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GEOHERMAL ENERGY - FEASIBILITY STUDY

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ACKNOWLEDGMENTS

The work reported herein represents the efforts of a number of individuals at Calspan Corporation and is an outgrowth and extension of the basic concepts of harnessing the geothermal energy of salt domes as patented by Mr. Charles H. Jacoby of the International Salt Company. The concept of the underground conversion of organic wastes to oil was suggested by D. H. Bock, who was responsible for the initial investigations. Investigations of the feasibility of generating cavities in salt domes by solution mining were made by R. C. Lockemer. Helpful suggestions were made throughout the study by D. B. Dahm, A. T. McCord and J. Y. Yang.

TABLE OF CONTENTS

<u>SECTION</u>	<u>TITLE</u>	<u>PAGE</u>
I	INTRODUCTION AND SUMMARY	I-1
II	ELECTRICAL POWER GENERATION	II-1
III	WASTE-TO-FUEL CONVERSION	III-1
IV	CONCLUSIONS	IV-1
	REFERENCES	
	ACKNOWLEDGMENTS	

LIST OF FIGURES

<u>FIGURE NO.</u>	<u>TITLE</u>	<u>PAGE</u>
1	EXPLOITATION OF DEEP-SEATED SALT CAVITY -----	II-2
2	D as a FUNCTION OF $(kt/a^2)^{1/2}$ -----	II-4
3	TEMPERATURE DECAY OF CAVITY WALL -----	II-5
4	CLOSURE OF CAVITY IN SALT FORMATION -----	II-8
5	SYSTEM CONCEPT: IN-GROUND WASTE-TO-OIL CONVERSION -----	III-6
6	CONVERSION OF ORGANIC WASTE TO METHANE -----	III-8
7	MUNICIPAL SYSTEM FOR METHANE PRODUCTION -----	III-11

Section 1

INTRODUCTION AND SUMMARY

In late spring of 1975, discussions were held between Calspan personnel and representatives of the International Salt Company concerning patents* held by C. H. Jacoby of that organization. Subsequently, an internal research program was initiated to investigate the feasibility of using the geothermal energy available in salt domes to generate electrical power and of using cavities developed in salt domes as high temperature, high pressure chemical reaction vessels for converting municipal wastes to fuel oil or gas.

Salt domes are massive underground salt formations originating at depths of 40,000 feet or more and extending upward, sometimes to within a few thousand feet or less of the earth's surface. The horizontal cross sections of salt domes are sometimes several miles in diameter. Temperatures of 330°F at 10,000 ft., 455°F at 15,000 ft., and 580°F at 20,000 ft. have been reported as being typical (Ref.1). Because the thermal conductivity of rock salt is two or more times that of other sedimentary rock, geological heat anomalies are observed in regions of salt domes.

The investigation of the feasibility of using the geothermal energy in salt domes to produce electricity showed that, while there is more than ample heat in a typical salt dome to operate an electrical power plant of economical size (>10 mw) for a **reasonably** long period of time, there are severe technical problems in developing feasible means for extracting the heat. A reasonable approach to heat extraction is to circulate a working fluid through a single large cavity or a system of thin cracks located deep in a salt dome, i.e., at depths of 10,000 to 20,000 feet. The heated fluid would be returned to the surface and passed through a heat exchanger coupled to a turbine loop. In order to extract heat at rates of 50 to 100 megawatts for periods of 20 years or more, a fluid-to-salt contact area of tens of millions of square feet is required. The practicality of generating a suitable

* Patent No's. 3,858,397 and 3,864,917

cavity configuration of the required size is doubtful because of the tendency of rock salt to flow at the temperatures of interest (several hundred degrees Fahrenheit). At depths where the desired temperatures are encountered, the salt pressure ranges from 10,000 to 20,000 psi. The corresponding hydrostatic pressure of 4300 to 8600 psi is insufficient to prevent the collapse of cavities at these depths because of the plastic behavior of salt at the prevailing temperatures. Thus, it would be virtually impossible to generate the required cavities initially and to maintain them even if they could be made. This is particularly true of a network of thin cracks which would be the most desirable configuration from the standpoint of heat transfer. The only way that this problem might be overcome is to apply an excess pressure to the system at ground level to reduce the pressure differential at depth between the cavity fluid and the surrounding salt to acceptable levels. The added complexity and cost of construction, and the increased cost of maintenance and operation make this potential solution generally unattractive.

