# Process for Refuse Disposal in Solution-Mined Salt Cavities

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## ABSTRACT

*With the process described here, refuse is deposited into a salt cavity after shredding and reclamation, by dumping into a disposal shaft connecting the cavity with the surface. Noxious odors and decomposition gases (including methane) are exhausted from the cavity through an airshaft during filling operations, and are later produced for use as fuel. A disposal cavity would preferably be cylindrically-shaped, of large volume, and would be operated brine-free at atmospheric pressure. Consideration is given to the effect on cavity structural stability of those characteristics, as well as decomposition heating, multiple cavity spacing, and cavity depth. It is concluded that such disposal cavities would be feasible, probably to depths of 4000–4500 feet if properly designed. Where cavity stability is a problem, alternate techniques, using either slurried refuse or cavity pressurization, may be possible. Disposal cost ex-land is estimated at $7.12 per ton, based on ultimate refuse densities of 50 lb./cu.ft., and cavity development costs of $1.00 per barrel. In a hypothetical disposal project, 6.08 million tons of refuse disposal capacity is developed in four cavities within a 15 acre area. These cavities would serve for over 23 years at a disposal rate of 1000 tons per weekday. The process has potentially widespread geographic application and appears to be economically competitive with some conventional disposal methods. In general, the advantages are in the areas of aesthetics, environment, health, conservation of land and natural gas, and public acceptance.*

## INTRODUCTION

The disposal of refuse is a serious problem today. Increased environmental concern and scarcity of acceptable sites have clouded the future of the traditional and still predominate disposal method, the open dump. Sanitary landfills, incinerators, compost plants, and hog-feeding lots face similar problems. The burden of disposing of the mounting refuse volumes must shift to new methods that are environmentally and economically acceptable. The purpose of this paper is to show how solution-mined salt cavities can be successfully applied to the problem of solid waste disposal.

## DESCRIPTION OF PROCESS

With the proposed process (Rogers and Kirk, 1972), refuse is deposited into impermeable solution-mined cavities formed in shallow subsurface rock salt formations, such as piercement salt domes or thick salt beds. As shown in Figure 1, the refuse is transferred from collection vehicles at the unloading area and is conveyed through a reclamation and shredding facility. From this facility, it is then moved to a large diameter disposal shaft extending from the ground surface to the top of the cavity. The shredded refuse is dumped into the disposal shaft and allowed to fall and accumulate at the bottom of the cavity. A small diameter airshaft connecting the cavity with the surface serves to ventilate the cavity during disposal operations. After the cavity is filled, the airshaft is used to produce decomposition gases for engine fuel.

## DISPOSAL CAVITY CHARACTERISTICS

The preferred configuration for a refuse disposal cavity is that of a vertical cylinder with the axial dimension much greater than the diameter. This arrangement facilitates complete filling of the cavity with refuse outward to the confining walls and maximizes natural compaction due to refuse overburden. Leaching techniques have been reported which yield this approximate form (Remson, et. al., 1965, p. 299; Martinez, 1970, p. 153–154).

The desired volume of the refuse disposal cavity will exceed the volume of many hydrocarbon storage caverns.

