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RISK ANALYSIS OF HAZARDOUS MATERIALS IN OIL SHALE

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Summary

A future oil shale industry will be a massive solids-handling industry generating large amounts of hazardous materials. A risk analysis was performed on a hypothetical oil shale industry to aid in the formulation and management of research. The analysis considered occupational, public, and ecosystem risks for a steady-state one million barrels per day (160 cubic dekameters per day) industry. The risks for designated groups of the occupational workforce were statistically described by accident and injury rates for fatalities, accidents with days lost from work, and accidents with no days lost from work. Workforce diseases analyzed were cancers, silicosis, pneumoconiosis, chronic bronchitis, chronic airway obstruction, and high-frequency hearing loss. The miners represented the group with the largest fatality and the most serious accident rate. Lung disease from inhalation exposure to dust about the nuisance dust threshold limit value presented the most significant risk for future concerns. Public health inhalation risks were estimated for lifetime cancer risks from As, Cd, Cr, Ni, polycyclic aromatic hydrocarbons, and radiation to be less than 10^{-7} occurrences per person per year. An air pollution surrogate, sulfate, as a measure of all air pollution exposure, yielded a result of 10^{-5} deaths per person per year with large uncertainties. Public health risks associated with oil shale solid waste were considered for leachates. Ecosystem risks considered impact on designator species, plant damage from sulfates, and disturbance in plant communities. The simple analysis approach indicated that the potential impact on the semi-arid, high-altitude ecosystem was minimal from air pollutants and land disturbances, but of potential concern for aquatic systems under extreme conditions. The methodology and treatment of uncertainties are oriented towards establishing research implications.

Introduction

A goal of an oil shale risk analysis was to estimate the potential health and environmental risks associated with a hypothetical one million barrels per day (BPD) (160 dekameters^3 per day or dam^3/d) oil shale industry. The purpose of this analysis was to establish research needs to aid in the formulation and management of a program of environmental research. The results were reported in the Health and Environmental Effects Document (HEED) for oil shale [1, 2] and are not intended for regulatory purposes.

The analysis of health and safety risks in a future oil shale industry can be used to identify high-risk concerns and to reduce occupational accidents and disease. The occupational workforce size for a one million BPD (160

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dam^3/d) industry was estimated and used to compute the occupational risks. Based on the estimated risks relative to general and analogous occupations, high-risk groups can be identified for application of risk management techniques.

Oil shale airborne emissions and waterborne leachates may increase the risk of health effects in the public populations living in and around the oil shale region. A one million BPD (160 dam^3/d) industry will emit a wide variety of air pollutants including the criteria pollutants, trace elements, and hydrocarbons. Under the goals of "zero discharge", there may be no direct discharge of oil shale process waters into surface waters. Oil shale solid waste leachates are a potential environmental problem that may persist for several centuries after final abandonment of facilities. Percolating water from rainfall and snowmelt, or groundwater intrusion into abandoned disposal sites may migrate through spent shale and dissolve a portion of the spent shale matrix. This organic- and mineral-laden water may migrate to underground aquifers and eventually contaminate surface drinking water supplies. Many of these pollutants have been associated with adverse health effects through toxicologic investigation or epidemiologic research.

The ecologic effects of oil shale development are related to the land disturbance, which removes vegetative cover and reduces forage productivity of the area. The vegetation of the area includes salt brush, greasewood, pinyon-juniper, sagebrush, mountain shrub, aspen, and conifers, occurring in relation to elevation. The wildlife dependent on these vegetative types for habitat, such as the mule deer population, would be affected by significant losses of its forage, such as the mountain shrub species. With proper revegetation procedures, much of the disturbed area and waste disposal areas can be rehabilitated. Waterborne pollutants described previously also present a hazard to aquatic systems and additional human health pathways. Ecosystems analysis approaches, for aquatic and terrestrial designator species and higher level approaches such as community diversity, are considered.

This paper presents the risk analysis associated with a steady-state oil shale production scenario [2]. Analysis divisions are used in the estimation process: a site-specific production scenario, the controlled pollutant source terms and accidents rates, an environmental transport or exposure model, the population at risk, and health effect dose—response or environmental response function. The resulting risk estimates are then put in perspective with appropriate sensitivity analysis and uncertainty analysis. This process is described below for occupational safety, occupational diseases, public exposure from air emissions and spent shale solid waste leachates, and ecosystem components.

Oil shale

Oil shale is a sedimentary rock that produces significant quantities of a petroleum-like liquid through destructive distillation (pyrolysis). Oil shale was formed when hydrogen-rich organic matter was gradually deposited, along with mineral matter, in oxygen-depleted water at the bottom of a stagnant or stratified lake or inland sea. Most oil shale is composed of clays and silicates deposited from inflowing water. Pyrite (FeS_2), a common constituent of oil shale, is produced from decaying organic matter and by anaerobic sulfate-reducing bacteria. When the water is alkaline, carbonate minerals may precipitate and become incorporated into the shale [3] .

Oil shale deposits in the United States represent an immense fossil fuel

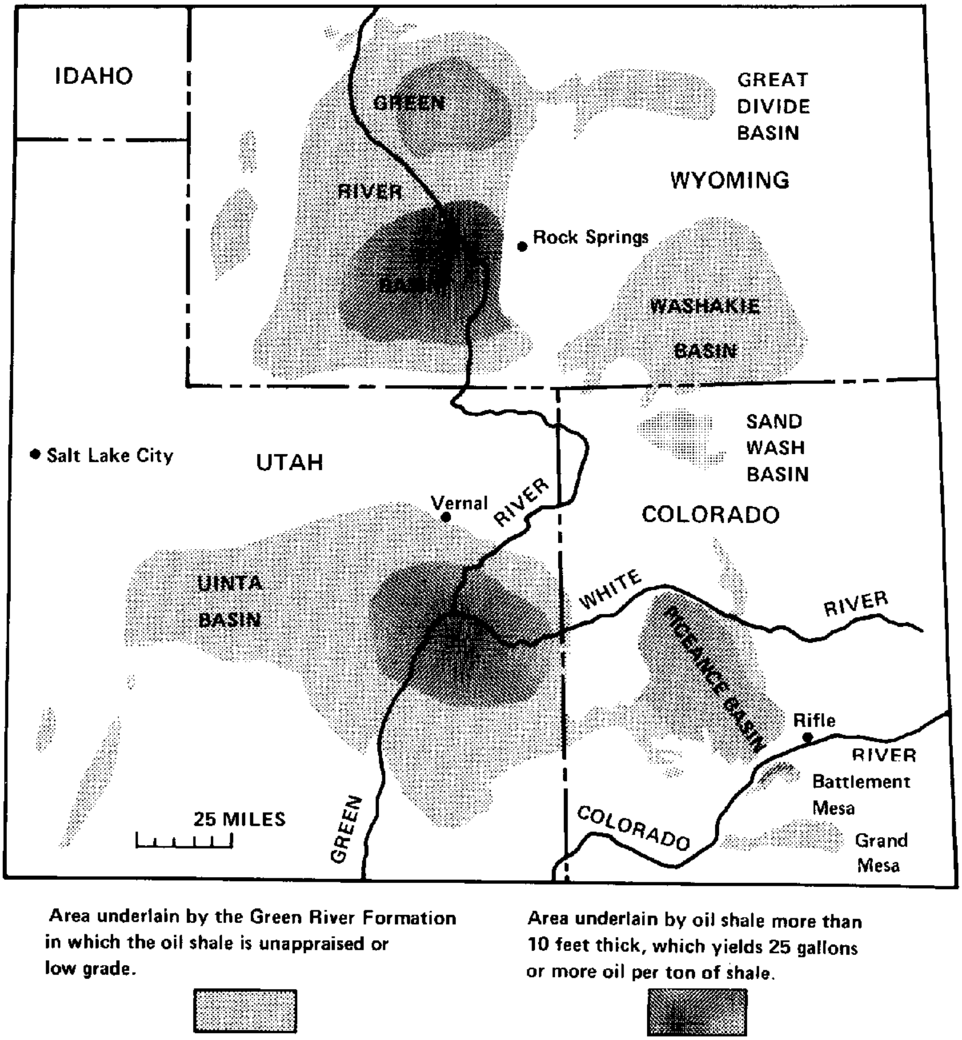

Fig.1. Oil shale deposits of the Green River formation [9]. (As found in D.C. Duncan and V.E. Swanson, Organic-Rich Shales of the United States and World Land Ares, U.S. Geological Survey Circular 523, 1965.)

resource capable of supplying our nation's liquid-fuel needs for centuries. The magnitude of the resource is well known, but commercial processing of the resource has been limited by economic considerations. The world's premier oil shale deposit is found in the Green River geologic formation in Colorado, Utah, and Wyoming as shown in Fig.1. Green River oil shale deposits represent a potential resource of 1.8 trillion barrels (228,000 dam^3) of shale oil [4].