The problem of cavity collapse in salt domes at great depths also presents severe difficulties in carrying out the schemes proposed initially for converting wastes to oil. Consequently, it became necessary to consider alternative approaches that could be implemented at shallower depths and at correspondingly lower temperatures. Two distinctly different methods for converting a slurry of sewage sludge and municipal solid wastes to fuel were investigated. In the first method, the slurry would be piped to an underground salt cavity located at a depth of 2000 to 8000 feet. The salt temperatures in this depth range are expected to vary from somewhat over 100°F at the shallow depth to a maximum of 280 to 300°F at the greatest depth. A constant pressure of between 800 and 3000 psi would be maintained in the cavity as a result of hydrostatic pressure. The heat required to maintain the temperature necessary to promote the desired chemical reactions would be supplied to the cavity by piping in heated carbon monoxide under pressure. This proves to be a convenient arrangement, since carbon monoxide is required as one of the reactants for the conversion process. The end product of the reactions would be a heavy-grade oil which would be brought to the surface through an exit pipe.

The second method for converting waste to fuel is based on the anaerobic digestion process in which facultative and anaerobic bacteria convert complex organic compounds to organic acids. Different bacteria, called "methane formers," then convert the acids to methane and carbon dioxide. This process is usually carried out at atmospheric pressure at temperatures in the range of 86 to 100°F. At temperatures in the range of 120 to 140°F, higher methane yields are possible. In the proposed waste conversion scheme, the waste slurry would be piped to an underground cavity located at any convenient depth, but not at depths where the temperature would exceed 140°F. The methane-carbon dioxide mixture could be vented to the surface and collected. The methane can be separated from the carbon dioxide by bubbling the mixture through water, since carbon dioxide has a higher solubility in water than does methane.

Considerations of means of avoiding the problems of cavity collapse led to the development of an underground flow-through chemical reactor. Because of the proprietary nature of this concept, it will not be discussed in this report. A patent disclosure has been filed by the inventors, A. McCord and E. Hodgson.

Section II

ELECTRICAL POWER GENERATION

The feasibility of generating electricity from heat extracted from salt domes at depths of 10,000 to 20,000 feet was investigated rather extensively. It was assumed that for economical operation an electrical power plant should have a minimum generating capacity of 10 megawatts and a minimum operating lifetime of 20 years. The overall heat-to-electricity conversion efficiency for a plant powered from a geothermal source having an initial maximum temperature of about 300°C (572°F) would be between 10 and 20 percent, although the theoretical efficiency at start up approaches 49 percent. Thus, for continuous generation of 10 megawatts of electrical power, the required heat input would be between 50 and 100 megawatts (1.7 to 3.4×10^8 BTU/hr).

For transferring heat to the surface, water (or some other liquid) would be circulated continuously through a cavity or a network of thin cracks located at the selected depth (See Figure 1). The heated water would be returned to the surface and transferred to a closed-loop turbine system by means of a heat exchanger. The turbine loop would probably operate on isobutane or freon cycles, which appear to be more suitable than a steam cycle, considering the relatively low temperatures available.

The first configuration studied was that of a spherical cavity. Of direct interest is the decrease in the temperature of the cavity wall as a function of time under the condition that the rate at which heat is transferred to the cavity fluid from the surrounding medium remains constant. The differential equation describing heat flow for the case of spherical symmetry is

$$\frac{\partial T}{\partial t} = \frac{k}{r} \frac{\partial^2 (rT)}{\partial r^2} \quad (1)$$

SALT DOME STUDY

II-2

Figure 1 - EXPLOITATION OF DEEP-SEATED SALT CAVITY

where T is temperature, t is time, r is the radial coordinate, and k is the thermal diffusivity of the material surrounding the cavity. Constant heat flow into the cavity requires that the temperature gradient at the cavity wall be constant. Thus, the boundary condition for the desired solution of Equation (1) is:

$$\left. \frac{\partial T}{\partial r} \right|_{r=a} = \frac{Q}{4\pi a^2 K} = \text{constant} \quad (2)$$

where " a " is the radius of the cavity, K is the thermal conductivity of the surrounding material, and Q is the total heat flux expressed as energy per unit time. Also, at $t = 0$, the temperature in the surrounding material is everywhere the same and $T_r = T_\infty$, where T_∞ denotes the temperature at points far from the cavity. The solution of Equation (1) for the boundary condition expressed in Equation (2) as given by Carslaw and Jaeger (Ref. 2) is:

$$T_{r,t} = T_\infty - \frac{Q}{4\pi Kr} \left\{ \operatorname{erfc} \frac{r-a}{2(kt)^{1/2}} - \exp \left[\frac{r-a}{a} + \frac{kt}{a^2} \right] \cdot \operatorname{erfc} \left[\frac{r-a}{2(kt)^{1/2}} + \left(\frac{kt}{a^2} \right)^{1/2} \right] \right\} \quad (3)$$

where $T_{r,t}$ is the temperature at a point a distance r from the center of the cavity at time t . Q is positive if heat flows into the cavity.

