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TECHNICAL ASSESSMENT OF BEDROCK WASTE STORAGE AT THE SAVANNAH RIVER PLANT

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ABSTRACT

This study indicates that a cavern with an excavated volume of 130 million gallons could contain 80 million gallons of concentrated radioactive SRP wastes with minimal risks if the cavern is located in the impermeable Triassic Basin underlying the Savannah River site. The cavern could be placed so that it would lie wholly within the boundaries of the plantsite.

The document summarizes the general geological, hydrological, and chemical knowledge of the geological structures beneath the plantsite; develops evaluation guidelines; and utilizes mathematical models to conduct risk analyses. The risk models are developed from known soil and salt solution mechanics; from past, present, and future geological behavior of the onsite rock formations; and from known waste handling technology. The greatest risk is assessed to exist during transfer of the radioactive wastes to the cavern. When the cavern is filled and sealed, further population risks are assessed to be very low.

FOREWORD

The suggestion that the bedrock beneath the Savannah River Plant (SRP) might serve as a repository for radioactive waste was made as early as 1951. Beginning in 1961 and ending in 1971, a detailed bedrock exploratory program was conducted at the site. The program included exploratory wells into the bedrock, hydrologic studies of the bedrock, seismic surveys, magnetic and gravity surveys, and laboratory measurements of rock-waste chemistry.

The document was written during 1971 and 1972 to summarize knowledge collected to that date and to use this information in an assessment of the safety and feasibility of onsite bedrock storage for the radioactive waste generated at SRP. Subsequent to the initiation of this assessment study in 1971, funding for the bedrock study was terminated (in mid-1972). The assessment was completed, but has remained in an unpublished draft form until the present (1976). It is being published now in the hope that the approaches and methods used in it will be of assistance to others currently working on the problems of waste storage. The data remain as of 1971.

The document consists of a series of parametric studies and evaluations that delineate the important factors that could affect waste behavior in bedrock. Preliminary system performance criteria were developed to critically evaluate conceptual system designs. The criteria chosen were deliberately conservative; however, this degree of conservatism may not be required as an absolute measure of system performance. Most helpful to the study were documents produced in response to guidance provided by the National Academy of Science through its Panel on Bedrock Disposal as a result of their two examinations of the bedrock storage concept.

The reader should realize that the many experimentally obtained parameters used in the migration rate equations for waste components were obtained from a very small sampling of the total bedrock volume. The values used in the prediction equations are believed to provide only an estimate of the maximum risk. These facts suggest this document should not be used as the sole judge of the suitability of the bedrock concept, rather it should be viewed as only a first step toward a satisfactory solution of the radioactive waste storage problem.

CONTENTS

INTRODUCTION

This report is an assessment of the safety and feasibility of ultimate storage of radioactive wastes produced at the Savannah River Plant (SRP) in horizontal tunnels excavated in the bedrock beneath the plant site. After placing the radioactive wastes in the tunnels and monitoring the system for an interim period, all access shafts would then be permanently sealed.

As a basis for this study the quantity of waste to be stored was assumed to be 80,000,000 gallons of reconstituted waste containing 17,000 curies of ^{239}Pu, 200,000,000 curies each of ^{90}Sr and ^{137}Cs, and other associated salts and radioisotopes.

The approach to the assessment consisted of three main efforts. First, the system, including the waste to be stored, the bedrock, and the region outside of the rock, was defined as well as possible based on existing knowledge. To do this, extensive use was made of documents prepared during the bedrock program. Second, an interim set of evaluation guidelines was developed to provide a quantitative measure of the desired system performance in terms of allowable concentrations and quantities of constituents released from the system. Third, mathematical models of the system and the evaluation guidelines were utilized to determine the feasibility and safety of the bedrock concept.

The third effort included:

1. A study to define the conceptual arrangement of a bedrock system (cavern volume, cavern arrangement, alteration of the waste before storage, etc.).

2. The development of mathematical models to predict the performance of a conceptual bedrock system, and the ability of the system to meet the evaluation guidelines for the expected operating conditions.

3. Application of the models and other appropriate calculations to perform a preliminary safety analysis of the system, including estimates of the risks involved for normal operation, abnormal operation, and accident conditions during the cavern filling period and after the final shaft sealing.

4. A consideration of residual risks associated with the concept assuming that the system performed as expected and none of the identified accidents occurred.

This assessment produced a number of conclusions concerning the conceptual system arrangement, cavern location, the potential value of bedrock storage, and its limitations. In addition to providing an assessment of the bedrock storage concept, the study should be useful as a basis for comparison when the costs, benefits, and risks of alternative ultimate storage concepts are considered.

The development of evaluation guidelines brought out a number of areas that appear to require additional consideration. An attempt was made to identify these areas, many of them involving basic philosophical approaches and judgment. For this assessment, emphasis was given to minimizing the uptake of radionuclides by the population as a whole over many generations.

The report consists of a number of sections. It is recommended that the reader with limited time read the Summary section only. If more time is available, Chapter II, *Evaluation Guidelines*, is an important section that presents the basis for evaluating the safety of the concept. The brief Introduction and Summary at the beginning of each chapter and section provide condensed but detailed synopses.

SUMMARY

Scope

The important aspects of this study are summarized for the following areas:

- Amounts and types of waste to be stored (Chapter I-1).
- Description of the pertinent geologic and hydrologic features of the site (Chapter I-2).
- Evaluation of guidelines used to assess the feasibility of the bedrock concept (Chapter II).
- Factors influencing the behavior of wastes placed in bedrock and the required conceptual system, including the necessary modifications to ensure waste retention in the cavern (Chapter III).
- Preliminary safety analysis including residual risks of the bedrock concept (Chapter V).
- Conclusions of the study (Chapter VI).
- Suggestions for further work to improve the level of information on the concept (Chapter VII).

SRP Liquid Wastes

The SRP liquid wastes are presently stored in large underground tanks, and although the bulk of the waste consists of stable chemical constituents, considerable quantities of radionuclides are present. In addition to the hazardous radionuclides, such as ^{90}Sr, ^{137}Cs, and ^{239}Pu, stable toxic constituents, such as nitrate, nitrite, and mercury, are also present.

The wastes, as presently constituted, consist of two phases, sludge and supernate. The sludge comprises approximately 5% of the volume. It is predominately ferric hydroxide and manganese dioxide, and presently contains most of the ^{90}Sr and ^{239}Pu. The supernate represents the bulk of the volume and mass. It is a solution containing large quantities of soluble salts (the largest single component is ~100,000 tons of sodium nitrate) and most of the ^{137}Cs.

As the radioactive constituents decay, heat and gases are produced from the interaction of the radiation with the surrounding salt solution. The radionuclide composition of the waste changes with time. Initially, the major radionuclides of interest are ^{90}Sr and ^{137}Cs; then after about 1000 years, ^{239}Pu becomes the predominant radionuclide. Finally, ^{135}Cs and ^{129}I, requiring millions of years for near-complete decay, predominate beyond 150,000 years.

Site Description

The bedrock beneath the plant site was investigated as a possible location for the wastes. Two kinds of bedrock, metamorphic (crystalline) and sedimentary (Triassic), occur beneath the plant site. The latter occurs beneath the southeastern one-third of the plant site, as part of a large (approximately 5 miles wide, 30 miles long, and one mile deep) Triassic basin. Both the crystalline and Triassic rocks are found approximately 1000 feet below the ground surface. Unconsolidated sand, silt, and clay comprise the material between bedrock and the land surface.

The crystalline and Triassic systems differ appreciably. The crystalline system is a fractured medium, whereas the Triassic rock is a relatively homogeneous porous medium.

Directly overlying the bedrock is the Tuscaloosa Formation, a very prolific water supply. The regional flow of water in the crystalline rock system and the Tuscaloosa aquifer appears to be arcuate in nature as seen in Figures I.3 and I.4. Flow patterns and gradients in Triassic rock are undefined at present.

Available data suggest water velocities, with an assumed gradient of 3 ft_{H_2O}/mile, are likely to be small, e.g., ten feet per million years in Triassic rock. The data suggest water velocities in crystalline rock may range widely (one to thousands of feet per thousand years) depending upon the condition of the intersected rock. The velocity assumed to be most likely encountered in crystalline rock and hence used for evaluation purposes of the concept is 1000 feet per 1000 years. The postulated outcrop area from the underground flow is the Savannah River, approximately 35,000 feet from the crystalline cavern location. Because the Triassic rock will behave as a porous medium, ion exchange will reduce the effective flow velocity in Triassic rock of most constituents of the waste. However, the flow pattern in fractured crystalline rock precludes significant effects of ion exchange on flow velocities of waste constituents due to the very limited exposed surface area of the rock.