This geologic formation was built over a 10 million year period 50 million years ago. Green River oil shale contains on a mass basis about 50% carbonate minerals, 2% pyrite, and 15% organic matter (corresponding to 30% on a volume basis), with the remainder being quartz, silicates, and clays. Green River oil shale is fine grained, with a median particle size of about 5 μm. The shale layers were deposited at a rate of about 0.1 mm/y. The different layer colors, light and dark bands, were caused by seasonal variations in algae deposition.

About 95% of the organic matter in Green River oil shale is kerogen, an insoluble polymeric material. The remaining organic matter, bitumen, is soluble in organic solvents. The liquid produced by heating oil shale, broken into pieces for efficient heat transfer, to about 550° C for extended periods is called shale oil, and the production process is called retorting.

The Green River formation occurs in a 25,000 mi^2 (65,000 km^2) area, which is semi-arid, sparsely populated, and at an elevation of 5000 to 8000 ft (1500 to 2500 m). The richest area is in the Piceance Basin of Colorado, where 2000 ft (600 m) beds, below 1000 to 2000 ft (300 to 600 m) of overburden, yield shales that can produce an average of 25 gal (95 L) of oil per ton of shale. This shale is rich in hydrogen compared to other oil shales and, from economic considerations based on converting a higher fraction of the organic matter to oil, should be the initial oil shale deposit to be developed as a supplement to the eventual diminution of conventional oil supplies.

Oil shale processing

The oil shale retorting process results in the decomposition of kerogen yielding oil vapor, water, gas, and a remaining solid carbonaceous residue (char). Heat for the retorting process can be provided by burning some of the retorting products. The oil is the most valuable product, and the gas, although recycled and burned in some technologies, is a source of hydrogen for upgrading and is a marketable product. Char is the least valuable energy source product and is usually left in the disposed spent shale. There are many different shale retorting technologies and each attempts to economically produce oil and other marketable products in an efficient manner. Improper temperature control can result in the burning of oil and gas and in excessive char formation. Also, depending on the technology used, the mineral matter in the shale may not be inert [5]. The mineral matter participation in the process can be disadvantageous when it requires a significant amount of energy, such as carbonate decomposition, but can be advantageous when sulfur-containing gases are removed and thereby reduce an air pollution source [3, 6].

Many different processes have been used for retorting oil shale. Historical records indicated that a British patent was granted in 1694 and the first commercial production began in France in 1838. Shale oil has been produced in many countries and required government support. The Scottish oil shale industry, started in 1850, produced fuels, chemicals, and waxes until termination in 1964. Interest in United States oil shale accelerated during petroleum shortages and waned as petroleum supplies increased [7].

The practical retorting technologies can be classified by the different methods for heating the solid particles. The shale can be heated by direct or indirect methods using hot gases or solids. Retorting can be performed above ground or underground by a number of true or modified *in situ* processing methods. The features of several selected processes will be described as examples of the generic technology available [8].

Union Oil

The retort developed by the Union Oil Company of California, Los Angeles, operates on a downward gas-flow principle. The shale is moved upward in the retorting vessel by a unique charging mechanism referred to as a rock pump. Heat is supplied by combustion of the organic matter remaining on the retorted shale and is transferred to the oil shale by direct gas-to-solids exchange. The oil is condensed on the cool, incoming shale and flows to an outlet at the bottom of the retort. In the Union B process, oxygen-free retort gases heated to 540°C are recycled through the shale to supply heat needed by the retort process. This retorting process is scheduled to be the first modern commercial-size production at Union Oil's Parachute Creek site.

Tosco

The Colony Development Corporation, Aurora, Colorado, operated a research facility in the 1960s with a "semi-works" plant using the TOSCO II retort, a rotary-type kiln utilizing external ceramic balls. Shale feed of 0.5 inch in size is preheated and pneumatically conveyed through a vertical pipe by flue gases from the ball heating furnace. The preheated shale then enters the rotary retorting kiln with the heated pellets, where it is brought to a retorting temperature of 480°C by conductive and radiant heat exchange with the hot ceramic balls. Passage of the kiln discharge over a trommel screen permits recovery of the balls from the spent shale for reheating and recycling.

Paraho

The Paraho process evolved from U.S. Bureau of Mines work at Anvil Points, Rifle, Colorado, resulting in the gas-combustion retort. This retort is a vertical, refractory-lined vessel through which crushed shale moves downward by gravity. Recycled gases enter the bottom of the retort and are heated by the hot retorted shale as they pass upward through the vessel. Air is injected into the retort at a point approximately one third of the way up from the bottom and is mixed with the rising, hot recycled gases. Combustion of the gases and some residual carbon from the spent shale heats the raw shale immediately above the combustion zone to retorting temperature. Oil vapors and gases are cooled by the incoming shale and leave the top of the retort as a mist. The manner in which retorting, combustion, heat exchange, and product recovery are carried out gives high retorting and thermal efficiencies, resulting in an overall energy recovery efficiency of 75%.

Others

In situ extraction of oil from shale is the alternative to conventional surface retorting procedures, but it is still in development. It may be accomplished by passing retorting gases and the liquids produced either vertically or horizontally through fractured shale. Application of the *in situ* retorting systems requires a method for obtaining a cavity filled with broken shale or increasing the permeability of the shale bed. The horizontal sweep approach is somewhat similar to thermal recovery methods in petroleum reservoirs. However, since oil shale deposits frequently have very low permeability, creating the appropriate fractures to increase the permeability is necessary.

The Occidental process utilizes a combined mining and explosive fracturing technique to prepare the oil shale for *in situ* processing. In this approach a portion of the shale bed is mined out from an underground area; adjacent shale is blasted into the mined area to create void volume. The broken shale in the room is then retorted from the top down. Results of tests in the Piceance Basin by Occidental at the Logan Wash site and by the Rio Blanco Oil Shale Company at the Cathedral Bluffs site indicate that the yields necessary for an economically viable technology remain to be demonstrated.

The Geokinetics Oil Shale Group in Near Willow Creek, Utah, has demonstrated an *in situ* oil shale processing technology applicable to thin beds near the surface. The Geokinetics processing scheme uses horizontal retorting designs in shallow (low overburden) oil shale deposits. The porosity is provided by conventional explosives used to displace the ground surface and shale beds.

Other retorting schemes that include radio frequency heating and the use of directly injected steam have been attempted [9] . Advanced retorting processes are currently being developed [6] using a hot-solids recirculation system with the burned shale as the heat transfer medium and inherent chemical reactions to eliminate sulfur in the product and combustion gas.

Oil shale products

Crude shale oils produced from surface retorts may be classified generally as low-gravity, moderate-sulfur, high-nitrogen oils by petroleum standards. These are more viscous and characteristically have higher pour points (congealing temperature) than many petroleum crudes. Oils from the different processes will vary widely, not only from the differences in the oil shale but also from the retorting operations. Conventional refineries are not expected to process crude shale oil directly because of high concentrations of nitrogen, arsenic, and metals, such as iron. Most commercial operations include an upgrading facility to produce the synthetic crude product referred to herein as shale oil. The general scheme for upgrading involves metal removal followed by hydrotreating. Processes to remove the trace amounts of metals convert oil-soluble organometallic compounds to oil-soluble inorganic forms, which can be removed from the oil [10] . Hydrotreating processes react the crude shale oil with hydrogen to convert long-chain molecules to smaller molecules and olefin hydrocarbons to paraffin equivalents to produce the product shale oil [9].

Gas produced from internal-combustion retorts has a low heating value of the order of 80 to 100 Btu/std ft^3 (3000 to 3750 kJ/std m^3), and cannot be economically transported a substantial distance; therefore, it must be utilized in the plant vicinity. Use of the higher value heating gas from the indirect-heated retort would be less limited. After treatment to remove sulfur compounds, this gas could be readily used in the plant as fuel.

Wastes

Oil shale development will produce hazardous wastes in the environment. Changes will occur to the land surfaces, water resources, air quality, and wildlife habitats in the region of oil shale deposits, due to the magnitude of the operations and materials to be handled. A major impact on the land itself will involve disposal of the vast amounts of retorted shale, which now has a volume greater than that of the original shale due to expansion during processing. The processed shale can be disposed on the surface or underground. Underground mining will allow for only a portion of the processed shale to be disposed of underground.

Solid wastes associated with oil shale processing can be diverse and come from all phases of processing, including mining, crushing, retorting, and upgrading. Major solid wastes of concern are retorted shale, raw shale fines, spent catalysts, activated carbon, elemental sulfur, and elemental arsenic. Concerns are also associated with the location and engineering of the disposal of the solid wastes. As an example, retorted shale may contain organic residues that may be leached, or off-gas from the shale, depending on many complex factors including the time-dependent flow of water, pH, pressure, and temperature of the waste material. Atmospheric emissions are generated due to blasting, equipment use, crushing, shale retorting, cleanup systems, upgrading, refining, and transporting.

