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POTENTIAL CONTAINMENT FAILURE MECHANISMS AND THEIR CONSEQUENCES AT A RADIOACTIVE WASTE REPOSITORY IN BEDDED SALT IN NEW MEXICO

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF TABLES (continued)

POTENTIAL CONTAINMENT FAILURE MECHANISMS AND THEIR CONSEQUENCES AT A RADIOACTIVE WASTE REPOSITORY IN BEDDED SALT IN NEW MEXICO

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ABSTRACT

This report examines potential containment failure mechanisms and estimates their probabilities and consequences, when possible, for a hypothetical waste repository located in bedded salt in southeastern New Mexico.

The primary conclusion of this study is that a serious breach of containment for such a repository, either by human action or natural events, is only a very remote possibility and falls into the category of least likely occurrences which affect society.

A sealed repository 600 m underground would be virtually sabotage proof; even the surface burst of a 50-megaton nuclear weapon could not breach the containment. Accidental drilling of boreholes through the disposal horizon could cause relatively minor local contamination.

The mechanism of containment failure with the most serious potential consequences seems to be the impact of a meteorite that produces a crater extending to the disposal horizon. The probability of such a catastrophic meteorite impact was estimated at 1.6×10^{-13} per year. The calculated exposure from the global fallout resulting from such an event would be of the same order of magnitude as that from nuclear bomb tests, provided the impact did not take place during the first few hundred years after closure of the mine. The ejecta falling back into the nearby area would cause a serious and protracted contamination problem. A pathway analysis showed that individuals living exclusively on foodstuffs produced in the contaminated area would be exposed to high radiation doses.

Based on the tectonic activity of the Delaware Basin over the past 200 million years, the probability of faulting through the repository has been estimated at 4×10^{-11} per year; however, the probability that faulting would cause failure of waste containment is only a small but unknown fraction of this value.

Exposure of the waste horizon to the action of ground water by a large fault with a vertical displacement of at least 350 m cannot be proved impossible. However, at least a few hundred thousand years would be required for an offset of 350 m to take place. A more sudden breach of containment could be effected by a large fault that cuts through the disposal zone and hydraulically connects the over- and underlying aquifers. In this case, any water flow along the fracture zone would be downward into the deep aquifers. Fortunately, the geologic evidence indicates that such a fracture could eventually be healed by plastic flow of the salt beds. Even in the event that the deep aquifers became contaminated, it is extremely unlikely that activity could be brought to the surface since the normal flow velocities in these aquifers are on the order of only a few kilometers per million years.

In view of the hydraulic heads of the various aquifers, it is difficult to visualize circumstances that could result in an upward flow and contamination of the fresh water in the Culebra Dolomite aquifer. The only possibility for the release of radioactive material to the Culebra Dolomite aquifer would appear to be on the basis of a model that permits faulting and progressive displacement of the disposal horizon until waste contacts the circulating ground water. The contamination of surface aquifers due to this mechanism of release could be relatively serious, despite the very long time necessary to produce such a displacement.

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1. INTRODUCTION

The most important single objective of radioactive waste disposal is to isolate the waste from the biological environment for the long periods of time during which it will remain hazardous, even if man's monitoring, surveillance, and control activities should be interrupted.

Since the most likely agent for dispersal of the radionuclides from deeply buried wastes is ground water, the most suitable geologic environment for waste disposal would be one which maximizes the integrity of the barrier separating the waste from circulating ground water. Consideration of these factors nearly 20 years ago led a committee of the National Academy of Sciences-National Research Council (NAS-NRC) to conclude that natural salt deposits represent the most promising geologic environment.[1] Subsequent reviews in 1961, 1966, and 1970 of the nuclear waste disposal problem by NAS committees again endorsed bedded salt as the most promising terrestrial medium for the ultimate disposal of high-level waste.[2-4]

Salt deposits, unlike most other rocks, are completely free of circulating ground water. This fact is perhaps best demonstrated by the existence today of extensive salt formations which were deposited hundreds of millions of years ago. The high solubility of salt would certainly have resulted in the complete removal of these deposits if there had been a persistent flow of even a small quantity of water through the formations.

The high plasticity of rock salt is primarily responsible for this "impermeability" and its preservation over long periods of time. When initially deposited, salt can be as porous and permeable as a coarse sandstone. As the newly formed deposit becomes slightly buried, the individual grains yield plastically, deform, and recrystallize. This collapses the pores and squeezes out the brine (although a small amount may be trapped as intracrystalline inclusions), resulting in the formation of a massive, virtually impermeable, polycrystalline rock. In a sandstone, the individual grains are strong enough to resist such reconsolidation, even when buried at great depth. At various periods of their history, rocks may be subjected to significant tectonic stresses and may suffer appreciable deformation. Many rock types respond to these influences in a brittle manner and develop an interconnected pattern of fractures that eventually become channels through which ground water circulates. Salt formations, because of their high plasticity, simply yield and flow while maintaining their massive, impermeable character.

Even if a salt formation should fail by fracturing (as in faulting), the fracture will be subsequently healed by plastic deformation, once again preserving the imperviousness of the salt to circulating ground water. This feature can be seen occasionally in salt mines.

In addition to these good mechanical properties, salt has a high thermal conductivity (as compared with many other rocks) which is advantageous in removing radioactive decay heat from the waste and in preventing excessive temperatures from being reached.

On the basis of the excellent properties of salt from a containment viewpoint and the generally known tectonic behavior of salt formations,[5] the conditions required for a serious release of activity to the biosphere from a repository in bedded salt tend to approach the bizarre and have considerably less credibility than the "maximum credible accident" assumed for nuclear power plant safety analyses. However, in keeping with the strict safety requirements for nuclear installations, the possibilities and, in some cases, the probabilities of potential mechanisms of containment failure are examined for a nuclear waste repository that is assumed to be located in the bedded salt of southeastern New Mexico. The potential mechanisms of containment failure considered are anthropogenic and geologic phenomena that range from the relatively minor one caused by drilling through the disposal horizon, assumed to be about 600 m below the surface, and the most catastrophic occurrence, namely, the impact of a meteorite that creates a crater deep enough to cause vaporization and atmospheric dispersal of part of the waste.

Possible events with potential consequences of intermediate gravity are: (1) exhumation of part of the radioactive waste by inception of volcanic activity, and (2) formation of a great fault that intersects the disposal area and either connects the over- and underlying aquifers or exposes the waste to the action of ground water as the result of a relative vertical displacement of several hundred meters between the two sides of the fault.

Other possible causes of containment failure that were examined include sabotage, nuclear warfare, increase of present rates of salt dissolution, and waste disinterment through erosion of the overburden.

Two conceivable mechanisms of containment failure that are neither clearly anthropogenic nor geologic, namely, nuclear criticality and release of stored energy, will not be discussed in this report, since they have been sufficiently analyzed elsewhere and have been shown to present no problem.[6,7,8]

2. DESCRIPTION OF ASSUMED REPOSITORY SITE

An area located in southeastern New Mexico, about 45 km east of Carlsbad, is currently being investigated for its suitability as the site of a radioactive waste repository. Obviously this is only one of the many possible locations for the first radioactive waste repository; however, the following discussion requires that the location of the repository be fixed. Therefore, it will be assumed that the repository is located in this particular area, whose location and geologic features are described here. The assumed repository is rectangular in shape with dimensions of 2.4 by 3.2 km, and oriented with the long side in the East-West direction. The northeast corner is in Lea County (about three-fourths of the area is in Eddy County) at the center of Section 31 in Township 21S, Range 32E, as shown in Fig. 1.

The surface elevation at the center of the repository site is 1090 m above mean sea level (m.s.l.). The general region surrounding the assumed site is sparsely populated, the climate is semiarid, topographic relief is low, surface drainage is poor, and collapse features are common. Tectonically the area is quite stable and is located in a zone characterized by minor seismic risk[9] (U.S. Coast and Geodetic Survey Zone 1).

The assumed site is located within the Delaware Basin, which is contained within the much larger Permian Basin. The proposed waste disposal horizon is about 600 m below the surface in the lower part of the Salado Formation. The general geologic and hydrologic features of Eddy and Lea counties have been described by Brokaw _et al._[10] as follows:

> "Sedimentary rocks attain thicknesses of more than 20,000 feet and range in age from Ordovician to Quaternary. The area includes the northern end of the Delaware basin and the largely buried Capitan Reef. The basin contains as much as 13,000 feet of Permian strata. The

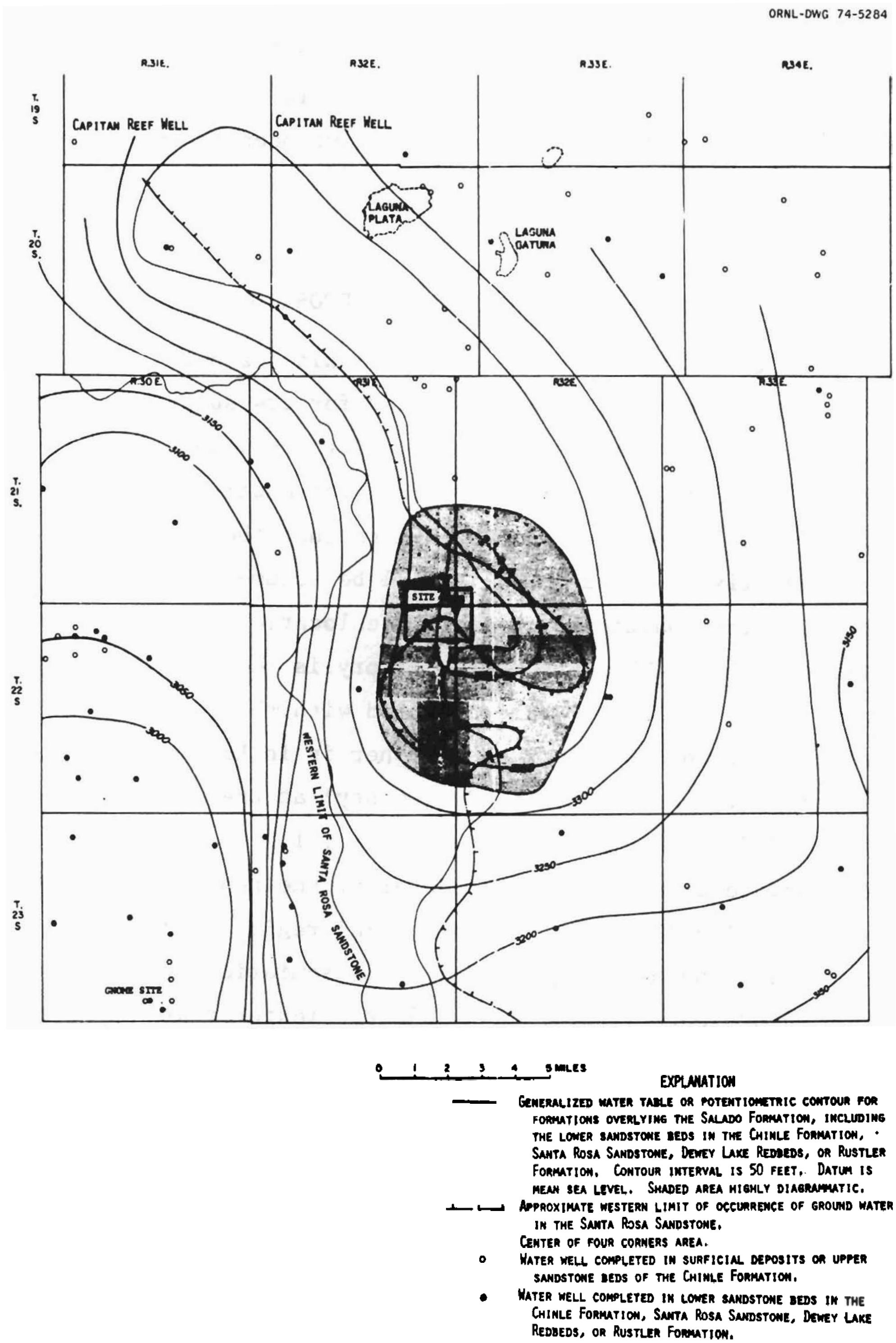

Fig. 1. Water Table and Potentiometric Contours in Formations Above the Salado Formation and the Locations of Water Wells.

oldest exposed rocks are of Late Permian age, but drilling has provided much data on the buried older rocks. The principal structures are broad gentle features related to late Paleozoic sedimentation: the northern Delaware basin, a shelf north and west of the basin, and a central basin platform to the east. These structures were tilted eastward before Pliocene time, have been inactive since, and now show a general eastward dip of less than 2°.

The salt deposits are in the Late Permian Ochoan Series composed of a thick salt-bearing evaporite lower part (Castile, Salado, and Rustler Formations) and a thin non-salt-bearing upper part (Dewey Redbeds).

The Castile Formation consists largely of interlaminated gray anhydrite and brownish-gray limestone, but includes much rock salt. It is about 1,500-1,600 feet thick along the southern edge of the potash area; it thins northward to about 1,000 feet near the margin of the Delaware basin and tongues out in the southernmost parts of the northwest shelf. All the salt is concentrated in a thick middle member which lies 200-300 feet above the base of the formation.

The Salado Formation, the main salt-bearing unit of the potash area, ranges in thickness from about 1,900 feet in the south to about 1,000 feet in the north. The formation is characterized by thick persistent units of rock salt alternating with thinner units of anhydrite and polyhalite. Thin seams of claystone underlie the anhydrite and polyhalite unit, and there are a few beds of sandstone and siltstone at large intervals. The Salado Formation is divided into three informal units: a lower and an upper salt member, generally free of sylvite and other potassium and magnesium evaporite minerals; and the McNutt potash zone, generally rich in these minerals.

The Rustler Formation mostly anhydrite and rock salt, thins from 300 to 400 feet in the southern part of the area to about 200-250 feet in the northern part. Some dolomite is present in the upper and lower parts of the formation, and thin to thick units of sandstone and shale are interbedded at long to short intervals.

The Dewey Lake Redbeds at the top of the Ochoan Series consist of reddish-brown siltstone and fine-grained sandstone. The formation is 250-550 feet thick in the potash area.

Three main hydrologic units control the ground-water hydrology of the Carlsbad potash mining area: the Pecos River, the water-bearing strata overlying the Salado Formation, and the Capitan Limestone and other water-bearing strata underlying the Salado. The distribution and development of large dissolution features, particularly in the Nash Draw and Clayton Basin areas, exert a major effect on the occurrence and movement of the ground water. The Pecos River receives nearly all of the ground-water outflow from the area. Most of that outflow reaches the Pecos near Malaga Bend.

The main water-yielding units overlying the Salado Formation are the basal solution breccia zone and the Culebra Dolomite Member of the Rustler Formation, the Santa Rosa Sandstone, and the alluvium. The basal solution breccia zone is the hydrologic unit most significant in the solution of halite from the upper part of the Salado Formation. The easternmost extent of evaporite solution in the potash mining area is roughly at the common boundary between Ranges 30 and 31 E. The formations above the Salado Formation seem to be connected hydrologically and can be considered a single multiple aquifer system. Solution activity and associated collapse, subsidence, and fracturing have increased the overall permeability of the rocks and the interformational movement of water in the aquifer system.

Ground water in the formations above the Salado moves generally southward and southwestward across the potash mining area toward the Pecos River. Although the total amount of ground water discharging to the Pecos River is not known, it has been estimated that 200 gallons per minute enter the river from the basal solution breccia zone.