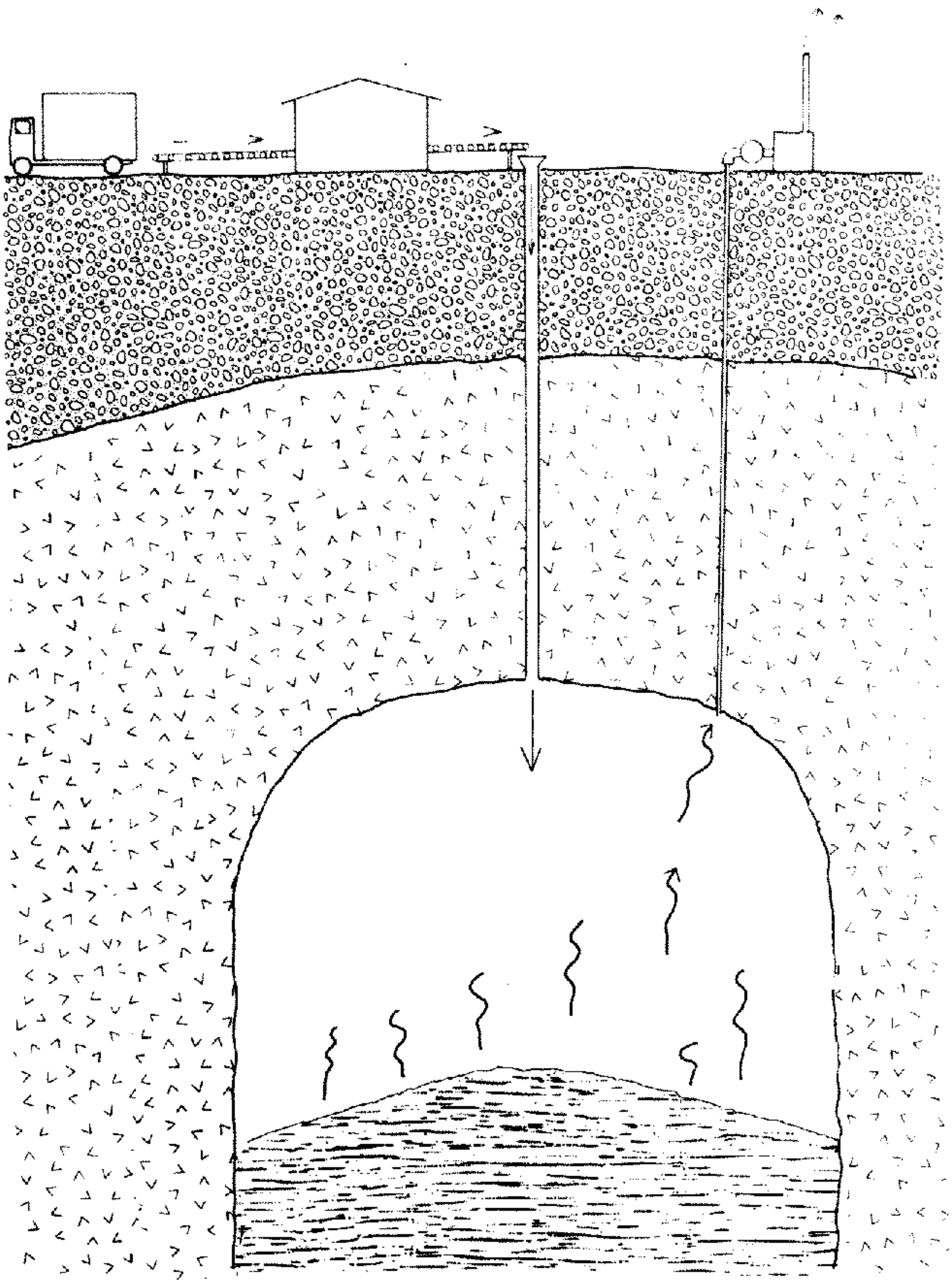

**Figure 1.** Refuse disposal in solution—mined salt cavities.

The capacity of the disposal cavity to accept large volumes of refuse is one factor in its potential as a competitive disposal method.

The internal pressure of the cavity will preferably be atmospheric and operation of the cavity will be brine-free. This allows the introduction of refuse into the cavity in the most direct manner possible.

The cavity temperature will rise above the ambient formation temperature as a result of decomposition of the contained refuse. Studies of test landfill cells filled 20 feet deep with typical municipal solid waste have shown that the primary mode of decomposition is anaerobic (Merz and Stone, 1964, p. 84–87). Temperatures in these cells and subsequent cells consistently reached a temporary maximum of 100°–120°F, or about 30°–50°F above the mean surface temperature (Merz and Stone, 1968, p. 87). Due to the high thermal conductivity of salt, the maximum temperature rise in the cavity should not exceed the rise in the anaerobic test cells.

A final characteristic of disposal cavities is that multiple cavities will be required and the spacing of the cavities will be as close as is structurally feasible. The expense of constructing access roads, a central stationary reclamation-shredding facility, and conveyor systems, dictates a compact and long term arrangement.

## CAVITY STABILITY CONSIDERATIONS

The volume, internal pressure, and temperature rise of disposal cavities represents a departure from hydrocarbon-storage applications of proven structural stability. Concerning cavity volume, Serata and Gloyna (1959, p. 159) concluded from theoretical and experimental studies that there is no structural restriction on the size to which a cavity may be developed, except that cavity radius should not exceed one-third of the overburden depth.