If we restrict our attention to the temperature of the cavity wall, Equation (3) simplifies to:

$$\Delta T_{a,t} = - \frac{Q}{4\pi Ka} \left\{ 1 - \exp \left(\frac{kt}{a^2} \right) \operatorname{erfc} \left(\frac{kt}{a^2} \right)^{1/2} \right\} \quad (4)$$

Figure 2 presents a plot of the value of $\left\{ \right\}$ in Equation (4) as a function of $(kt/a^2)^{1/2}$. Figure 3 shows the decay of the wall temperature for spherical cavities having radii of 500, 1000, and 2000 feet. The cavities were assumed to be located in a salt dome. For all three

$$D = \left\{ 1 - \exp \left(- \frac{kt}{a^2} \right) \operatorname{erfc} \left(\frac{\sqrt{kt}}{a} \right) \right\}$$

Figure 2 - D as a Function of $(kt/a^2)^{1/2}$

Figure 3 - TEMPERATURE DECAY OF CAVITY WALL

cases, Q , K and k were assigned the following values: $Q = 3.41 \times 10^8$ BTU/hr; $K = 4.0$ BTU/hr $\cdot$ ft $\cdot$ $^{\circ}$ F; and $k = 0.1471$ ft²/hr. The heat flux corresponds to the generation of 10 Mw of electrical power at a heat-to-electricity conversion efficiency of 0.1. The values for K and k are for rock salt, although they are on the high end of the range of values available for rock salt. Lower values for K and k would result in a more rapid decrease in the temperature of the cavity wall.

Computations show that for a spherical cavity in salt, a radius of at least 2000' is needed to allow the extraction of heat at the required rate of 3.4×10^8 BTU/hr for periods of twenty years or more. One major difficulty in having such a large cavity is the massive amount of water that it would contain (3.35×10^{10} ft³). All of the heat extracted from the surrounding salt at a constant rate of 3.4×10^8 BTU/hr over a 30-year period would raise the temperature of the water in the cavity by only 43 $^{\circ}$ F, even if no heat were removed from the water by circulation through a heat exchanger at the surface. Clearly, a spherical cavity large enough to allow the extraction of the required amount of heat from the salt is not a practical configuration. A sphere has the largest volume-to-surface area ratio of any shape and, as such, is undesirable from the standpoint of a heat exchanger.

A better configuration for the extraction of heat from salt domes by the circulation of a fluid is a network of thin cracks, or a single large crack, having a large surface area. In this case, then, the volume-to-area ratio is small, and the average temperature of the working fluid can approach the temperature of the salt in contact with the fluid. For the purpose of estimating the required surface area of a single crack, the solution for heat flow at the surface of a semi-infinite solid was assumed. The temperature drop of the surface is given as

$$\Delta T = - \frac{2q \sqrt{kt}}{\sqrt{\pi} K} \quad (5)$$

where q is the heat flux crossing the surface per unit area (+ q corresponds to heat flow from the solid), and the other symbols are the same as those defined previously.

A temperature decrease of 350°F over a period of 30 years corresponds to a constant heat flux density of 6.31 BTU/hr ft² as determined from Equation (5) using the same values of K and k given previously for rock salt. Thus, a surface area of 54 x 10⁶ ft² is required to meet the total heat requirement of 3.4 x 10⁸ BTU/hr. Since heat can be extracted from both faces of the crack, the areal extent of the crack would be 27 x 10⁶ ft².

Instead of a single crack, a series of smaller cracks spaced sufficiently far apart and having approximately the same total surface area as a single crack could be used. Another alternative is to break up, or "rubble-ize" a large volume of salt to the extent that an extensive network of fine cracks or passageways are formed throughout the entire volume to facilitate the circulation of water. The volume of salt that would have to be broken up to allow the extraction of heat at a constant rate of 3.4 x 10⁸ BTU/hr over a 30-year period with a temperature drop of no more than 350°F is 9.4 x 10⁹ ft³.