The potentiometric and water-table contours outline a series of ground-water ridges and troughs which are imposed on the regional southward to southwestward pattern of ground-water movement. A large southwestward-plunging ground-water trough extends from Malaga Bend northeastward roughly through Nash Draw to beyond the mining area in the vicinity of Laguna Plata. Another much smaller trough is east and southeast of the Project Gnome site.

The Salado Formation has an intergranular porosity and permeability that ranges from low to virtually none. Locally, fractures and solution openings impart a spotty formational permeability. In the potash mining area, the Salado Formation is dry except for water in the leached zone at the top of the formation and small pockets of water or water and gas encountered occasionally during mining.

The Cambrian to Permian sedimentary rocks underlying the Salado Formation contain water of brine composition and are under high artesian pressure. These rocks are not exposed in the potash mining area but lie deeply buried throughout much of southeastern New Mexico and western Texas. In the potash mining area the elevations of the potentiometric surfaces of different zones of these rocks range from a few feet to a few hundred feet above or below the land surface."

3. POTENTIAL MECHANISMS OF CONTAINMENT FAILURE

The potential causes of containment failure for a nuclear waste repository contained in bedded salt can be divided into two classes - anthropogenic and natural. It seems unlikely that man could cause a serious and permanent breach of containment through an accident or malicious intent. Nature, however, does possess the potential for breaching the waste containment, for example, via the impact of a giant meteorite or the inception of intense tectonic activity in the area. Obviously, the probabilities of these events are extremely low, and they are usually neglected in relation to practically all human endeavors. Nevertheless, long-lived radioactive wastes need to be isolated from the biosphere for such long time periods that a new approach to hazards evaluation might be necessary. Therefore, the probabilities and consequences of even the most extravagant sequences of events are examined in this report.

3.1 Anthropogenic Causes of Containment Failure

Potential anthropogenic causes of serious breaching of the containment of a nuclear waste repository include sabotage, nuclear warfare, and drilling. Each type of event is discussed individually in the following sections; however, no estimate of the probability of its occurrence is attempted.

3.1.1 Sabotage

Sabotage directed at a nuclear waste repository could result in damage or destruction of property of considerable monetary value and cause some radioactive material to be released.

During operation of a repository, it is conceivable that a few determined fanatics could attempt sabotage which, if successful, could lead to the release of a fraction or all of the radioactive materials present in the surface facility. The probability of success of such sabotage efforts can be minimized by security measures such as the use of armed guards, security fences, and routine inspection of incoming vehicles and personnel for firearms and explosives.

Review and consideration of repository design and operation concepts invariably lead to the conclusion that the probability for successful sabotage is much greater during transportation of the waste to the repository than after arrival. At the repository, the waste is most vulnerable to sabotage if stored on-site before being unloaded from the railcars. The waste is less vulnerable after it has been moved inside the waste receiving buildings, since these structures will be designed to provide containment under most conceivable accidental conditions. Effective sabotage after burial would be extremely difficult if the intent is to release large quantities of radioactive materials to the environment.

Once the repository is sealed, however, sabotage that would cause a significant release of radioactive material to the external environment is impossible without intervention by an armed force that is equipped with machinery for drilling and excavating and has sufficient strength to to resist countermeasures by the authorities for considerable periods of time.

3.1.2 Nuclear Warfare

Current nuclear weapons are of such size that a surface burst would penetrate a sealed repository no deeper than 500 m. The largest deployed missile is reported to be capable of carrying a 25-megaton warhead. Using the information given by Glasstone,[11] a surface burst of this magnitude would generate a 270-m-deep crater with a fracture zone down to about 400 m in a geologic material with the physical properties of dry soil. The crater would be somewhat smaller in salt. Assuming the development of a 50-megaton weapon, the potential crater depth in dry soil would increase to only 340 m and the fracture zone to 500 m. Since the waste horizon will be about 600 m below the surface, the containment would not be breached even for the larger weapon.

3.1.3 Drilling

Following the decommissioning of a repository and sealing of the mine, it is planned that the site and certain subsurface mineral rights in a 1500- and 3000-m-wide buffer zone bordering the repository will be maintained in the perpetual care of the government and that permanent markers will be placed to warn of the potential hazard associated with drilling operations. Site and regional monitoring will be continued indefinitely, and permanent records will be maintained of the temperatures in the ground as well as in the aquifers around the waste burial area and of the levels of radioactivity in air and in surface and ground water.

It can be argued that records can be lost through wars or political and social upheavals. In this context, even the complete collapse of our civilization could be postulated. On the other hand, such loss of records and markers would not appear to present serious problems because the mine would remain inaccessible (barring an improbable natural catastrophe which will be discussed in later sections) to a civilization that did not possess the technology for drilling several hundreds of meters in search of underground resources. Drilling for fresh water below the Rustler Formation would be completely illogical for a civilization having the necessary drilling technology.

The capability for drilling to the depth of the disposal horizon would seem to imply that either the present civilization did not collapse (in which case records of the waste location should not be lost) or that following its collapse, a new technological culture was eventually developed. In the second case, it is reasonable to assume that at least a few thousand years would be necessary to achieve the necessary drilling know-how, so that only the long-lived nuclides and their decay products would be left in the repository at the end of such a period.

In the event that drilling were to take place, the probability of intersecting a canister would be small, namely, about 10^{-2} for hitting within 50 cm of a canister when drilling randomly over the mine area. Assuming that the drill passed close to a canister, some radioactive material could be brought to the surface by the drilling mud. However, even if the drillers were too unsophisticated to detect it, the resulting contamination would not present more than a local hazard because of the relatively small amount brought to the surface and the limited biologic availability of the long-lived nuclides present in the waste.

Another potential problem related to drilling is the possibility of failure of borehole plugs. The site has no deep boreholes within a radius of 2000 or 3000 m and it is envisioned that the wells drilled to investigate the site and the mine shafts would be plugged in the best possible manner. Both the exploratory wells and the mine shafts will not penetrate below the salt formation. Thus, even if plugging were to fail, any water moving downward to the salt would eventually saturate and form a stagnant column in the salt formation. In all cases where boreholes extend down to the aquifers underlying the salt, circulation between aquifers and formation of solution cavities in the salt can be envisioned. As a matter of fact, salt dissolution around a few abandoned boreholes has been observed in Kansas. The potential for this type of salt dissolution at the site in New Mexico is lower than in Kansas due to several reasons, namely, (1) less ground water is available, (2) no highly permeable aquifer exists, (3) the head differential between aquifers above and below the salt is only a few meters, and (4) most importantly, the wells in Kansas had been previously used as brine disposal wells and therefore were kept intentionally open.

While there is no way to assess the probability of water reaching the disposal zone through failure of the plugs of future boreholes, it is possible to conclude that the consequences of this type of containment failure would be relatively minor when we also consider that any hydraulic connection formed between the aquifers above and below the salt would allow water to move only downward into the deep aquifers (see Section 4.2).

3.2 Natural Causes of Containment Failure

Some of the natural events capable of breaching the salt formation and causing dispersal of radionuclides to the environment are sudden and catastrophic while others are slow and gradual. It is possible to combine the sudden and slow processes in various hypothetical mechanisms of containment failure. Ground water is undoubtedly the best candidate for removing radioactive material from the disposal area. Mobilization of such material by ground water is necessarily a slow process controlled by the dissolution rate of the salt and the leaching rate of radionuclides. However, the water could gain access to the disposal horizon as a consequence of a sudden event such as faulting or the impact of a giant meteorite.

As an event, the impact of a giant meteorite falls into a special class since it is conceivably capable of causing the atmospheric release of part of the activity and the probability of its occurrence is not site-related.

3.2.1 Impact of Meteorites

The impact of meteorites with planetary bodies is a normal geologic process. It is very likely that the population of meteorites has been progressively decreasing throughout most of the life of the solar system; thus the current frequency of impacts is probably somewhat lower than in the past.

The surfaces of Mars, Mercury, and the moon are characterized by a great number of impact features. The earth has undoubtedly been exposed to a bombardment of similar intensity, but most craters have been destroyed by the geologic processes that are active on our planet. However, some impact structures are known, and they provide useful indications of the morphology of impact craters and of the frequency of large impacts.

The impact of meteorites will be considered here as a random process, which means that the probability of any area on earth being hit is a function only of the area's dimensions and the impact frequency. This is not rigorously true since a slight latitude effect seems to exist;[12] however, it is certainly acceptable as a first approximation.

Large impact craters have a total depth about one-third of the diameter. The total depth is defined as the distance between the plane passing through the surrounding ground surface and the bottom of the "crushing zone." The crushing zone is formed by allogenic breccia, that is, by shattered rock fragments that were originally dispersed into the air by the impact and then fell back into the crater. Below the crushing zone is a "fracture zone," where the geologic materials were intensively fractures but left in situ.[13]

In the event of an impact at any waste repository, two cases can be kept distinct: (1) the depth of cratering reaches or exceeds the depth of burial; and (2) the depth of the crater is less than the depth of burial, but the fracture zone extends to or approaches the disposal horizon.

In the first case it is conceivable that a fraction of the radioactive material would become airborne, while in the second case the overburden would be shattered and ground water could gain access to the salt and possibly to the waste, although no instantaneous release of radionuclides would occur.

The frequency of impact on earth of large meteorites can be assessed from two lines of evidence: observation of meteorite falls and analysis of astroblemes.*

*From the Greek: "astron" + "blema" ("star" + "wound") a cosmic scar; synonymous for "fossil meteorite crater."

The extrapolation of empirical relations between meteorite masses and frequency of falls gives a frequency of about 10^{-12} km^{-2} $year^{-1}$ for impacts of meteorites of mass 2 X 10^7 kg or larger.[14-16] At an impacting speed of 20 km/sec, a meteorite of that size would form an impact crater about 1 km in diameter and 300 m deep.[17] With this impact frequency, more than 100 impact craters larger than 1 km in diameter should have formed on land throughout the last one million years. The geologic evidence does not support such high frequency of large impacts. Several impact craters younger than one million years are known; Barringer Crater (also known as Meteor Crater) in Arizona, which was formed about 25,000 years ago, is probably the most famous.[18] In addition, several more impact craters of much greater age have been identified.[19,20]

The Canadian shield is an area where astroblemes formed during the last two billion years should be recognizable, provided that the impact affected the basement rocks.[21] Hartmann[21] has calculated that all Canadian craters with diameters greater than 10 km have probably been preserved. To determine the probable number of craters of different diameter, it is reasonable to use the relationship between number of craters and size observed for the moon;[21] namely,

$$N = KD^{-2.4} , \tag{1}$$

where

N = the number of craters with diameters larger than D,

K = empirical constant.

On the basis of the Canadian astroblemes, the frequency of impacts producing craters larger than 1 km in diameter falls between 0.8 X 10^{-13} and 17 X 10^{-13} km^{-2} $year^{-1}$.[21] The lower limit seems to be more consistent with the geologic evidence; therefore, 10^{-13} km^{-2} $year^{-1}$ will be taken as the best estimate of the frequency of impacts of giant meteorites in Quaternary time. This value is in fairly good agreement with Dietz's estimate of one every ten thousand years.[18]

Probability of a Catastrophic Impact.--The assumed depth of burial of the waste in New Mexico is about 600 m; thus it would take a crater nearly 2 km in diameter to cause the instantaneous release of part of the radioactive material. On the basis of Eq. (1), the probability of formation of a crater 2 km in diameter or greater is about five times lower than the probability of a 1-km or greater crater; consequently, 2×10^{-14} km^{-2} $year^{-1}$ may be taken as the probability of an impact capable of causing some atmospheric release. The area of the assumed repository is about 8 km^2, and the probability of a catastrophic hit on this area in a one-million-year period is about 2×10^{-7}.

To put this number in perspective with regard to other risks that society obviously considers acceptable, let us compare it with the probability of a scheduled airline flight crashing into a packed football stadium, calculated at 3×10^{-8}/year,[22] or with the probability of an airplane crash on a nuclear power station located in New Jersey, estimated at 3×10^{-7}/year.[23]

Airborne Radioactivity.--The evaluation of the consequences of an impact of a meteorite at the site of a repository is necessarily hypothetical since it is based on several arbitrary assumptions. Only the case of an impact large enough to cause some atmospheric release will be discussed here. An impact resulting in failure of the overburden and exposure of the disposal horizon to ground water without atmospheric release of activity would have much less serious consequences. The atmospheric release of a fraction of the radioactive material contained in the waste repository is obviously the worst possible case since the radionuclides would achieve wide distribution and inhalation would become a possible exposure mechanism. The radiotoxicity of many long-lived alpha-emitters is three to four orders of magnitude higher if the intake is assumed to take place through inhalation rather than ingestion.

Table 1 shows the number of limits of annual intake by inhalation (LAI_{inh}) of heavy nuclides present in a repository containing all the high-level waste to be generated by the U.S. Nuclear power industry*

*The small differences between the inventories of radioactive material given in Table 1 and those given in Table 6 are due to different assumptions about the development of nuclear power and the types of reactors. Both calculations were already available, and the small differences do not seem to require recalculation of any of the tables.

Table 1. Activity and Number of LAI_{inh}[a] of Heavy Nuclides in a Repository Containing All High-Level Waste[b] Generated by the U.S. Nuclear Power Industry Through the Year 2000[c]

Decay Time (years)	Activity (Ci)	Number of LAI_{inh}
10^3	4.6×10^7	3.4×10^{16}
10^4	7.3×10^6	8.2×10^{15}
5×10^4	1.3×10^6	2.2×10^{15}
10^5	6.9×10^5	6.5×10^{14}
5×10^5	7.6×10^5	2.0×10^{14}
10^6	6.8×10^5	1.7×10^{14}
5×10^6	1.8×10^5	4.5×10^{13}
10^7	3.9×10^4	1.0×10^{13}

[a] Taken from Ferruccio Gera, Long-Lived Radioactive Wastes - How Long Do They Have to be Contained, ORNL-TM-4481 (1974). Values are based on the limits of annual intake recommended by the International Commission on Radiological Protection as listed in Table IIA of ref. 25.

[b] Waste produced by reprocessing 110,000 metric tons of LWR fuel and 59,000 metric tons of LMFBR fuel.

[c] The waste is assumed to be aged for 10 years before shipment to the repository; therefore, the closure of the repository would take place in the year 2010.

up to the year 2000 after various decay periods.[24,25]

Prior to making an assessment of the possible consequences of a catastrophic meteorite fall, it is necessary to consider the nature of the events likely to take place at the time of the impact.

The energy released in the impact would be on the order of several megatons of TNT,[17] and the explosion would be similar to a nuclear blast - complete with fireball, shock waves, and mushroom cloud. Temperature in the fireball would reach millions of degrees, and most of the meteorite mass would be vaporized together with some of the indigenous rocks.* Some more of the geologic materials would be pulverized and thrown in the air, the destiny of the fine ejecta being controlled by the size of the particles and the height reached. Large particles would fall rapidly to the ground, but fine particles (submicron to a few microns) would remain airborne for significant periods. A certain amount of fine dust would be injected into the stratosphere and, in turn, would achieve worldwide distribution. However, the observation of young impact craters shows that by far the greatest part of the ejected material would fall back inside the crater and its immediate vicinity to form the crater rim and fill.

If the analogy with cratering by nuclear explosions is valid, the observation of the vented fraction in nuclear excavations can be instructive. Bonner and Miskel[26] have reported that in the Danny Boy event, a 0.43-kiloton nuclear excavation in basalt, a few tenths of one percent of the nonvolatile radionuclides escaped beyond the immediate vicinity of the crater. The fraction of volatile radionuclides released was much higher, 10 to 20%; however, this is not relevant to the present discussion since all heavy nuclides are refractory.**

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*This is the reason why the search for large meteorite bodies below the floor of impact craters has always been unsuccessful.

