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Dumping, Storage and Handling of Nuclear Waste in Deep Underground Mines

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ABSTRACT

Nations that utilization thermal power decide to store Low-Level and Intermediate-Level radioactive waste in mined vaults, which are comprised of a progression of passages or floats connected to removal burrows at a profundity of a couple hundred meters. Deserted mines might be utilized as waste dumps, and the flow research proposes that this could likewise be finished with High-Level Waste as spent reactor fuel. The strategy involves encasing such trash in metal canisters encompassed by vigorously compacted smectite dirt in both shallow mining storehouses and very profound drag openings. Transitional level radioactive waste, as heaps of metal canisters cast in low-pH concrete and imbedded in thick smectitic mud, might be discarded in caves.

INTRODUCTION

One of the possibilities for the disposal of radioactive waste products derived from the operation of nuclear power plants is its underground storage in space formed within deposits of rock salt. This report contains information concerning the characteristics of rock salt, its occurrence in the United States, and the underground space resulting from mining operations. Consideration is then given to the feasibility of using such space for waste disposal. The Division of Earth Sciences, National Research Council, at the request of the Atomic Energy Commission, has undertaken a study of the underground disposal of atomic waste and the preparation of a report and recommendations on the subject. A conference for the discussion of the subject was held at Princeton University, September 10–12, 1955, and a Steering Committee was appointed to function in the preparation of a report.

(1) During the period subsequent to the conference, as a member of the Steering Committee, the writer of this memorandum had an opportunity to investigate further the possibility of underground disposal particularly in cavities formed by the mining of salt. The information obtained has been compiled in this paper as a matter of record and for such value as it may have in further consideration of the disposal problem. The paper is preliminary in character, and is not a complete presentation of this phase of the problem.

CHARACTERISTICS OF SALT DEPOSITS

Rock salt in its crystalline form is the mineral halite (NaCl; sodium 39.4, chlorine 60.6%). Halite is isometric and occurs in crystals with cubical cleavage, which are transparent or translucent. Hardness is 2.5. Specific gravity of pure crystal salt is about 2.17 (136 Ibs. per cu. ft.). Index of refraction is 1.5442. It is highly non-conductive of electricity. The melting point of salt is 801° C. and the boiling point, 1413° C. Solubility in water in grams per 100 ml. is 35.7 at 0° C. and 39.12 at 100° C.(2) (3)

In its usual occurrence, rock salt contains impurities. As mined for commercial purposes, it is generally not less than 97% pure, with grades used in the chemical industry over 99% pure. As mined, the specific gravity ranges from 2.1 to 2.6, depending upon the degree of purity. It has a coarse granular to compact structure. Its toughness makes it resistant to mining with power machines and explosives are used in its production in solid form. Its solubility in water permits its solution and extraction as brine.

From the geological standpoint, salt is plastic and flows under pressure. In that respect it is similar to ice, but the pressure and time required to produce observable plastic flow in salt are very much greater. The pressure required for the rapid deformation of rock salt is very great but, over long periods of time, much lower pressure may be expected to result in flowage. Plastic movement of rock salt has apparently not been observed in the pillars left in salt mines in the United States, with the amount of overburden as much as 2,000 feet. In mining potash in New Mexico, where the depth of the deposit is about 900 feet, the sylvinite ore (a mixture of halite, NaCl, and sylvite, KCl) shows positive evidence of plastic flow. Horizontal drill holes in the sylvinite ore show vertical compression of about 25% in about ten years. Sylvite, the principal potash-bearing mineral in the ore, is apparently more plastic than halite.

Salt deposits are of sedimentary origin and commonly occur interbedded with other rocks, such as limestone, dolomite, anhydrite and shale. Under conditions of temperature and pressure present at great depths and during geologic time, bedded salt has flowed along lines of weakness and risen into overlying beds in the form of plugs and domes.

PRODUCTION OF SALT IN THE UNITED STATES

The total production of salt in the United States now exceeds 20 million tons per year, either as dry salt or in the form of brine.(15) This amount is about 35% of the world's total production. Because salt is widely distributed, the United States imports very little salt; it exports less than 2% of the production.

4.2 About 60% of the salt is produced as brine, natural and artificial. Natural brines, occurring in porous formations, are pumped to the surface and evaporated. Artificial brines are formed by drilling wells into beds of rock salt, pumping in water, which dissolves the salt, and then pumping the resulting solution to the surface. Salt is more economically produced by this method them by mining. But the process of solution eventually causes cavities to be formed beneath the surface. Where the salt is thick and underlies a large area, the overlying rocks may eventually be left without support and caving follows.