Both man-made and natural effects that could potentially occur at the site in the future must be considered in evaluating the bedrock storage concept. The man-made categories include local pumping, drilling, mining, and waste disposal into either the bedrock or the Tuscaloosa formations. None of these possible penetrations are considered likely except for pumping from the Tuscaloosa aquifer. This practice occurs now and will likely increase in the future. Natural occurrences that might influence the safety of the concept are earthquakes and floods. Earthquakes have occurred within 100 miles of the site during the past 300 years, and their effects must be considered in any safety analysis of the system. Floods would not affect the bedrock system.

Evaluation Guidelines

Quantitative guidelines were developed for this study to evaluate the operating parameters of a bedrock waste storage system.

Throughout this study, drinking water was assumed to be the critical pathway to man, and no recycling of the nuclides was assumed.

The guidelines were based on two general criteria. The first general criterion was that there should be at most a very small deleterious effect on a single individual by any toxic constituents eventually released to the environment. To meet the first general criterion the following guideline was developed:

Guideline No. 1

> The sum of the individual percentages of maximum permissible concentration (MPC_w) in drinking water for the toxic constituents from the waste which may migrate into public zone water should not exceed 1%.

This guideline is a necessary condition, but is not sufficient since it could be met by simple dilution of the waste by water. The stable toxic constituents are included in this guideline.

The second general criterion adopted for this study was that there should be an as-low-as practical effect on the population as a whole over extended time periods covering many generations. The second criterion implies a limit to the total quantity of any radionuclide that can be released to the environment. The following additional assumptions were made for this study to develop a guideline based on the second criterion. Both assumptions are conservative.

- The biomedical cost to society, i.e., the increased health care costs and reduced productivity of both the exposed population and their offspring per man-rem of radiation exposure to the population is $1,000.

- The biomedical cost to society i. e., the increased health care costs and reduced productivity of both the exposed population and their offspring per man-rem of radiation exposure to the population is $1,000.

Based on these assumptions and preliminary evaluation of costs-benefits and risks the second guideline is:

Guideline No. 2

> No significant quantities of the ^{90}Sr (<<1 Ci), ^{137}Cs (<<1 Ci), or ^{239}Pu (20 Ci) in the waste should be released to the environment. This restriction implies that the ^{239}Pu must remain within the bedrock for at least 250,000 years (10 half-lives).

It should be noted that the stable toxic constituents were not included in the second guideline since there is presently insufficient information to evaluate their effects in small concentrations on the population as a whole over extended time periods. This analysis also indicated the need to investigate further the possibility of alternative pathways or to recycle the extremely long-lived radionuclides such as ^{135}Cs and ^{129}I.

Conceptual Bedrock Waste Storage System

Evaluation of the performance and safety of a bedrock waste storage system required that the general features controlling the system behavior be defined. These features include the condition of the wastes to be stored, and the size and arrangement of the caverns. The following factors were considered in establishing a conceptual bedrock waste storage system in either crystalline or Triassic sedimentary rock:

- General Facilities Arrangement
- Geology and Hydrology
- Rock Mechanics
- Waste-Rock Chemistry
- Cavern Pressurization from Radiolytic Gas
- Density Gradients and Waste Migration
- Effects of Heat Generation
- Shaft Sealing Requirements

Consideration of these factors permitted a number of observations to be made. The following paragraphs summarize these observations.

The relatively higher permeability and lower porosity of the crystalline rock, coupled with its more inhomogeneous nature, makes the crystalline system sensitive to the radiolytic gas drive as well as to the gravitational drive on the liquid waste phase, and requires that the waste be altered significantly before it is charged to a crystalline cavern. Such an alteration does not appear to be required for a Triassic cavern with the properties assumed for this analysis.

The consequences of gas evolution are closely coupled with the inleakage rate to the cavern. Initial water inleakage rates for crystalline caverns are estimated to be as high as 30 gpm, compared with less than 1 gpm for a Triassic cavern, assuming no credit for engineered reductions (grouting, etc.) of the permeability of the rock surrounding the caverns. Inasmuch as water inleakage rates are assumed to be uncontrollable, the most practical approach for reducing the radiolytic gas drive on the crystalline system is adsorption of the ^{90}Sr and ^{137}Cs on inert materials. If gassing in the crystalline system is reduced to 1 or 2% of that projected with unmodified waste, a 100 million gallon cavern will suffice (80 million gallons for waste, 20 million gallons for water inleakage and radiolytic gas formation).

Alteration of the waste for a Triassic cavern at the expected less than 1 gpm inleakage rate does not appear to be necessary to control the gas drive; rather a slightly larger cavern appears to be the simplest solution. A Triassic cavern located in rock equivalent to that found near the center of the Triassic basin would require approximately a volume of 130 million gallons: 80 million gallons for waste, 40 million gallons for water inleakage and radiolytic gas formation, and 10 million gallons for cavern volume reduction due to long-term creep of the rock.

The Triassic conglomerate rock at the edge of the basin does not appear to be acceptable due to excessive reduction of the cavern volume from long-term creep of the rock.

The driving force present due to the waste solution being more dense than the rock water far exceeds any of the natural gradients in the crystalline system. This density difference creates a potential for the waste to move rapidly into zones of higher permeability outside of the region of tighter rock in which the cavern would be located. Migration of the dense liquid waste supernate phase from a crystalline cavern would be much more rapid and extensive than from a Triassic cavern due to the higher permeability and lower porosity expected for the crystalline rock. It is estimated that at the end of about 50 years, the dense waste phase would begin to flow down and laterally out from a crystalline cavern, travelling distances of as much as 10,000 feet in 1000 years.

Removal of the majority of toxic radionuclides from this dense supernate waste phase (such as by sorption on zeolite exchange, etc.) and storage in separate caverns would prevent activity from being carried along with the denser waste solution. This alteration is consistent with the requirements for eliminating the gas drive within the crystalline rock system.

Downward migration of the dense liquid waste phase from a Triassic cavern does not appear to represent a significant problem, although this effect would appear to control waste movement from a Triassic cavern. Water would be expected to flow into a Triassic cavern for about 1000 years before the system would approach hydrostatic equilibrium and waste would begin to flow down through the relatively homogeneous Triassic rock. For a Triassic cavern located 2000 feet above the underlying crystalline rock, more than an estimated 10,000,000 years would be required before the supernate begins to enter the crystalline rock.

Other considerations that influence the safety of the concept include thermal effects and shaft sealing. Thermal effects should be considered in the final detailed design and arrangement of the caverns, but it appears that temperatures can be kept to an acceptable level by proper distribution of the ^{90}Sr and ^{137}Cs along the caverns, and by proper cavern size and arrangement. Shaft sealing should be such that there will be no significant path for waste migration. Further attention to this aspect is necessary to design the system; however, a suitable seal is feasible. As a consequence of the relative importance of certain factors influencing waste migration in the two rock systems, it became apparent that the waste in either a crystalline or Triassic cavern can be modified in order to avoid potential difficulties from radiolytic gassing, waste-rock interactions, density gradients, and heat generation. Caverns in these formations will not be difficult to seal, nor are they likely to have construction restrictions from a mechanical viewpoint. These evaluations indicated that the most likely conceptual systems for the crystalline and Triassic caverns are as follows:

Crystalline:

- Waste altered sufficiently to eliminate gassing and gravitational drive.
- Total cavern volume of approximately 100 million gallons (assumes 80 million gallons waste after alteration).
- 50 years to reach hydrostatic equilibrium.

Triassic:

- No alteration of waste.
- Total cavern volume of approximately 130 million gallons.
- 1000 years to reach hydrostatic equilibrium.

Mathematical Models of Bedrock Performance

To expand the analysis, mathematical models were derived for predicting the concentration and quantity of various waste constituents as they leave the bedrock (Table 1). The models were in terms of the chemical characteristics of the waste and the chemistry and hydrology of the bedrock in which the cavern would be located. Parameters included in these models were:

- Waste form.
- Travel time required for non-adsorbed waste to leave the rock along the principal flow path.
- Adsorption coefficients for the radioisotopes on the rock.
- Time to reach hydrostatic equilibrium.
- Volumetric flow rate of waste from the cavern.
- Solubility of isotopes in liquid waste phase.
- Dispersion.