**It must be emphasized that in a nuclear explosion most radioactive materials are initially in the fireball, while in the impact of a giant meteorite over the repository only a fraction of the radioactive waste would have a chance to be contained in the fireball. Therefore, the potential for environmental dispersal of radionuclides is much lower for the meteorite impact.

It seems obvious, therefore, that only a very small fraction of the radioactive nuclides contained in the repository would be ejected. The value of the fraction released would depend on the depth of the crater; for example, it would be very small for a crater barely reaching the disposal horizon but somewhat larger for a crater of greater dimensions.

A reasonable assumption seems to be that the impact would release to the atmosphere less than 1% of the refractory nuclides contained in the repository. However, in consideration of the great uncertainty associated with this assessment we will make the conservative assumption that 10% of these nuclides would be released by the impact. Of the materials ejected into the atmosphere, only a fraction would reach the stratosphere and subsequently achieve global distribution.

The fraction of radioactivity associated with the very fine particles would behave like the fallout from weapons testing; therefore, the possible consequences of cratering could be estimated by analogy with the behavior of fallout nuclides. The fraction of radioactivity associated with the large particles would fall back in the vicinity of the crater and cause only local contamination.

Intuitively we know that only a small fraction of the ejected radioactivity would be associated with fine particles and would achieve large-scale distribution; however, again we will make the conservative assumption that one-half of it will behave as weapons testing fallout. Therefore, an impact taking place 1000 years after closure of the repository was assumed to release to the atmosphere 3.4×10^{15} LAI_{inh} of heavy nuclides, of which one-half would fall back in the proximity of the repository and one-half would achieve large-scale dispersion. In summary, the consequences of the hypothetical impact was estimated by assuming that 5% of the activity in the repository would behave like weapons testing fallout; 5% would cause local contamination by deposition in the area surrounding the repository, and 90% would remain in the ground where it would be exposed to the action of ground water.

The amount of ^{239}Pu released by weapons testing through the year 1970 has been estimated at 400 to 600 kCi,[24,27] of which between 300 and 500 kCi are likely to have received global dispersion. Taking 400 kCi

(~6500 kg) as the amount globally dispersed in the environment, we find that the equivalent number of LAI_{inh} is about 10^{15}.

After 1000 years of decay, 5% of the radioactivity of the heavy nuclides in the repository is equivalent to 1.7×10^{15} LAI_{inh}. Therefore, the global consequences of the meteorite impact would be of the same order of magnitude as the consequences of fallout plutonium, which has contributed a negligible fraction of the total exposure from fallout.[28]

Inhalation is the critical exposure mechanism for fallout plutonium, despite the fact that the intake by ingestion is two to four times greater than that by inhalation;[29] this is due to the very low absorption from the gastrointestinal tract of this element, which causes the LAI_{inh}/LAI_{ing} ratio to be close to 10^{-4}.

Bennett[27] has calculated that the cumulative inhalation intake of ^{239}Pu through the year 1972 in the New York area is 42 pCi; this value can be considered typical for middle latitude regions of the northern hemisphere, which have received the highest fallout. The doses corresponding to this intake, applying the ICRP Task Group Lung Model, are shown in Table 2.[27,30]

Table 2. Cumulative Doses (in Millirems) from Fallout ^{239}Pu[a]

	Organ			
Time Period	Lung	Lymph Nodes	Liver	Bone
1954-1972	15	500	4	7
1954-2000[b]	16	950	17	34

[a]From B. G. Bennett, Fallout ^{239}Pu Dose to Man, HASL-278 (1974), pp. I-41 - I-63.

[b]Assumes an average air concentration of 10^{-5} pCi/m^3 in 1973 and no further intake after 1973.

These doses, which are extremely low, are expected to result in negligible radiological consequences. If the assumed analogy between fallout plutonium and the fraction of heavy nuclides in the waste achieving global dispersion is valid, we can conclude that the global consequences of the impact would be minor. Of course, the validity of such analogy is only partial since some of the other heavy nuclides in the waste are characterized by greater biologic availability after deposition and by greater absorption from the gastrointestinal tract than plutonium; in these cases ingestion would be expected to contribute somewhat more to the total exposure. However, the analysis does show that the global consequences of this most catastrophic event would not be serious.

The consequences of an impact taking place shortly after the closure of the repository could be much more serious due to the large inventory of fission products. Let us consider ^{90}Sr, which is by far the most hazardous nuclide in the waste during the first 400 years. Ingestion is assumed to be the critical exposure mechanism.* The repository is expected to contain 10^{10} Ci of ^{90}Sr at the time of closure. If the impact of a giant meteorite were to coincide with the time of closure, 500 MCi of ^{90}Sr (5%) would achieve global dispersion; this is about 25 times the amount produced by weapons testing through the year 1972, which has been estimated to be about 21 MCi.[31] The dose commitments from ^{90}Sr fallout have been estimated as 62 and 85 mrads for bone marrow and endosteal cells, respectively, for inhabitants of the temperate latitudes of the northern hemisphere.[28] It can be assumed that the dispersal of 500 MCi of ^{90}Sr could result in dose commitments 25 times higher.

However, after 130 years of decay, 5% of the ^{90}Sr in the repository becomes less than 21 MCi. The probability of a meteorite of critical mass hitting the repository in the 130 years following closure of the mine can be estimated as 2×10^{-11}.

*Fallout data show that ingestion of contaminated foodstuff is the critical exposure mechanism for all fallout nuclides except ^{239}Pu.

Local Contamination by Ejecta.--In this section, an evaluation is made of the consequences of contamination by ejecta of the area surrounding the repository. The assumption is that 5% of the total radioactive material, or 50% of that ejected, would fall back to the ground within a radius of about 18 km from the center of the crater, which comprises about 1000 km^2. It is assumed that deposition over the area will be uniform, an assumption that is obviously not true but is acceptable for this necessarily rough evaluation.

Assuming that the impact would take place 1000 years after closure of the mine (when the inventory of heavy nuclides in the repository is 4.6×10^7 Ci), a total of 2.3×10^6 Ci would be deposited in the 1000-km^2 area surrounding the repository. The deposition would amount to 2.3×10^3 $\mu Ci/m^2$. The individual activities of the most significant nuclides that would be present are shown in Table 3.

For an impact occurring 100,000 years after closure of the mine (when the activity of the heavy nuclides would have decreased to 6.9×10^5 Ci), a total of 3.4×10^4 Ci, or 34 $\mu Ci/m^2$, would be deposited locally. The nuclides shown in Table 4 would represent about 60% of the total activity.

The resulting doses for a hypothetical population living in the contaminated area have been calculated by J. P. Witherspoon of the Environmental Sciences Division at ORNL. His calculations are based on a generalized model to predict quantitative radionuclide movement through terrestrial food pathways (TERMOD) and on the computer programs EXREM and INREM.[32-34] The results of the calculations are shown in Tables 5 and 6 for two impacts taking place 1000 and 100,000 years after closure of the mine, respectively. Obviously, the local consequences are potentially serious, and occupancy and use of the contaminated area would have to be restricted for a fairly long time period following the impact. It is also obvious that such a cataclysmic meteorite impact would cause great devastation, regardless of the dispersal of radioactive wastes.

Table 3. Activity of Heavy Nuclides Deposited in the Area Surrounding the Repository if Impact Takes Place 1000 Years After Closure of the Mine

Nuclide	Activity (Ci)	Deposition ($\mu Ci/m^2$)	Percent of Total Activity[a]
^{210}Pb	1.1	1.1×10^{-3}	0.00005
^{210}Po	1.1	1.1×10^{-3}	0.00005
^{226}Ra	1.1	1.1×10^{-3}	0.00005
^{230}Th	6.3	6.3×10^{-3}	0.0003
^{234}U	8.0×10^{2}	8.0×10^{-1}	0.03
^{237}Np	3.5×10^{3}	3.5	0.15
^{238}Pu	4.1×10^{3}	4.1	0.18
^{239}Pu	7.1×10^{4}	7.1×10	3.09
^{240}Pu	1.2×10^{5}	1.2×10^{2}	5.22
^{241}Am	1.6×10^{6}	1.6×10^{3}	69.56
^{242m}Am	4.0×10^{3}	4.0	0.17
^{243}Am	2.4×10^{5}	2.4×10^{2}	10.43
^{242}Cm	3.2×10^{3}	3.2	0.14
^{245}Cm	1.9×10^{3}	1.9	0.08
Total	2.1×10^{6}	2.1×10^{3}	91.30

[a]Percent calculated on the basis of 2.3×10^{6} Ci as the total activity of the local fallout of heavy nuclides.

Table 4. Activity of Heavy Nuclides Deposited in the Area Surrounding the Repository if Impact Takes Place 100,000 Years After Closure of the Mine

Nuclide	Activity (Ci)	Deposition ($\mu Ci/m^2$)	Percent of Total Activity[a]
^{210}Pb	4.0×10^2	4.0×10^{-1}	1.18
^{210}Po	4.0×10^2	4.0×10^{-1}	1.18
^{226}Ra	4.0×10^2	4.0×10^{-1}	1.18
^{229}Th	1.2×10^3	1.2	3.53
^{230}Th	4.0×10^2	4.0×10^{-1}	1.18
^{233}U	1.3×10^3	1.3	3.82
^{234}U	6.2×10^2	6.2×10^{-1}	1.82
^{238}U	1.3×10	1.3×10^{-2}	0.04
^{237}Np	3.8×10^3	3.8	11.18
^{239}Pu	1.1×10^4	1.1×10	32.35
^{242}Pu	2.4×10^2	2.4×10^{-1}	0.71
^{243}Am	3.0×10	3.0×10^{-2}	0.09
Total	2.0×10^4	2.0×10	58.82

[a]Percent calculated on the basis of 3.4×10^4 Ci as the total activity of local fallout of heavy nuclides.

Table 5. Calculated Doses for Impact After 1000 Years of Decay

Radio-Nuclide	50-Year Dose Commitment (rem) Due to First Year of Exposure						
	Total Body Dose from Exposure to Ground Surface	Bone Dose from Inhalation of Resuspended Activity	Organ Dose Due to Ingestion via the Terrestrial Food Chain				
			Total Body	Bone	Liver	Kidneys	G. I. Tract
^{210}Pb	7.3×10^{-6}	4.6×10^{-7}	2.0×10^{-3}	5.6×10^{-2}	1.6×10^{-2}	4.7×10^{-2}	3.8×10^{-5}
^{210}Po	0	1.4×10^{-8}	4.5×10^{-3}	1.8×10^{-2}	3.9×10^{-2}	1.3×10^{-1}	3.3×10^{-3}
^{226}Ra	1.3×10^{-6}	3.2×10^{-6}	2.8	2.7×10^{1}			5.7×10^{-3}
^{230}Th	1.4×10^{-5}	2.4×10^{-4}	5.0×10^{-4}	1.8×10^{-2}	1.0×10^{-3}	4.9×10^{-3}	5.6×10^{-4}
^{234}U	2.1×10^{-3}	1.2×10^{-4}	1.3×10^{-1}	2.1		5.0×10^{-1}	1.6×10^{-2}
^{237}Np	5.7×10^{-2}	8.5×10^{-2}	4.8×10^{-1}	1.2×10^{1}	1.0	3.6	5.6×10^{-1}
^{238}Pu	1.1×10^{-2}	1.7×10^{-1}	8.9×10^{-2}	3.5	5.0×10^{-1}	3.8×10^{-1}	3.3×10^{-1}
^{239}Pu	7.0×10^{-2}	3.4	1.7	7.0×10^{1}	9.5	7.3	5.8
^{240}Pu	2.7×10^{-1}	5.7	2.9	1.2×10^{2}	1.6×10^{1}	1.2×10^{1}	9.8
^{241}Am	1.9×10^{1}	2.4×10^{1}	1.2×10^{2}	1.8×10^{3}	6.3×10^{2}	9.0×10^{2}	1.4×10^{2}
^{242m}Am		6.1×10^{-2}					
^{243}Am	9.7	3.6	1.8×10^{1}	2.7×10^{2}	9.3	1.3×10^{2}	2.2×10^{1}
^{242}Cm	7.6×10^{-3}	1.2×10^{-3}	5.2×10^{-3}	7.8×10^{-2}	7.9×10^{-2}	2.4×10^{-2}	3.7×10^{-1}
^{245}Cm		3.5×10^{-2}					
Total	2.9×10^{1}	3.7×10^{1}	1.5×10^{2}	2.3×10^{3}	6.7×10^{2}	1.1×10^{3}	1.8×10^{2}

Table 6. Calculated Doses for mpact After 100,000 Years of Decay

Radio-Nuclide	50-Year Dose Commitment (rem) Due to First Year of Exposure						
	Total Body Dose from Exposure to Ground Surface	Bone Dose from Inhalation of Resuspended Activity	Organ Dose Due to Ingestion via the Terrestrial Food Chain				
			Total Body	B e	Liver	Kidneys	G. I. Tract
^{210}Pb	2.6×10^{-3}	2.0×10^{-4}	$7.4 \times 10^{-}$	2.0×10^{1}	5.8	1.7×10^{1}	1.4×10^{-2}
^{210}Po	0	5.1×10^{-6}	1.6	6.6	1.4×10^{1}	4.6×10^{1}	1.2
^{226}Ra	5.0×10^{-4}	1.2×10^{-3}	1.0×10^{3}	9.8×10^{3}			
^{230}Th	9.0×10^{-4}	1.5×10^{-2}	3.1×10^{-2}	1.1	6.4×10^{-2}	3.1×10^{-1}	3.6×10^{-2}
^{233}U	2.3×10^{-3}	2.0×10^{-4}	2.2×10^{-1}	3.6		8.3×10^{-1}	2.7×10^{-1}
^{234}U	9.0×10^{-4}	1.0×10^{-4}	1.0×10^{-1}	1.6		3.9×10^{-1}	1.3×10^{-1}
^{238}U	5.5×10^{-5}	1.8×10^{-6}	1.9×10^{-3}	3.1×10^{-2}		7.1×10^{-3}	2.0×10^{-3}
^{237}Np	6.2×10^{-2}	9.3×10^{-2}	5.2×10^{-1}	1.3×10^{1}	1.1	3.9	6.1×10^{-1}
^{239}Pu	1.1×10^{-2}	5.3×10^{-1}	2.6×10^{-1}	1.1×10^{1}	1.5	1.1	9.0×10^{-1}
^{242}Pu	5.0×10^{-4}	1.1×10^{-2}	5.6×10^{-3}	2.2×10^{-1}	3.1×10^{-2}	2.4×10^{-2}	2.0×10^{-2}
^{243}Am	1.2×10^{-3}	4.0×10^{-4}	2.2×10^{-3}	3.4×10^{-2}	1.2×10^{-3}	1.7×10^{-2}	2.7×10^{-3}
Total	8.1×10^{-2}	6.5×10^{-1}	1.0×10^{3}	9.8×10^{3}	1.0×10^{3} [a]	1.1×10^{3} [a]	1.0×10^{3} [a]

[a] These totals assume organ dose from ^{226}Ra equal to total body dose

It is interesting to notice that the dose commitments due to ingestion of contaminated foodstuffs are higher for the impact taking place after 100,000 years of decay. This is due to the buildup of ^{226}Ra, which is characterized by greater biologic availability and much greater absorption through the intestinal wall than the actinides.

If we were to consider an impact that occurred before the decay of ^{90}Sr to nonhazardous levels, we would be faced by potential consequences of an even more serious nature.