Most of the brine brought to the surface is supplied directly to chemical plants in which the sodium chloride is used as a raw material for the manufacture of other sodium compounds and chlorine, useful as reagents. A smaller part of the brine is evaporated to produce refined salt for human consumption and for many industrial applications.

About 20% of the salt production is obtained by underground mining of salt deposits. By careful selection of the source bed, salt of great chemical purity is obtained for use in chemical applications. Large amounts of rock salt are also used for highways, for stabilizing the surface, and, in winter, for ice removal.

MINING OF ROCK SALT

Rock salt was mined at fourteen localities in the United States in 1953. The distribution of these mines by states is as follows: New York, 2; Michigan, 1; Kansas, 3; Louisiana, 4; Texas, 2; Utah, The location of these mines is shown on

The principal operating mine in is that of the International Salt Company at Retsof, Livingston County-The salt is produced from a bed in the upper part of the Salina formation that has a thickness of feet: The mine shaft is 9′×26′ and has a depth of 1063 feet from the collar to the bottom of the salt bed. The salt dips approximately 1/2° to the south. The capacity is about 4,000 tons in 8 hours. The mine commenced operation in 1923. About 60% of the salt is extracted and 40% left as pillars. Assuming a production of 1,200,000 tons per year and 15 cubic feet of salt per ton, the space mined out would be 414 acre-feet. With a thickness of salt of 10 feet and 60% recovery, about 68 acres would be mined out annually. The total production of the mine has not been published, but, with 30 years of operation, it is probably not less than 1500 acres.

At Portland Point, on the east side of Cayuga Lake, Tompkins County, a mine has been operated for about 20 years. Details of production, etc. are not known.

Several other rock-salt mines were formerly operated in New York but have been closed down. The oldest mine was at Livonia, Livingston County, and was operated from 1883 to 1890. It was 1430 feet in depth. The mine is now filled with water and the condition of the shaft is now known. About 50 acres was mined out. Another mine at Lehigh, Genessee County, had a depth of 825 feet and was operated about 4 years. The quantity mined was about 15 acre-feet. The shaft is filled with water to the surface.

The mine of the International Salt Company, at Detroit, is the only producer of rock salt in Michigan.(17) It is operated through two shafts about 1100 feet deep and the uppermost bed of the Salina formation is worked. It varies in thickness throughout the mine from about 19′ to 40′. The greatest thickness mined is about 36′, 4′ being left for roof. About 60% of the area is mined, the remainder being left for pillars. The rooms are limited to a width of 60'. About 700 acres has been mined out. The mine is dry, except for an occasional seeping of a few cubic feet of bittern from the formation. The mine has been in operation since 1910 and, during that period, only one small roof-fall has occurred. The shaft is located about 1 1/2 miles from the Detroit River and about 1/4 mile from the River Rouge. The surface above the mine is chiefly property of the Pennsylvanian and Wabash railroads used for yards and shops. About 20′ below the bottom of the bed now mined and separated from it by a bed of dolomitic limestone, is a second bed of salt, much thicker than the one being worked. The top of this lower bed is exposed in one of the mine workings.

In Kansas, three rock salt mines are now operated.(18) The Carey Salt Company operates a mine near Hutchison through a shaft 645' deep. The bed mined has a thickness of 10'. The total volume mined out is about 145 acre-feet, equivalent to about 14 acres. At Kanopolis, the Independent Salt Company has two shafts 846' deep and is mining a bed 15–16' thick. The total mined-out space is about 4,000 acre-feet, equivalent to about 25 acres. The American Salt Corporation has a mine near Lyons 993' deep working a bed 8 1/2' thick. The space mined out is about 100 acre-feet.

Several other mines are either closed down or have been abandoned. The largest is owned by the Morton Salt Company near Kanopolis and was closed in 1948. It is thought to be still dry. Depth to bottom is 810' and the volume mined out is about 1500 acre-feet. The average ceiling is about 9'. The Carey Salt Company has a shut-down mine at Lyons closed in 1948. Its depth is 1024' average ceiling 10', and the volume mined out is about 1000 acre-feet.

The three producing mines produced 534,658 tons of rock salt in 1954. This is equivalent to about 185 acre-feet. Assuming an average thickness mined of 10' and 50% left for pillars, the area mined out would be about 37.