Potential water problems associated with oil shale are non-potable water treatment or disposal and consumptive water requirement. Water is a direct product of oil shale retorting, resulting from pyrolysis of kerogen and combustion of organic material in shale. Water can be separated from the crude shale oil, condensed during cooling or gas cleanup, or appear in the flue gas stream. Water separated from crude shale oil will contain mainly carbonate and bicarbonates, sodium, sulfate, organic acids, hydrocarbons, and ammonia. Smaller quantities of calcium, magnesium, sulfides, and trace elements may also be present. Condensed water primarily contains carbonates, traces of organic substances and sulfur-containing compounds. Retort waters contact shale oil and contain substantial amounts of organic materials. On-site treatment of retort water has been indicated [11].

It has been estimated that from 2 to 5 barrels (300 to 800 L) of water are needed for each barrel of oil produced from typical 50,000 BPD (8 dam^3/d) oil shale facilities [9]. A production site of 100,000 BPD (16

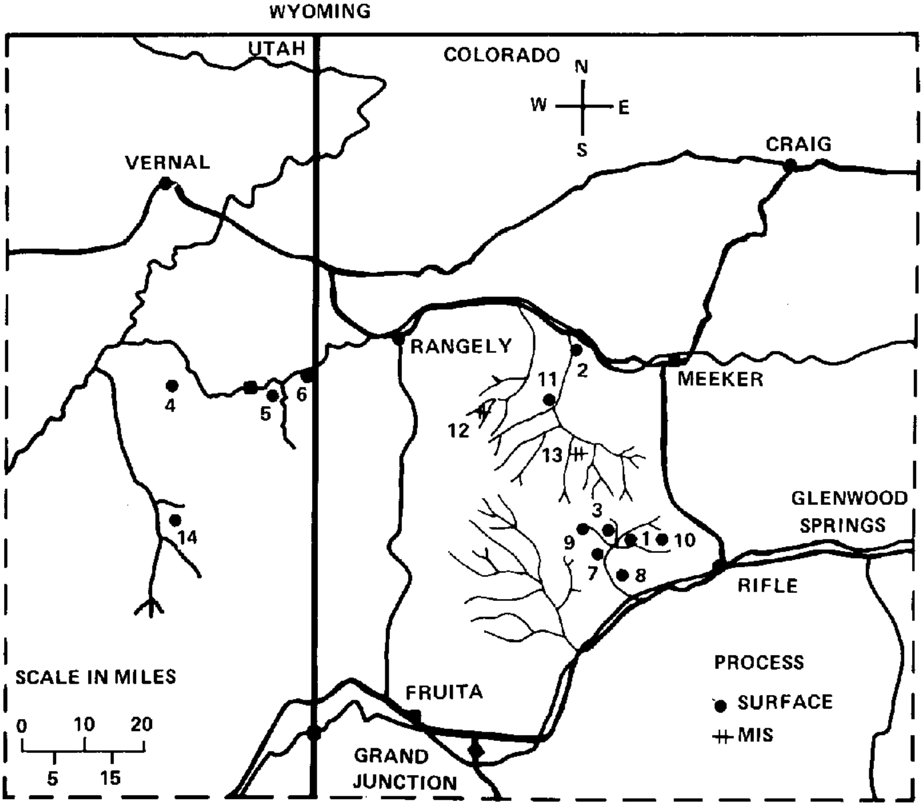

Fig.2. Oil shale region used in risk analysis (14 development sites and leachate calculation points). Numbered sites refer to million BPD (160 dam^3/d) sites. ■ Represents location of leachate impact calculation points. Lees Ferry, Arizona not shown.

dam^3/d) may require 10,000 to 23,000 acre ft (12,300 to 28,400 dam^3) of water per year. Although hydrologic conditions vary both laterally and vertically, 18,000 acre ft (22,200 dam^3) per year may be produced in dewatering. The availability of water appears to be an economic question dependent on the clean-up costs versus alternative supplies.

For total water management considerations, most development site plans will show zero discharge of their wastewater. Reasons for total reuse of water include scarcity of water in the oil shale areas, compliance with pollution control regulations on water discharged to surface and ground water sources, and needs for in-plant processing.

Scenario

The risk analysis scenario shown in Fig.2 has 14 production sites distributed along the major creek systems feeding the Colorado River. This hypothetical scenario occurs in the year 2010. The production level for sites 1, 5, 7, 8, 12, and 13 is 100,000 BPD (16 dam^3/d). The production is based on underground room-and-pillar mining with above ground retorting (AGR) for all sites except site 13 which is a modified *in situ* (MIS) operation with 50% of the production coming from the MIS.

Occupational health and safety

Workforce size

For the purposes of analysis, the oil shale fuel cycle was divided into the following segments:

1. Extraction (mining and crushing)
2. Retorting and Upgrading
3. Construction
4. Refining
5. Transportation

The segments were designed to establish work groups representing each major operation of the oil shale fuel cycle. The transportation segment encompasses the transport of upgraded shale oil to the refineries and distribution of refined products to consumers. Segments 1 through 3 occur at the plant site, while segments 4 and 5 are off-site operations. Estimates of the workforce size were made for both on-site and off-site processes for the 14 production sites using the methodology described elsewhere [12] and are shown in Table 1.

Occupational safety

Accident and injury occurrences were estimated for each segment of the oil shale fuel cycle using the incidence (normally specified in occurrences per 100 workers per year or per 200,000 man-hours per year) from surrogate or actual industries. The methodology for the safety estimate, which has

TABLE 1

Workforce size estimates for a one million BPD (160 dam^3/d) oil shale industry

Location	Work group	Estimate (range)
On-site	Mining	14,200 (12,000–21,000)
	Crushing	6,200 (5,500– 9,300)
	Retorting and upgrading	9,400 (3,700–11,000)
	Construction	3,300 (2,400– 4,600)
Off-site	Refining	5,600 (5,500– 5,800)
	Transportation	2,200 (740– 3,600)
Total[a]		41,000 (35,000–49,000)

[a] $\text{Upper bound} = \text{nominal estimate} + [\sum_{i=1}^{6} (\text{upper bound} - \text{nominal estimate})^2]^{1/2}$

$\text{Lower bound} = \text{nominal estimate} - [\sum_{i=1}^{6} (\text{nominal estimate} - \text{lower bound})^2]^{1/2}$

$i = 1$ for mining, 2 for crushing, 3 for retorting and upgrading, 4 for refining, 5 for transportation, and 6 for construction.

been summarized elsewhere [2, 12], incorporates statistics showing larger-scale mining operations to be safer than smaller operations. Commercial oil shale mines are expected to be the largest mines in the United States. Mining safety statistics were analyzed to establish a mine size factor, a multiple to adjust the mining incidences for the size of the mining operation. The mine size factor was 0.59 for fatalities and approximately 1 for the other incidences. Uncertainty factors were used to generate uncertainty ranges for accident and injury occurrences. The uncertainty factors for work group size and incidence estimates were calculated by taking the maximum value of the mean divided by the lower bound or the upper bound divided by the mean. The factors for occurrences were calculated by taking a root-mean-square sum of the logarithmic values of corresponding work group size and incidence uncertainty factors. Table 2 is a summary of the resulting accident and injury occurrences for a one million BPD (160 dam^3/d) oil shale industry.

Further inferences about oil shale mining were made from an investigation of injury severity in U.S. underground bituminous coal mines from 1975 to 1982 [13]. Underground coal mining accident severity and frequency data were used to predict the accident consequences in the oil shale scenario shown in Table 3. Using the total estimated 1600 expected occurrences of serious accidents for oil shale mining and the mine size factor, the underground coal mining severity surrogate yielded 7.6 fatalities versus the 7.1 previously shown (Table 2).

TABLE 2

Annual accident and injury occurrences for a one million BPD (160 dam^3/d) oil shale industry

Work Group	Occurrences (range)		
	Fatalities	NFDL[a]	NDL[b]
Mining	7.1 (4.6—11)	1600 (1100—2400)	440 (290—660)
Crushing	2.2 (1.1—4.4)	310 (210—460)	170 (110—280)
Retorting and upgrading	1.7 (0.61—4.8)	130 (51—340)	300 (120—770)
Construction	0.77 (0.54—1.1)	140 (100—190)	280 (200—390)
Refining	1.00 (0.67—1.5)	78 (74—82)	180 (170—190)
Transportation	0.5 (0.10—2.5)	140 (18—1100)	81 (27—240)
Total	13 (10—19)	2400 (1800—3600)	1500 (1200—2000)

[a] NFDL is non-fatal occurrences with workdays lost.
[b] NDL is occurrences with no workdays lost.

TABLE 3

Surrogate accident severity and frequency summary

Accident consequence	Occurrences for underground coal mining[a]	Percent of total	Predicted oil shale occurrences[b]
Death	558	0.8	7.6[c]
Permanent total or partial disability	961	1.4	22
Restricted activity with days lost	63,871	92.3	1500
Restricted activity only	3,786	5.5	88
Total	69,176	100.0	1600

[a] For U.S. underground bituminous coal mines, 1975—1982 [13].
[b] Based on percent of total applied to 1600 estimated occurrences.
[c] 1600 occurrences for serious accidents × 0.008 (deaths per occurrence of serious accident) × 0.59 (mine size factor) = 7.6 deaths.