Flooding of Crater by Ground Water.--With the assumed model, most of the radioactive material would remain in the ground and therefore could be exposed to the action of ground water. The potentiometric surface of the multiple aquifer system (all water-bearing zones above the Salado) at the assumed repository site averages about 80 m below the surface.

The apparent crater discussed here would certainly be much deeper than 80 m; thus a lake should form in the depression. However, the assumed site is located on a ground-water divide so that the availability of ground water would be limited by local recharge. Infiltration at the assumed site is probably less than the evaporation that would take place from a free water surface. Hence it is doubtful whether a lake could become a permanent feature with present climatic conditions. On the other hand, the future climate in southeastern New Mexico could very well become more humid, as it has been several times during the Quaternary. However, regardless of the climate and of the presence of a lake in the crater, ground water would infiltrate the fracture zone and possibly contact the waste. However, any ground water entering the fracture zone in the salt formation would become saturated and the high density would effectively exclude it from the overlying circulation. Any activity leached out of the waste, then, would essentially remain in the vicinity of the disposal zone since very limited potential for activity transport exists in stagnant ground water. If the impact were to take place when significant heat generation still existed in the waste, it is possible that some radioactive material would reach the zone of moving ground water through thermal convection. In this case, transport of activity in the multiple aquifer system would take place. The ground water at the site moves west for about 7 or 8 km until it reaches Nash Draw, where the flow is to the southwest.[35] The discharge area of the multiple aquifer is at Malaga bend, where ground water enters the Pecos River. The straight-line distance from the repository site to Malaga bend is about 32 km, but the ground water travels somewhat further.

The velocity of ground water in the Culebra Dolomite Member of the Rustler Formation has been estimated as 55 m/year at the Project Gnome site.[36] If this value is accepted as representative of the average water velocity in the multiple aquifer system, we find that ground water would require a minimum of 600 years to travel from the repository site to Malaga bend. The velocity of migration of radionuclides present in ground water is usually lower than the velocity of the water due to the interaction of the radionuclides with the surface of rock particles. A few radionuclides, for example, ^{3}H, ^{99}Tc, and ^{129}I, are not significantly affected by ion exchange or surface adsorption and are usually assumed to migrate at the same velocity as ground water. The retardation of radionuclides that undergo ion exchange with the solid matrix is expressed by:

$$v_r = \frac{v_\omega}{1 + (\frac{1-p}{p})\rho\ Kd} , \qquad (2)$$

where

v_r = velocity of the radionuclides,

v_ω = velocity of ground water,

p = porosity of the aquifer,

ρ = grain density,

Kd = distribution coefficient.[37]

The value of Kd depends on the properties of the rock and on the composition of the ground water.

No determinations of Kd in the water-bearing strata above the Salado are available; thus no reliable estimates can be made concerning the migration velocities of the various nuclides. From the general behavior of natural radioactive elements in geologic systems and from a few observations of the mobility of transuranium elements, it is expected that migration rates for practically all heavy nuclides would be much slower than for ground water.[24,38] For example, assuming a Kd of 100 (similar to the value observed for plutonium and pure quartz),[38] it would take more than a million years for the adsorbed species to reach Malaga bend and be further diluted by the Pecos River.

If leaching of the radioactive material from the crater were to contaminate ground water to a level in excess of the Radiation Concentration Guide (RCG)* for unrestricted use of water, the salt content under such circumstances would make it unfit for human consumption or irrigation purposes. It must be noted, however, that the high salinity of the water would decrease the Kd for the radionuclides and their transport would be retarded less than that for transport by fresh ground water. Assuming that the knowledge of the repository was still in existence at the time of impact, a radioactive monitoring system could be developed for protection of the population.

3.2.2 Volcanism

Volcanic activity is not a random process like the impact of meteorites. Most active volcanoes are located in the proximity of the boundaries between crustal plates. However, midplate volcanism is possible, both in oceanic and continental areas. About 62% of all volcanoes active in historic time are located in the circum-Pacific "girdle of fire"; about 14% of these are in the Indonesian island arc. Only 24% are located throughout the rest of the world; of these, 3% are in the islands of the central Pacific (Hawaii, Samoa, etc.), 1% on the islands of the Indian Ocean, and 13% in the Atlantic Ocean (Azores, Cape Verde Islands, Canaries, Madeira, Iceland, etc.). About 4% are located in the Mediterranean Sea and in northern Asia Minor. The remaining 3% are found in midcontinental areas; most of them are associated with the African rift system.[39,40]

Intense volcanic activity goes on, primarily without observable manifestations, in connection with the midoceanic ridge system, where mantle material rises and new crust is formed. It is obvious that volcanic activity is associated with well-defined tectonic features.

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*The radiation concentration guides (RCGs) are listed in Table II of the Code of Federal Regulations, Title 10, Part 20 (10 CFR 20).

The rise of magmatic materials in the earth's crust requires tensional faulting on a grand scale.

The western United States is characterized by extensive volcanism of Quaternary age. It has been proposed that the North American plate is overriding a previous center of crustal spreading, thus providing an elegant explanation for the numerous manifestations of volcanic activity in the western part of the plate. In New Mexico the Quaternary lava beds nearest the assumed repository site are located about 250 km to the northwest.

The only indications of past magmatic activity in the Delaware Basin are one or more mid-Tertiary lamprophyre dikes that have been observed in two potash mines, in drill holes, and in a surface exposure. These observations could be of a single dike or of several related dikes in echelon. The orientation of the dike is northeast-southwest, more or less parallel to several tectonic lineaments in the area. The dike[35] is located northwest of the assumed site with the closest approach being 6 or 7 km (see Fig. 4).

The location of the magmatic chamber from which the dike originated is unknown; however, the dike must certainly extend to some depth in the crystalline basement, which in the area is overlain by about 5500 m of sedimentary cover.

No displacement exists between the salt beds on the two sides of the dike, and in one of the mines the end of the dike can be observed. In cases where the intrusive mass terminates, a vein of polyhalite extends upward through the salt formation, indicating that some migration of fluids along the dike must have taken place.[41] However, recrystallization and plastic flowage have successfully healed any permeable zones formed at the time of the intrusion.

The emplacement of the lamprophyre dikes apparently occurred about 30 million years ago.[35,42] This is ample time for complete cooling of even the largest intrusive bodies. At the present time, there is no evidence of magmatic masses, such as thermal springs or anomalous values of the heat flow from the earth's interior, unusually close to the surface.

In conclusion, volcanic activity exists in conjunction with intense tectonic deformation of the earth's crust. The rise of the magma requires extensive faulting of the lithosphere; however, while there are no volcanoes without great faults, there are many faults without volcanic manifestations. Thus we can state that, in general, the probability that volcanic activity will be initiated in a tectonically stable area, with no magmatic manifestations, must be significantly lower than the probability of formation of a great fault.

The assessment of the consequences of the hypothetical inception of volcanic activity at the site of the repository will not be attempted here; however, it appears that the consequences would be less serious than those for the impact of a giant meteorite (described previously).

3.2.3 Faulting

It is generally accepted that faulting of thick salt formations does not lead to the formation of permeable zones; on the contrary, the plastic deformation of salt is known to heal any fracture or opening.[1-4] As a matter of fact, most of the known faults in salt formations confirm the self-healing behavior of halite. Fault breccias, which are common in brittle rocks, are completely unknown in salt formations. On the other hand, it could be maintained that permeable fracture zones could be formed in salt but would eventually be obliterated by salt dissolution or recrystallization; thus the lack of documented examples would not prove the impossibility of the event. A possible example of salt dissolution due to faulting has recently been reported by Jones[43] for the Clovis-Portales area, which is located in east-central New Mexico about 120 km north of the repository site. Piper[44,45] has proposed a salt dissolutioning process due to movement of water across the salt formations as a possible cause of the San Simon sink, located in the Delaware Basin, about 30 km southeast of the site. The mechanism of salt dissolutioning at San Simon sink is not clear, and water movement across the salt is only a hypothesis.

An insight into the rate of cavity closure in the Salado Formation could be provided by the small pockets of entrapped water and the small cavities containing nitrogen that have been found during mining and drilling in southeastern New Mexico.[36]

The gas in the cavities is occasionally under fairly high pressure, but nonpressurized cavities are also known primarily from mining. Figure 2 shows a detail of the largest cavity found in the Salado Formation.

The presence of nonpressurized cavities would seem to indicate that closure of openings at the depth of the existing mines (300 to 400 m) is not necessarily a rapid process. This conclusion is valid only if the fluid pressure in the cavities has been low for long periods. If depressurization were a result of bleed-off of the fluids in the approaching mine in the period preceding discovery of the cavity, the inference of the stability of the cavities would be invalid since past closure would have been prevented by the internal pressure and present closure would go unnoticed in the absence of appropriate measurements.

It is obvious that a fault through the repository would breach the waste containment only if permanent water circulation were established along the fault zone or if vertical displacement were sufficient to bring the disposal horizon into contact with circulating ground water.

In the event that a permeable fracture zone were formed and a hydraulic connection were established between the aquifers above and below the salt, the permanency of the water circulation would depend on the relative rates of salt dissolution and fracture healing.

The removal of salt would not be uniform along the fracture; it would be highest at the point where the unsaturated water enters the salt formation and would progressively decrease as the circulating brine becomes saturated. In a thick evaporite sequence such as the Castile and Salado Formations, it is likely that salt dissolution could not extend throughout the total thickness and that plastic flow would eventually close the fracture and stop the circulation of water. The chance that this will occur would be much higher when water is moving downward through the salt since, in this case, the minimum removal of salt would take place in the deeper part of the sequence where the

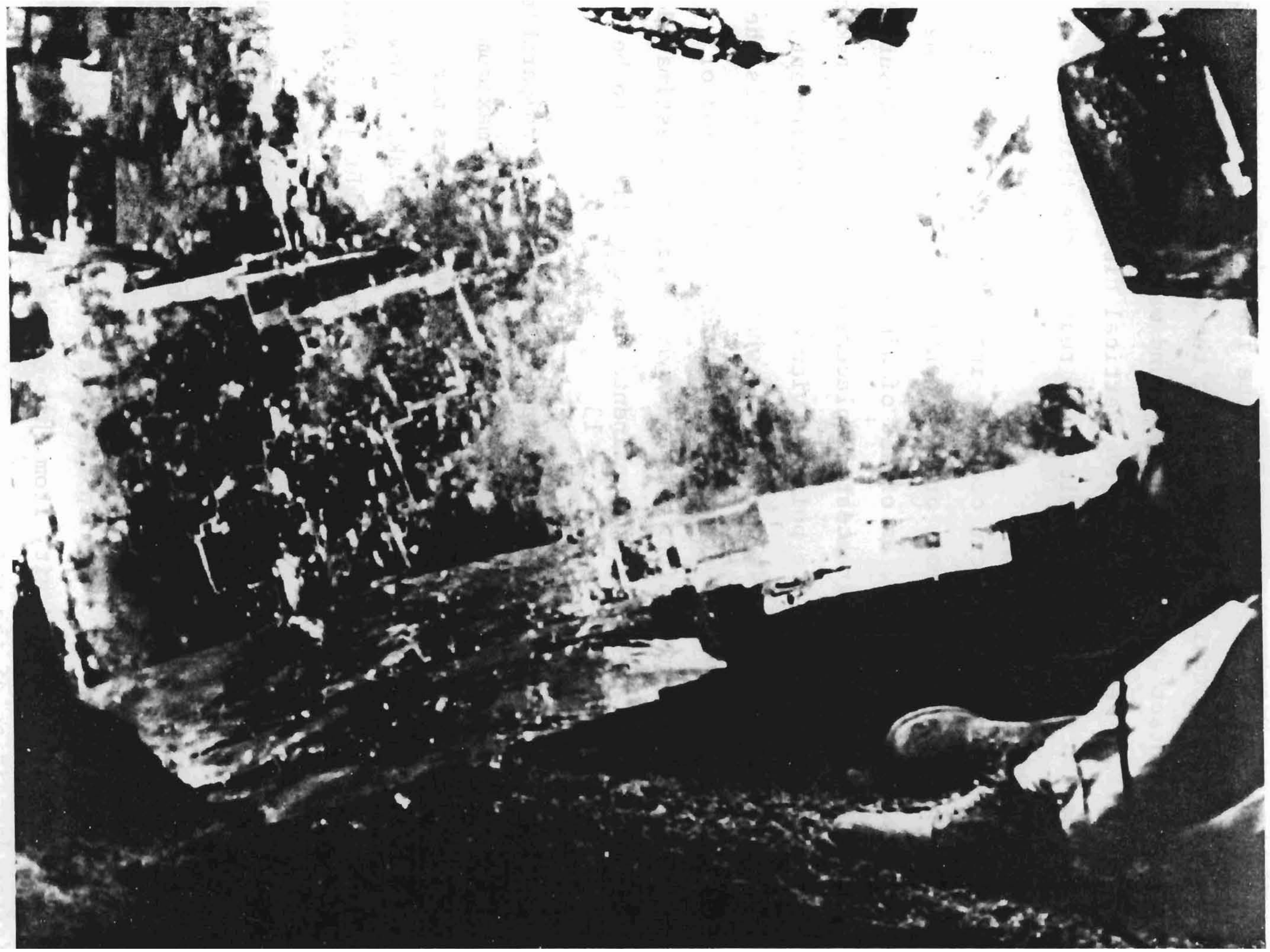

Fig. 2. Giant Halite Crystal in Crystal Cave. The cavity, which has been destroyed, was 90 to 120 cm high and about 15 m in diameter. Neither brine nor pressurized gas was present in the cavity at the time of discovery. (Reproduced by courtesy of the Potash Company of America.)

higher pressure would cause the maximum closure rate. For an upward flow, the probability of establishing a permanent hydraulic connection would seem to be much higher.

If no permeable zone were formed along the fault, faulting could still cause failure of waste containment by bringing the waste present on one side of the fault into contact with circulating ground water. This mechanism of containment failure requires a relative vertical displacement of at least 350 m between the two sides of the fault since that is the thickness of salt above the disposal horizon.

Movement along fault planes can occur in intermittent, occasionally catastrophic slippages, or in a more or less continuous creep. In the great Alaskan earthquake of 1899, an offset of almost 15 m was measured on the main fault; this is the greatest displacement known to have taken place in a single event. From the point of view of waste containment, the mechanism of fault slippage is irrelevant; what is important is the possible rate of this movement averaged over a fairly long period of time. The horizontal movement along the San Andreas Fault is estimated to be about 4 cm/year. No stable midcontinental area is likely to be subjected to such a high rate of movement.[13]

Possible rates of vertical movement can theoretically be comparable with the values for uplift and subsidence; in this context, a maximum rate of vertical displacement on the order of a few millimeters per year would be possible as shown in Fig. 3. Thus, it would take a few hundred thousand years for the disposal horizon to be brought into contact with the first aquifer overlying the salt.[13]

Tectonic Features of the Delaware Basin.--Since faulting as a potential mechanism of containment failure cannot be proved impossible, we will proceed with an assessment of its probability and possible consequences. In the absence of any data indicating incipient tectonic activity, our estimate will assume that tectonism in the area over the near geologic future will not differ in intensity from that of the last 200 million years (after deposition of the salt).