While a single crack, a series of several cracks, or a network of cracks would enable heat to be extracted from deep down in salt domes at rates sufficient to operate a 10 Mw electrical power plant for about 30 years, there appears to be no feasible way to generate and maintain the desired crack configurations. The difficulty arises from the plastic behavior of salt at the temperatures of interest (>450°F) and the high salt pressures at the depths where these temperatures prevail. Since the density of rock salt is about 136 lb/ft³, the salt pressure in the depth range of 10,000 to 20,000 ft varies from approximately 9,500 to 19,000 psi. A cavity or a network of cracks would close very quickly under the temperature and pressure conditions encountered. The hydrostatic pressure of the water in the cavity would tend to offset the external pressure of the salt, but at the depths considered the net pressure tending to close the cavity would still be in the range of 5,100 to 10,200 psi. Available data on the problem of cavity closure in salt domes indicate that at temperatures of 300°F or higher and at pressures greater than 4,000 psi, complete collapse or a significant reduction in the volume of the cavity is likely to occur. Figure 4 shows the percentage reduction in volume

Figure 4 - CLOSURE OF CAVITY IN SALT FORMATION

of a 100 ml cylindrical cavity in salt at 300°F as a function of time for pressures ranging from 1000 to 8000 psi. The results were derived from one of a number of laboratory tests performed at the Sanitary Engineering Research Laboratory of the Civil Engineering Department of the University of Texas (Ref. 3). The tests utilized cylindrical salt cores having dimensions on the order of six inches. Cavities approximately 100 ml in volume were formed in the salt cores and filled with mercury at the start of the pressure-temperature tests. As the tests proceeded, the volume of mercury displaced was recorded.

The results of the laboratory tests appear to be in general agreement with the analytical investigations of Serata and Gloyna (Ref. 4) and Anderson (Ref. 5). Results given by Anderson predict that the collapse velocity of the top of an unpressurized 650 foot (200 m) radius salt cavity at a temperature of 266°F (130°C) and a depth of 13,100 feet (4.0 km) would be about 400 feet/day (45 km/year).

Because of the large surface areas required to extract heat at the rate required to operate even a relatively small (compared with modern plants) electrical power plant and the problem of producing and maintaining a suitable cavity or system of cracks, it was concluded that it is not practical to generate electrical power by extracting heat from salt domes at depths greater than 10,000 feet. At depths less than 10,000 feet, the salt temperatures would be less than 300°F. The lower available temperature at the shallower depths would result in even lower heat-to-electricity conversion efficiencies than estimated previously. Also, the allowable temperature drop of the surrounding salt over the operating lifetime of the system would be less than that for higher initial temperatures.

A 10-megawatt electrical power plant operating continuously at full capacity produces 87,000,000 kilowatt-hours of electricity per year. The revenue anticipated from the sale of this amount of electricity ranges between \$876,000 and \$1,752,000 per year, assuming a selling price of one-to-two cents

per kilowatt-hour. If the annual operating and maintenance costs are \$250,000 and the higher selling price of 2¢/kw-hr prevails, then about \$1,500,000 would be available per year for amortization of the initial capital investment. Payments in the amount of \$1,500,000 per year over 30 years at an interest rate of 7% correspond to an initial investment of \$18.6 million. An investment of this amount for construction of an electrical power plant operating by the extraction of geothermal energy from a salt dome might not be unreasonable if the technology for creating and maintaining the required crack network were available.

SECTION III

WASTE-TO-FUEL CONVERSION

Early in the development of salt dome geothermal applications, the concept of conducting waste-to-fuel conversions in cavities in salt domes was recognized as having great potential. These conversions have been successfully performed in the laboratory at elevated temperatures and (in some cases) pressures. Major limitations on their successful large scale application arise in capital equipment requirements for pressure vessels, high pressure pumps, etc., and in the cost of energy required for the conversion. By using a cavity in a salt dome as the reaction vessel, a large reaction volume which would withstand any required pressure could be provided at a low cost. Further, process heat would be partially or totally supplied by geothermal heat, and since required pressures would result automatically from hydrostatic head, pumping energy requirements would be drastically decreased.

A. Exploitation of Deep-Seated Cavities

The first concepts explored were geared to the exploitation of deep-seated cavities remaining at the end of the useful life of a geothermal power project as illustrated in Fig. 1. These cavities which would result from the extraction of byproduct salt over the 20 + year life of a geothermal extractor were expected to occupy significant volumes and would also provide a continuing input of low-grade heat. A two-stage process for the conversion of garbage and sewage solids to fuel evolved, involving first the evaporation of water content and pyrolysis of the wastes yielding a fuel gas, and subsequently, the liquefaction of the residual char by techniques currently under development for coal liquefaction.