Safety life-loss expectancy

The life-loss extectancy (LLE) for oil shale accidents is defined as the average life expectancy minus the average age at death for accident victims. The average age of an oil shale worker was assumed to be equal to the average age of underground coal miners [13], 32.3 y. Based on 13.3 total expected fatalities per year, the LLE for the safety portion of the risk was (74.9–32.3) × 13.3 or 567 man-year per year. Dividing the LLE by the total workforce of 41,000 oil shale workers yielded an average LLE of 0.014 man-year per worker per year. Similar results for just the 14,200 oil shale miners as a group yielded a LLE of 305 man-year per year or 0.02 man-year per worker per year. These estimates assume fatal accidents occur equally in all age groups. The LLE for accidents and injuries for the oil shale work groups is shown in Table 4, indicating the high relative risk for the oil shale miners.

TABLE 4

Annual accident and injury life-loss expectancies for a one million BPD (160 dam^3/d) oil shale industry

Work group	Life-loss expectancy in total years (range)	Life-loss expectancy in man-years per man (range)
Mining	305 (550—170)	0.021 (0.034—0.014)
Crushing	94 (190—40)	0.015 (0.027—0.008)
Retorting and upgrading	73 (200—30)	0.0077 (0.012—0.005)
Construction	33 (50—20)	0.0099 (0.012—0.008)
Refining	43 (70—30)	0.0077 (0.012—0.005)
Transportation	21 (100—4)	0.0099 (0.033—0.003)

Occupational diseases

The potential occupational health hazards involved in the extraction, retorting, upgrading, transporting, and refining of shale oil (including exposure to dusts, toxic gases, heat, noise, and the oil) were discussed previously [2] . Risks from inhalation of dust particles potentially occurring in the oil shale industrial environment as a result of mining, crushing, and retorting operations were analyzed by considering four non-neoplastic lung responses: pneumoconiosis (simple and complicated), silicosis, chronic bronchitis and chronic airway obstruction. Simple pneumoconiosis (0/1+) referred to all grades of simple pneumoconiosis, while complicated pneumoconiosis referred to progressive massive fibrosis (PMF) and was treated independently Pneumoconiosis dust exposure risk was estimated using the sum of simple and complicated pneumoconiosis. This risk was based on the exposure—response relationship derived from British coal industry data. The silicosis risk, another form of pneumoconiosis, was treated independently. This disease is caused by inhalation of silica (alpha quartz form). Chronic bron-

TABLE 5

Life-loss expectancy (LLE) from occupational diseases for a one million BPD (160 dam^3/d) oil shale industry

Cause of death	Cases	Case fatality rate, %	Premature fatalities per year	Years of life-loss per death[a]	Total LLE per year
Lung: Exposure A					
Pneumoconiosis					
Simple (0/1+)	121	16	21	3.05	59
Complicated (PMF)	12	23	2.6	3.05	8.4
Silicosis	295	33	97	3.05	300
Chronic bronchitis[b]	55	38	15	3.05	64
Chronic airway obstruction[b] ($FEV_1 < 65\%$)	51	44	6.5	3.27	69
Lung: Exposure B					
Pneunoconiosis					
Simple (0/1+)	24	16	6.9	3.05	12
Complicated (PMF)	2.4	23	0.14	3.05	1.7
Silicosis	41	33	13	3.05	41
Chronic bronchitis	11	38	0	3.02	12.7
Chronic airway obstruction ($FEV_1 < 65\%$)	5.1	44	0	3.27	6.9
Internal cancers					
Lung	2	91	1.6	8.83	14
Stomach	0.6	88	0.52	6.03	3.1
Kidney	0.3	56	0.18	9.35	1.7
Brain	1	82	0.85	16.3	14
Skin cancers					
Melanoma	0.44	38	0.17	13.7	2.3
Basal cell	16.2	1	0.16	13.7	2.2
Squamous cell	4.4	1	0.04	13.7	0.6

Exposure A: 5 mg $(dust)/m^3$ or 500 μg $(SiO_2)/m^3$ at 10% free silica.

Exposure B: 1 mg $(dust)/m^3$ or 100 μg $(SiO_2)/m^3$ at 10% free silica.

[a] Based on a life expectancy in 1977 for a 20-y old white male of 74.9 y.

[b] To correct for chronic bronchitis and chronic airway obstruction overlap subtract when combining: Exposure A: 14 cases, 6 premature fatalities per year, and 19 y LLE; Exposure B: 3 cases, 1 premature fatality per year and 4 y LLE.

chitis and chronic airway obstruction both have cigarette smoking as an important etiologic factor, and both have common occurrence. The exposure—response relationship and joint occurrence were derived from the same British coal industry data used for pneumoconiosis.

Initial concerns of health effects from an oil shale industry included carcinogens. An example of the level of concern [14] states:

> "What appears to be the greatest concern, one shared by numerous industry and government officials, as well as several public interest groups, is the potential carcinogenic effect raw shale oil may have on humans."

Skin and internal cancers from hydrocarbons [15] along with internal cancers from radioactivity were also analyzed for the appropriate work groups. The potential for high-frequency hearing loss was also included [2], since noise levels in various locations of the oil shale industry are expected to be high.

The results for the occurrences of the occupational diseases analyzed for the oil shale fuel cycle workforce based on regressions of the results of Marine et al. [16] are summarized in Table 5. These results indicate that excess incidence of lung diseases in the oil shale miners and crushers represents a risk of primary concern, if the high dust exposure level exists in the future oil shale industry. The level of concern for carcinogens appears to be unfounded based on comparison of the diseases analyzed.

Mortality due to occupational diseases

The estimates of potential occurrence of occupational diseases were useful measures of the hazard, but their comparison is difficult. For example, a case of squamous cell carcinoma of the skin is not easily compared to a case of respiratory silicosis. Further analysis of the number of occurrences of diseases to the number of fatalities caused by the disease improves the comparison. This conversion is based on a case fatality rate for each disease. The mortality attributable to cancers of the lung, stomach, kidney, brain and skin was approximated based on 5-y relative survival data [17, 18]. The resulting range was from 56% (kidney) to 91% (lung). Skin cancers have a very low case fatality rate for basal and squamous cell types (about 1%) but a rate of 38% for the much less frequently occurring melanoma. Estimates of case fatality rates for occupational non-neoplastic lung diseases [16] ranged from 16% for simple pneumoconiosis to 44% for chronic airway obstruction. The case fatality rates are shown in Table 5. The premature fatality estimate from an occupational disease was calculated by multiplying the disease occurrence estimate by the case fatality rate. The expected premature fatalities for the exposed workers are summarized in Table 5.

Disease life-loss expectancy

Life-loss expectancy (LLE) was another measure of risk computed for comparison of deaths due to accidents and death due to disease. The number of years lost for each disease is shown in Table 5. The total years of life lost due to occupational disease mortality was based on the average age at death for each disease. The distribution of ages at death for white males in 1977 [19] was used to establish the average age at death. In some instances, the precise disease entity of interest could not be used and a surrogate was selected. The average age at death was subtracted from the life expectancy for a 20-y old white male with a life expectancy of 74.9 y [19] to estimate

TABLE 6

Annual life-loss expectancies for a one million BPD (160 dam^3/d) oil shale industry

Cause of death	Annual excess life-loss expectancy			
	Total	(Range)	per man	(Range)
Lung: Exposure A				
Pneumoconiosis				
Simple (0/1+)	59	(17—210)	0.0029	(0.0009—0.0096)
Complicated (PMF)	8.4	(2—30)	0.0004	(0.0001—0.0014)
Silicosis	300	(83—1060)	0.015	(0.0044—0.049)
Chronic bronchitis	64	(18—227)	0.0031	(0.0009—0.010)
Chronic airway obstruction ($FEV_1 < 65\%$)	69	(19—245)	0.0034	(0.0010—0.011)
Lung: Exposure B				
Pneunoconiosis				
Simple (0/1+)	12	(3—42)	0.0006	(0.0002—0.0019)
Complicated (PMF)	1.7	(0.5—6)	0.00008	(0.00002—0.00028)
Silicosis	41	(12—147)	0.0020	(0.0006—0.00671)
Chronic bronchitis	13	(4—45)	0.0006	(0.0002—0.0021)
Chronic airway obstruction ($FEV_1 < 65\%$)	6.9	(2—25)	0.0003	(0.0001—0.0011)
Internal cancers				
Lung	14	(1—139)	0.0009	(0.0001—0.0083)
Stomach	3.1	(0.3—31)	0.0002	(0.00002—0.0019)
Kidney	1.7	(0.2—17)	0.0001	(0.00001—0.0010)
Brain	14	(1—139)	0.0009	(0.0001—0.0083)
Skin cancers				
Melanoma	2.3	(0.2—23)	0.0002	(0.00002—0.0014)
Basal cell	2.2	(0.2—29)	0.0002	(0.00001—0.0017)
Squamous cell	0.6	(0.05—8)	0.00004	(0—0.00047)

Exposure A: 5 mg (dust)/m^3 or 500 μg (SiO_2)/m^3 at 10% free silica.
Exposure B: 1 mg (dust)/m^3 or 100 μg (SiO_2)/m^3 at 10% free silica.
Uncertainties based on range of health effects data, range of population estimates; 10% error in case fatality rate; ± 1 year for years of life-loss for less than 5 years, ± 2 years for less than 10 and ± 3 years for less than 20.

the average number of years of life lost per death. Multiplying this by the expected number of excess deaths produced an estimated LLE for each occupational illness.