Salt is produced in Louisiana from four mines.(19) The International Salt Company has a mine at the salt dome at Avery Island, Iberia Parish. The rock salt was first discovered at a depth of 18' below the surface. The present mine was opened in 1898 with a shaft 518' in depth.

At the Jefferson Island salt dome, where the mine is operated by the Morton Salt Company, a circular shaft has been sunk to a depth of 900'. Myles Salt Company produces salt at the Weeks Island salt dome from a shaft reported to be 645' in depth. Carey Salt Company is mining salt from the Winfield salt dome, Union Parish, from a depth of 838'. The shallowest depth at which the salt has been found in this structure is 437'. Rooms are 50' in width and 20 to 80' in height. Mining began in 1931 and the production for several years averaged about 60,000 tons annually, increasing to 120,000 tons in 1941. Recent figures of the individual mines are not available.

In Texas, the Morton Salt Company, Grand Saline, Van Zandt County, has a shaft to a depth of 700', which enters the salt at 213'. Rooms are 60' wide by 80' high. The production is about 1000 tons per day and 100 acres has been mined.(19)

The United Salt Corporation operates a mine on the Hockley dome, Harris County. The shaft is 1525' deep.

ROCK SALT ESTIMATED PRODUCTION BY STATES

5.8 In the potash mines of New Mexico, a large volume of underground space is produced by the removal of the sylvanite ore. The total amount of ore mined in 1952 was approximately 7,850,000 short tons. Assuming 15 cubic feet of ore to the ton, the volume would be about 2700 acre-feet per year. If the average thickness mined is 8', the total number of acres mined out annually would be about 335 acres. Pillars are left to support the roof during the mining operations but these are usually pulled after mining operations cease to recover the additional ore. Because of the plasticity of the sylvanite it is doubtful if the mined out space would be suitable for long-time storage of atomic waste. The subjacent salt would provide a more suitable potential storage space because of the greater resistance of the halite to pressure.

PRODUCTION OF RADIOACTIVE WASTE

Fission-product waste is produced when a nuclear fuel, such as U^{235}, U^{233}, or Pu^{239}, is fissioned in a nuclear reactor.(20) In nuclear reactors, the fission of one gram of U^{235} produces about 1 gram of fission products. The fission products are, in part, gaseous and, in part, in liquid or solid form, depending upon the fuel used.

Fuel systems used or considered for power reactors may be grouped as follows:

Liquid-fuel systems, in which the fuel is dissolved in water or heavy water;

Solid-fuel systems, using metals such as uranium and plutonium, in which these metals are contained in corrosion- and temperature-resistant cans;

Liquid-metal systems, using sodium, bismuth, etc. as a solvent;

Fused-salt systems, in which the nuclear fuel is mixed, for example, with a fluoride or hydroxide of sodium, lithium, etc.

Where the nuclear fuel is introduced in the reactor in aqueous solution the output of the reactor is directly processed to remove the waste. If the waste from the reactor is in solid form and included in the spent fuel elements, the waste is separated from the unconsumed uranium and plutonium in a chemical processing plant, in which the solids are dissolved and the waste thereafter separated by one of several methods.(21)

Natural uranium contains one part of fissionable U^{235} in 139 parts of fertile U^{238}. Thus, if natural uranium is used as a fuel, it is possible to consume U^{235} both to support the chain reaction and to give excess neutrons which, when captured in U^{238}, will produce plutonium 239. Theoretically, in power breeders, it is possible to produce more Pu^{239} than the combined consumption of U^{235} and Pu in the reactor. In a system where highly enriched U^{235} is used, Pu is not produced because of the absence of fertile U^{238}. If, in such a system, the reaction proceeded until 30% of the initial U^{235} were consumed, approximately 250 grams of fission products would be produced per kilogram of U^{235} charged.(22) Thus, from one metric ton of natural uranium irradiated to 30% burn up of U^{235}, approximately 2 kg of fission products will be derived. If enriched U^{238} were used as fuel, the quantity of fission products per ton of charge would be increased, depending upon the extent of the enrichment.

REQUIREMENT FOR NUCLEAR ENERGY

has been calculated that the fission of 1 gram of U^{235} will produce approximately 24,000 kilowatt hours at 100% thermal efficiency.(23) The efficiency of production of electrical power from heat is usually taken as 25% for statistical calculations.(24)

The present installed capacity of electric utility generating stations in the United States is about 115,000,000 kw (115,000 megawatts).(25) The production of electrical energy for the year ended January 31, 1956, was 553,568,952,000 kwh; equivalent to 63,000,000 kw-years. This represents an average load factor of about 55%.