### Effect of atmospheric internal cavity pressure

The internal cavity pressure and temperature represent significant considerations to the feasibility of refuse disposal cavities. Even though cavities seldom collapse under direct earth pressure (Serata and Gloyna, 1960, p. 2979), they will undergo a reduction of volume under certain conditions of loading and temperature due to the elasto-plastic nature of salt (ibid, p. 2986). The loading condition of an underground salt cavity has been defined as

$X = (P_o - P_i)/\sigma_o$ (Serata and Gloyna, 1959, p. 66) (1)

or

$X = (P_o - P_i)/K_Y$ (Serata and Gloyna, 1960, p. 2986) (2)

where $X$ = the factor of structural loading.
$P_o$ = the overburden pressure of the cavity.
$P_i$ = the internal pressure of the cavity.
$\sigma_o$ = the equivalent plastic limit of salt.
$K_Y$ = the yielding octahedral shearing strength of salt.

The volume reduction of a salt cavity has been shown to be a function of the factor of structural loading, such that for a given cavity temperature rise and structural loading factor, the reduction of cavity volume can be theoretically predicted (Serata and Gloyna, 1959, p. 66, 70). The wide variation in reported values of $\sigma_o$ and $K_Y$ (ibid, p. 110, 111; 1960, p. 2985) introduces uncertainties in such a prediction. This variation is attributable to possible errors in the complex triaxial measurements and/or to different properties in different types of salt (ibid, p. 111). Experiments by Dreyer (1967, p. 7–21) confirm that the compressive strength of halitic rock salt is dependent on mineral composition (impurities) and several textural parameters, but these variations occur within relatively narrow limits. Regardless of the value of $\sigma_o$ (or $K_Y$), it can be be determined from equations (1) and (2) that the structural loading factor of a disposal cavity at atmospheric pressure is 2.07 times that of a similar shaped cavity of equal depth filled with saturated brine. This follows from the overburden pressure gradient of 1 psi/ft. and the hydrostatic gradient of saturated brine of approximately 0.518 psi/ft. Due to the geothermal gradient and the decrease of the $\sigma_o$ (or $K_Y$) value with increased temperature (Serata and Gloyna, 1959, p. 111), a disposal cavity will have a lower structural loading factor, and thus greater structural stability, than a brine-filled cavity 2.07 times deeper.

Dreyer (1967, p. 123–126) investigated the convergence behavior of deep holes in salt masses through model experiments with various pressures and temperatures. The test body was a hollow rock salt cylinder modeled after in situ proportions with a 20cm. height, 4cm. inside diameter and wall thickness of 16cm. Tests were conducted over periods as long as 5 months. Test conditions corresponding to a depth of 1640 ft. (1664 psi, 68°F) yielded the relationship

$$K = 1.450\ t^{0.700}, \quad (3)$$

The relationship obtained for a depth equivalent of 6562 ft. (6784 psi, 181°F) is

$$K = 3.131\ t^{0.678}, \quad (4)$$

Putting time t in months into these equations yields the convergence K in %. The decrease in convergence rate with time is attributed mainly to the strain hardening of rock salt with increasing deformation.

The convergence of a disposal cavity is of concern mainly during the time span required to fill the cavity. Cavity volume reduction subsequent to complete filling of the cavity will diminish due to the increased internal cavity pressure and the temporal reduction of the convergence rate by strain hardening. Reasonable additional volume reduction is acceptable in view of the readily compressible nature of solid waste. For a disposal cavity to be filled in 5.75 years (69 months), as in an example to be shown later, Dreyer's equations predict convergence of 14.93% and 32.21% at respective depths of 1640 feet and 6562 feet.

**Effect of cavity temperature rise**

As previously stated, it is expected that a disposal cavity will experience a modest ultimate temperature rise of 30°–50°F due to the decomposition of refuse. In further experiments conducted by Dreyer (1967, p. 114–115), a rock sample deformed at 18°C (64.4°F) under loading stress of 200 kp/cm$^2$ (2845 psi) underwent a longitudinal compression of about 9.8% after 7.5 months. An identical sample at 35°C (96.8°F) deformed about 13.5% under the same stress and over the same time period. The quantitive effects of a cavity temperature rise on cylindrical cavity volume reduction for various conditions of structural loading have also been investigated by Serata and Gloyna (1959, p. 69).