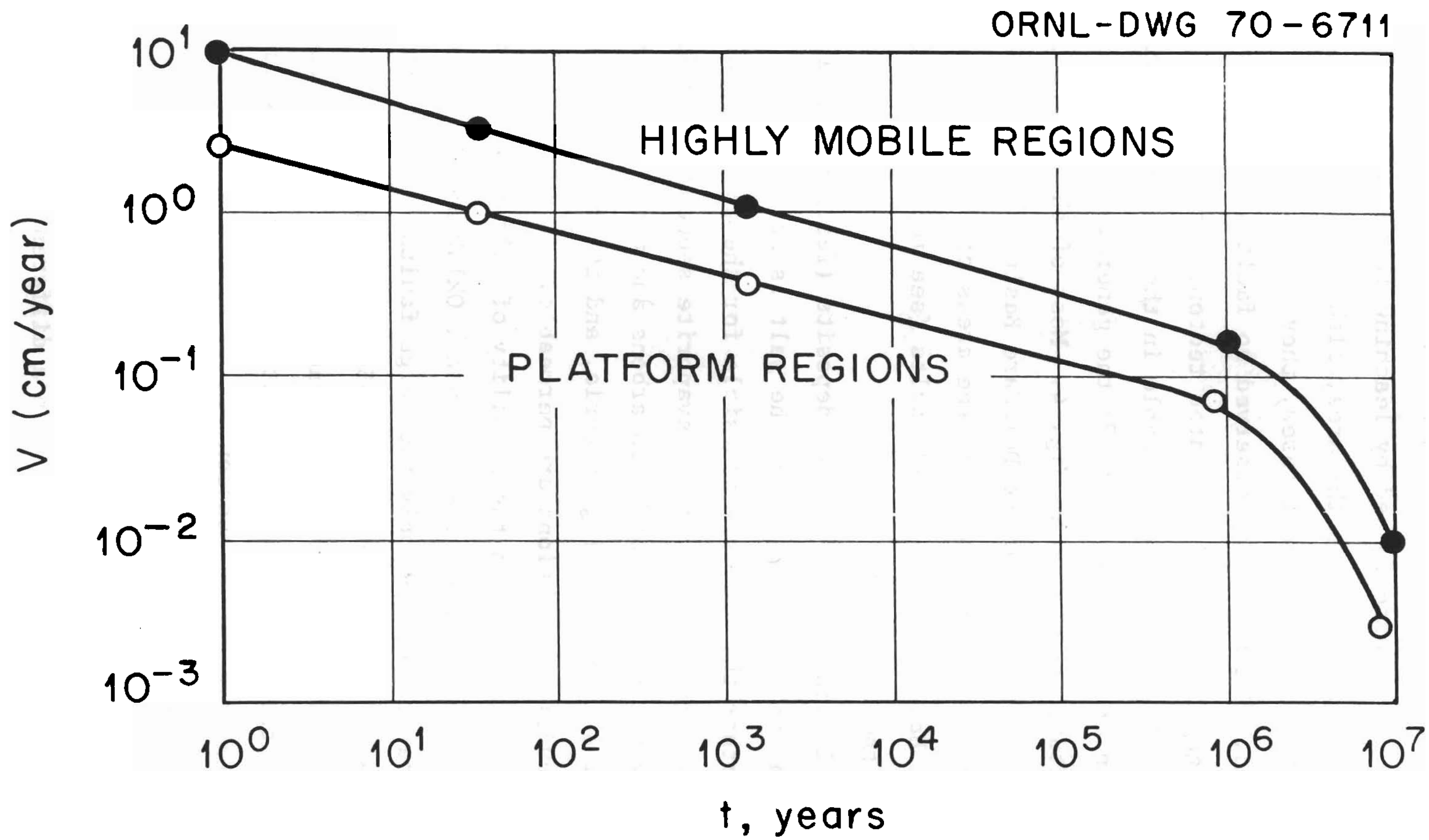

Fig. 3. Dependence of the Average Velocity of Vertical Movements (V) on the Time Interval over Which the Movement Takes Place. (From ref. 13.)

According to Jones,[46] deep-seated faults with more than 6 m of vertical displacement are not known in the Delaware Basin. Small faults due to surface subsidence caused by leaching in the Rustler and subrosion on top of the Salado exist in the area, although not in the immediate proximity of the site. In most cases, they are masked by the cover of windblown sand. Bachman[47] has observed no fault scarps in the Delaware Basin that might be due to deep-seated tectonic movements.

The tectonic features recognizable in the area surrounding the Delaware Basin are listed in Table 7; the general locations of the various structures are shown in Fig. 4. Most of the listed tectonic features are located outside the Delaware Basin; exceptions are the already discussed lamprophyre dike, the areas of sulfur deposits, and the controversial Barrera and Carlsbad faults (see features 2 and 3 of Table 7), which are at the edge of the basin.

The significance of the sulfur deposits (feature 5 in Table 7) for the assessment of the stability of the salt is not clear since it is not known whether the fluids responsible for the accumulation of sulfur have actually migrated through the evaporite sequence. Sulfur deposits are formed by the reaction of hydrocarbons and water with anhydrite, via the action of sulfate-reducing bacteria, and it is well known that fractured anhydrite formations are permeable.

Bachman[47] has examined the stability of salt in the entire Permian Basin, which extends into parts of Kansas, Oklahoma, Texas, and New Mexico, and has recognized only two large faults: the Bonita fault with a length of about 25 km and the 65-km-long Meade fault. The latter fault, however, may have been caused by subsidence due to salt dissolution rather than by tectonic activity, and so it would not be relevant to the present discussion.

Sanford and Toppozada[62] described a 60- to 100-km-long fault with a maximum displacement in Quaternary time of about 30 m, located along the margin of the San Andres and Sacramento Mountains, more than 100 km west of the site; however, this is in a different tectonic province.

Table 7. Description of Structural Features and Igneous Activity in the Vicinity of Delaware Basin, Southeastern New Mexico and West Texas[a]

	Feature[b]	Location[b]	Age	Remarks	Reference
1	Subsurface faults outlining Central Basin Platform	East of Delaware Basin	Probably Pre-Permian	Permian and younger beds unfaulted. Not identifiable on ERTS photos.	1,48
2	Barrera Fault	32 km southwest of Carlsbad	Late Tertiary with possible Quaternary movement	Both faults as mapped by Kelley front the Reef Front Escarpment. Kelley projects them northeast beneath alluvium. Although Kelley describes faults in detail, including measured dips, there appears to be considerable controversy about their existence. Many other geologists, including Hayes, Bachman, Jones, Cooley, and Motts have examined the area in detail and are not convinced that the linear features seen on aerial photos are actually faults. There is apparently no offset of beds at depth as determined from drill holes, although Kelley reiterates his stand on the presence of the faults and states that near-surface beds have several hundred feet of throw. He states that faults either die out at depth or flatten out so that deeper beds are not affected. Not identifiable on ERTS photos.	49,50
3	Carlsbad Fault	16 km southwest of Carlsbad	Late Tertiary with possible Quaternary movement		49,50
4	Linear scarps in Castile Formation and normal faults which cut Bell Canyon-Castile contact	Southwest of Carlsbad, mainly in Texas	Post-Permian (Laramide?)	Probably either joints or minor faults confined to Castile Formation. Visible on ERTS photos.	49,51 52,53
5	Areas of sulfur deposits	Southwest of Carlsbad, mainly in Texas	Post-Cretaceous	Local accumulations in areas of extensive salt solution and upward migration of fluids. Not identifiable on ERTS photos.	54,55

Table 7 (continued)

	Feature[b]	Location[b]	Age	Remarks	Reference
6 6a 6b	Lamprophyre dikes	In Delaware Basin, Central Basin Platform, and Northwestern shelf. South and southeast of Carlsbad.	Mid-Tertiary	Dikes found in drill hole 6, surface exposure 6a, and potash mines 6b. Trend northeast, may be connected but probably in echelon. Range in width from several centimeters to 30 cm but almost 45 m thick in Kerr-McGee mine 6b. Not visible on ERTS photos.	34,41
7	Astrobleme	16 km southwest of Odessa, Texas	Late Pleistocene	Main crater 170 m in diameter. Four smaller associated craters. Not identifiable on ERTS photos.	56
8	Haupache Monocline	Guadalupe Mountains and Delaware Basin	Pennsylvanian	Probably faulted at depth. Indicates compression. Area obscured by cloud cover on ERTS photos.	53
9	Guadalupe Mountains and Delaware Mountains	Southern New Mexico and Texas	Mainly Cenozoic	Basin-Range uplifted fault block mountains. Bounded on west by steep faults. Tilted gently eastward. Prominent feature on ERTS photos.	51,53
10	Carlsbad folds	North of Carlsbad	?	Belt of domical uplifts just behind Capitan Reef front according to Kelley. Orientation of eliptical domes normal to axis of belt. Do not extend below Artesia Group rocks. Probably not tectonic but depositional features according to Motts. Not identifiable on ERTS photos.	49,57
11	Artesia-Vacuum Arch	Near Artesia	Pre-Permian	Oil producing structure. Not identifiable on ERTS photos.	49,58

Table 7 (continued)

	Feature[b]	Location[b]	Age	Remarks	Reference
12	Border, Six-Mile, Y-O } Buckles	West and south of Roswell	Pre-Cenozoic	Referred to as "buckles" by Kelley. Zones of compressional folding and faulting. Border and Y-O structures prominent on ERTS photos. Six-Mile structure not identifiable.	49,59
13	Matad r Arch	In Texas, ast of Roswell	Pre-Permian	Structural arch trending east. Line up with railroad dike n rtheast of Roswell. Not identifiable on ERTS photos.	49,60
14	Capit n St ck	West of Roswell	T rti ry	Mainly fine-grained leucocratic quartz syenite stock about 6.4 km wide by 34 km long. Intrudes Mesa Verde Formation (Cretaceous). Prominent on ERTS photos.	49
15	Railroad dike	Northeast of Roswell	T rti ry?	East-trending, 50 km long, as much as 30 wide, medium-grained olivine gabbro. Indicate tension. Topographically expressed as ridge. Cut Triassic sands. Visible on ERTS photos.	49,61
16	Cami o del Diablo dike	Northeast of Roswell	Terti ry?	East-tre ding, 40 km long, as much as 15 m wide, diabase. Topographically expressed as swale cut Triassic sandstone. Not identifiable on ERTS photos.	49,61

[a]Table compiled by U.S. Geological Survey

[b]Locations shown in Fig. 4.

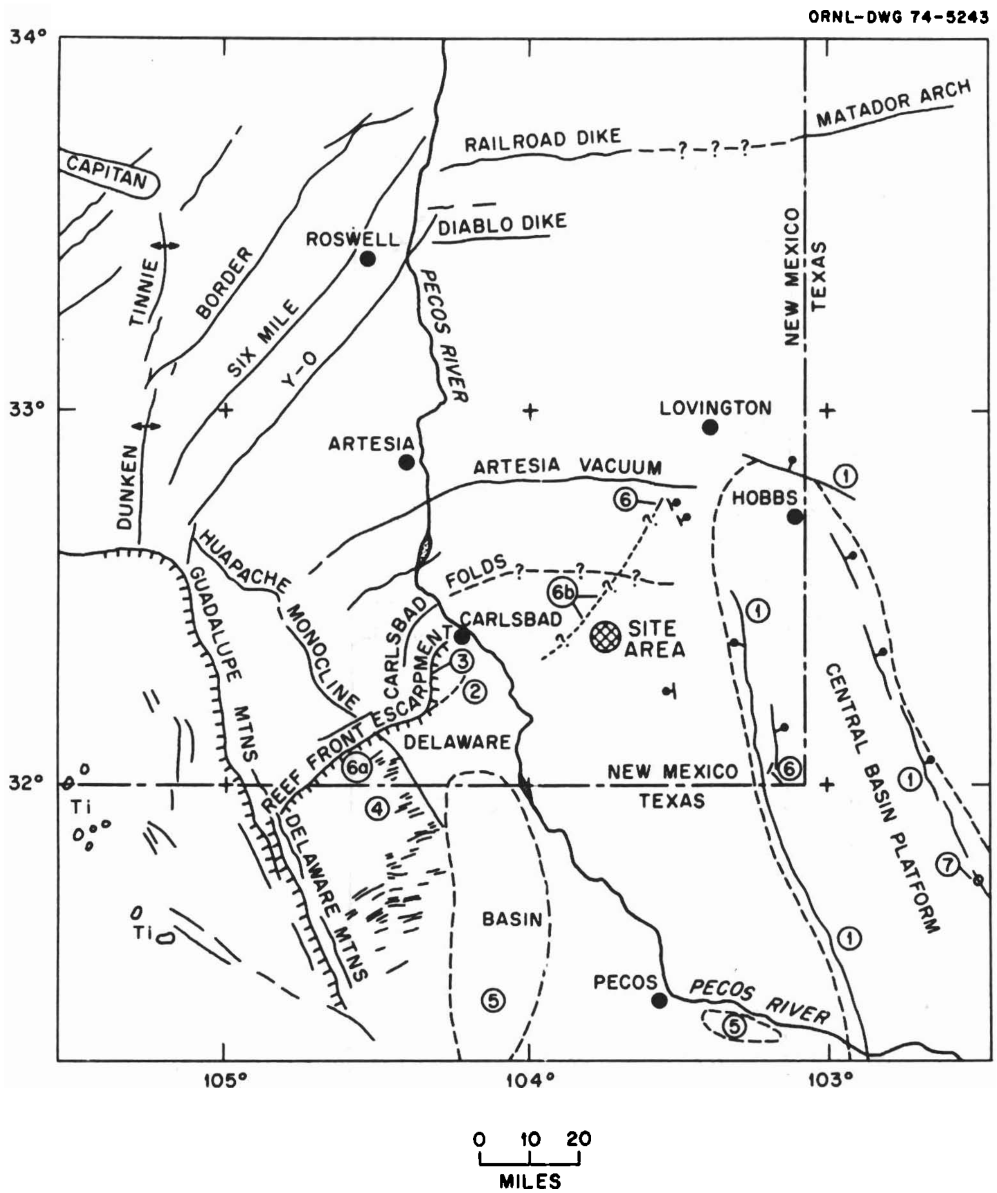

Fig. 4. Sketch Map Showing Locations of Structural Features and Igneous Activity in Vicinity of Delaware Basin, Southeastern New Mexico and West Texas. (Prepared by U.S. Geological Survey.)

A recent study on the seismicity within 300 km of the assumed site confirmed that no significant tectonic activity is evident in the Delaware Basin.[62] However, several earthquakes with epicenters on the Central Basin Platform, about 80 km southeast of the assumed site, were reported since 1966. They might have been caused by the injection of water for secondary recovery of oil, or might indicate rejuvenated tectonic activity of the Central Basin Platform. A study of the seismicity of the Central Basin Platform will be initiated in 1975. A microseismic study at the site is currently in progress.

Probability of Faulting in the Delaware Basin.--In the absence of actual data on tectonic structures in the Delaware Basin, particularly buried faults in the crystalline basement and in the pre-Permian sedimentary formations, faulting in the basin will be treated as a random process.

Since the controversial Barrera and Carlsbad faults are the only known possible tectonic faults of post-Permian age in the Delaware Basin, we will assume that two faults of the same lengths will occur in the next 200 million years, namely, 18 and 4 km respectively (see Fig. 4). The area of the Delaware Basin has been assumed to be about 30,000 km^2; the area of the repository is about 8 km^2. Using these data and Fig. 5 (see Appendix I for the derivation, which relates the probability of a line intersecting a circular area when both are contained in a much larger area), the sum of the probabilities that either fault will intersect the repository is 4×10^{-5} in any million-year period, or 4×10^{-11} per year.

It must be emphasized that this value, even if accepted as the probability of a fault intersecting the repository, does not necessarily indicate the probability of containment failure. The relationship between the two probabilities is dependent on the probability that the fault would either cause a permeable fracture zone and a permanent hydraulic connection or bring the disposal horizon into contact with the overlying aquifers. Therefore, the probability of containment failure through faulting must be much lower than the probability of faulting, but there is no method for estimating this quantitatively.