The LLE for occupational illness was dominated by the non-neoplastic lung diseases. At the extreme exposure of 5 mg/m^3, the associated 500 μg SiO_2/m^3 (based on an estimated 10% average free-silica content of dusts) exceeded the threshold limit value (TLV) and resulted in a 300-y annual LLE from silicosis, a 67-y annual LLE from pneumoconiosis, a 114-y annual LLE from chronic bronchitis and chronic airway obstruction (which includes a correction based on combined cases of chronic bronchitis and chronic airway obstruction) for a total non-neoplastic lung disease annual LLE of 480 y. At a lower dust level of 1 mg/m^3, with the associated 100 μg SiO_2/m^3, the non-neoplastic lung disease annual LLE decreased to 70 y, with about two thirds due to silicosis. At this level, the LLE from cancers was about one half of the LLE from lung disease.

The uncertainty analysis for these estimates is summarized in Table 6 following the methodology for safety. The analysis reflects the exposure, toxicologic, population, and epidemiologic uncertainties as well as variations in the case fatality rates and life-loss expectancies.

Public health risks of air emissions

Source terms

Generic emission terms for the basic retorting process types were estimated from prevention of significant deterioration (PSD) permit air emission data. For the three basic above-ground retorting processes, the estimates were based on averaging data from Union Oil Co. [20, 21], TOSCO Development Corp. [22], and Paraho Development Corp. [23]. For the MIS process, Cathedral Bluffs Shale Oil Co. [24] was used. Trace element source terms were found by scaling the particulate source terms by the concentration of each element in raw and spent shale from the Colony site [25]. The generic source terms are summarized in Table 7.

The scenario included two power plants to support the oil shale industry and the regional population. The power plants were sited at Moon Lake, Utah and Grand Junction, Colorado. The air emissions from each four unit power plant were 10,000 kg/d of sulfur dioxide, 2,640 kg/d particles and 48,600 kg/d of nitrogen based on the Bonanza Power Plant [26]. Based on the one million BPD (160 dam^3/d) scenario and the generic air source terms, the emissions for each site were computed.

Transport and transformation

The results of Huang and Sandusky [27] were adapted to estimate public exposure to air pollution from the generic source terms within the oil shale region. These results were based on a Gaussian plume distribution without correction of plume centerline near elevated terrain. A joint fre-

TABLE 7

Generic values for oil shale air emissions

Process type	Controlled emissions (g/L)						
	SO_2	NO_x	CO	HC	Particulates	H_2S	CO_2
AGRs							
Union	0.63	1.2	0.46	0.46	0.26	NA[a]	NA[a]
TOSCO	0.37	2.5	0.063	0.51	0.37	0.0034	780
Paraho	0.66	1.7	0.26	0.049	0.34	0.0037	NA[a]
All sites	0.19	1.2	0.029	0.049	0.25	0.000025	
(range)	to	to	to	to	to	to	NA[a]
	0.66	2.6	0.57	0.63	0.43	0.0037	
Generic AGR							
Normal	0.54	1.8	0.26	0.34	0.31	0.0034	780
Range	0.18	1.2	0.026	0.034	0.26	0.000025	
	to	to	to	to	to	to	NA[a]
	0.66	2.6	0.57	0.69	0.43	0.0037	
Generic							
MIS site	1.1	4.4	1.5	0.0057	0.43	0	NA[a]

	Emissions (10^{-6} kg/L)								
	As	Be	Cd	Cr	Pb	Hg	Ni	Se	V
AGRs									
Union	11	0.22	2.8	9.1	6.3	0.046	5.4	3.1	13
TOSCO	14	0.20	0.34	12	9.1	0.31	6.3	2.0	16
Paraho	12	0.29	0.049	9.1	7.1	0.063	7.1	0.77	24
All sites	8.3	0.15	0.049	6.6	4.3	0.017	3.4	0.77	8.9
(range)	to	to	to	to	to	to	to	to	to
	20	0.29	2.8	17	74	0.80	8.9	3.1	24
Generic AGR									
Normal	12	0.23	0.23	10	7.4	0.14	6.3	2.0	17
Range	8.3	0.12	0.46	6.6	4.0	0.017	3.4	0.77	8.9
	to	to	to	to	to	to	to	to	to
	20	0.29	2.8	17	74	0.63	8.9	3.1	24
Generic									
MIS site	28	NA[a]	NA[a]	16	20	0.40	21	1.1	0.71

[a] NA = Not Available.

Note: Trace element source terms are based on particulate source terms and elemental concentrations in raw and spent shale.

quency distribution of wind speed, wind direction, and stability was obtained from data taken at Federal Oil Shale Lease Tract C-a and was used to construct a long-term average two-dimensional wind field. The results are for a non-buoyant release, which overpredicts concentrations closer to the source. Air exposure contours were calculated by integration of the plumes from the point sources at 14 oil shale sites and the 2 power plants.

The long-range transport model of Fay and Rosenzweig [28] was used to estimate public exposure to air pollution across the United States. Fay and Rosenzweig solved a steady-state two-dimensional diffusion equation, which is a suitable model for predicting ambient air pollutant concentrations averaged over a long time period at distances greater than about 100 km from the source. The model uses a constant horizontal diffusion coefficient to determine horizontal puff dispersion. Pollutants are assumed to be mixed uniformly in the vertical direction up to a constant mixing height. Precipitation rate, dry deposition rate, transformation rate, and wind speed/direction were considered as fixed parameters over the geographic region of interest.

Population at risk

The oil shale regional population was estimated by adding a baseline population to an "oil shale worker" population. The baseline population was estimated using a growth rate of 3.2%/y [29,30] on the estimated 1980 population of 152,000 persons. The 33,200 oil shale workers were multiplied by 6.8 to account for other developments, indirect employment, and worker families, resulting in 226,000 persons moving into the region. Adding the "oil shale worker" population and baseline population results in an estimated 616,000 persons at risk for the public regional population. The distribution of the projected population throughout the region was based on historical patterns and studies on the commuting patterns of the oil shale workers. Most of the resident population is expected to be concentrated along the Colorado River corridor.

The U.S. population was estimated to be 313 million persons in 2010. The 1980 population of 226 million was extrapolated 30 y at a growth rate of 11.4% per decade [31].

Health effects

Estimation of public health risk at low doses considered both threshold and non-threshold health effects. A threshold is an exposure level below which there are no health effects in a population. An apparent threshold is an exposure level below which there are no observed health effects. An apparent threshold may be due to the difficulty in detecting very small effects in the population. In the analysis, carcinogenic and air-pollutant surrogate risks were assumed to have no threshold. All other effects were assumed to have thresholds. A particular pollutant may be associated with multiple effects. In this way, a pollutant could be analyzed for both a threshold effect and a non-threshold effect. The pollutants analyzed as having threshold effects were sulfur oxides, particulates, nitrogen oxides, ozone, carbon monoxide, hydrogen sulfide, arsenic, beryllium, cadmium, chromium, fluoride, lead, mercury, nickel, selenium, and vanadium.

Sulfur oxides and particulates have been associated with acute and chronic respiratory disease including respiratory tract infection, increased bronchitis, and decreased lung function [32]. Nitrogen dioxide, a strong oxidant, has been associated with changes in pulmonary function with chronic exposure [33]. Ozone can affect pre-existing respiratory disease although the effect of ozone is difficult to separate from other pollutant effects [34]. Carbon monoxide chronic exposure has not been determined to cause detrimental effects in humans although there is evidence of behavioral effects of elevated carboxyhemoglobin levels [35]. Hydrogen sulfide was considered in this analysis for its nuisance odor potential, although it can cause eye and respiratory effects at much higher exposures [36].

The non-carcinogenic effects of arsenic exposure include gastrointestinal involvement, skin changes, peripheral neuropathy, and liver damage [37]. Chronic beryllium disease, berylliosis, is a systemic intoxication characterized by effects of the respiratory system [38]. Chronic exposure to cadmium is associated with two major health effects: decreased lung function and, at lower exposures, renal damage [39]. Chromium dusts have caused skin ulcers, dermatitis, allergic responses, and the classic chromium-related symptom, perforation of the nasal septum [40]. At elevated exposures, fluoride causes acute fluoride poisoning, dental fluorosis, and crippling skeletal fluorosis [41] . While the most sensitive adverse effect of lead toxicity is subclinical peripheral toxicity, a range of effects occurs at higher levels including anemia, renal damage, and encephalopathy [42] . Classic mercuralism, caused by inhalation of mercury vapors, is characterized by a variety of neurologic disorders including tremor, lung irriation, and possibly proteinuria as a result of renal damage [43]. Nickel carbonyl causes systemic poisoning with acute exposures. Pulmonary effects predominate the clinical course but parenchymal degeneration is observed in the liver, kidneys, and other organs [44] . Selenium chronic effects are damage to the liver and kidneys [45] . Finally, vanadium effects include chronic bronchitis, chronic rhinitus, and pharyngitis [46].