From all of these considerations, a certain reduction of disposal cavity volume can be expected due to the structural effects of decomposition heating. However, this reduction should be minimized during the filling of the cavity by ventilation cooling and by reduction of lithostatic stress loading through ever-increasing refuse overburden pressure. After the cavity has been filled, the temperature rise would appear to be of little significance for the same reason discussed above under *effect of atmospheric internal cavity pressure;* that is, increased internal cavity pressure, strain-hardening of the salt, and compressibility of solid waste.

**Effect of multiple cavity spacing**

It is known that stress concentration around tunnel openings is increased by the construction of additional tunnels. The distribution of this stress concentration is related to the number of additional openings and to the partition thickness or distance between them (Serata and Gloyna, 1959, p. 23, 25–26). The critical stress concentration factor rapidly approaches the value for a single opening as the partition thickness increases. Also, although only 2 or 3 additional openings has a significant effect on the critical stress concentration factor, the increase diminishes rapidly with additional openings and reaches a constant value for an infinite number of openings. Serata and Gloyna (1959, p. 26) concluded that a partition thickness of twice the opening diameter would generally be sufficient to minimize the effect of openings upon stress distribution.

**Conclusions on the stability of disposal cavities**

Reliable quantitative assessment of the maximum permissible depth of disposal cavity development is difficult to make due to 1) variations in reported strength properties of salt and 2) the problems of extending laboratory determinations to actual in situ behavior. Nonetheless, based on the structural loading factor relationships and the depths of brine cavities of known structural stability, it appears that disposal cavities would exhibit similar stability to a depth of at least 2000 feet. Increased cavity volume reduction (convergence) at greater overburden depths imposes a practical limitation on the maximum disposal cavity depth, which depends on the cavity volume reduction that is acceptable. If 20–25% reduction is tolerable, then the limit is probably around 4000–4500 feet.

**Alternate disposal techniques**

If a prospective salt deposit is found to be too deep or of insufficient stability to permit operation of a disposal cavity at atmospheric pressure, it may still be used by increasing internal cavity pressure. This may be done either by producing a water-base slurry from the refuse or by maintaining high air pressure within the cavity. Either method will increase both the complexity and the cost of the refuse disposal operation.

The slurry approach represents the more inefficient utilization of cavity volume of the two methods since there will be no compaction due to refuse overburden pressure. Extraction of brine to accommodate the addition of refuse slurry presents problems from possible plugging of tubing and valves. If the extracted brine is to be disposed of by injection into a nearby salt-water aquifer, there is also the problem of wall-cake plugging of the injection zone by suspended refuse sediment. These problems may possibly be solved by extracting the brine from within a gravel-packed sump at the base of the cavity and running the brine through a settling-pond or centrifuge prior to injection into the disposal well.

The pressurization method would require the use of a compressor and a large pressurized hopper tied into the disposal shaft casing. With this technique, when the completed cavity is ready for the initiation of disposal operations, the brine is displaced from the cavity with compressed air, and the cavity is shut-in by a lower valve between the hopper and the disposal shaft casing. At this time, the hopper is filled with refuse at atmospheric pressure. It is then shut-in by an upper valve and pressurized to cavity pressure. The contained refuse is then introduced into the cavity by opening the lower valve. When the hopper is empty, the lower valve is closed, the hopper is depressurized, and the process repeated. The hopper may be provided with augers or rotary plow to ensure positive displacement of the refuse into the disposal shaft. The cavity ventilation shaft and air purification equipment can be designed to provide a closed system with the purified air being returned to the cavity.

## GAS PRODUCTION FROM DECOMPOSITION

In the previously mentioned studies of test land fill cells, Merz and Stone (1964, p. 102–103; 1964a, p. 84–87;

1968, p. 86–87) found that gases produced from the anaerobic decomposition of municipal refuse are primarily carbon dioxide, nitrogen and methane. The methane concentration can be increased by increasing the moisture content of the refuse through irrigation. In a saturated test fill, methane constituted more than 50% of the gas produced. Only small concentrations of oxygen and hydrogen were found. A quantitative study of 15 tons of refuse sealed in a 10,000 gallon storage tank showed that gas production totalled about 2025 cubic feet, or approximately 135 cubic feet per ton (Merz and Stone, 1968, p. 86–87). The bulk of this gas was produced in the 370 day period between the 230th and the 600th days of the experiment. Gas production from the 600th day to the 750th day was extremely small, indicating perhaps the termination of significant gas production.