Since the solubility of salt in water increases with increasing temperature, almost any scheme for the production of energy by heating water within a salt dome and extracting heat at the surface will result in a net transport of salt to the surface as well. For example, the extraction of 100 Mw of thermal power with hot and cold water temperatures of 200°C and 50°C

respectively, would yield approximately 10×10^6 tons of byproduct salt in 20 years of operation. The resultant cavity would provide a reaction volume of approximately 150 million cubic feet, equivalent to a 2000 foot diameter vessel 50 feet high. It could contain all of the garbage and sewage solids produced over an eight-year period by a city of 100,000 persons as a slurry with a solids density of 20% or 40 years' wastes if the water was removed.

The first use foreseen for such a cavity was the drying and thermal decomposition of urban waste streams consisting of combustible trash and sewage solids. Various processes yielding gaseous fuels were considered including pyrolysis, partial combustion, and synthetic gas production by the water-gas shift reaction.

Calculations of the heat required to dry the waste slurry delivered to the cavity indicated that achieving the highest practicable degree of dewatering prior to delivery to the reactor would be important to success. Evaporation of the water contained in the waste stream from a city of 100,000 at a 20% solids content would require 40 MW of thermal power, nearly half the power drawn during power plant operation. An input density of 50% solids would decrease heat requirements to approximately 10 MW allowing higher cavity temperatures and a longer, useful life.

Pyrolysis reactions (thermal decomposition in the absence of oxygen) are reported to occur (references 6, 7 and 8) at temperatures of from 200°C to 900°C and are endothermic. Since high yields of useful fuel gases are reported at the highest temperature and decrease sharply as temperature is decreased toward the 200°C (or lower) temperatures expected in the salt cavity, conversion processes based on partial combustion of the waste appeared more favorable. These processes are exothermic and yield a fuel gas containing CO , H_2 , CH_4 , H_2O and other constituents in amounts which depend on conversion conditions and feed composition. Energy released in the combustion reactions could contribute to the evaporation of water in the influent stream and/or serve to raise temperatures above the temperature of the surrounding salt enhancing the pyrolytic decomposition reactions.

In addition to the aforementioned gaseous products, the reactions yield small quantities of light oil which might be condensed and recovered at the surface, tars, and significant quantities of residual char. The tars and char would remain in the reaction chamber, accumulating as a highly carbonaceous residue similar to natural coal deposits. After an extended period of gasification, (20 years or more), the operating mode in the cavity could be switched from gasification of raw wastes to liquefaction (or gasification) of the residual carbon. Techniques currently under development for coal conversion would be applicable to these deposits, and conditions within the salt dome appeared to favor the economic operation of the conversion processes.

Basically, the liquefaction of coal involves breaking down very large multi-carbon molecules into smaller units with the addition of hydrogen. In the laboratory and in pilot plant studies this has been accomplished at high temperatures and pressures using hydrogen gas, carbon monoxide, methane, steam and hydrogen-rich organic compounds as reagents. Commercial development has been limited primarily by cost factors, especially the capital cost for pressure vessels and high pressure pumping equipment, and the cost of pumping and heat energy (reference 9). Pressure and temperature requirements would be met at much lower costs in the salt dome cavity, and the loss of gases (a factor in earlier consideration of underground conversion) would be minimized by the impermeability of the salt dome formation.

Studies have shown that coal conversion efficiencies are significantly improved by the presence of an oil vehicle (references 10 & 11). This oil is not consumed in the conversion process and may be recycled many times through the reaction vessel with product oil withdrawn at each pass. Conversion is also enhanced by a variety of catalysts including salts of molybdenum, hydrochloric acid and some metallic chlorides. The evidence thus suggests that extensive contact with salt would not hamper the reaction, and might, in fact be beneficial.

For the conversion process in the salt dome, the use of an oil vehicle, probably waste oil, was tentatively selected as the most favorable approach. Where conditions permitted, the requirement for conversion gases could be partially or completely satisfied by the products from a nearby cavity in the gasification phase of operation. Pressurization in the reaction zone would be provided by the static head of the influent and product streams, and since inlet and discharge would be at the same level, minimal pumping energy would be required. The conversion process itself is neutral or mildly exothermic, and since influent and product could be heat exchanged and losses from the cavity will be small or zero (depending on operating temperature and local salt temperature), little or no input of heat energy should be required. Since the conversion processes work on cellulose as well as coal, the feed stream could be augmented with waste wood products as hog fuel providing long-term production of oil from the cavity. It was calculated that a steady production of approximately 250 bbl/day could be readily achieved from a single cavity like that described above.