The results obtained using these mathematical models show that, in a crystalline cavern, if ^{135}Cs and ^{239}Pu are assumed to be completely in solution, releases of these isotopes to the environment would exceed the guidelines used in this analysis (Table 1). Modifications of the waste, in addition to that required to eliminate gassing, may be necessary to ensure retention of ^{135}Cs and ^{239}Pu in a stable solid phase for a crystalline cavern.

The models also indicate that waste, in unaltered form, can be placed in the Triassic cavern, with all radionuclides from the most likely flow path and conditions reaching the biosphere at concentrations well below 1% of the maximum permissible concentrations (Table 1). Less likely flow paths that could release larger concentrations of radioactivity are discussed further in the text. All flow path configurations in either rock formation result in nitrate-nitrite concentrations in excess of 1% of MPC reaching the biosphere; however, for the Triassic cavern the nitrate-nitrite concentration is still less than 10% of MPC.

TABLE 1

Predicted Concentrations of Waste Components Leaving the Rock

Component	Concentrations[a] in Terms of MPC	
	Crystalline	Triassic
^{90}Sr	<<0.01	<<0.01
^{137}Cs	<<0.01	<<0.01
^{135}Cs	100	<<0.01
^{239}Pu	2000	<<0.01
$-NO_3^-$, $-NO_2^-$	300	0.08

a. The estimates were derived using mathematical models of bedrock performance and it was arbitrarily assumed that all constituents were in the liquid phase.

Preliminary Safety Analysis

The preliminary safety analysis utilized the information on the hydrology, geology, waste forms, conceptual design, and mathematical models to produce an assessment of the risks of bedrock storage under normal, abnormal, and accident conditions for the cavern concept. The conditions, consequences, and probabilities are summarized for two time periods: the cavern filling period (Table 2) and the period following sealing of the cavern (Table 3).

Analysis of possible conditions during the cavern filling period identified a number of potential areas where personnel radiation exposure could occur. Routine removal and transfer operations employing currently accepted operating procedures are estimated to result in approximately 200 man-rem of exposure during the time required to transfer the waste to the cavern (approximately 3 to 4 years). Additional exposure from unanticipated problems and decontamination of the tanks would be expected to increase the total dose to approximately 1000 man-rem.

The potential for a serious accident would exist during the cavern filling period unless appropriate shaft design and/or waste forms are employed. A major catastrophic accident, such as an earthquake of unanticipated intensity or an explosion, could destroy both the shaft in the Tuscaloosa aquifer and the additional engineering safeguards (possibly including concrete bulkheads, separating the base of the shaft from the caverns containing the waste). If such an event occurred after unaltered waste had been added to the cavern but before any of the shaft had been sealed, sealing the shaft would be required to prevent the liquid wastes from migrating up the open shaft and into the Tuscaloosa aquifer. The occurrence of such a postulated accident would be readily detectable and appropriate measures could be taken to mitigate the consequences.

An additional postulated cavern filling accident is a spill of the supernate or sludge during transfer from the waste tanks to the cavern. The consequences of these spills are small and adequate design should eliminate such occurrences.

Normal operation in the period following cavern sealing is estimated to result in a dose of about 240 man-rem. This is assuming that all of the ^{129}I is released (but all of the ^{90}Sr, ^{137}Cs, ^{135}Cs, and ^{239}Pu is retained) and a small percentage 0.016% of the ^{129}I is ingested through the drinking water pathway. This uptake would occur over a period of thousands of years.

After the cavern is sealed, the accident with the largest potential effect is the reduction in head in the Tuscaloosa aquifer from the removal of large amounts of water for industrial, domestic, and agricultural needs. This reduction in head increases the gradient between the cavern and the Tuscaloosa aquifer forcing waste toward the aquifer. The consequences of this effect are a function of the properties of the rock. Adverse consequences could occur with a cavern in crystalline rock in the event significant reductions in the Tuscaloosa head occurred. Similar reductions in head above a Triassic cavern appear to have no adverse effect.

TABLE 2

Potential Consequences of Bedrock Storage Situations during Cavern Filling Period

Situations	Consequences	Probability
Expected Occupational Exposures	ca. 1,000 man-rem	ca. 1
Incidents		
1. Simultaneous destruction of a portion of the shaft in the Tuscaloosa aquifer and the engineered safeguards separating the base of shaft from the cavern being filled.	Loss of use of Tuscaloosa aquifer at present plant site for several centuries if shaft in rock cannot be sealed or all activity retrieved. Minimum potential biomedical consequences assuming Tuscaloosa aquifer at plant site used for drinking water 100 years after accident is 20,000 man-rem (negligible thermal convection in shaft, 99.9% of activity in solid phase at equilibrium). Maximum potential consequences at plant site after accident (assuming 25% of all activity in waste flows into Tuscaloosa aquifer due to thermal convection in open shaft and aquifer is used for drinking water 100 years after accident) is ca. 5×10^{8} man-rem.	ca. 10^{-4} [a]
2. Sludge Spill	20 man-rem to a single individual drinking water (1.2 liters) directly from Savannah River as activity passes by.	Less than 0.2[b]
3. Supernate Spill	0.05 man-rem to a single individual drinking water directly from Savannah River as activity passes by.	Less than 0.2[b]

a. Assumes one earthquake of intensity VIII every 300 years covering an area equivalent to that of Charleston earthquake of 1886, but occurring randomly in the area designated 2 and 3 in vicinity of South Carolina in Figure I-13, Chapter I. Assumes three years to charge caverns. Also assumes engineered safeguards separating the base of the shaft from the cavern being filled adds a safety factor of 10.

b. Based on ca. 15 year operation of existing waste facilities without a spill of this magnitude. Assumes 3 year operation.

TABLE 3

Potential Consequences of Bedrock Storage Situations After Cavern is Sealed

Situation	Crystalline		Triassic	
	Consequences, man-rem	Probability	Consequences, man-rem	Probability
Normal and Abnormal Operating Conditions	ca. 240	ca. 1	ca. 240	ca. 1
Incidents				
1. Extremely large quantities of water removed from Tuscaloosa aquifer at present plant site	5,500,000 (Maximum)	*a*	760 (Maximum)	*a*
2. Unexpectedly high rate migration	ca. 160,000	ca. 0.1[b]	<1	$<10^{-1}$[c]
3. Earthquake occurring 100 years after sealing and resulting in ca. 1 mm fracture connecting liquid waste phase to Tuscaloosa aquifer	2,700,000 (All activity in liquid)	$<<10^{-4}$[d]	2,700,000 (All activity in liquid)	$<<10^{-4}$[d]
4. Explosion in cavern	<1	ca. 10^{-3}[e]	<1	ca. 10^{-3}[e]

a. Although the probability of removing all water from the Tuscaloosa aquifer is very low, the probability of drawing down the water level to some extent is relatively high.

b. Based on approximate fraction of rock that is highly fractured.

c. Assumed to be less probable than for crystalline due to greater homogeneity.

d. The probability of an earthquake causing such a fracture in the rock is assumed to be significantly less than the probability of an earthquake that could destroy the shaft in the Tuscaloosa aquifer and the engineered safeguards to the cavern (Footnote *a*, Table 1).

e. Assumes explosion set off by minor spalling of rocks in cavern during earthquake of VIII intensity.

Other potential accidents following sealing of the cavern include unexpectedly high rates of migration and rupture of the cavern due to an earthquake. For the accident conditions it is assumed that the waste takes one of the less likely flow paths (Chapter III) rather than the expected flow path considered under normal operating conditions. These alternative paths are not considered to be very probable, but their existence cannot be ruled out on the basis of existing data. These flow paths result in radioactivity rapidly (less than 100 years) reaching the biosphere in the case of the crystalline rock. Even if the waste is assumed to be sorbed on a stable solid phase so that at equilibrium 99.9% of any radionuclide is in the solid phase and 0.1% is in the liquid, there is a potential consequence of 160,000 man-rem for such rapid waste migration from a crystalline cavern.

In the case of Triassic rock the activity would still require very long time periods (about 10^5 years) before reaching the biosphere along such paths. The expected dose due to release of activity following one of the less likely flow paths from a Triassic cavern is estimated to be only one man-rem.

