables Within Mine	5	0.28	0.25	Percent			
PAH Content[c] Within Mine	5	797	509	ng/g			

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[a] MMAD = mass median aerodynamic diameter
[b] GSD = geometric standard deviation
[c] Sum of 16 PAH and 5 N-PAH, analysis by GC/MS.

TABLE 5
DUST SAMPLING AND ANALYSIS
RIO BLANCO MODIFIED IN SITU RETORTING FACILITY

PARAMETER AND LOCATION	NO. OF SAMPLES	CONCENTRATION			PARTICLE SIZE		
		Max.	Mean	Unit	No. of Samples	MMAD[a] (μm)	GSD[b] (σ_g)
Total Dust							
Within Mine							
Before Retort Burn	36	3.9	1.1	mg/m^3	20	2.8	3.5
During Retort Burn	28	2.9	1.2	mg/m^3	4	0.7	3.5
Respirable Dust							
Within Mine							
Before Retort Burn	21	1.2	0.5	mg/m^3			
During Retort Burn	12	0.3	0.2	mg/m^3			
Free Silica Content							
Within Mine	20	4	3	Percent			
Cyclohexane Extractables							
Within Mine							
During Retort Burn	4	46.1	18.4	Percent			
PAH Content[c]							
Within Mine							
Before Retort Burn	2	600	450	ng/g			
During Retort Burn	3	1600	1333	ng/g			

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[a] MMAD = mass median aerodynamic diameter

[b] GSD = geometric standard deviation

[c] Sum of 6 PAH, analysis by HPLC.