Further work on the exploitation of these very deep, hot cavities was discontinued when it became evident that rapid closure of the cavities by viscous flow of the salt would make implementation of any of the proposed schemes impossible. These studies had, however, pointed the way to conversion processes which could profitably be carried out at lesser depths. While a free source of heat for the evaporation of slurry water and pyrolysis of wastes would not be available at shallower depths, advantages of hydrostatic pressure, reaction volume, and safety could still be realized by operating underground.

B. Waste to Oil Conversion

Extensive work by the U.S. Bureau of Mines (references 12 and 13) has proven the feasibility of direct conversions of urban refuse, sewage solids, and wood waste to liquid fuels by reactions in an aqueous medium. The conversion is carried out at elevated temperatures (250°C - 425°C) and

pressures (1,500-4,000 psig.) in an atmosphere of carbon monoxide. As was the case in coal liquefaction, conversion was aided by the presence of organic solvents and of some catalysts. In this case, cobalt molybdate and sodium carbonate were found to increase production of oil. Gross yields of two barrels of oil per ton of urban refuse were indicated by experimental work. With the consumption of energy equivalent to 0.75 barrels of oil per ton in processing, a net yield of 1.25 barrels of oil per ton of refuse is achieved.

This conversion process could be implemented in a cavity at depths of 2,000 - 8,000 feet in a salt dome as illustrated in Figure 5, with significant potential savings in capital and operating costs. A waste slurry and pressurized CO would be delivered to the cavity, and a stream containing water and oil would flow from it. After oil-water separation, a portion of the oil would be recycled to the cavity, and the balance removed for processing to fuels or chemical products. Since these shallower cavities will not naturally be at the elevated temperatures needed for the conversion, the addition of some heat to the cavity will most likely be required. This could be accomplished by heating the CO delivered to the cavity. Since heating the influent water to required temperatures would generate high steam pressures at the surface, requiring pressure equipment and excessive pumping energy, the delivery of heat to the cavity in the influent stream is not desirable. Requirements for both pumping and thermal energy inputs should be reduced for underground operation and a net yield of oil in excess of 1.25 barrels per ton of refuse is anticipated. A net production of 240 barrels per day or more of oil is predicted from the wastes for a city of 100,000 persons.

Uncertainties in this approach to underground waste conversion reside in its economics and in two technical areas. While the economics of the process appear favorable, more detailed engineering studies are necessary as a basis for reliable predictions of profitable operation. These in turn will depend on the determination of cavity conversion parameters and of effective product recovery techniques.

Laboratory experiments to date have focussed on conditions compatible with above ground conversion: short reaction times (one hour and less) and high throughput have been emphasized to allow payout on high capital investments. For underground conversions, on the other hand, large reaction volumes will allow retention times of months or even years while cost will more likely be driven by requirements for heat and carbon monoxide. The theoretical base does not exist for reliable predictions of conversion results at lower temperatures and/or CO pressures with very long reaction times. Experimentation is clearly required to provide a basis for design of an underground conversion system. Preliminary results could be obtained at very low cost using apparatus as simple as a length of threaded pipe, a CO cylinder with regulator, and an oven.

Recovery from the cavity of the oil formed may present technical problems and influence operating costs. Some tendency to adhere to the cavity walls is anticipated as is collection in pockets in the cavity. Since some of the reaction products show very high viscosity, plugging of the exit pipe may also be a problem, especially near the surface where temperatures will be appreciably lower than those prevailing in the cavity. The assessment and solution of these and other similar problems could be undertaken in pilot-scale experiments after verification of the basic viability of the waste-fuel conversion under cavity conditions.

C. Conversion of Wastes to Methane

The possibility of using underground cavities as reaction chambers for converting municipal refuse and sewage sludge to methane gas by anaerobic digestion was considered as part of this program. Anaerobic digestion of wastes has been studied rather extensively by Pfeffer (Ref. 14) under controlled laboratory conditions. In anaerobic digestion, complex organic materials are converted to organic acids by facultative and anaerobic bacteria called "acid formers," as shown in Figure 6. These organic acids are converted in turn to methane and carbon dioxide by a different group of

PROCESS

CONDITIONS

TEMPERATURE: 60°C

PRESSURE: 14.7 psi

pH: ~7.0

YIELD

NET: 7300 cu ft METHANE (7.3×10^6 Btu) PER TON
(DRY WEIGHT) OF ORGANIC WASTE

GROSS: 7900 cu ft METHANE (7.9×10^6 Btu) PER TON
(DRY WEIGHT) OF ORGANIC WASTE

Figure 6 - CONVERSION OF ORGANIC WASTE TO METHANE

strictly anaerobic bacteria called "methane formers." Because "methane formers" of a given type have the ability to ferment only specific compounds, different bacteria are required to promote the complete conversion of the spectrum of compounds present in mixtures of sewage sludge and garbage.