Extension of these findings to a disposal cavity involve uncertainties as to the effects of increased temperature and the presence of NaCl in solution. However, it will probably be necessary to ventilate the cavity while it is being filled with refuse to preclude possible explosion hazards as well as to control emission of noxious odors. For this purpose, a small diameter well bore is drilled into the top of the cavity near its outer margins. An air pump serves to create a slight pressure reduction within the cavity so that fresh air flows downward through the disposal shaft into the cavity where it mixes with the decomposition gases. The diluted gaseous mixture then exits the cavity through the air shaft and air pump, into an air purification unit which removes objectionable odors and gases. The scrubbed air is then vented to the atmosphere. When, after a period of time, the cavity has been completely filled with refuse, water is added to the cavity to raise the moisture content of the refuse and thus increase methane production. The air pump and air purification unit are removed for use on subsequent cavities in the disposal "field." Valves are then attached to the air shaft of the filled cavity to facilitate the production of gas for use as fuel in the reclamation and shredding facility.

## POTENTIAL CAPACITY OF DISPOSAL CAVITIES

Tests conducted by Kaiser, et al. (1968, p. 142–153) in a 30 ft. deep incinerator receiving pit filled with household refuse showed densities of 349 pounds per cubic yard at 26% moisture content. At 42% moisture content, the density was 480 pounds per cubic yard. *In Municipal Refuse Disposal* (1970, p. 43), prepared by the Institute for Solid Wastes of the American Public Works Association, household refuse is reported to range from 300 to 600 lb./cu.yd. with a 400 lb./cu.yd. average, as collected in ordinary packer trucks. As shown in Figure 2, a hydraulic ram-type baler can increase refuse density to over 90 lb./cu.ft. (2430 lb./cu.yd.) at ram pressures above 2700 psi. A 50 lb./cu.ft. density is produced by the baler at

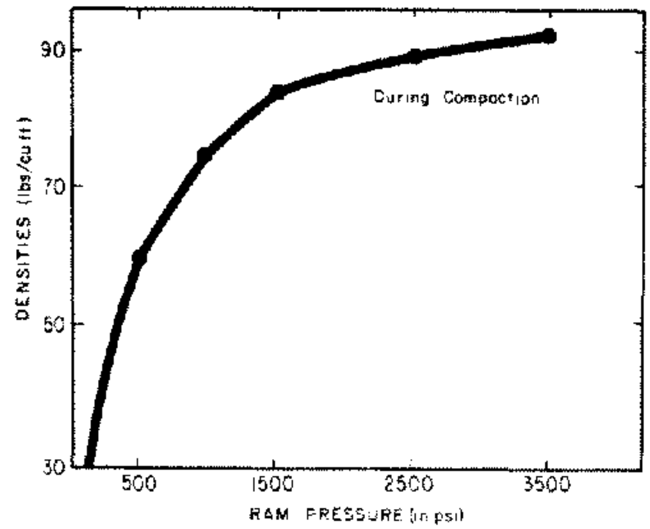


**Figure 2.** Average density of residential wastes during compaction. Data from report of study of high-pressure compaction baling of solid wastes by the City of Chicago, 1968, in *Municipal Refuse Disposal*, prepared by the Institute for Solid Wastes of the American Public Works Assn. (p. 54).

about 350 psi. This increase in density is largely due to reduction of void space. Compaction machines designed for use in sanitary landfill operations are claimed to be capable of reducing refuse to one-tenth its original volume (Billings, 1966, p. 87; Evans, 1967, p. 114). Similar volume reduction is claimed for shredding machines in anonymously authored reports.

From the combined effects of 1) pre-disposal shredding 2) impaction of falling refuse and 3) compaction due to refuse overburden, it is assumed that refuse will reach an ultimate average density of 1350 lb./cu.yd. or 50 lb./cu.ft. within the cavity. Such a density yields a depth-pressure gradient of 0.347 psi./ft., or 347 psi. per thousand feet of depth. It is further assumed that the additional reduction of refuse volume through decomposition will offset the stress reduction of cavity volume during filling operations. On this basis, estimates of the disposal capacity of solution cavities can be made.