Earthquakes in the general area of the cavern are not expected to influence the integrity of the system. Only if a fracture resulting from the formation of a new fault through the cavern should occur, would a readily accessible path to the biosphere result. The consequences are a function of the time of occurrence and the size of the fracture. If a fracture approximately 1 mm in width or larger should develop soon after the cavern was filled, the consequences would be of a similar magnitude to those from shaft rupture during filling. The probability of such a fracture in the bedrock is considered to be much lower than the probability of an earthquake shearing both the shaft in the Tuscaloosa Formation during cavern filling and the additional safeguards, possibly including concrete bulkheads, separating the base of the shaft from the caverns containing the waste (i.e., $<10^{-4}$/yr).

Analysis of postulated explosions in the cavern after sealing indicates that such accidents would have minor consequences.

Residual Risks

Residual risks are defined for this analysis as those risks that remain even if the bedrock system performs as expected, and if the potential accidents identified in the safety analysis do not occur. Releases from the cavern can be divided into two general categories: anticipated and unanticipated. An anticipated occurrence is the release of all of the stable constituents such as nitrate, nitrite, and mercury along with long-lived radionuclides (such as ^{129}I) with half-lives measured on a geologic time scale. These releases are considered acceptable if the release produces dilute concentrations over a long period of time.

Unanticipated releases were examined from two directions: accidental entry by man and unanticipated natural phenomena. In the bedrock concept, no permanent provision is delineated that would guarantee the prevention of man from drilling into the caverns at some future time and inadvertently releasing the contents of the cavern; nor is there any guarantee that some totally unanticipated large-scale natural phenomena might not occur that would release the activity in the cavern. Both of these unanticipated releases are inherent risks of the bedrock activity and are residual risks of the concept.

Principal Conclusions

The principal conclusions of this assessment are given below:

1. In order to avoid unacceptable uptake of radionuclides by man through drinking water, the waste should be excluded from the biosphere at least until most of the ^{239}Pu has decayed (ca. 250,000 years). It may be acceptable to release all of the ^{135}Cs and ^{129}I if they are greatly diluted.

2. The properties of the crystalline and Triassic rock systems beneath SRP differ significantly and affect their potential waste storage ability. Based on present data and the evaluation guidelines developed for this study, Triassic rock shows much more promise as a potential long-term waste storage location for unaltered Savannah River Plant waste. Crystalline rock would probably require significant modification of the waste for compliance with the guidelines assumed for this study.

3. Any bedrock waste storage system theoretically will release, after an extremely long time and in greatly diluted concentrations, all of the stable constituents (such as nitrate and mercury) and all of the extremely long-lived radionuclides (such as ^{129}I). The consequences of this release appear to be acceptable.

4. The postulated accident having the greatest risk and the greatest potential consequences is the destruction of both the shaft connecting the cavern to the ground surface through the Tuscaloosa aquifer and the engineered safeguards separating the base of the shaft from the caverns containing the waste by an earthquake (or other means) during filling of the caverns with waste. This accident should be easily preventable through proper engineering design of the shaft and/or waste forms, but it could result in a loss of the use of the Tuscaloosa aquifer beneath the existing SRP site for centuries. The calculations indicate that any released activity from the accident is unlikely to spread beyond the existing plant site.

5. Risks after sealing of the shaft are generally lower than the risks during filling of the cavern.

Recommendations for Further Work

The study indicated a number of areas where further work could be expended profitably. Listed below are those areas of major importance.

1. There is a definite need for comparing the estimated costs and risks of bedrock storage with other potential alternative methods for long-term storage of SRP wastes.

2. The preliminary safety analysis indicated the potentially hazardous accidents that can occur. The potential consequences of the postulated accident involving destruction of the shaft in the Tuscaloosa aquifer during filling requires the development of engineered approaches for reducing the probability and consequences of such an accident to acceptable levels.

3. If completion of Items 1 and 2 continues to indicate that further efforts along a bedrock program are warranted, additional information on the overall geology and hydrology of the Triassic basin is necessary to provide appropriate ranges of hydrologic parameters for use in predictive equations.

4. An additional technical reassessment of the bedrock concept should be conducted following completion of the preceding items to determine if bedrock storage is the most suitable technique for ultimate storage of SRP wastes.

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CHAPTER 1. GENERAL INFORMATION

I-1. CHEMICAL AND RADIONUCLIDE COMPOSITION OF STORED WASTE

INTRODUCTION

High level liquid wastes from all sources on the plant site are currently stored in the SRP waste tanks. As a consequence of the variety of waste sources, the waste tanks are not completely homogeneous in content, but all correspond generally to the description below. This section summarizes our knowledge of the contents of the tanks and illustrates possible modes of altering the waste to reduce the amount of activity in the mobile supernate before placement in bedrock.

SUMMARY

The contents of the tanks can be divided into two fractions: a relatively insoluble fraction that is locally referred to as sludge and the remainder of the contents, called supernate. The sludge layer consists principally of two stable compounds, ferric hydroxide and manganese dioxide, and the radioisotopes, ^{90}Sr, ^{239}Pu, and U. The biological hazard of the sludge comprises 96% of the total hazard of the waste but only 5% of the waste volume. The supernate consists of water soluble compounds and would be the mobile fraction of waste following emplacement in the cavern. The principal stable compounds in the supernate are $NaNO_3$ (125,000 tons), $NaNO_2$ (53,000 tons), NaOH (39,000 tons), Na_2SO_4 (3,900 tons), $NaAlO_2$ (17,000 tons), and Na_2CO_3 (2,700 tons). The principal radionuclide is ^{137}Cs although trace quantities of other radionuclides are present. The form and location of iodine, mercury (80 tons), and various trace metals are not completely known for each tank.

DISCUSSION

Up-to-date and detailed information on the relative amounts of sludge and supernate in each of the existing high level waste tanks is still being obtained. Experimental evidence indicates approximately five percent of the waste volume (before evaporation of the supernate to reduce the tank volume necessary for storage) is sludge. The sludge is primarily $Fe(OH)_3$ and MnO_2. Stable element analyses of the supernate indicate the bulk of the stable salts are $NaNO_3$ (Table I.1), with progressively smaller quantities of $NaNO_2$, NaOH, Na_2AlO_2, Na_2SO_4, and Na_2CO_3 in the supernate.

TABLE I.1. Synthetic Plant Waste

Compound	Waste Composition, mol/liter		
	F Purex	H Purex	H ^{235}U-Al
$NaNO_3$	3.4	5.4	6.2
$NaNO_2$	3.0	1.6	-
NaOH	1.9	4.0	1.7
$NaAlO_2$	0.13	1.1	1.7
Na_2SO_4	0.14	0.024	0.025
Na_2CO_3	0.07	0.08	-
Na_3PO_4	0.002	0.02	-
NaCl	0.003	0.002	-
$Fe(NO_3)_2$	0.01	0.009	0.045
$Hg(NO_3)_2$	-	0.008	0.05

The physical properties of simulated waste have been studied in detail. The viscosity and other properties are generally a function of temperature and concentration. The reader is referred to the original articles for specific details.[1,2] The specific gravity of the supernate is approximately 1.2 and that of the sludge is 1.5 - 1.8 g/cm^3.

Detailed information on the radioactivity in the supernate and the sludge for three tanks is available. ^{137}Cs, ^{60}Co, ^{90}Sr, ^{239}Pu, ^{99}Tc, and ^{106}Ru have been detected in the supernate. Analyses of the sludge indicate the presence of ^{137}Cs, ^{125}Sb, ^{60}Co, ^{154}Eu, ^{144}Ce, ^{106}Ru, ^{65}Zn, ^{90}Sr, ^{147}Pm, ^{239}Pu, ^{241}Am, ^{237}Np, and ^{238}Pu.[1] The ratios of gross beta, gross alpha, and gross gamma activities between the sludge and the supernate indicate that the lowest activity in disintegrations/minute per milliliter (d/m/ml) is the alpha activity in the supernate and the highest activity/unit volume is the gross beta activity in the sludge (Table I.2). The alpha and beta activity tend to be in the sludge while the gamma activity is uniformly distributed on a unit volume basis.

The radionuclide make-up of the waste will change with time through decay. The projected quantities of the radionuclides of interest are summarized in Table I.3. Initially, ^{90}Sr and ^{137}Cs are the predominant radionuclides. After 1000 years of storage, ^{99}Tc and ^{239}Pu are the major constituents and the total number of curies has been reduced from 4.1×10^8 to 6.0×10^4.