For anaerobic digestion, two temperature ranges have generally proven to be optimum, the mesophilic range (30°C to 37.5°C) and the thermophilic range (49°C to 51°C). However, the investigations of Pfeffer (Ref. 14) indicate that the production of methane is optimized at somewhat higher temperatures, namely, 42°C and 60°C. Digestion is usually carried out at, or slightly above, atmospheric pressure. Because the methane-forming bacteria are strict anaerobes, care must be taken to ensure that even small amounts of oxygen do not enter the reaction chamber. The optimum pH level is in the range of 7.0 to 7.2, although the process can proceed well over a pH range of 6.6 to 7.6. Trace quantities of nitrogen, phosphorus, and other materials are required for optimum growth of the bacteria. On the other hand, the waste must be free of toxic materials.

In the laboratory experiments conducted by Pfeffer (Ref. 14), samples of "typical" domestic refuse were introduced into two banks of plexiglass reactors, each having a volume of approximately 24 liters. The reactors were housed in a constant temperature room in which the temperature could be varied over the range of 35°C to 60°C. Each reactor had a stirrer that was operated continuously at 60 rpm over the test periods. The effects of retention time on gas yields were studied by replacing specified volumes of the contents of the reactors with fresh feed stock on a daily basis. Thus, in the reactor designated for a retention time of four days, one-fourth of the slurry volume was replaced each day. For eight days retention time, one-eighth of the volume was replaced each day, etc. The fresh feed stock was introduced into a stoppered opening at the top of each reactor. A plexiglass nozzle at the bottom of each reactor allowed the effluent to be withdrawn. A plexiglass nozzle at the top of each reactor allowed the gas yield to be measured.

Pfeffer's investigations demonstrated that the conversion of organic refuse to methane by anaerobic digestion is possible and that the addition of sewage sludge to the feed stock significantly improves the biological breakdown of the refuse. Tests using a mixed slurry of organic refuse and sewage sludge were conducted for retention times up to 30 days and at selected temperatures. For mesophilic organisms, the optimum temperature range for gas production was determined to be 42°C. For thermophilic organisms, the best methane yields occurred at 60°C, the highest operating temperature. Higher temperatures were not used because previous studies showed complete inactivation at 65°. For both the mesophilic and thermophilic conditions, gas production increased with increasing retention time. At retention times of 30 days, the gas yield (methane and carbon dioxide) at 40°C was about 5.7 scf per pound of volatile solids added to the reactors. At 60°C, the gas yield was 7.2 scf per pound of volatile solids. Although 30 days was the maximum retention time used, plots of gas yield as a function of retention time indicate that slightly higher yields might be expected for longer retention times.

A conceptual system for converting sewage sludge and municipal refuse to methane gas in an underground cavity is shown in Figure 7. The indicated values are based on an assumed city population of 100,000, and a digester temperature of 60°C. The total solids loading to the cavity is estimated to be 199 tons/day, assuming 10 tons/day from the sewage treatment plant as sludge, and 189 tons/day of shredded waste from the refuse separation plant. Of the total solids, approximately 95 percent, or 189 tons/day, would be volatile. For digestion at 60°C, Pfeffer's data predict a total gas yield of 7.2 scf per pound of volatile solids, 55 percent of which is methane. Thus, the anticipated methane yield is about $1.5 \times 10^6 \text{ ft}^3/\text{day}$ for a city of 100,000. However, in order to operate at the higher temperature of 60°C, heat would have to be supplied to the slurry at the rate of $1.35 \times 10^8 \text{ BTU/day}$. The required heat could be supplied by burning about $140,000 \text{ ft}^3/\text{day}$ of the methane generated.

PRODUCTION OF METHANE GAS FROM MUNICIPAL REFUSE AND SEWAGE SLUDGE

CITY - POPULATION 100,000

Figure 7 - MUNICIPAL SYSTEM FOR METHANE PRODUCTION

The cavity pressure for the system shown would be only slightly greater than atmospheric pressure and could be controlled by adjusting the rate at which the methane gas is collected. Since the solubility of carbon dioxide is greater than that of methane, separation of the two gases can be accomplished by bubbling the mixture through water.