The analysis for threshold effects involved addition of the calculated air concentration due to oil shale to a background concentration and comparison of the total to the threshold. The expected number of persons having an exposure above the threshold was calculated. The threshold analysis was performed for exposures in the oil shale region. Table 8 presents the thresholds and estimates of predevelopment background concentrations used in the analysis.

Four trace elements have been associated with increased cancer risks: arsenic, cadmium, chromium, and nickel. Cadmium is associated with prostate cancer, while the others are related to respiratory cancers. Polycyclic aromatic hydrocarbons (PAHs) are a class of organics that includes several carcinogenic species. Benzo (a) pyrene (BaP) is often used as an indicator of the carcinogenicity of the class. Use of BaP assumes that BaP concentrations are proportional to the carcinogenicity of the entire class. The dose—response relationships are shown in Table 9. The arsenic, cadmium,

TABLE 8

Health effect thresholds and background concentrations for the public health air exposure risk analysis

Pollutant	Threshold, $\mu g/m^3$	Background, $\mu g/m^3$
Sulfur oxides	120	25.0
Particulates	180	50.0
Nitrogen oxides	100	—
Ozone	100	—
Carbon monoxide	3300	100.0
Hydrogen sulfide	50	—
Arsenic	60	0.01
Beryllium	0.01	0.0001
Cadmium	0.4	0.002
Chromium	160	0.01
Fluoride	10	0.05
Lead	5	0.8
Mercury	1	0.02
Nickel	30	0.01
Selenium	17	0.01
Vanadium	10	0.02

TABLE 9

Dose—response relationships for carcinogenic health effects for the public health air exposure risk analysis

Pollutant	Site	Cancers per year per 100,000 persons per $\mu g/m^3$
Arsenic	Respiratory	4.14
Cadmium	Prostate	2.9
Chromium	Lung	0.13
Nickel	Respiratory	0.105
PAHs (BaP)	Respiratory	0.124×10^{-3}

and PAHs (BaP) functions are from the Environmental Protection Agency's Carcinogen Assessment Group [47, 48, 49]. The chromium and nickel dose—response functions are based on occupational epidemiologic studies [50, 51, 52, 53] . Public exposure to radon gas and particulate-borne radioactivity can cause an increased cancer risk. The BEIR III dose—response model [54] of 403 cancer deaths per million person rads per year was used to estimate this risk. These dose—response functions were applied to the estimated oil shale region exposures.

To assess the effect of air pollution below the apparent thresholds, a sulfate health damage function of 3.5 premature deaths per year per 100,000 persons per microgram per cubic meter of sulfate was used. This function is the result of combining several expert opinions [55] including Lave and Seskin [56], who examined the differential mortality rates of 117 Standard Metropolitan Statistical Areas in the United States. This controversial model uses sulfates as a surrogate for all air pollution and has large uncertainties, especially when applied to a new mix of air pollutants. The sulfur surrogate model was applied both to the oil shale region population exposure and the U.S. population exposure calculated with the Fay and Rosenzweig transport model.

Risks and uncertainty

The following pollutants were found to have no general population exposures greater than the chosen thresholds for potential health effects previously described: sulfur oxides, particulates, carbon monoxide, hydrogen sulfide, beryllium, fluoride, lead, mercury, selenium, and vanadium.

Table 10 shows the results and uncertainty of the public health risk analysis. The largest individual pollutant cancer risk was due to arsenic at 1.0×10^{-3} cancers per year in a population of 616,000 persons. The uncertainty

TABLE 10

Public health risks due to airborne oil shale industry emissions and associated uncertainty

Pollutant	Site	Uncertainty factors[a]				Cases per year[c]	Uncertainty range
		U_S	U_E	U_H	U_R[b]		
Arsenic	Respiratory	1.4	2.1	2.2	3.1	1.01×10^{-3}	0—3.13×10^{-3}
Cadmium	Prostate	1.3	2.2	2.6	3.5	5.55×10^{-6}	0—1.95×10^{-5}
Chromium	Lung	1.3	2.2	3.16	4.1	2.33×10^{-5}	0—9.55×10^{-5}
Nickel	Respiratory	1.3	2.2	3.16	4.1	1.26×10^{-5}	0—5.17×10^{-5}
PAH (BaP)	Respiratory	1.9	2.4	10.00	12.7	2.49×10^{-5}	0—3.16×10^{-4}
Radiation	Respiratory	1.4	2.1	2.2	3.1	2.50×10^{-3}	0—7.75×10^{-3}

Transport distance	Uncertainty factors[d]							Premature deaths per year	Uncertainty range
	U_S	U_C	U_{DD}	U_{WD}	U_P	U_H	U_R[e]		
Regional	2.2	2.0	—	—	1.8	3.1	5.3	14.5	0—76
Long distance	1.8	1.7	3.0	10.0	—	3.1	18.3	12.0	0—220
Total								26.5	0—296

[a] S = source terms; E = exposure model; H = health dose—response; R = risk estimate.

[b] Computations based on $\log U_R = [(\log U_S)^2 + (\log U_E)^2 + (\log U_H)^2]^{1/2}$.

[c] Population at risk is 616,000 persons for all cancers except prostate for which it is half this number.

[d] S = source term; C = sulfur oxide to sulfate conversion rate; DD = dry deposition; WD = wet deposition; P = population distribution; H = health dose—response function; R = risk measure.

[e] Computations based on $\log U_R = [(\log U_S)^2 + (\log U_C)^2 + (\log U_{DD})^2 + (\log U_{WD})^2 + (\log U_P)^2 + (\log U_H)^2]^{1/2}$

of the source term, the exposure transport models, and the health effect functions were determined independently. They were then combined by a root-mean-square approach in the log domain to yield the uncertainty factors.

The risk estimates due to air pollution using sulfates as a surrogate were 15 premature deaths per year (with a range of 0—76 deaths) in the oil shale region population of 616,000 persons, and 12 premature deaths per year (with a range of 0—220 deaths) for the U.S. population of 313 million persons in 2010. The total risk estimate was 27 premature deaths per year with a range of 0—296. Results of a sensitivity analysis were used in the determination of the uncertainty factors.

A sensitivity analysis was performed on the sulfate surrogate model by independently varying different parameters of the model across their reported ranges [57]. In the oil shale region, the dominating parameter is the sulfate health damage function. For long-distance transport, the wet deposition rate constant is the most sensitive parameter followed by the sulfate health function and the dry deposition velocity. The results are less sensitive to changes in conversion rate and source strength.

As shale oil is produced, an equivalent amount of imported petroleum could be replaced in U.S. refineries. Despite the uncertainty and controversy regarding the sulfate surrogate model, a comparison of the health damage due to oil shale development with the health benefit caused by reduction of petroleum refinery emissions in the densely populated Midwest and Northeast was calculated [57]. The results show that the replacement can decrease refinery sulfur dioxide emissions about 167 tons per day and that there is a significant reduction in premature deaths as a result of oil shale production.

Solid waste leachates

Surface water quality changes

Surface water quality changes from solid waste leachates are difficult to estimate because of the uncertainties in operator water treatment, water and waste disposal practices, and abandonment requirements. Limited data from current research were used to perform a simplified calculation of ground and surface water quality changes due to leachates percolating through spent shale piles generated from a one million BPD (160 dam^3/d) oil shale industry.

A series of simplifying assumptions, listed in the HEED [2], were necessary to proceed with the analysis. The analysis should be considered an extreme case because potential removal mechanisms were not considered, and accumulated upper bounds were chosen for many of the important parameters.

The spent shale piles were assumed to be generated over a 30-y operating period. Surface processes were estimated to generate 1.4 ton spent shale per barrel of oil (8.0 kg/L) and MIS processes were estimated to generate

2.3 ton spent shale per barrel of oil (13 kg/L). MIS processes were assumed to result in 0.4 ton spent shale per barrel of oil (2.3 kg/L) disposed in the abandoned retorts. Leachate migration from abandoned MIS retorts was not included in the analysis.

The estimated production in the drainage systems of the Parachute Creek, Piceance Creek, White River and Green River was 450,000 BPD (72 dam^3/d), 300,000 BPD (48 dam^3/d), 150,000 BPD (24 dam^3/d), and 100,000 BPD (16 dam^3/d), respectively. Spent shale volume was distributed over the oil shale region based on these production rates. Leachate concentrations for Paraho and TOSCO retorted shale were averaged to obtain the values used in the analysis. A water flux of 0 to 8 cm/y [58] and the pile surface area were combined to obtain the volume of leachate entering each drainage that was assumed to be flowing at the minimum flow rate on record [59]. The diluted leachate concentration was found for each downstream river segment. Estimated increases in concentrations at the White River at Watson, Utah, Green River at Green River, Utah, Colorado River at the Colorado—Utah state line, and the Colorado River at Lees Ferry, Arizona (locations shown in Fig.2) are presented in Table 11.