TABLE I.2. Relative Activities of Sludge and Supernate

	Relative Activity[a]		
	Gross Beta	Gross Gamma	Gross Alpha
Sludge	1.8×10^6	14.8×10^3	5.5×10^3
Supernate	4.1×10^3	1.8×10^3	1

a. Gross alpha activity in the supernate is the denominator for calculating these ratios.

TABLE I.3. The Quantities and Half-Lives of the Principal Radionuclides of Interest

Isotope	$T^{1/2}$, yr	Total Quantities, Ci		
		Initial	1000 Years	150,000 Years
^{90}Sr	28.9	2×10^8	7×10^{-3}	0
^{137}Cs	30.2	2×10^8	2×10^{-2}	0
^{151}Sm	93.	4.8×10^6	2.8×10^3	0
^{238}Pu	87.4	1.7×10^5	6.1×10^1	0
^{244}Cm	18.1	1.7×10^5	4×10^{-12}	0
^{99}Tc	2.13×10^5	3×10^4	3×10^4	1.8×10^4
^{239}Pu	24,390	1.7×10^4	1.6×10^4	2×10^2
^{93}Zr	9.5×10^5	6.7×10^3	6.7×10^3	6×10^3
^{135}Cs	2.3×10^6	2.8×10^3	2.8×10^3	2.7×10^3
^{126}Sn	10^5	1×10^3	1×10^3	3.5×10^2
^{79}Se	6.5×10^4	5.4×10^2	5.3×10^2	1.1×10^2
^{129}I	1.6×10^7	6.2×10^1	6.2×10^1	6.2×10^1
^{107}Pd	7×10^6	2.6×10^1	2.6×10^1	2.6×10^1
Totals:		4.1×10^8	6.0×10^4	2.7×10^4

The location and chemical form of a number of important constituents of the waste are not known at the present time. The location of iodine in the tanks is undocumented. Iodine likely resides in the sludge, precipitated with MnO_2 inasmuch as this precipitation has been shown to be successful in reducing iodine releases during dissolving of SRP fuel tubes in the Separations Areas. Mercury is used in several processes in the Separations Areas and subsequently placed in the waste tanks. A total of 80 tons of mercury has been placed in the tanks to date as a result of these processes and its location and chemical form remain to be determined.

I-2. GEOLOGY AND HYDROLOGY OF THE PLANT SITE

INTRODUCTION

In any evaluation of the suitability of an underground site for the ultimate or engineered storage of radioactive waste, the geology and hydrology of the area is of specific interest and concern. A suitable site for waste disposal must have (1) geological material of adequate strength to support an underground cavern, (2) rock with sufficiently low permeability that waste migration is very slow, and (3) sufficient rock of the proper qualities between the waste and the biosphere that an insignificant quantity of radioactivity reaches the biosphere. In order to evaluate the bedrock below the Savannah River Plant (SRP) for the ultimate storage of 80,000,000 gallons of high level radioactive waste generated by SRP, an extensive exploratory program (Appendix I-A) has been conducted. In the course of this program a number of wells have been drilled through the overlying sediments (Tuscaloosa, McBean, etc.) into the bedrock, cores examined, and hydrologic studies made. The regional geology and hydrology of both the overlying sediments and the bedrock have been described using information obtained from the well drilling program, and seismic, aeromagnetic, gravity, and magnetic surveys.

SUMMARY

An extensive drilling program has been conducted in conjunction with laboratory and field measurements of rock properties for a number of years at SRP to evaluate the suitability of the bedrock beneath the plant as a depository for radioactive waste. Two distinctly different types of rock, one crystalline metamorphic and the other sedimentary, have been delineated as a consequence of the bedrock exploratory program. The bedrock beneath the northwest two-thirds of the plant is crystalline while the southern one-third of the plant is underlain by part of a consolidated Triassic sedimentary rock basin approximately 5 miles wide, 30 miles long and 1 mile deep. Beneath this Triassic basin is crystalline rock. Both the crystalline and Triassic formations are approximately 1000 feet beneath the ground surface. The crystalline rock has some properties that make it less desirable than the Triassic rock for storage of unmodified waste. The Triassic rock appears to have properties that are well-suited for waste storage.

From the crystalline bedrock investigations:

1. Some areas of crystalline rock are well suited to waste storage. These areas have a low permeability (0.015 ft^3/ft^2 per year) indicating waste will move slowly and the rock comprising these areas has been referred to as "virtually impermeable."

2. The driving force causing water to move is called the hydraulic gradient. This gradient is small, approximately 3 to 4 ft/mile on the plant site. The low permeability mentioned above and the very small effective porosity (0.01%) when coupled with the gradient indicate that water movement will be around 0.1 ft/year in the "virtually impermeable" regions.

3. Other areas of crystalline rock have zones of much higher permeability (48.8 ft^3/ft^2 per year). These zones are regions of fractures which could provide preferred flow paths from caverns to the biosphere. For calculation purposes discussed in later sections, the expected average values for permeability and porosity along a 6000 ft cavern are estimated to be 1 ft^3/ft^2 per year and 0.1%, respectively.

4. The crystalline rock water is high in salt. Evidence, primarily helium content of the water, suggests that the water is very old.

5. Piezometric measurements before plant startup in the vicinity of the 200 Areas (assumed location for cavern placed in crystalline rock) indicate the maximum water pressure difference between the Tuscaloosa aquifer and the crystalline rock was less than 7 ft of water. This differential may be due to higher pressure in the rock because of osmotic effects, or higher recharge and discharge locations of the crystalline rock compared with the aquifer areas. Flow will be from crystalline rock to the Tuscaloosa Formation in the latter two situations and provide a short-circuit from the cavern to the biosphere (Tuscaloosa aquifer). With a head difference of 7 ft of water, a flow path of 500 ft, permeability of one $ft^3/ft^2/yr$, and a porosity of 0.1%, the flow time from the cavern to the Tuscaloosa Formation will be less than 40 years. This calculation assumes that saprolite, a low permeability clay layer that overlies the crystalline rock in certain areas of the plantsite is absent and that increased head differences from pumping of the Tuscaloosa aquifer due to plant operations do not occur at the time of cavern use.

6. Seismic, gravity, and magnetic surveys have indicated the possible presence of vertical faults. These faults may or may not provide preferential flow paths into the Tuscaloosa aquifer depending on whether the rock fractures are filled with fine grained materials that effectively block the path, or are relatively open cracks.

7. Ion exchange capacity of finely ground crystalline rock is low (0.1-0.4 meq/100 g of ground rock). Inasmuch as flow is through fractures in crystalline rock, no credit can be given to this process in retarding migration rates of radionuclides.

8. Although there has been an extensive local drilling program, little is known about rock hydrology on a regional basis. By analogy with hydrology of the Tuscaloosa Formation, a much better defined system, flow paths are anticipated to be arcuate in nature. This assumption is supported by the piezometric heads of 7 onsite wells as well as offsite wells in the Tuscaloosa aquifer.

9. The exploratory program has resulted in a number of well-documented penetrations of the bedrock, each of which provides potentially rapid access to the Tuscaloosa aquifer. Two of these exploratory wells have been abandoned after removal of the casing (35H and DRB 6).

From the Triassic bedrock investigations:

1. The Triassic rock appears to be relatively homogeneous, only one fracture zone has been encountered in the well drilling, to date. The Triassic rock is extremely low in permeability (2.9×10^{-4} ft^3/ft^2 per year) indicating waste will move approximately 100 times slower for the same gradient and porosity as it will in the "virtually impermeable" crystalline rock.

2. The hydraulic gradient across the system is unknown so velocities can be only estimated.

3. The rock water is high in salt.

4. Piezometric measurements indicate the pressure in the Triassic rock (400 ft above sea level) is considerably above the existing pressure (190 ft above sea level) in the overlying sediments even though the final static pressure in the Triassic has not been reached. The source of this pressure is unknown. The low permeability of the Triassic rock (estimated value 3×10^{-4} ft^3/ft^2-year) coupled with a porosity of 3%, results in a very low calculated velocity (5 ft/1000 years) for flow between the anticipated cavern position (500 ft below the

Triassic-Tuscaloosa interface) and the Tuscaloosa Formation even with a high gradient of approximately 5 ft of water/10 ft of distance.

5. Seismic, gravity, and magnetic surveys indicated the possible presence of vertical faults. These faults may provide preferential flow paths into the Tuscaloosa aquifer. A drilling program to investigate these faults found one fault. The study did not find increased water inleakage in the fracture zone associated with this fault.