CHARACTERISTICS OF RADIOACTIVE WASTE

If natural or enriched uranium is used in metallic form in a heterogeneous reactor, the fissioning process proceeds to some point limited by economics, corrosion or mechanical stability. It is probable that large quantities of fissionable and fertile material will remain in the irradiated fuel. Thus spent fuel elements are still very valuable since they contain part of the initial charge of fissionable and fertile material along with any new fissionable material produced. They are transported, usually in solid form, to a chemical processing plant for recovery and separation of fissionable and fertile material from fission products in diluent. This is accomplished by dissolving the elements in an acid such as nitric acid, followed by selective solvent extraction of valuable components from diluents and fission products. This leaves the fission products in the bulk of the depleted processing stream or raffinate. This raffinate stream is the high level waste and poses the principal disposal problem.

After irradiation in a reactor, the metallic elements in which unconsumed fuel and waste are mixed are highly radioactive and they are accordingly stored before processing for a period of time, during which further decay of fission products occurs. Cooling periods vary. However, the rate of decay of fission products is approximately the same; e.g., after 135 days the activity of the fission products is reduced by a factor 10−4 from their activity level at the time of discharge from the reactor. At the time of discharge from reactor, the gross fission product activity is 5.7 per cent of the rated power of the reactor.

If the fuel is fed to a reactor of homogeneous type in liquid form, the spent fuel must also be processed in liquid form. Because it is, under present conditions, more difficult to transport the waste in liquid than in solid form, the chemical processing for the removal of the waste from the fuel will presumably be accomplished at each reactor. Future developments may make it feasible to transport such liquid waste economically and safely.

In either case, the waste products of the reactor, except for those disposed of to the atmosphere in gaseous form, will be presented for disposal as liquids. The characteristics of the liquid waste are determined by the particular method of chemical processing used. Wastes resulting from the operation of nuclear reactors are classified as high-level wastes.

These high-level wastes, as produced by processing plants, have concentrations varying from 0.5 gals, to 20 gals, per gram of U^{235} burned.(29) One figure used for calculations of waste volumes resulting from solvent extraction is 820 gals, per metric ton of fuel charged to the reactor, which is equivalent, at 4000 mwd/ton, to 2 gals, of waste per mwd of heat produced by a nuclear reactor.(30)

The principal problems in connection with the transportation and storage of radioactive waste arise from its chemical character, the energy given off as heat, and radioactivity. The waste is produced as an acid solution, and, unless neutralized by an alkali, such as sodium hydroxide, is corrosive to processing equipment. The corrosion is increased with high temperature and it may, therefore, be desirable that the temperature of waste in metallic storage be moderate; below 120–150° F. is desirable.

Depending upon the concentration of fission products in the waste, the power produced per unit of fuel charged to the reactor, and the decay cooling time, fission products in the waste will produce heat at the rate of about 1 to 3 Btu/gal/hr.(31) This rate of heat production would be sufficient to raise high-level waste above the boiling point in a few days. In storage of waste underground in liquid form, it would therefore be necessary to provide means for cooling the waste and removing the heat, unless the waste were greatly diluted.

The radioactivity of liquid waste from natural uranium is from 20 to 400 curies per gallon depending upon its chemical character. (32) Adequate protection of personnel from this amount of energy requires heavy shielding. The weight of the shielding adds greatly to the cost of transportation.

WASTE PRODUCTION IN NUCLEAR POWER PLANTS

In a preceding paragraph it was assumed that the thermal capacity of nuclear power plants would reach 700,000 mw by the year 2000, requiring a feed of about 63,500 tons of natural uranium, or equivalent, per year. Using a figure of 820 gallons of high-activity waste per metric ton of fuel charged gives a total annual volume of waste of about 52 million gallons, equivalent to 7,000,000 cu. ft. or about 160 acre-feet. If this power were produced in 350 power plants, the amount of underground space required annually for each power plant would be about 0.5 acre-foot.

This amount of total space is approximately 10% of the amount of space being produced annually in the mining of rock salt at the present time. By the year 2000 it is to be expected that the volume of salt production will increase several times, production having doubled in the last 15 years.