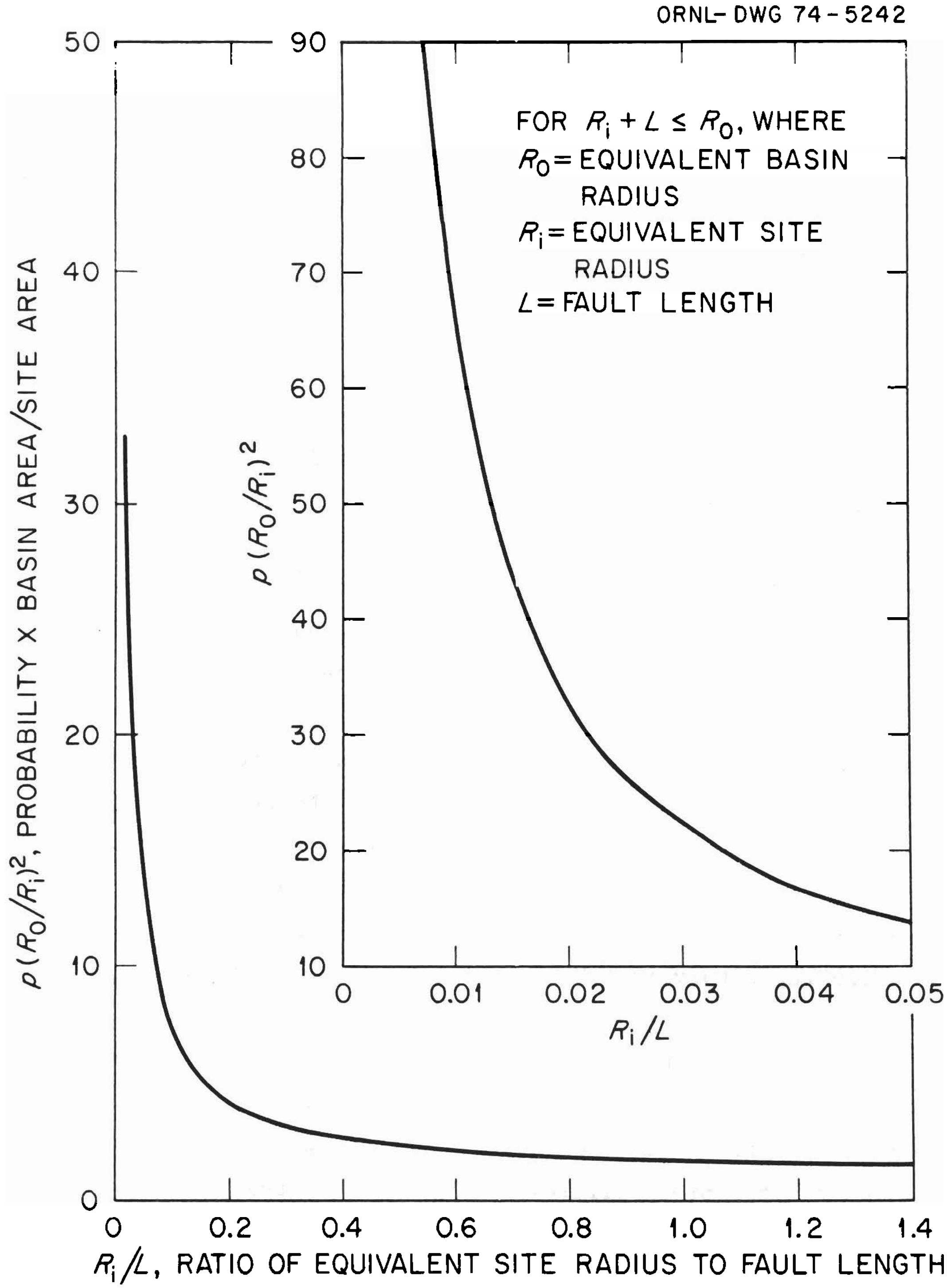

Fig. 5. Probability of Intersection of a Line and a Circular Area.

If it were assumed that one fault out of a hundred could cause failure of waste containment, the probability of releasing radioactive material due to faulting would be the same as that for impact of a giant meteorite Obviously, the potential consequences of containment failure via faulting depend on the actual mechanism assumed to bring the waste into contact with ground water. For the flow through a permeable fracture zone, the direction of water movement and the flow rate through the salt formation would be controlling. For the progressive dissolution of salt from the upthrown side of a fault, the rate of activity release would depend on the total radionuclide content in the waste, the amount of waste in contact with ground water, and the rate at which the radionuclides are leached from the waste.

3.2.4 Erosion

Average rates of erosion in the United States, based on recent stream load records, are on the order of a few centimeters per thousand years.[13] Occasionally erosion rates can be higher; for example, small drainage basins or river valleys are known where materials are removed at rates ranging from tens of centimeters up to meters per thousand years.[13]

The selected site for this report is located in the Mescalero plain, a geomorphic surface in southeastern New Mexico situated between the Pecos River on the west and the High Plains on the east. The Mescalero plain has limited relief and is covered by windblown sand over large areas; the surface is usually underlain by a layer of caliche of Pleistocene age.

No significant lowering of the land surface by erosion occurred during Quaternary time as indicated by the existence of the caliche layer. Large depressions are due more to subrosion and subsidence than surface erosion. Small depressions can be formed either by subrosion or wind deflation. Bachman[63] has reviewed removal processes in the Mescalero plain, concluding that the site area underwent very limited erosion and salt dissolution in Quaternary time. A southeast-flowing stream of probable Pleistocene age may have eroded San Simon Swale; the bottom of the swale is 60 to 70 m below the surrounding high land surface.

The surface lowering at one place in Nash Draw has been estimated at 60 m during the past 600,000 years (a rate of 10 cm/1000 years); salt dissolution and subsidence have been responsible for most of the lowering.[63] Based on this estimate, it seems reasonable to assume that, even if a future climate were to favor increased rates of erosion, no disinterment of waste could take place before several million years.

A drastic change in the rate of erosion could be caused by a significant uplift of the area. There is no indication that the Mescalero plain is presently being uplifted. It is obviously impossible to prove that uplift will not occur in the future; however, the known rates of large-scale vertical movements in midcontinental areas indicate that an uplift of 500 m would require several hundred thousand years.[13,64]

On the basis of these considerations it seems reasonable to conclude that erosion, as a potential mechanism of containment failure for waste buried in southeastern New Mexico at a depth of 600 m, can be neglected.

4. POTENTIAL CONTAMINATION OF GROUND WATER

The hypothetical mechanisms of containment failure that are potentially capable of bringing ground water into sudden contact with the waste include fracturing of a great thickness of materials by faulting, followed by water circulation through the fracture zone, and the previously discussed meteorite impact. A more gradual mechanism could involve faulting through the repository and progressive displacement until the waste in the upthrown side of the fault is brought into contact with the overlying aquifers.

It is also conceivable that water could reach the disposal zone as a consequence of the natural dissolution that is occurring on the western margin of the salt deposits and occasionally on top of the Salado. Eventually, this natural dissolution process could remove enough salt to expose the waste to the action of ground water. However, the rate of salt removal is so low and the areas of present subrosion are so far from the assumed site that, even if the process became accelerated, the waste would not come into contact with the ground water until after several million years had passed.[44,45,63] Therefore, subrosion can be neglected as a potential cause of contamination of ground water by radioactive nuclides.

In the following sections the allowable contamination of the Culebra Dolomite aquifer is estimated, the potential for flow between aquifers is examined, and a simplified model for dissolution of activity is applied.

4.1 Acceptable Rates for Release of Radionuclides into the Culebra Dolomite Aquifer

In considering the possibility of contamination of aquifers from buried nuclear waste, fresh-water aquifers lying near the surface cause the greatest concern because of their potential use by man for potable water and for irrigation purposes.

The Culebra Dolomite Member of the Rustler Formation is the largest, most persistent fresh-water aquifer above the Salado in the general area of the site. Fresh water also can be present in the Santa Rosa Sandstone of Triassic age and in the Magenta Dolomite Member of the Rustler Formation, both of which lie above the Culebra Dolomite. However, these aquifers are considered to be interconnected, and the Culebra Dolomite is generally recharged from the aquifers above. Consequently, it does not seem likely that contaminants contained in the Culebra Dolomite could be transferred in any significant amount to the aquifers above.

This section presents calculations showing the quantities of radionuclides that could enter the Culebra Dolomite aquifer without exceeding the RCGs for unrestricted use of water (as listed in 10 CFR 20).

The canisters that will be placed in a federal repository will probably contain high-level waste from the reprocessing of spent fuels from four types of reactors: the PWR, the PWR operating in an equilibrium plutonium recycle mode, the LMFBR, and the HTGR.

Table 8 was prepared from calculations on waste accumulation to the year 2000 by a U.S. nuclear power industry.[65] It shows the expected waste accumulation, in curies, for the entire nuclear economy and the average ingestion hazard per curie of activity as a function of time after mine closure for both fission products and the actinides and their decay products. The ingestion hazard is defined as the sum of the volumes (in cubic meters) of water required to dilute each radioactive nuclide in the mixture to its RCG for unrestricted use of water. The RCGs calculated by LaVerne[66] were used for nuclides unlisted in 10 CFR 20.

A more definitive mapping of the geological strata and hydrology at the assumed site must await completion of field drilling and testing programs; however, the information available for the Project Gnome area,[36] which is about 22 km southwest of the repository site, seems applicable for a preliminary hazards evaluation.

At the Gnome site, the Culebra Dolomite aquifer is about 9 m thick. The calculated ground-water velocity is 0.15 m/day, and the effective porosity is about 10%.[36] Using these data, a flow of 130 liters/day per meter of aquifer width is obtained.

The aquifer discharges through some alluvial deposits into the Pecos River at Malaga bend, a distance of about 32 km in a straight line from the proposed site. A minimum of 600 years would be required for any radioactive material entering the aquifer to reach the river at the average water velocity. The actual travel time would be significantly greater because of nonstraight line flow and holdup in the aquifer.

The radioactivity reaching the discharge area would be adsorbed and delayed in the alluvial deposits at the Malaga bend which contain a significant fraction of clay minerals. The radioactivity finally entering the Pecos River would be diluted in the river flow. The flow of the Pecos River at Pierce Canyon crossing, just below Malaga bend, averaged 1.87×10^3 liters/sec over the five-year period 1961-1965.[67] The lowest flow rate in any one-year period was 5.15×10^2 liters/sec, or 1.63×10^7 m^3/year, during 1964.[67]

Table 8. Ingestion Hazard of High-Level Waste[a] Accumulated in the Repository by the Year 2010

Time After Mine Closure (years)	Heavy Nuclides			Fission Products[c]		
	Activity (Ci)	Hazard/Ci (m^3/Ci)	Ingestion Hazard[b] (m^3 of H_2O)	Activity (Ci)	Hazard/Ci (m^3/Ci)	Ingestion Hazard[b] (m^3 of H_2O)
10^2	1.96×10^8	2.02×10^5	3.96×10^{13}	4.79×10^9	6.35×10^5	3.04×10^{15}
3×10^2	8.84×10^7	2.10×10^5	1.86×10^{13}	7.07×10^7	3.13×10^5	2.21×10^{13}
10^3	3.45×10^7	2.12×10^5	7.30×10^{12}	4.36×10^6	3.97×10^3	1.73×10^{10}
3×10^3	1.78×10^7	1.63×10^5	2.90×10^{12}	4.24×10^6	3.99×10^3	1.69×10^{10}
10^4	1.04×10^7	1.88×10^5	1.95×10^{12}	4.15×10^6	4.09×10^3	1.66×10^{10}
3×10^4	3.48×10^6	4.40×10^5	1.53×10^{12}	3.90×10^6	4.03×10^3	1.57×10^{10}
10^5	1.27×10^6	1.82×10^6	2.31×10^{12}	3.18×10^6	4.06×10^3	1.29×10^{10}
3×10^5	1.26×10^6	1.98×10^6	2.50×10^{12}	1.93×10^6	3.99×10^3	7.70×10^9
10^6	0.18×10^5	8.35×10^5	6.83×10^{11}	6.89×10^5	3.35×10^3	2.31×10^9

[a] When delivered to the repository, the waste is 10 years old.

[b] Sum of volumes required to dilute all radionuclides to RCG values for unrestricted use of water.

[c] 99.9% of ^{129}I removed.

The total thermal power of the nuclear waste shipped to the repository through the year 2010 has been estimated at 253,000 kW. Using 370 kW/hectare[68] as the allowable heat load and allowing an additional 10% for corridors, etc., the total area required is about 800 hectares or 8 km^2.

The assumed repository has an aspect ratio of about 1.3 and is oriented with the long side in the east-west direction. The aquifer flow is normal to the short side, which is 2.4 km long. Assuming a water flow in the Culebra Dolomite Member at the site similar to that calculated for the Project Gnome area, the flow across the repository is 1.1×10^5 m^3/year.

It is this amount of water that is assumed to be available for dilution of any radioactive nuclides released to the aquifer. The minimum annual average flow of 1.6×10^7 m^3/year in the Pecos River would provide sufficient dilution to increase the permissible rates of release by a factor of more than 100 as shown in column 5 of Table 9. If the repository were oriented with the long side normal to the aquifer flow, the flow available for dilution would be a factor of 1.3 higher on the basis of the assumed model.

Based on the availability of 1.1×10^5 m^3 of water per year for dilution, Table 9 shows release rates into the aquifer that could occur and still not exceed the permissible RCG for the mixture of nuclides for unrestricted use of water. If ingestion of water were the exposure mechanism, such activity present in the aquifer would cause no exposure in excess of the applicable dose limits.

The results shown in Table 9 are conservative in that lateral mixing in the aquifer outside the repository area and adsorption on the rock particles are not considered, but are not conservative in that uniform vertical mixing is assumed throughout the 9-m-thickness of the aquifer.

It must be emphasized that the flow rate in the Culebra Dolomite aquifer at the repository site may be different from that at the Project Gnome site. In fact, the probability is that the average flow will be smaller because the repository is located in an area of doubtful water presence in the Triassic formations (see Fig. 1) and on a high on the

Table 9. Rates of Release of Radioactive Material Yielding a Concentration Equal to the RCG for Unrestricted Use of Water[a]

Time After Repository Closure (years)	Release Rate (Ci/year)			
	In Culebra Dolomite Aquifer			In Pecos River
	Fission Products	Heavy Elements	Total Activity	Total Activity
10^3	28	0.52	0.58	85
3×10^3	28	0.67	0.83	120
10^4	28	0.59	0.81	120
3×10^4	27	0.25	0.53	77
10^5	27	0.06	0.21	31
3×10^5	28	0.056	0.14	21
10^6	33	0.13	0.24	36

[a]Multiply tabulated value by 1.3 if the repository is assumed to be oriented with the long side normal to flow.

potentiometric surface for the multiple aquifer system. Construction of flow streamlines normal to the potentiometric contour lines of Fig. 1 indicates a direction of flow that is initially westward, then turning in the southwesterly direction past the Gnome site. Consequently, on the average, any potentially contaminated water from the repository area will be mixed with the flow of the Culebra Dolomite aquifer in the vicinity of the Project Gnome area prior to being discharged into the Pecos River at the Malaga bend.

4.2 Potential for Water Flow Through the Disposal Horizon

Despite the fact that there is no known fault-caused permeable fracture zone in the Salado Formation, such an event cannot be considered impossible. Consequently, it is conceivable that a hydraulic connection could be created between all the aquifers existing in the stratigraphic column. The resulting flow through the Salado would be controlled by the relationship between the heads in the various aquifers and their hydraulic transmissivities.