Because a large volume of water would flow into the chamber, provisions would have to be made to remove it periodically to prevent the cavity from becoming completely filled. Excess water could be pumped from the cavity by means of a submersible type pump and possibly recirculated through the refuse separation plant or returned to the municipal sewer system. The amount of water entering the cavity should be limited to the minimum amount required to allow the slurry of mixed solids to flow freely. The quantity of 766 tons/day indicated in Figure 7, for a city of 100,000 is a best estimate based on Pfeffer's work (Ref. 14).

The conversion of the organic material to methane results in a 70% reduction in the solids. Taking account of this beneficial reduction in solids, the rate that residual (unconverted) solids will accumulate in the cavity is estimated to be $1800 \text{ ft}^3/\text{day}$ or $657,000 \text{ ft}^3/\text{year}$. Once the capacity of the cavity is reached, it would be necessary to abandon the operation. However, salt cavities with volumes of tens to hundreds of million cubic feet exist. A thirty year operation would require a cavity volume of about 20 million cubic feet.

There are several potential problems that would have to be studied before the feasibility of the underground system shown in Figure 7 could be determined. First, in Pfeffer's laboratory investigations, the slurry in the digesters was mixed continuously. It is anticipated that some degree of mixing would be also required in the cavity. One potential means for doing this might be to re-circulate a fraction of the methane back into the cavity through a series of perforated pipes located on the floor to allow continuous agitation of the feed material. Second, if the cavity is located in a salt

dome, the salt dissolved from the walls of the cavity would almost certainly destroy the bacteria with which it comes in contact. Precoating the cavity walls with a sealant or finding a "methane forming" group of bacteria that can survive in a saline environment might provide solutions to this problem. For other types of underground cavities, potential contamination with salt would not be a problem. Third, care would have to be taken to prevent oxygen from entering the system. Flushing the cavity initially with a heavier-than-air gas such as CO₂ to prevent further infiltration of air might prove to be sufficient.

Revenue for operation, maintenance, and amortization would be derived from sale of the methane gas (and possibly the carbon dioxide). In addition, since garbage collection and disposal companies and/or agencies must pay a fee for disposing of refuse at landfill sites, a fee could be charged for each truck load of waste brought to the refuse separation plant. This fee would have to be competitive with local disposal alternatives. However, if local landfill sites are farther from the collection routes than is the proposed facility, then somewhat higher fees could be charged. Conversely, if the landfill disposal sites are closer than the proposed facility, then the disposal fees would have to be lower to be economically attractive to the operators of the disposal services.

The non-volatile materials separated from the refuse, primarily the metals and glass, would provide an additional source of income. Municipal waste contains about 8 percent metals and 6 percent glass. Therefore, metals would account for about 28 tons of the total refuse generated daily by a city of 100,000 people, and glass would account for 21 tons.

Assuming a selling price of \$0.50/ft³ for the methane, a charge of \$1.00 for each ton of raw refuse accepted at the separation plant, and selling prices of \$35/ton and \$9/ton for the recovered metal and glass, respectively, the annual income for a facility accommodating 100,000 people would be about \$800,000. For operating and maintenance costs of \$300,000 per year, a total

of \$500,000 would be available to cover amortization of the capital expenses. For amortization over a 20 year period at 7 percent, an initial capital expenditure of about $\$5.3 \times 10^6$ is feasible. The largest capital item is the refuse separation plant.

SECTION IV

CONCLUSIONS

As a result of the studies conducted on this internal research project it has been concluded that:

- There is little likelihood of economic generation of power from geothermal heat in salt domes although some benefits might be derived from the extraction of low grade heat for process or space heating requirements.
- Economic benefits may be realized from the conduct of waste-to-fuel conversion processes in cavities at moderate depths in salt domes.
- The subterranean generation of methane has the potential for significant cost savings in reactor volumes and waste disposal, but due to salt intoxication problems may be more easily implemented in cavities in formations other than salt domes.
- The proprietary underground flow-through reactor concept has sufficient promise to warrant further study.

Conclusions concerning the economic advantages of underground waste conversion and of the flow-through reactor must be considered tentative. Key elements in the analysis are speculative and must be verified by laboratory experiments and detailed engineering analysis before firm conclusions can be drawn. The potential benefits of these techniques in terms of turning an environmental problem into a long term supplement to dwindling energy supplies clearly justify support for their further development.

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