TRANSPORTATION OF NUCLEAR WASTE

The three methods in use for transportation of high-level nuclear waste, trucks on highways, barges and ships on waterways, and cars by railway, are all costly because of the necessity for shielding and other requirements for safety in transit.(33). Trucks are used for transportation of waste for relatively short distances and generally in areas where safety is carefully controlled. The transportation of waste from processing plants to points of disposal is principally by rail or water. Estimates of cost indicate that rail transportation costs several times as much as water transportation for equivalent distances. The hazards of transportation of highly radioactive materials by rail through populated areas are also greater than is generally the case along water routes. For these reasons it maybe advantageous to locate plants for the processing of spent fuel at points where the spent fuel can be transported by water from the reactor.

ACCESSIBILITY OF SALT SPACE FOR WASTE DISPOSAL

The principal areas in which salt deposits occur are those in the north central states and in the southern states along the Gulf Coast.

The salt deposits of the north central states, New York, Pennsylvania, Ohio and Michigan, are adjacent to the Great Lakes and lie in part beneath these bodies of water. It is possible in this region to use water transportation for the movement of spent fuel to a processing plant from points as far separated as New York City on the east to Chicago or Duluth on the west.

In southeastern Michigan or in northern Ohio a processing plant could be located on the shore of Lake Erie directly above salt deposits occurring at a depth of about 2,000 feet. Suitable facilities for unloading barges could be provided at the plant. Shafts could be driven to the underlying salt and the salt produced and marketed. The mined-out space could be so planned as to provide adequate roof support and safe routes for the transportation of waste to points of storage. The mining operations could be performed by an industrial contractor so that the net cost of the mined-out storage space might be very small. Detailed consideration should also be given to the suitability and availability of space in existing or abandoned salt mines in this area.

The area along the Gulf Coast in which salt domes occur is accessible to water transportation through the Mississippi River and its distributaries and the intercoastal canal. Numerous salt domes are present in the area but in many of them the salt is at uneconomic depths. Some of the salt domes are being mined and worked-out space now exists. The feasibility of utilizing such space for the storage of radioactive waste and at the same time continuing the operation of the salt mines would require detailed investigation. A few salt domes exist in the area in which mines have not been opened and which are favorable as to depth of salt and convenience of transportation.

12. UTILIZATION OF SALT SPACE FOR WASTE DISPOSAL

The storage of radioactive waste in properly located space obtained by the mining out of rock salt has many advantages as compared with other methods of disposal. Some of these are the following:

a. The salt itself has considerable strength so that pillars left in mining may provide sufficient strength to support the roof. In bedded salt deposits the overlying strata such as limestone and dolomite provide truss-like support to the overburden. The possibility of roof collapse causing the release of radioactive materials stored under these conditions appears very small but merits verification.

b. The salt is impervious to the passage of water because of its plasticity and crystalline structure, so that the mined-out space is very dry. This dryness increases the life of metals by reducing rust and corrosion.

c. The salt deposits are quite level so that suitable vehicles can be used in transportation underground.

d. The two principal areas where deposits of rock salt occur in the United States have very low seismicity and the possibility of space in mined-out areas being collapsed by earth movements is extremely small. Geological examination of mined-out areas indicates that faults are not present, confirming a geological history of stability.

e. The comparatively high thermal conductivity of salt and its sufficiently high melting point would permit the storage of wastes at moderate temperature without effect on the walls of the cavity, provided the plasticity of salt is not increased by long-continued exposure to elevated temperatures.

12.2 These advantages would not exist to the same extent if the salt cavities were produced by pumping water into the salt formations and the removal of the salt as brine. The large extent of cavities formed by this method, the absence of roof support, and the lack of control over the underground distribution of radioactive waste introduced into such cavities are disadvantages which make it inadvisable to consider the use of such space for disposal. The possibilities of collapse of such cavities are considerable and instances of surface subsistence from such collapse are known to the salt industry.

PROBLEMS OF UTILIZATION OF MINED-OUT SPACE

The storage of high-level radioactive waste in underground salt space presents several problems of an engineering character. These problems differ in some respects depending upon the physical form and characteristics of the waste as it would be produced by reactors or processing plants.

High-level waste now being produced from these sources is in liquid form. The liquid as produced is chemically active, radioactive, and produces heat through radioactive decay. It is therefore desirable that the waste be treated before storage to minimize these hazardous characteristics. It is also, in some cases, diluted in the course of the chemical separation process so that the volume is materially increased.

The activity of the waste is now chemically neutralized by treatment with alkaline solutions before it is placed in surface storage tanks for aging. This process results in an increase of about four times in the volume of the waste but this can be reduced by evaporation to a point where the slurry contains about 35% solids.(34) Waste so neutralized would apparently not have any chemical effect on the walls of a salt cavity with which it moves into direct contact but further study should be given to this problem.

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