As previously discussed, the Culebra Dolomite Member of the Rustler Formation is the most widespread aquifer above the Salado in the site area and is generally hydraulically connected with any water present in the Santa Rosa Sandstone of Triassic age, in the Magenta Dolomite Member of the Rustler Formation, and in the brine aquifer immediately on top of the salt. Figure 1 shows that the elevation of the piezometric surface at the site for this multiple aquifer system is about 1020 m above mean sea level (m.s.l.).

Several deep aquifers exist below the salt formations and are listed in Table 10. The depths below the surface have been estimated on the basis of the general stratigraphy of the area as reported for the Project Gnome site.[36] The fresh-water heads and the salinities are obtained from a report by McNeal[69] on the deep hydrodynamics of the Permian Basin. No appropriate data for the Strawn and Mississippian have been found in McNeal's paper. However, these aquifers are usually connected with the Wolfcamp and Devonian, respectively, as indicated by the known similarities of head and composition;[70] therefore, the same characteristics have been assumed for the Strawn and Mississippian.

When the fresh-water head, in meters above mean sea level (m.s.l.), is converted to the equivalent height of rise for saline water (sixth column of Table 10), all the heads are below the 1020-m elevation for aquifers above the Salado. This indicates that flow would be downward into the aquifers below the Salado if the postulated hydraulic connection were created by a vertical fracture. However, because of the uncertainty of head estimates for the site area, the rise of water from the deep aquifers through the salt sequence cannot be proved impossible. Any water flowing upward through the Salado and Castile Formations would dissolve more salt, and the increase in density of the water in the evaporite sequence would decrease the elevations of the columns of water in equilibrium with the heads of the deep aquifers listed in Table 10.

Table 10. Artesian Pressures of Deep Aquifers at the Repository Site[a]

Aquifer	Depth Below Surface (m)	Fresh-Water Head (m above m.s.l.)	Salinity (ppm)	Density (g/cm^3)	Level of Standing Saline Water (m above m.s.l.)	Level with Salt Dissolutioning (m above m.s.l.)
Delaware	1220	975	200,000	1.14	840	795
San Andres	1525	975	50,000	1.03	945	780
Wolfcamp	3350	1000	150,000	1.1	700	640
Strawn	3960	1000	150,000	1.1	700	590
Mississippian	4725	1130	50,000	1.03	975	825
Devonian	4900	1130	50,000	1.03	975	825
Ellenburger	5200	975	150,000	1.1	520	460

[a]Elevation at the center of the site is 1090 m above m.s.l. The Salado Formation is 300 m below surface, or 790 m above m.s.l. Piezometric surface of the multiple aquifer system above the Salado is 1020 m above m.s.l.

For the purpose of estimating the water levels after dissolutioning of salt, it was assumed that water rising in the hypothetical fracture would begin solutioning at the top of the lower layer of anhydrite in the Castile (which is about 60% salt and consists essentially of a sequence of anhydrite and salt layers with a thick anhydrite bed at the bottom) and leave the Salado completely saturated. For this solutioning model, the potentiometric head in the deep aquifer, expressed in meters of fresh water, will be balanced by a column of water of small height and of variable density. This column of saline water is considered to be composed of three zones of different densities. The density of the lower zone is equal to that of the saline water actually contained in the deep aquifer. This lower zone extends up to the lowest salt bed in the Castile Formation, where the middle zone begins; this middle part extends up to the top of the Salado, and its density is some average of the inlet and saturation densities. Any portion of the water column rising above the Salado is considered to be completely saturated.

The pressure balance is:

(Height of fresh water) 1.0 = (Lower saline water height) ρ + (Middle saline water height) $\bar{\rho}$ + (Upper saturated water height) ρ_s,

which in equation form becomes:

$$1.0\ (D - S + H) = [D - (TS + TC + SD)]\rho + (TS + TC)\bar{\rho} + (h - S + SD)\rho_s, \qquad (3)$$

where

h = height of column of saline water with salt dissolutioning, m,

D = depth of formation below the surface, m,

H = fresh-water head above m.s.l., m,

ρ = density of saline water in formation, g/cm^3,

$\bar{\rho}$ = average density of saline water passing through the Salado and salt portions of the Castile, g/cm^3,

ρ_s = density of saturated brine, 1.19 g/cm^3,

S = surface elevation, m,

TS = Salado thickness, m,

TC = Castile thickness above bottom anhydrite member, m,

SD = depth to the Salado, m.

Taking the midpoint of the site as the reference point, the pertinent formation depths and thicknesses are:[31]

S = 1090 m above m.s.l., TS = 585 m, TC = 415 m, and SD = 305 m.

Substituting these values into Eq. (3) and solving for h, we have:

$$h = \frac{D - 1090 + H - (D - 1300)\rho - 1000\bar{\rho}}{\rho_s} + 790. \qquad (4)$$

Using $\bar{\rho} \cong \rho_s$ (since any possible flow will be very slow), Eq. (4) was used to calculate the heights of rise with salt dissolutioning shown in the last column of Table 10. Assuming that the base of the Culebra Dolomite aquifer is 50 m above the Salado (same as at the Gnome site), the elevation is 830 m above m.s.l. The highest level reached by the deep aquifers, as shown in Table 10, is only 825 m above m.s.l.; consequently, flow from the aquifers underlying the salt into the Culebra Dolomite could not occur even if this aquifer were assumed to be the only water-bearing horizon above the salt and under water-table conditions. The lowest head is present in the deepest aquifer, the Ellenburger, which would be the recipient of the flow through any hypothetical fracture. However, in case the permeability of the Ellenburger were low, some flow into the other aquifers with low heads could take place.

The Water Resources Division of the U.S. Geological Survey in Albuquerque, New Mexico, has performed a dynamic analysis of the water flow through a hypothetical fracture intersecting the repository site.[71] A simple simulation model was used, assuming the existence of only three aquifers, one above and two below the salt. The best available hydrologic parameters for Rustler, Delaware, and Devonian were used for the three aquifers. The resulting simulated flow through the hypothetical fracture was 3.5 liters per second per kilometer of fracture 25 years after faulting. The initial flow rate is somewhat higher; however, only the steady-state flow is relevant to the present discussion. The flow is downward into both Delaware and Devonian, which is not surprising when one considers that the effective heads in the two aquifers are quite similar (see Table 10). The flow rate of 3.5 liters sec^{-1} km^{-1} could be maintained over geologic time periods only if sufficient recharge of ground water in the area surrounding the site did occur. This analysis has confirmed that, in case a permeable fracture zone were formed, the likely direction of flow would be downward and that the potential for significant flow rates would exist. A simulation with the Capitan Reef Limestone as the aquifer immediately below the salt gave higher flow rates due to the greater hydraulic transmissivity of this aquifer. Of course, this case does not apply to the site; on the other hand, if the hypothetical fracture were to extend to the Capitan Reef, higher flow rates would be expected along the portion of fracture intersecting the reef. The Capitan Reef surrounds the Delaware Basin, and its closest approach to the site is about 8 km to the northeast.

An additional consideration is that the model does not include the deep aquifers with lower heads (e.g., the Ellenburger or the Strawn) and, if these aquifers had hydraulic transmissivities comparable to the deep aquifers included in the model, they not only would accept most of the flow, but the flow rates could be higher, due to the greater head difference with the aquifers above the salt.

Therefore, it seems reasonable to conclude that the flow rate through the hypothetical fracture would be controlled by the availability of water in the aquifers above the salt and, over the long term, by the rate of recharge in the area.

Considering that the future climate could very well be more humid than at present, the hypothetical fracture zone discussed here could cause extensive dissolution of salt in the Salado and Castile Formations and exposure of large amounts of waste to the action of ground water. Fortunately, the probable direction of flow is downward into the deep aquifers underlying the salt, a condition with less serious potential radiological consequences than the contamination of the fresh-water aquifers above the salt.

4.3 Leaching of Radioactive Material by Ground Water

As already discussed, any water flow in a permeable fracture zone across the salt should be downward; however, some doubt exists about this conclusion as a result of the limited number and the uncertainty of the observations on which the heads and salinities of the various aquifers are based. In addition, a mechanism that is potentially capable of bringing activity into contact with the overlying aquifers has been identified in the fault. This mechanism causes progressive vertical displacement of more than 350 m. Hence, it is reasonable to assess the consequences of activity release to the overlying aquifers, particularly to the Culebra Dolomite Member of the Rustler Formation.

The amount of radioactive material leached from solid waste is a function of the amount of waste in contact with ground water, the leach rate, and the surface-to-volume ratio of the solid. The hazard presented by the leached activity depends on the activity, age, and composition of the waste; the transport velocity in the aquifer; and the potential pathways that lead to exposure of man.

It is assumed that the repository will contain about 75,000 canisters of solidified waste, which will accommodate all the high-level waste generated by the production of electric energy by nuclear stations in the United States through the year 2000.[65]

It is further assumed that the waste was originally solidified by a vitrification process and that at the time of leaching, the glass will have undergone sufficient degradation to change it to a granular form and drastically increase the original surface-to-volume ratio.

4.3.1 Arrangement of Canisters

The placement of the canisters in the mined regions will depend on the heat generation rates in the canisters and, to some extent, the order of burial. Assuming that the waste will generate 5 kW of heat per canister (which is presently considered to be the maximum permissible), the canisters will be placed in a line on 6-m centers in 5.5-m-wide rooms separated by 18-m-thick pillars of salt.[68] The room will be about 90 m long with the axis oriented in the east-west direction. Distances between the back ends of the rooms will be a function of burial time. However, this latter distance is unimportant for the model used in the analysis of the consequences of a breach in containment. Assuming that a 30-m strip on each side of the mine area is free of canisters and that about 18 m is allowed for corridors, only 98 canisters can be placed in a line within the 2400-m length of the short side. The remaining canisters in the east-west direction will be aligned (765 per line) at 6-m intervals, interspersed by suitable intervals between the back ends of the rooms.

4.3.2 Derivation of Equations

We assume that the waste particles are spheres and that the dissolution rate is uniform over the surface. This implies no significant effect on the leach rate by internal diffusion of radionuclides within the particle.

The equation for the change in mass, with time, of a spherical particle is:

$$\frac{dm}{dt} = -4\pi r^2 \dot{\ell} , \qquad (5)$$

and

$$m = \frac{4}{3}\pi r^3 \rho, \qquad (6)$$

where

m = mass, g,

t = time, days,

r = radial distance from particle center, cm,

ℓ = leach rate, $g/cm^2 \cdot day$,

ρ = density of particle, g/cm^3.

Combining Eqs. (5) and (6) and integrating, we have:

$$r = R\left(1 - \frac{t}{\alpha}\right), \tag{7}$$

where

R = particle radius, cm,

α = parameter, $R\rho/\ell$, day.

It is obvious that Eq. (7) and all subsequent equations are restricted to $t \leq \alpha$ since the particle is completely dissolved at $t = \alpha$. Dividing Eq. (5) by the initial mass of the particle gives the fractional loss of mass (or activity) with time:

$$\frac{dF}{dt} = -\frac{3}{\alpha}\left(\frac{r}{R}\right)^2. \tag{8}$$

On combining Eqs. (7) and (8) and integrating, the remaining fractional mass (or activity) becomes:

$$F = \left(1 - \frac{t}{\alpha}\right)^3. \tag{9}$$

The maximum fractional loss rate occurs at $t = 0$ when $r = R$ and is:

$$\left(\frac{dF}{dt}\right)_{max} = 3/\alpha. \tag{10}$$

If the waste particles were assumed to be cubes or right circular cylinders (diameter equal to height), the equations would be identical with those above, provided that the diameter of the spherical particles and the edge of the cube or height of the cylinder were equal. In this case, for these three geometries, the surface-to-volume ratio is the same, namely 6/D, where D is the diameter of the sphere, the edge of the cube, or the height of the right circular cylinder.

4.4 Consequences of Leaching

According to Eq. (5), the maximum rate of mobilization of radioactive material will occur on the first contact between water and the waste particles, regardless of the age of the waste or the mechanism of containment failure.

The radioactivity release rates shown in Table 11 are based on the leaching of a single row of waste canisters at a time. If several rows are exposed to ground water simultaneously, the given values should be multiplied by the number of rows.

Table 11. Maximum Leach Rates from One Row of Waste Canisters[a]

Time After Repository Closure (years)	Unleached Activity[b] (Ci/can)	Maximum Leach Rates (Ci/year)	
		Short Row, 98 Canisters	Long Row, 765 Canisters
10^3	520	16	130
3×10^3	290	10	77
10^4	190	6.5	51
3×10^4	98	3.3	26
10^5	59	2.0	16
3×10^5	42	1.4	11
10^6	20	0.7	5.3

[a] Waste in glass form; diameter of particles, 2 mm; leach rate, 10^{-7} g/cm^2 · day; density, 3.2 g/cm^3.

[b] Based on 75,000 canisters of high-level waste present in the repository and on total activities given in Table 8.

For a vertical flow through a fracture of 3.5 liters per second per kilometer of fracture, the rate of salt removal would be about 2 cm/year if we assume a total thickness of salt of 900 m. The distance between short rows is 6 m; the distance between rows in the other direction is 24 m. If the fracture is assumed to intersect a short row of canisters, a period of 600 years would be required for the dissolution front to migrate to the two adjacent rows. In the case of a fracture intersecting a long row, 2400 years would be required for the dissolution front to reach the two adjacent rows. If a dissolution front were moving downward, several rows of canisters could become exposed roughly at the same time. However, no leaching could take place in this case before an offset of at least 350 m had been produced on the fault, which would require at least a few hundred thousand years.

We assume that the waste is in the form of borosilicate glass or a similar material with $\ell = 10^{-7}$ $g/cm^2 \cdot$ day (a value that has been obtained for some glasses), $\rho = 3.2$ g/cc, and R = 1 mm; therefore, $\alpha = 3.2 \times 10^6$ days. It is conceivable that the waste will originally be in the form of 30-cm-diam, 240-cm-long glass cylinders. Devitrification of the waste will cause cracking and crumbling, but it seems reasonable to assume that the particles thus produced will be at least about 1 mm in radius. Using the above value of α, Eq. (8) gives the time for complete dissolution of a glass particle at about 9000 years. With the present dissolution model, the same time would be sufficient to achieve complete dissolution of a row of waste canisters.

The maximum rates of leaching of activity calculated with Eq. (9) for a short row of canisters (98 canisters) under the assumed conditions are shown in column 3 of Table 11 for waste aged 10^3 to 10^6 years. The leach rate from each long row, which contains 765 waste canisters, would be about eight times higher, as shown in column 4 of Table 11.

Obviously, the assumed waste leaching implies the simultaneous dissolution of salt. Therefore, the leachate would be contaminated by radionuclides and almost saturated with sodium chloride as well. This would seem to effectively eliminate the possibility that the contaminated water could be used for drinking or irrigation, at least not until significant dilution had drastically reduced the salt concentrations. However, in the following estimates of the potential consequences of waste leaching, the high salt content of the contaminated water is neglected.

We first consider the case of radioactive materials released into the Culebra Dolomite aquifer. A comparison of the maximum leach rates given in Table 11 with acceptable rates of activity release listed in Table 9 shows that, even for a low average annual flow of the Pecos River, dilution of the material leached from a single long row is sufficient for unrestricted use of water except when the waste is aged only 1000 years. However, when credit is taken for decay during the time required to reach the river and for sorption in the alluvial deposits, the activity of the 1000-year-old-waste would also be diluted to within the limits for unrestricted use of water. In the Culebra Dolomite aquifer, the concentrations would exceed the limits for unrestricted use of water, even if leaching were restricted to a single row of canisters. It is not possible to estimate the number of rows that could be exposed to leaching simultaneously with the upward flow implied by this discussion since the data show that flow along the fracture should be downward. Obviously, the flow rate calculated for a downward movement of water cannot be used if we assume that the direction of flow, for some reason, could be reversed.