6. Ion exchange capacity of the rock is similar to surface soils (4 meq/100 g of ground rock) and 10 times higher than crystalline rock. This value, coupled with the likelihood of porous media flow conditions, suggests ion exchange will reduce the rate of waste migration below that of rock water.

Overlying the bedrock is a series of unconsolidated sediments, the most important of these formations in the regional flow regime is the Tuscaloosa. If solutions should enter the Tuscaloosa Formation in the vicinity of the plant site, it will follow an arcuate path in the upstream direction along the South Carolina side of the Savannah River, surfacing downstream from North Augusta. Between these sediments and the bedrock is a layer of clay of unknown lateral extent and continuity known as saprolite.

Specific parameters of the geologic formations beneath the plant site are summarized in Table 1.4. All of the formations are at least 13 million years old. Triassic rock has the lowest permeability of all formations. In the crystalline rock, the porosity varies from 0.01% in some areas, to around 40% in the unconsolidated sediments. Ion exchange capacities of the crystalline rock are small, generally less than 1 meq/100 g of material.

Certain future developments or natural phenomena can influence the hydrology and integrity of cavern storage.

- Earthquakes in the immediate vicinity of the waste storage facility cannot be ruled out over the time scale of interest. Evidence from other underground structures that have been exposed to earthquakes suggests that effects will be minor unless the cavern crosses the fault.

- Changes in rainfall will not significantly alter flow rates through the rock. Dams on the Savannah River in the vicinity of the caverns will reduce gradients through the rock and thereby reduce flow velocities. Floods or elimination of existing dams will not influence hydrology beneath the plant site.

- Water extraction from the Tuscaloosa aquifer will increase the gradient from the bedrock and thereby increase the potential for waste to flow from a cavern in the rock into the Tuscaloosa Formation.

A number of studies should be completed before commencing design work on an SRP bedrock storage system. Completion of these studies would add confidence to conclusions drawn in the present evaluation. Some of these are:

1. Clarification of the cause of high piezometric head in the Triassic system.

2. Evaluation of Tuscaloosa Formation hydrology in the lower one-third of the plant site.

3. Ion exchange capacity measurements of technicium, iodine, mercury, nitrate, zirconium, palladium, selenium, and samarium with representative samples from each of the important geologic formations.

SITE DESCRIPTION

General Information[1]

The Savannah River Plant occupies an approximately circular site in South Carolina of about 300 square miles, bounded on the southwest by the Savannah River and centered approximately 25 miles southeast of Augusta, Georgia. The plant occupies parts of Aiken, Barnwell, and Allendale Counties. The maximum on-site population is approximately 5,000 employees; no residents abide on the site. The number of employees on-site varies with the time of day and day of the week. The population is distributed among the various facilities on the plant site.

Transportation facilities linking the plant with the surrounding areas are excellent. Road access to the plant site is via state routes 19, 278, 39, 54, 64, 125, and 641. Rail service to the plant is provided by the Seaboard Coast Line Railroad passing through the plant. Air transportation is available at the Augusta, Georgia (25 miles) and Columbia, South Carolina (56 miles) terminals. Water transportation by shallow-draft barge service is available via the Savannah River.

TABLE I.4.A. Summary of Various Properties of Bedrock System Beneath SRP

Property	Strata Crystalline	Triassic	Saprolite
Type of Material	Gneiss, schist	Mudstone, claystone, siltstone, sandstone	Clay
Elevation Mean Sea Level, ft			
Top	-770	-1000	-700
Bottom	?	-7000	-770
Age, 10^6 yr	>230	181 - 230	135
Type of medium	Fractured	Consolidated, porous	Unconsolidated, porous
Porosity, %	0.01 - 0.2	3	35
Regional gradient, ft/mile	3	Unknown	Unknown
Permeability, gpd/ft^2	0.0003 - 1	6×10^{-6}	0.02
Flow direction	Arcuate to Savannah River	Unknown	Unknown
Flow rate, ft/yr	1 - 40	Unknown	Unknown
Length of flow path, miles	20	Unknown	Unknown
Ion exchange capacity, meq/100 g	<1	4	Unknown

TABLE I.4.B. Summary of Various Properties of Sediments Beneath SRP

Property	Strata: Tuscaloosa, Ellenton	Congaree, McBean	Barnwell	Hawthorn
Type of Material	Sand, gravel	Sand, marl, clay	Sand, sandy clay	Clayey sand
Elevation Mean Sea Level, ft				
Top	+50	+200	+250	+290
Bottom	-700	+50	+200	+250
Age, 10^6 yr	63 - 135	36 - 58	36 - 58	13 - 25
Type of Medium	Unconsolidated, porous	Unconsolidated, porous	Unconsolidated, porous	Unconsolidated, porous
Porosity, %	25 - 40	25 - 40	25 - 40	25 - 40
Regional Gradient, ft/mile	4	Variable	Variable	Above water table
Permeability, gpd/ft^2	200 - 2600	140 - 980	Variable	Variable
Flow Direction	Arcuate to Savannah River	To nearest stream	To nearest stream	Vertical
Flow rate, ft/yr	365	Variable	Variable	Variable
Length of flow path, miles	20	Variable	Variable	Variable
Ion exchange capacity, meq/100 g	0 - 7	1 - 6	0 - 2	0 - 5

A number of nuclear facilities are present on the site: three operating production reactors, two fuel reprocessing plants, a fuel fabrication plant and waste handling and storage facilities.

Surface Soil Erosion Rates

Erosion rates in the South Atlantic and Eastern Gulf regions of the U. S.[2] are approximately 4.1 cm/1000 years. The forested plant site is likely to approximate this rate fairly closely unless dramatic climatic changes occur in the future. This low rate suggests surface erosion can be eliminated as a factor influencing the release of radioactivity from the cavern.

Surface and Near-Surface Hydrology

Surface water leaves the plant site by a number of streams (Figure I.1) that originate both on and off the plant site and flow into the Savannah River. The stream flow characteristics of the unclassified portions of some of these streams are summarized in Table I.5. Most plant streams have small natural flow rates (less than 30 cfs). The Savannah River is the major river in the area and has a guaranteed flow rate of 5000 ft^3/sec. The Savannah River's flow rate is regulated by Clark Hill Reservoir.

Stream velocities are an important variable in waste management assessments. The length of time for water from any point in a stream on the plant site to flow to the swamps lying alongside the Savannah River is generally less than a day. The flow time across the swamp is from 0.5 to 3 days. The flow time from SRP to Savannah by the Savannah River is approximately 3 to 5 days.

The time of flow from the ground surface to the water table is a function of water additions to the soil surface and distance to the water table. Measurements of movement of rainfall on the plant site indicate that under natural conditions a downward displacement of 0.94 inch per inch of rainfall occurs.[3] Under rainfall conditions of 49.11 in./yr, and approximate depths to water tables between 20 and 60 ft, travel times from the ground surface to the water table are 5.2 and 15.6 years, respectively.

Ground water movement from the shallow ground water body to the surrounding surface streams is complex because of great variations in permeability. In general, water moves slowly away from the ground water divide and then at an accelerating rate down the gradient to outcrop areas such as springs, swamps, and