TABLE 11

Upper bound increases in concentration of selected leachate trace elements at selected locations in the Colorado River system (mg/L)

Trace element	White River (Watson, UT)	Green River (Green River, UT)	Colorado River (CO—UT line)	Colorado River (Lees Ferry, AZ)
F	0.11	0.031	0.018	0.032
Na	41	11	6.8	12
As	2.5×10^{-4}	4.6×10^{-5}	2.7×10^{-5}	4.7×10^{-5}
Se	2.9×10^{-4}	8.0×10^{-5}	4.8×10^{-5}	8.3×10^{-5}

Health effects

Estimating public exposure to leachates is complicated by the transport mechanisms, water treatment, ingestion patterns, contributions from other pathways, and health response variability. The potential health risk from increases in concentration of pollutants in drinking water is based on two key assumptions: two liters of water were assumed to be ingested per day and the increased pollutant concentrations were added to average ingestion levels for pollutants from all sources.

The health effects associated with ingestion of arsenic, fluoride, selenium and sodium were considered. Ingestion of arsenic compounds has been associated with increased risk of skin cancer [60]. The dose—response relationship of 0.59 skin cancers per year per 100,000 mg of arsenic was used. The relationship is considered very conservative due to the problem of extrapolation from a very high dose to a low dose. Fluoride in drinking water is protective against dental caries at low concentrations but can cause dental mottling with intake as low as 4 mg/d. At very high concentrations, fluoride can cause crippling skeletal fluorosis. A conservative threshold of 20 mg/d is used in the analysis for this effect. A background estimate of 2 mg/d was assumed [61]. Selenium may be an essential element, although chronic health effects are seen at high doses. Sakurai and Tsuchiya [62] recommended a maximum daily intake of 500 μg/d. It was assumed that as much as 100 μg/d was from inhalation, resulting in a conservative threshold for daily ingestion of 400 μg/d. Background concentrations were estimated at 100 μg/d for food [62] and 6 μg/d from water [45]. Drinking water sodium has been shown to be a contributor to hypertension in healthy populations [63]. Persons on sodium-restricted diets (3% of the population) have been shown to have adverse health effects with high sodium drinking water [64]. The National Academy of Sciences (NAS) [61] recommended sodium maximum intake of 200 mg/d was used in the analysis with a background intake of 150 mg/d.

Risks

Based on the leachate analysis, only the population receiving water from the Watson, Utah area (the maximum of the extreme analysis) may be exposed to sodium concentration 16% above the NAS recommendation. Selenium and fluoride thresholds are not exceeded for any segment of the population. The analysis assumed no water treatment. Considering the extreme nature of the assumptions, such as minimum recorded flow rate, the risks due to water exposure are felt to be minimal for the pollutants analyzed.

Individuals in Watson, Utah drinking 2 L of untreated water per day (with an elevated arsenic concentration of 2.5×10^{-4} mg/L) may have an increased individual risk of excess skin cancer of 1.5×10^{9} per year.

Ecosystem risk

Two approaches were used to estimate the effect of the oil shale industry on the ecosystem: (1) through the risks to individual species that occupy important niches or represent an industry development concern, and (2) a quantitative analysis was developed to estimate the potential risk to various plant communities from acreage disturbed by solid waste disposal.

Individual species

A list of potential representative species of animals and plants in the oil shale region ecosystems was developed. The list contained mule deer (*Odocoileus hemionus*), long-tailed weasel (*Mustela frenata*), rainbow trout (*Salmo gairdneri*), American kestrel (*Falco sparverius*), pinyon-pine (*Pinus edulis*), Indian ricegrass (*Oryzopsis hymenoides*), and big sagebrush (*Artemisia tridentata*). The literature was researched to determine the feasibility of performing risk estimates for these representative species. The available data were very limited. The representative species analysis was limited to mule deer based on new solid waste disposal models and Indian ricegrass response to sulfur dioxide emissions.

Mule deer (*Odocoileus hemionus*) can be considered to be one of the oil shale region's most important big game species. It occupies a revealing niche within the ecosystem, it is one of the largest wild herbivores in the area, and it is of high social and monetary value. An oil shale industry can disrupt the mule deer population by removing critical habitat and vegetation, erecting migration barriers, and increasing mortality from road kills and poaching.

Two solid waste disposal models have been developed to calculate the acreage disturbed in the Piceance Basin: the Valley fill and the Mesa fill disposal methods. The land requirements of each fill model are based on two production values, e.g., 10,000 BPD (1.6 dam^3/d) and 46,000 BPD (7.4 dam^3/d) for the Valley and Mesa fill model, respectively, and are shown in Table 12. The land requirements for the life of the industry were calculated by the formula: (total waste pile) + (roads and rights-of-way) + 30 y (land required annually–land reclaimed annually). In the Valley fill model, there will be 554 acres (2.22 km^2) of solid waste disposed per 10,000 barrels of shale oil per day (1.6 dam^3/d). The Mesa fill model predicts 2,040 acres per 46,000 BPD (8.2 $km^2/7.4$ dam^3). These estimates were normalized by production in conjunction with the industry scenario. Currently calculated solid waste disposal needs of the oil shale industry indicate the eventual removal of 36,000 acres (144 km^2) and 29,000 acres (116 km^2) based on the Valley fill and Mesa fill models, respectively. In the Piceance Basin, this represents 1.8% and 1.4% of the total acreage.

TABLE 12

Land requirements for fill models in square kilometers

	Land disturbance	
	Valley model	Mesa model
Total waste pile	1.25	3.60
Land required annually	0.06	0.18
Land reclaimed annually	0.06	0.11
Roads and right-of-way	0.80	2.40

The acreage loss occurs in the winter range of the mule deer, and it is this winter habitat that is a critical factor to the population of the deer herd. The most serious mortality factors currently affecting the mule deer are the winter range condition and the severity of the weather. At times, the mortality rate can reach over 40% of the total population [65]. The estimated relationship of mule deer population decline and land disturbance indicates a projected population loss of 1000 to 2500 deer or 4% to 9%. This is based on an estimated average winter baseline population of 28,000 deer in the Piceance Creek Basin and total habitat size of 425,000 acres (1700 km^2) [66]. The uncertainty in this projected decline is estimated at −50% to +200%. The effect of migration barriers is unclear at present and studies are now being conducted by Los Alamos National Laboratory to map the deer migration routes. Mortality from poaching and road kills should increase proportionately with the increase in human population. A doubling or tripling of road kills may be expected over the life of the industry [67]. Currently, it is estimated that 6000–7000 deer are killed annually on the Colorado highways [65].

The assumptions required to arrive at a crude estimate of mule deer population decline from oil shale habitat disturbance [1] lack validity, indicating significant data deficiencies. Further research into the mule deer–habitat relationship is needed to develop a better understanding and the model parameters for better estimates.

Indian ricegrass (*Oryzopsis hymenoides*) was chosen to reflect the effect of oil shale air emissions on the surrounding plant environment because it has a wide ecological amplitude and a high sensitivity to atmospheric sulfur dioxide [68]. Damage data, in combination with previously calculated air emissions from the industry source term of 115 tons of sulfur dioxide per day, allows for quantification of the plant-sulfate damage levels in the oil shale region. A second-order regression of dose–response data yields the percent injury of Indian ricegrass per milligram per cubic meter SO_2:

$$Y = 0.77 + 0.19826\,X + 0.13494\,X^2\,, \tag{1}$$

where X is sulfur oxide concentration (mg/m^3) and Y is percent injury. The range of exposure in the derivation of the dose–response function was 1.3 mg/m^3 to 26.4 mg/m^3. The sulfur dioxide emissions from each site in the oil shale risk analysis scenario were determined by the method previously described for the public health analysis. Concentration contours indicate that the largest oil shale-produced sulfur dioxide concentration is in the range of 0.1 mg/m^3. This is well below the range of exposure for the dose–response function. This figure is not inclusive of the background concentration of several milligrams per cubic meter. The risk estimate (percent injury) at the highest sulfur dioxide concentration of 0.1 mg/m^3 is 0.79% . This concentration occurs in less than 1% of the region analyzed. The oil shale industry contribution to the sulfur dioxide in the atmosphere of the oil shale region will have a minimal effect upon Indian ricegrass. Indian ricegrass is one of the most sulfur dioxide-sensitive plants in the region [69]; thus, by extrapolation, the effect on other plant species of the region should be minimal.