If we hypothesize an upward flow that is one-tenth of the hypothetical downward flow through the fracture,* the times required to remove the 6 and 24 m of salt between rows would be 6000 and 24,000 years, respectively. Thus we can assume that not more than one long row would be exposed to leaching at any one time.

It is conceivable that water from the Culebra Dolomite aquifer could be brought to the surface and used either for drinking or for irrigation of hypothetical future crops. If we assume no reduction in the concentration of activity between the repository and the first water well and if we further assume that individuals use this water as their only source of drinking water, the dose they would receive through this exposure mechanism would be about 240 times higher than the dose limit for the population at large, or about 80 times higher than the dose limit for individual members of the public.

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*The reader can figure out for himself the reliability of estimates obtained by compounding hypotheses in this way.

If we assume that the water were used for farming and that a group of individuals lived by eating contaminated foodstuff exclusively, the TERMOD model[34] could be employed to assess the potential exposure.

The input must be expressed as a deposition. Therefore, we will assume that 50 cm of water will be used annually for irrigation and that all the activity contained in the water will be accumulated in the soil.

Table 12 shows the concentrations of radioactive material in the Culebra Dolomite aquifer and the relative deposition rates. Table 13 shows the doses received by people living exclusively on contaminated foods, due to the ingestion of the significant heavy nuclides only. The doses are given for the mixtures of heavy nuclides existing after 1000 and 100,000 years of decay since the calculations shown in Tables 5 and 6 could be used for these two cases. These are only partial doses since the fission products and some heavy nuclides have been neglected; however, the error is not expected to be significant and the calculated values are certainly within a factor of 2 of the total doses.

For the case of faulting through the repository and continuous displacement accompanied by removal of salt from the upthrown side of the fault, it is possible to envision that several rows of waste canisters could be brought into contact with ground water at the same time. As previously discussed, the first contact between waste and ground water as a result of this mechanism could not take place before a few hundred thousand years. Therefore, assuming contact between ground water and about 8000 canisters of 300,000-year-old waste (approximately ten long rows), we find that the maximum rate of release to the Culebra Dolomite aquifer could be 110 Ci/year, or about 800 times higher than the value shown in Table 9, which corresponds to the release rate that would result in a concentration of activity in the Culebra Dolomite aquifer equal to the RCG for the mixture of radionuclides existing in the waste at that time. Obviously, the envisioned mechanism of containment failure could result in significant contamination of ground water at some time in the remote future. The calculated doses for a hypothetical group of people using the water for farming would be proportionally high.

Table 12. Ground-Water Contamination[a] and Deposition of Radioactive Material on the Ground When Water Is Used for Irrigation[b]

Time After Mine Closure (years)	Radioactivity Entering Aquifer (Ci/year)	Concentration of Radioactivity in Aquifer ($\mu Ci/cm^3$)	Concentration of Heavy Nuclides in Aquifer ($\mu Ci/cm^3$)	Total Deposition ($\mu Ci/m^2$)	Deposition of Heavy Nuclides ($\mu Ci/m^2$)
10^3	130	1.2×10^{-3}	1.0×10^{-3}	600	500
10^4	51	4.6×10^{-4}	3.3×10^{-4}	230	165
10^5	16	1.5×10^{-5}	4.2×10^{-6}	7.5	2.1
10^6	5.3	4.8×10^{-6}	2.7×10^{-6}	2.4	1.3

[a]Assumes leaching of 765 canisters and flow in the Culebra of 130 liters per year per meter of width.

[b]Assumes an irrigation rate of 50 cm/year.

Table 13. Calculated Doses from Heavy Nuclides[a] When Farm Land Is Irrigated with Contaminated Ground Water

Dose	50-year Dose Commitment (rem) due to First Year of Exposure	
	After 1000 years of Decay	After 100,000 years of Decay
Total Body Dose from Exposure to Ground Surface	6.3	5.0×10^{-3}
Bone Dose from Inhalation of Resuspended Activity	8.0	4.0×10^{-2}
Organ Dose due to Ingestion via the Terrestrial Food Chain		
Total body	3.3×10	6.0×10
Bone	5.0×10^{2}	6.0×10^{2}
Liver	1.5×10^{2}	6.0×10
Kidneys	2.4×10^{2}	6.5×10
G.I. Tract	3.9×10	6.0×10

[a]Based on depositions shown in Table 12 and on nuclides listed in Tables 3 and 4.

It must be emphasized that these dose calculations are very conservative. It is likely that adsorption in the aquifer would restrict the migration of radioactive material; in addition, a group of people drinking only contaminated well water or eating only foods produced by the use of contaminated ground water is a most remote possibility. Of course, the most important consideration is that, if the assumed waste leaching were to take place, salt would be dissolved at the same time and the salt content would make the water unfit for human consumption or irrigation.

In the event of the permeable fracture zone across the repository, we have seen that the probable direction of water flow would be downward and that the Ellenburger would be the likely recipient of most of the contaminated water. The radiological consequences of the contamination of the deep aquifers would be minor. The ground-water velocity in the Ellenburger is not known; for the San Andres, the flow rate has been estimated at 0.5 cm/year or 5 km/million years.[47] Assuming the same water velocity in the Ellenburger, it is clear that any radioactive material entering the aquifer at the site would never reach the areas of Ellenburger outcrops in western and central Texas,[69] even considering that the fracture would increase the hydraulic gradient in the deep aquifers and so cause a somewhat increased water velocity. Hence, any radionuclides in the deep aquifers could be brought to the surface only by drilling and intentional pumping of the water.

The rate of activity release to the deep aquifer would be controlled by the flow rate through the salt; with the calculated flow of 3.5 liters per second per kilometer of fracture, as many as 8 long rows or 30 short rows of waste canisters could be exposed to leaching at the same time. Naturally the waste canisters in different rows would be at various stages of dissolution; thus the maximum amount of released activity would not be eight times the maximum leach rate from one long row but something less. In this case also, the salinity of the water emerging from the salt-bearing formations would preclude its use for drinking or irrigation, even if someone were to pursue the economically absurd action of drilling for water below the Castile.

The transfer of radionuclides from ground water to pools of hydrocarbons that might exist in the deep permeable formations seems very unlikely; nevertheless on the basis of available knowledge, it cannot be proved impossible. However, considering that the initial activity concentrations in ground water would be relatively low and that the boundary between water and hydrocarbon phases should represent a barrier to the transfer of radionuclides, any significant contamination of accumulations of hydrocarbons seems far-fetched.

5. CONCLUSIONS

The primary conclusion of this study is that a serious breach of containment of a waste repository buried in the bedded salt of the Delaware Basin in southeastern New Mexico, either by natural events or human action, is an extremely remote possibility that is a much smaller risk than many others acceptable to society and of such small magnitude to be beyond the ken of human experience. Whether the small risk described in this report should be accepted by society in exchange for the benefit to be derived by the peaceful uses of nuclear energy is not for the writers to decide. However, it is clear that the location of the waste in a deep repository in the Delaware Basin in southeastern New Mexico is a way to reduce the risk associated with the waste to an extremely low level. Furthermore, once the waste has been placed in such a configuration, only the most extreme of natural events have any potential for release of radioactivity from the disposal zone. In addition, a sealed repository would be sabotage proof without armed intervention and temporary occupation of the area. Even the surface burst of a 50-megaton nuclear weapon could not breach the containment.

The review of the geologic data has confirmed that the Delaware Basin is one of the most tectonically stable regions in the United States. There are no signs of tectonic activity whatsoever.

Exposure of the waste horizon to the action of ground water by a large fault with a vertical displacement of at least 350 m is highly improbable but cannot be proved impossible. However, in the event that New Mexico were to become affected by intense diastrophism, at least a few hundred thousand years would be required for an offset of 350 m to take place. A more sudden breach of containment could be caused by a large fault that cuts through the disposal zone and hydraulically connects the over- and underlying aquifers. Any water flow along the fracture zone would be downward into the deep aquifers. The geologic evidence indicates that such a fracture could eventually close by plastic flow of the salt beds. In the event that the deep aquifers became contaminated, it is extremely unlikely that activity could be brought to the surface except by drilling in or near the buffer zone since the normal flow velocities in these aquifers are on the order of a few kilometers per million years.

In view of the relative potentiometric heads, it is difficult to visualize circumstances that could cause an upward flow and contamination of the fresh water in the Culebra Dolomite aquifer. The only possibility for the release of activity to the Cülebra Dolomite aquifer would seem to be on the basis of the previously mentioned model that permits faulting and progressive displacement of the disposal horizon until waste is raised up and brought into contact with circulating ground water. The contamination of surface aquifers due to this mechanism of releasing radioactive material could be relatively serious, despite the very long time that would be necessary to produce such a displacement. Based on the tectonic activity of the Delaware Basin in the last 200 million years, the probability of faulting through the repository has been estimated at 4×10^{-11} per year; however, the probability that faulting would cause failure of waste containment is only a small but unknown fraction of this value.

The mechanism of containment failure with the most serious potential consequences seems to be the impact of a giant meteorite that produces a crater extending to the disposal horizon. The probability of such a catastrophic meteorite impact was estimated at 1.6×10^{-13} per year. The calculated exposure from the resulting global fallout would be on the same order of magnitude as that from the past nuclear bomb tests, provided ^{90}Sr had decayed for at least a few hundred years. The ejecta falling back into the nearby area would cause a serious and protracted contamination problem. A pathway analysis showed that individuals living exclusively on foodstuff produced in the contaminated area would eventually suffer serious, and perhaps fatal, somatic damage.

The evaluations and conclusions presented in this report are subject to uncertainty due to the scarcity of data on the behavior of thick salt formations if extensive faulting occurred and on the hydrologic properties of the various aquifers present in the area of the repository.

A problem that would deserve additional consideration involves determining whether extensive faulting in the Delaware Basin could lead to extensive salt dissolution through either one of the envisioned mechanisms. Some information on the actual amounts of ground water present at the site in the aquifers above the salt can be supplied by the boreholes currently being drilled. Data on the ion exchange capacity of the geologic materials in the aquifers could be obtained from the cores or by in-situ experiments. It is possible that valuable information on the hydrologic properties of the deep aquifers could be obtained by studying the logs of the many deep wells that have been drilled in the past few years in the Delaware Basin for oil and gas.

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APPENDIX: CALCULATION OF THE PROBABILITY OF A FAULT INTERSECTING A WASTE REPOSITORY

An estimation of the probability of a fault intersecting the repository was made based on a simple model. It was assumed that the fault, which could be represented by a line, occurs randomly within a given area and that the repository could be represented by a smaller circular area that is located at least the length of the fault line away from the boundary of the larger basin area. For such a restriction on fault length, the shape of the basin area is immaterial. If the repository is located closer than a line length from a boundary, the calculated probability would be conservative.

The probability of the end of a randomly occurring line lying within an incremental area $2\pi r dr$ is:

$$2\pi r \, dr/\pi R_o^2 ,$$

where R_o is the effective radius of the area of the basin, the domain of the calculation.

The probability of a line lying in the direction contained within an angle $d\theta$ is

$$d\theta/2\pi ,$$

and the probability of all lines lying within $d\theta$ is the product of the two:

$$dp = (r/\pi R_o^2) \, dr \, d\theta . \qquad (1)$$

The total probability of intersection with a circle of radius R_i (repository) is obtained by integrating Eq. (1) over appropriate limits. The integration is most easily performed in three parts, and the total probability is the sum of the parts. An obvious restriction is that $R_o \geq R_i + L$. In carrying out the procedure, it is convenient to think of one end of the line as painted red and that the red end lies within the incremental area.

We consider first all red lines lying within the circle. The probability of this occurring is obviously the ratio of the two areas, namely,

$$p_1 = (R_i/R_o)^2 , \tag{2}$$

a result that is also obtainable by integrating Eq. (1) from r = 0 to $r = R_i$ and over an angle 2π.

For the second part, we consider only those lines whose red end falls within an incremental area contained in

$$R_i \leqq r \leqq \sqrt{R_i^2 + L^2}$$

and lying within the $2\theta_1$ angle formed by a line of length L that is always tangent to the circle. Since the radius is normal to the tangent line, the angle is $2 \sin^{-1} (R_i/r)$ and

$$p_2 = \frac{2}{\pi R_i^2} \int_{R_i}^{\sqrt{R_i^2 + L^2}} r \, dr \int_0^{\sin^{-1}(R_i/r)} d\theta \tag{3}$$

Integration of Eq. (3) gives:

$$p_2 = \left(\frac{R_i}{R_o}\right)^2 \left[\frac{\alpha^2 + 1}{\pi\alpha^2} \sin^{-1} \left(\frac{\alpha}{\sqrt{1 + \alpha^2}}\right) + \frac{1}{\alpha\pi} - \frac{1}{2}\right] , \tag{4}$$

where

$\alpha = (R_i/L)$.

For the third part we consider the remaining lines that intersect the circle, namely, those whose red ends fall within an incremental area contained in

$$\sqrt{R_i^2 + L^2} \leqq r \leqq R_i + L .$$

In this case, the intersecting line is not tangent to the circle and the limiting angle is determined by the cosine law. Therefore,

$$\theta_1 = \cos^{-1}\left(\frac{L^2 + r^2 - R_i^2}{2rL}\right) \tag{5}$$

and

$$P_3 = \frac{2}{\pi R_o^2} \int_{\sqrt{R_i^2 + L^2}}^{R_i + L} r \, dr \int_{\theta}^{\theta_1} d\theta . \tag{6}$$

Integrating with respect to θ and letting $r = R_i y/\alpha$, we have:

$$P_3 = \frac{2R_i^2}{\pi R_o^2 \alpha^2} \int_{\sqrt{1 + \alpha^2}}^{(1 + \alpha)} y \cos^{-1} \frac{y^2 + 1 - \alpha^2}{2y} \, dy . \tag{7}$$

A closed-form analytical solution to Eq. (7) does not seem possible (except when $\alpha = 1$), but numerical evaluation is simple and straightforward.

The total probability of intersection, then, is:

$$p = p_1 + p_2 + p_3 \; . \tag{8}$$

Consideration of the behavior of Eq. (7) indicates little sensitivity to the inverse cosine function. Therefore, a reasonable approximation can be obtained using the mean value of the limits ($\bar{y}$) and writing Eq. (7) as:

$$p_3 = \frac{2R_i^2}{\pi R_o^2 \alpha^2} \cos^{-1}\left(\frac{\bar{y}^2 + 1 - \alpha^2}{2\bar{y}}\right) \int_{\sqrt{1+\alpha^2}}^{(1+\alpha)} y \, dy \; . \tag{9}$$

Integration of Eq. (9) gives:

$$p_3 \cong \frac{2R_i^2}{\pi R_o^2 \alpha} \cos^{-1}\left(\frac{\bar{y}^2 + 1 - \alpha^2}{2\bar{y}}\right) \tag{10}$$

Figure 5 shows Eq. (8) plotted with numerical integration used to obtain p_3. The error in total probability resulting from the use of Eq. (10) varies from +0.1% at $\alpha = 0.01$ rises to a maximum of about +2% in the range of $\alpha = 0.8$ and then falls off to +0.6% at $\alpha = 5$. Errors in the total probability for $\alpha < 0.01$ and $\alpha > 5$ will be even smaller because of the small contribution of p_3 to the total.

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