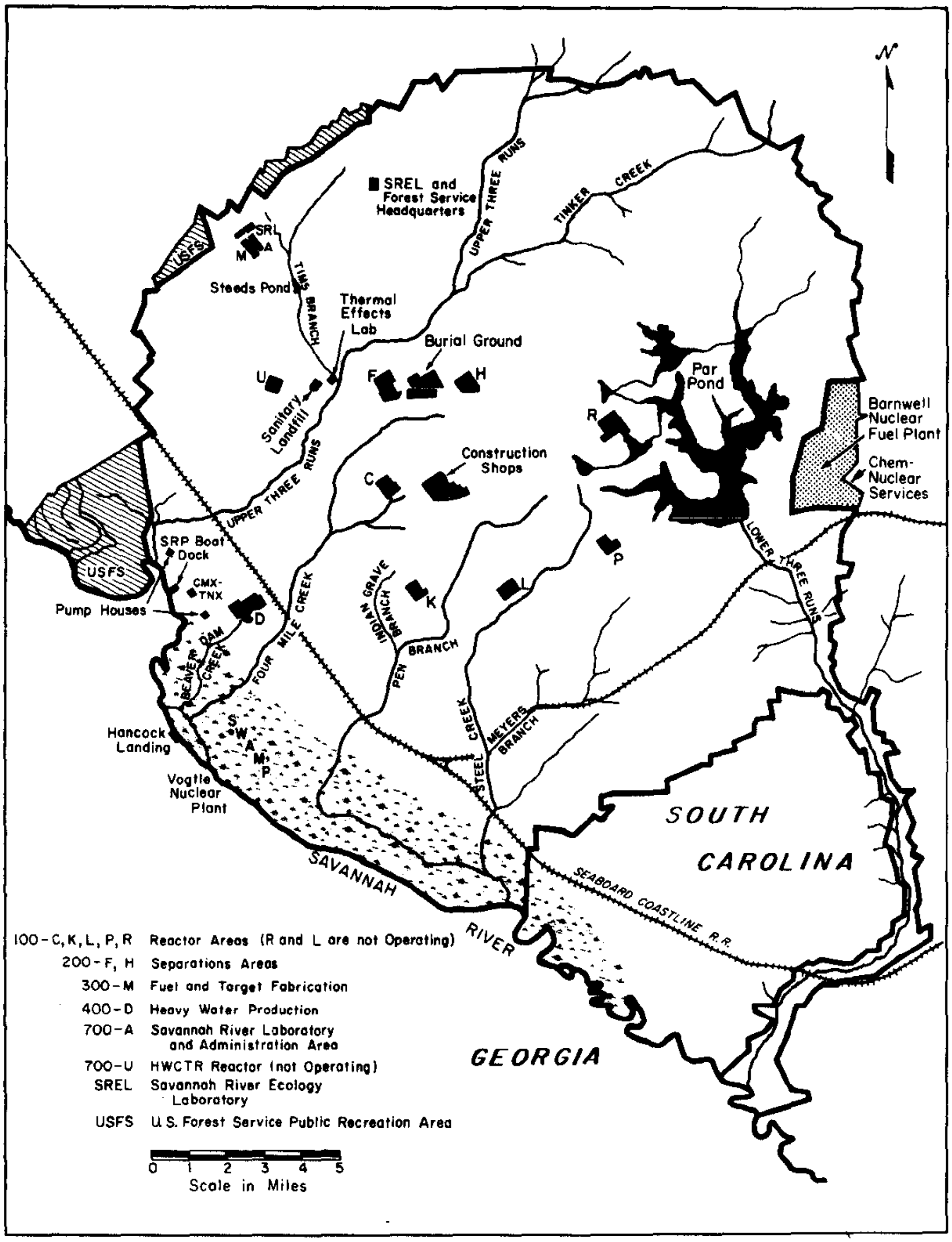


FIGURE I-1. Streams of the Savannah River Plantsite

TABLE I.5. Measurements on Discharge Volumes of Plant Streams

Stream:	Discharge, ft^3/sec
Upper Three Runs	
Road C (May, 1951)[a]	230
Road C (Aug, 1951)[a]	141
Road C (Sept, 1951)[a]	395
Road C (June, 1972)[b]	346
Four Mile Creek	
Road C (June, 1972)[b]	6
Road A (June, 1972)[b]	17
Savannah River	
Augusta, Ga. (April, 1970)[c]	23,200
Augusta, Ga. (Sept, 1970)[c]	5,870
Steel Creek	
Road A (June, 1972)[b]	28
Road A17 (June, 1972)[b]	35
Road B (June, 1972)[b]	16
Lower Three Runs	
Patterson Mill Bridge (1970 monthly average)[b]	21

a. Freeman, Harry W. *Fishes of the Savannah River Project Area.* Univ. of South Carolina Publications, 1:119-120 (1954).

b. D. I. Ross. Personal communication.

c. *Water Resources Data for South Carolina.* U. S. Dept. of Interior. U. S. Geological Survey (1972).

stream beds. The shortest flow path from F Area waste tanks to Four Mile Creek is 5000 feet. With measured flow velocities along the flow path ranging from 0.006 to 0.08 ft/day, estimating the travel time is difficult, but the best estimate is 200 years. The shortest flow path from H Area waste tanks to Upper Three Runs Creek is 9000 ft. With measured flow velocities along the flow path ranging from 0.01 to 1.3 ft/day, an estimate of travel time is 350 years.

GENERAL SUBSURFACE GEOLOGY AND HYDROLOGY

South Carolina is underlain by a stable basement of igneous and metamorphic rocks extending from the Blue Ridge Mountains on the west to the continental shelf on the east, a width greater than 200 miles, and trending NE-SW. The bedrock in the vicinity of the Savannah River Plant is overlapped by 900-1000 feet of Coastal Plain sediments (Figure I.2). The rocks constituting the basement were formed, folded, faulted, metamorphosed, and intruded during the pre-Cambrian and Paleozoic Eras (Table I.6). They underwent the last major metamorphism during upper Paleozoic time when the Appalachian Mountains were uplifted. By Triassic time, the areas which are now Piedmont Plateau and Coastal Plain had been reduced by erosion to subdued uplands and plains. The crust was then broken by large normal faults which developed basins in which Triassic sediments accumulated. The eastern side of the crystalline basement began to warp down during the Cretaceous period. Sediments might have accumulated locally on the eroded crystalline surface during the Jurassic and Lower Cretaceous periods but were subsequently removed. Deposition became widespread only during Upper Cretaceous time when the Tuscaloosa Formation was laid down. Overlying the Tuscaloosa Formation are the Ellenton Formation of Cretaceous age and the McBean, Barnwell, and Hawthorne Formations of Tertiary age which comprise the present day strata.

The hydrology of the sediments beneath SRP is both local and regional in character. The hydrology of the shallow sediments is local in nature, and they tend to discharge water into nearby streams. The hydrology of the deep sediments (Tuscaloosa) is regional. The Tuscaloosa sediments are recharged by direct infiltration of precipitation in the outcrop area (a band 10 to 30 miles wide along the fall line that runs NE from Augusta, Georgia) and by leakage through the overlying sediments near the outcrop area. The water in the deep sediments beneath the plant site discharges into the Savannah River (Figure I.3) after following an arcuate path from the recharge area.

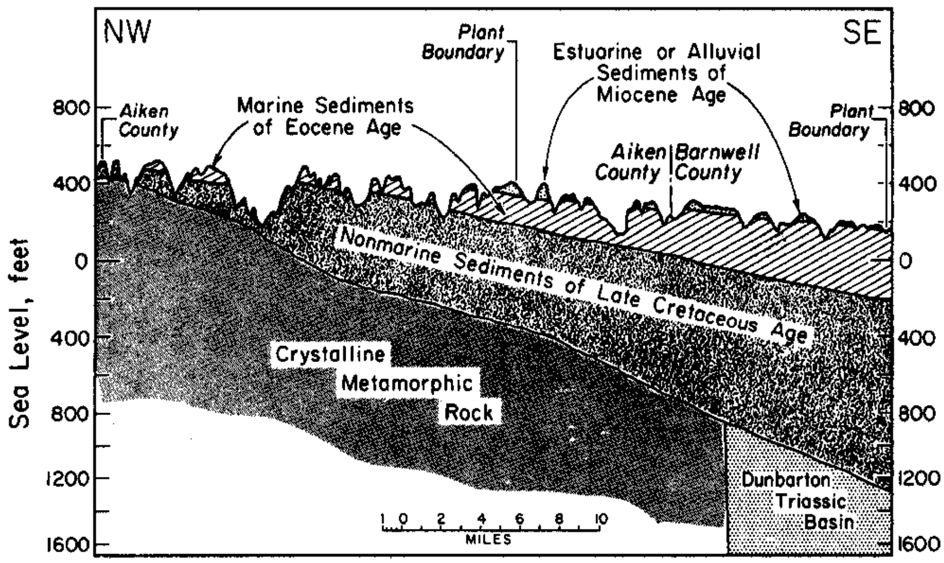


FIGURE I.2. Generalized Geologic Profile of the Savannah River Plant Area

TABLE I.6. The Geologic Time Scale

ERA	PERIOD	EPOCH	MILLIONS OF YEARS AGO (APPROX.)	DURATION IN MILLIONS OF YEARS (APPROX.)	RELATIVE DURATIONS OF MAJOR GEOLOGICAL INTERVALS
CENOZOIC	QUATERNARY	RECENT	0-1	1	CENOZOIC
		PLEISTOCENE			MESOZOIC
	TERTIARY	PLIOCENE	1-13	13	
		MIOCENE	13-25	12	PALEOZOIC
		OLIGOCENE	25-36	11	
		EOCENE	36-58	22	
		PALEOCENE	58-63	6	
MESOZOIC	CRETACEOUS		63-135	72	
	JURASSIC		135-181	46	
	TRIASSIC		181-230	49	
PALEOZOIC	PERMIAN		230-280	50	PRECAMBRIAN
	PENNSYLVANIAN		280-310	30	
	MISSISSIPPIAN		310-345	35	
	DEVONIAN		345-405	60	
	SILURIAN		405-425	20	
	ORDOVICIAN		425-500	75	
	CAMBRIAN		500-600	100	
PRECAMBRIAN	UPPER	Although many local subdivisions are recognized, no world-wide system has been evolved. The Precambrian lasted for at least 2½ billion years. Oldest dated rocks are at least 2,700 million, possibly 3,300 million, years old.			
	MIDDLE				
	LOWER				