A representative species for the aquatic systems was also studied [70]. However, turnover rates in aquatic communities are usually much higher than terrestrial communities, and natural fluctuations in populations can be extreme, although risk to a specific species can be determined from probability of effluent discharge resulting in a population change. Aquatic effects are a strong function of water quality. Water quality changes can result from direct effluent discharge leaching of solid wastes, erosion, and air pollutant deposition.

Threatened or endangered fish species would serve as excellent species of ecosystem risk, if suitable life history and toxicological information were known. However, because there are so few individuals of these diminishing populations, it is difficult to obtain suitable numbers for laboratory or field study. Toxicological tests inevitably involve fish mortality, which is unacceptable when studying threatened or endangered species. Based on these considerations, trout (*Salmo sp.*) may be a suitable species for aquatic ecosystem risk. Adult trout are carnivorous and at the top of the aquatic ecosystem food chain. Trout also have a substantial history in the Piceance and Uinta Basins, and estimates of trout abundance can be found from 1969 to the present. The most recent study indicates that brook, brown, and rainbow trout are most common in the upper reaches of Piceance Creek and its tributaries [71] . Brook and brown trout are reproducing naturally in Piceance Creek, but rainbow trout seem to be declining. All of these introduced trout are adaptable; they can live in a variety of environments ranging from small brooks to large rivers and lakes, and they feed on a broad spectrum of organisms. All trouts are opportunistic and eclectic in their diet, which essentially reflects the availability of food organisms in their particular environment. Growth depends primarily on food availability, size of prey, the degree of intraspecific and interspecific competition, water temperatures, and length of the growing season. Fecundity, in turn, depends on size. All of non-domesticated western trouts of the genus *Salmo* spawn in the spring; increasing water temperatures trigger reproduction.

Ammonia concentrations will also cause trout mortality, depress egg hatchability, and reduce the growth of fry. The 96-h LC_{50}-value (concentration resulting in 50% lethality) calculated for un-ionized ammonia in oil shale retort waters ranges between 0.26 and 0.49 mg/L [72]. Under the scenario of large accidental discharges of plant waters, the temporary disappearance of trout populations from Piceance and Parachute Creeks could occur. Although the available data are inconclusive, trout mortality and morbidity may also occur from heavy metal burdens. Fish tissue concentrations will be highest during periods of high water flow, which allows metals bound to bottom sediments to become resuspended and available.

Plant community disturbance

The second approach used to quantify ecosystem effects involves individual plant community loss due to solid waste disposal. The percentage of land disturbance at each lease site was calculated for both fill models using the land requirements previously illustrated. The plant communities present on each lease site have been identified and cataloged by soil type [73]. The effects of acreage disturbance upon plant communities were estimated by applying the percent acreage disturbed by site to the acreage of each plant community on the site.

TABLE 13

Thirty year plant community disturbance within the oil shale development region using the Valley fill and Mesa fill solid waste disposal models

Plant community[a]	Total area, km²	Area disturbed, km² (% disturbance)			
		Mesa fill		Valley fill	
Aspen woodland	218	21.9	(10.0).	27.3	(12.5)
Pinyon juniper	2936	18.4	(0.6)	22.9	(0.8)
Brushy loam	1500	12.8	(0.8)	16.0	(1.0)
Mountain and brushy loam	484	20.2	(4.2)	25.2	(5.2)
Mountain loam	15	1.2	(7.1)	1.5	(9.7)
Douglas fir forest	167	1.2	(0.7)	1.5	(0.9)
Loamy slopes	56	2.4	(3.7)	3.0	(5.3)
Steep and rocky	259	10.9	(4.2)	13.6	(5.3)
Irrigated cropland, pasturelands	171	3.7	(2.1)	2.9	(1.7)
Rolling loam + loamy slopes	103	14.0	(13.5)	17.4	(16.8)
Stoney foothills + foothill swale	94	1.6	(1.7)	2.0	(2.1)
Stoney foothills + rolling swale	74	0.4	(0.5)	0.5	(0.6)
Pinyon juniper + clayey slopes	62	7.9	(12.6)	9.8	(15.7)
Alkaline slopes	33	0.3	(0.9)	0.4	(2.2)
Rolling loam	185	0.6	(0.3)	0.8	(0.4)

[a]Plant community names and descriptions taken from soil composition types as given in "Land Use and Natural Plant Communities" Maps [73].

The results of the plant community disturbance analysis are summarized in Table 13 and indicate the effect on the Piceance Basin over 30 y. In the Mesa fill model, the majority of communities present will be disturbed less than 10% . The three communities disturbed more than 10% , e.g., pinyon-juniper + clayey slopes (12.6%), rolling loam + loamy slopes (13.5%), and aspen woodland (10.0%), have significant plant population overlap with the other plant communities and do not represent unique habitats. In the Valley fill model, the majority of the communities present will also be disturbed less than 10% . The Pinyon-juniper + clayey slopes (15.7%) and the rolling loam + loamy slopes (16.8%), as well as the aspen woodland (12.5%) are the most disturbed. Thus, with few exceptions, the Valley and Mesa fill models for solid waste disposal do not produce reductions in excess of 10% in plant community populations in the oil shale development area.

Other concerns

The increasing level of salinity, i.e., the concentration of dissolved salts, in the Colorado River is a significant water quality problem for agricultural and municipal users. Increased water consumption by the oil shale industry and new municipalities may increase the salt concentration of the Colorado River; the potential leachates from spent shale piles may also increase the salt load. Ferraro and Nazaryk [74] presented the increase in salinity at the Imperial Dam to be 13.4 mg/L for a 1,163,000 BDP (186 dam^3/d) oil shale industry and an increase in the range of 0.30—0.75 mg/L due to municipal waste water treatment facilities. Some laboratory tests and a few small field studies have indicated that the spent shale piles can be fairly stable, non-leaching land forms.

Acid precipitation is also of concern in the oil shale region. Preliminary studies have identified vulnerable areas in the mountains to the east of the Piceance Basin development area. The Flat Top Wilderness Area and the Mt. Zirkel—Dome Peak Wilderness Area are particularly susceptible to acid rain because their underlying geology shows little buffering capacity. Studies of various lakes indicate that they are currently unaffected by acid rain and have a pH between 7.0 and 9.0 [75] . The high-elevation lakes are most sensitive; at over 11,000 feet (3400 m) some changes in lake chemistry can be expected from even a small amount of acid deposition.

Discussion

Comparing the estimated risks for the oil shale workforce illustrated that the mining and crushing workers are in "high risk" work groups both for accidents (Table 2) and occupational diseases (Table 5). These workers represent 50% of the workforce but account for 70% of the expected fatalities and the majority of occupational diseases [75]. On an LLE basis, a similar relationship occurred. For the overall workforce at the 5 mg/m^3 nuisance dust level, the LLE for diseases and accidents were about equal. At the 100 $\mu g\ SiO_2/m^3$ exposure level, the hydrocarbon-induced cancers represented one third of the disease LLE. The disease LLE decreased to 15% of the total LLE. At the lower dust exposure, safety issues dominate.

The estimate of premature deaths due to air pollution (as found with the controversial sulfate surrogate model) is the predominant result of the public health risk analysis. The total public cancer risk is over three orders of magnitude less than the sulfate surrogate premature death risk. No part of the population was exposed to pollution concentrations over the threshold for the other effects analyzed. Another risk estimate [76] as a surrogate for all air pollution, fine particles ($d < 2.5\ \mu m$), resulted in 60% less premature deaths.

A large variety of organic compounds is known to be present in retorted shales and waters. The uncertainty of environmental transformation and removal of these organics is great, and the health effect dose—response is unknown for complex organic mixtures in water.

Significant research efforts are underway in Scotland to study the health of the public around the now defunct Scottish oil shale industry. The results of this research are providing substantial insight into risk [77].

The methodology for the risk analysis of a future oil shale industry has been reviewed. Based on the magnitude of the estimated risks and the importance of the disease in terms of worker productivity and health, pneumoconiosis from silica and dust, chronic bronchitis, and chronic airway obstruction stand out among the diseases analyzed. This result stresses the need for future consideration of mine dust control. Research is needed to reduce the uncertainties in the dust-related diseases, such as an improved dose—response relationship and dust exposures for oil shale workers. The free-silica content of oil shale dusts inhaled by workers has been shown to be a key element for the potential risk of silicosis. If the environmental dust exposure of the worker is improved, safety improvements in the mining sector are of prime importance to reduce the oil shale worker's life-loss expectancy.

The analysis of public health risks from a hypothetical one million BPD (160 dam^3/d) steady-state oil shale industry indicates that air emissions present the predominant risk. A trade-off analysis suggests that replacement of high sulfur imported oil may provide an overall health benefit for the U.S. population. Analysis of surface water quality changes from solid waste leachates shows minimal public health risk for those pollutants considered, although further analysis is needed on waterborne organics. The results to date do not indicate that the oil shale industry will pose any significant risks to the public beyond those of other fossil fuel energy cycles. The large uncertainties in various components of the analysis serve as a guide to research needs for the reduction of risk uncertainties. Data from the study of past, present, and future oil shale plants will be used in future iterations of this analysis process.

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