Since disposal capacity will be influenced by design restrictions imposed by local geological considerations, a hypothetical situation is offered as shown in Figure 3. A prospective disposal site is located on a salt dome and the top of salt is 1,000 feet below the surface. A cylindrical cavity 200 feet in diameter is developed in the depth interval between 1500 ft. and 3500 ft. The volume of the cavity is approximately 11.3 million barrels or 62.8 million cubic feet. Based on ultimate refuse density of 50 pounds per cubic feet, the cavity has a disposal capacity of 1.52 million tons. Figure 4 shows that four such cavities may be developed on approximately 15 acres with the recommended partition thickness of twice the cavity diameter. If the cavities are spaced no closer than 1 diameter (200 ft.) to the property line, 33 acres are required.

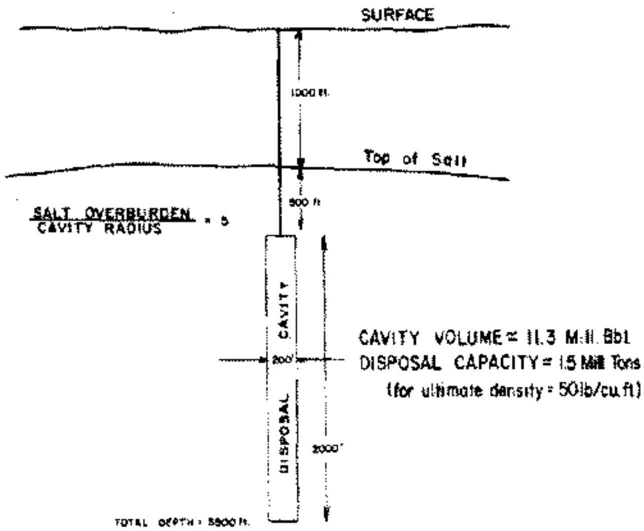


**Figure 3.** Scale cross-section of hypothetical refuse disposal project.

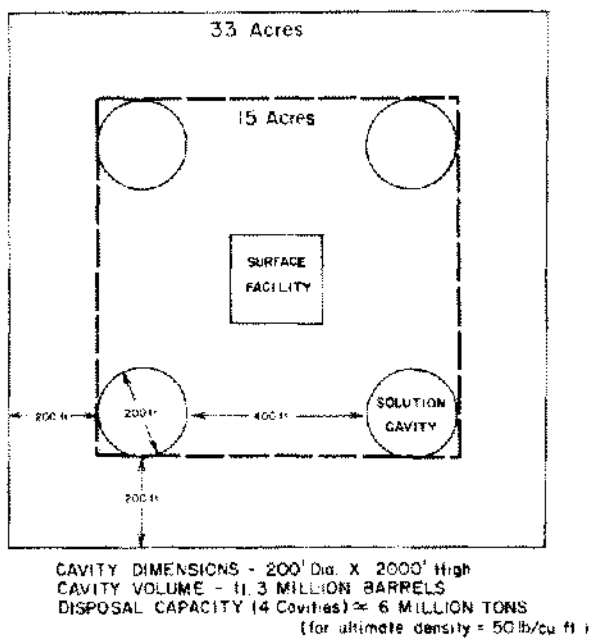


**Figure 4.** Plan view of hypothetical refuse disposal project.

The four cavities have a total volume of 45.2 million barrels, or approximately 5826 acre-feet. This volume is equivalent to a 250 acre excavation to a depth of over 23 feet, or a 33 acre excavation to a depth of 175 feet. The refuse capacity of the four cavities is 6.08 million tons. At a disposal rate of 1000 tons per day, these cavities would serve for over 23 years. It should be noted that the capacity of a refuse disposal cavity will exceed that of either an open dump or sanitary landfill of equal volume due to the greater degree of compaction in the disposal cavity.

## ECONOMICS

The cost of developing solution cavities in salt depends on drilling costs related to depth, brine disposal problems, and capital equipment costs (Halbouty, 1967, p. 146). Halbouty (1967, p. 146) reported that the cost of developing storage space in Gulf Coast salt domes averaged less than $1.00 per barrel. A report by Allen (1972, p. 1301) showed that development of two 1.1 million barrel natural gas storage cavities in a Mississippi dome in 1969–70 cost approximately $1.30 per barrel. Hawkins and Jirik (1966, p. 22) reported a cost range of $0.15 to $2.50 per barrel. The large volumes required for disposal cavities should reduce the cost per barrel by averaging down the one-time drilling and capital expenses of cavity development.

Based on cavity development costs of $1.00 per barrel, and an ultimate density of 50 lb./cu.ft., disposal cost per ton is $7.12, excluding land. In the preceding hypothetical example where 33 acres may be required, land costs of $10,000 per acre would add only 5.43 cents per ton to disposal costs.

If 5% of the total refuse volume is reclaimed, the cost of disposing into the solution cavities is reduced correspondingly to $6.77, excluding land. It is assumed that income from reclaimed materials will offset the expenses of handling and processing the refuse from the collection vehicle to the disposal cavity.

Figure 5 compares the cost of solution-cavity disposal with costs reported by Golueke and McCauley (1970, p. 18) for various other disposal methods. Residues remaining after processing by each of these methods is also shown. It is apparent that solution cavity disposal would be competitive with most conventional disposal methods, except for the landfill.

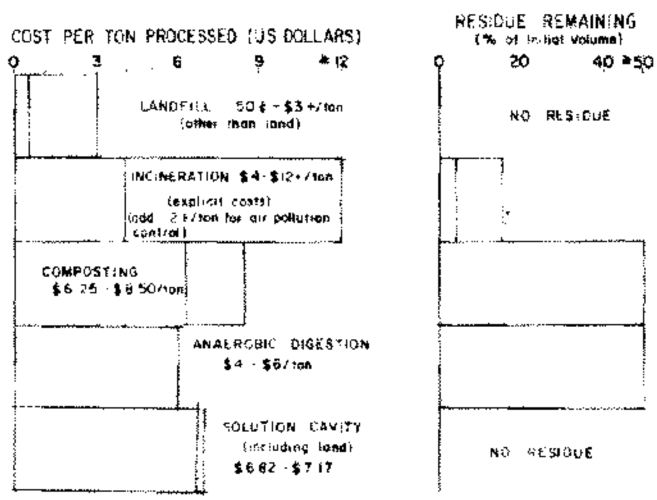


**Figure 5.** Processing cost and residue remaining for various disposal and/or reduction methods (Golueke and McCauley, 1970, p. 18), compared with estimated cost for disposal into solution cavities.

## ADVANTAGES

Disposal of refuse into solution-cavities would appear to have many advantages over conventional methods. Some of these advantages are as follows: 1) It would be aesthetically and environmentally neutral. Salt under compressive stress is essentially impermeable to gases and liquids and is not subject to fracture. Refuse leachate would not escape to pollute ground-water resources. Noxious odors and decomposition gases would be controlled so that the atmosphere is not polluted. The refuse would be deep underground where it could not be seen. There would be no insects or vermin and attendant health problems. 2) It would conserve land space. Less acreage is required for a given disposal capacity than conventional dumps or landfills. There would be no permanent effect on the land surface and co-extensive uses of the land surface would be possible. There should be less adverse effect on adjacent property values. 3) Natural gas, presently in short supply, would not be consumed by the process but may be produced as a product of decomposition. 4) There would be no residue remaining from the process to be disposed of elsewhere. 5) The process would be economically competitive with many conventional disposal methods. 6) It has potentially widespread application. There are many areas in the United States and elsewhere in which suitable salt deposits occur.

## CONCLUSIONS

It is feasible to use brine-free solution cavities for disposal of refuse at atmospheric pressure if care is taken to control the depth, salt overburden thickness, and partition thickness. In general, it appears that the cylindrical cavity preferred for refuse disposal purposes will have adequate structural stability at any size if 1) depth is limited to 4000–4500 ft. or less, 2) salt overburden thickness is at least 3 times the cavity radius and 3) partition thickness between cavities is at least twice their diameter. A certain degree of stress reduction of cavity volume must be accepted. If the salt formation is too deep or of insufficient stability, disposal cavities may still be feasible if the internal cavity pressure is increased by using a water-base refuse slurry or an air pressurization technique.

Refuse will decompose anaerobically within the solution cavity and cause an ultimate internal cavity temperature rise of 30°–50°F. Decomposition will produce odors and combustible gases which must be ventilated from the cavity during filling operations. Increasing moisture content of the refuse by irrigation may increase in the production of methane gas which can then be used to fuel engines in the surface facility.

The cost of this disposal method is estimated at $7.12 per ton, excluding land. Land costs will add only a few cents per ton. Disposal costs will be less if recyclable materials are reclaimed, if average ultimate refuse density exceeds 50 lb./cu.ft., or if cavity development costs are less than $1.00 per barrel of volume. Income from reclaimed materials is expected to offset the expense of handling and shredding the refuse prior to disposal in the cavity.

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