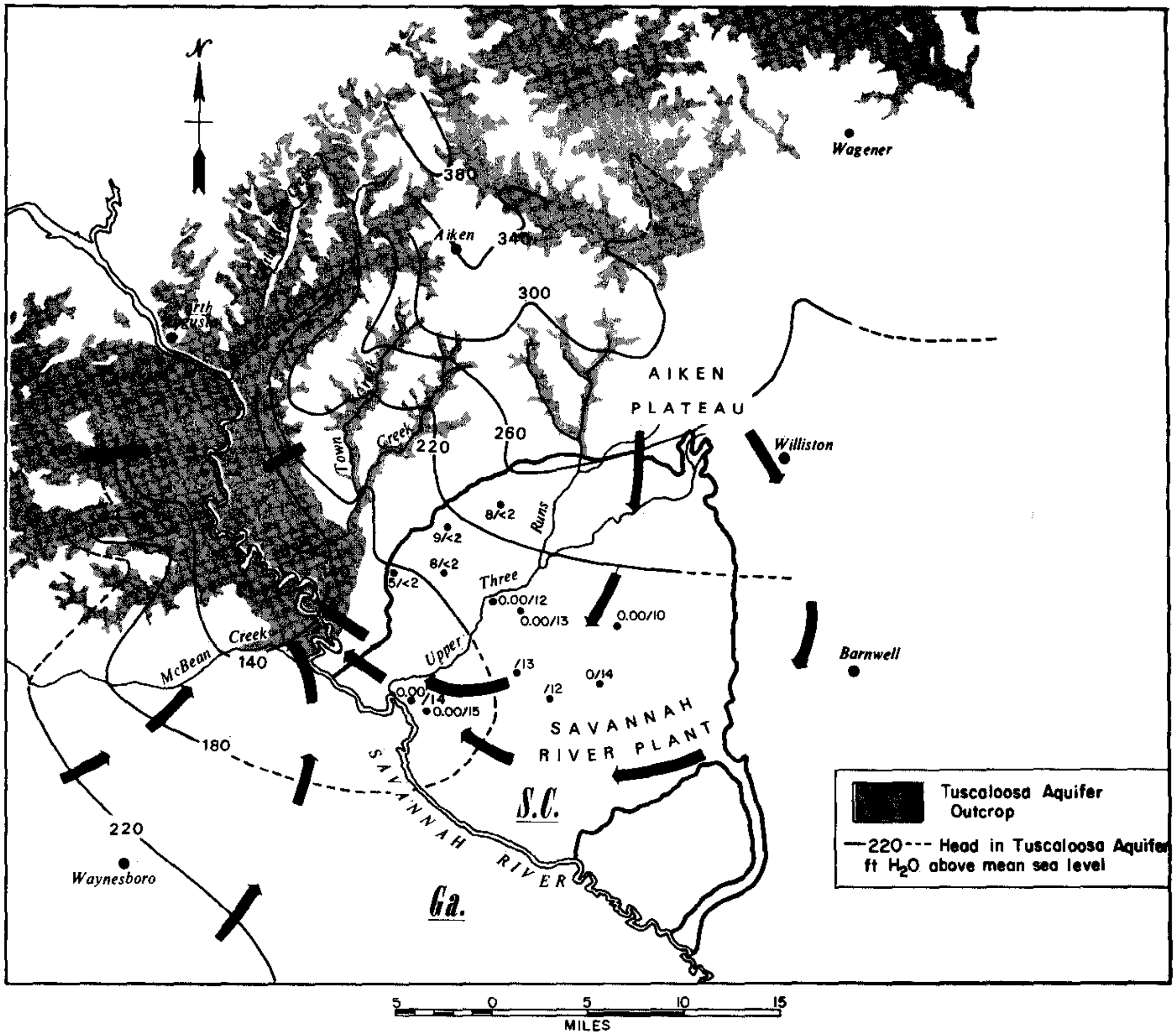


FIGURE I.3. Subterranean Flow of Water in the Tuscaloosa Aquifer

The hydrology of the crystalline rock is regional in nature. The recharge area is above the fall line and the discharge area is thought to be the Savannah River (Figure I.4) based on measurements at the limited well locations presently available. The hydrology of the Triassic basin is unknown because very few well locations exist in this formation.

HYDROLOGIC CONCEPTS

Water always moves from areas of high head to areas of discharge or low head. The direction of movement can be determined by looking at a contour map (Figure I.5) showing isopiestic lines (lines connecting points of equal piezometric heights). (A piezometer is generally a well casing inserted to a given depth of rock or soil to measure the water pressure at that depth. The

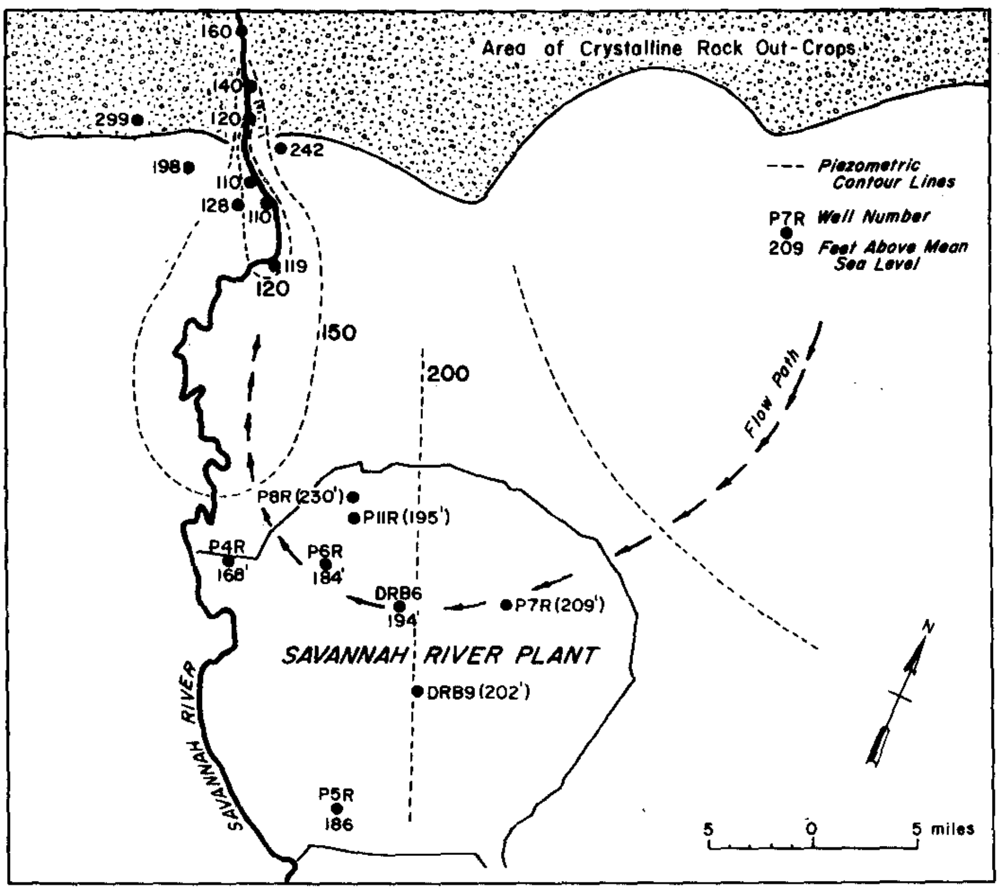


FIGURE I.4. Inferred Regional Water Circulation in the Bedrock System

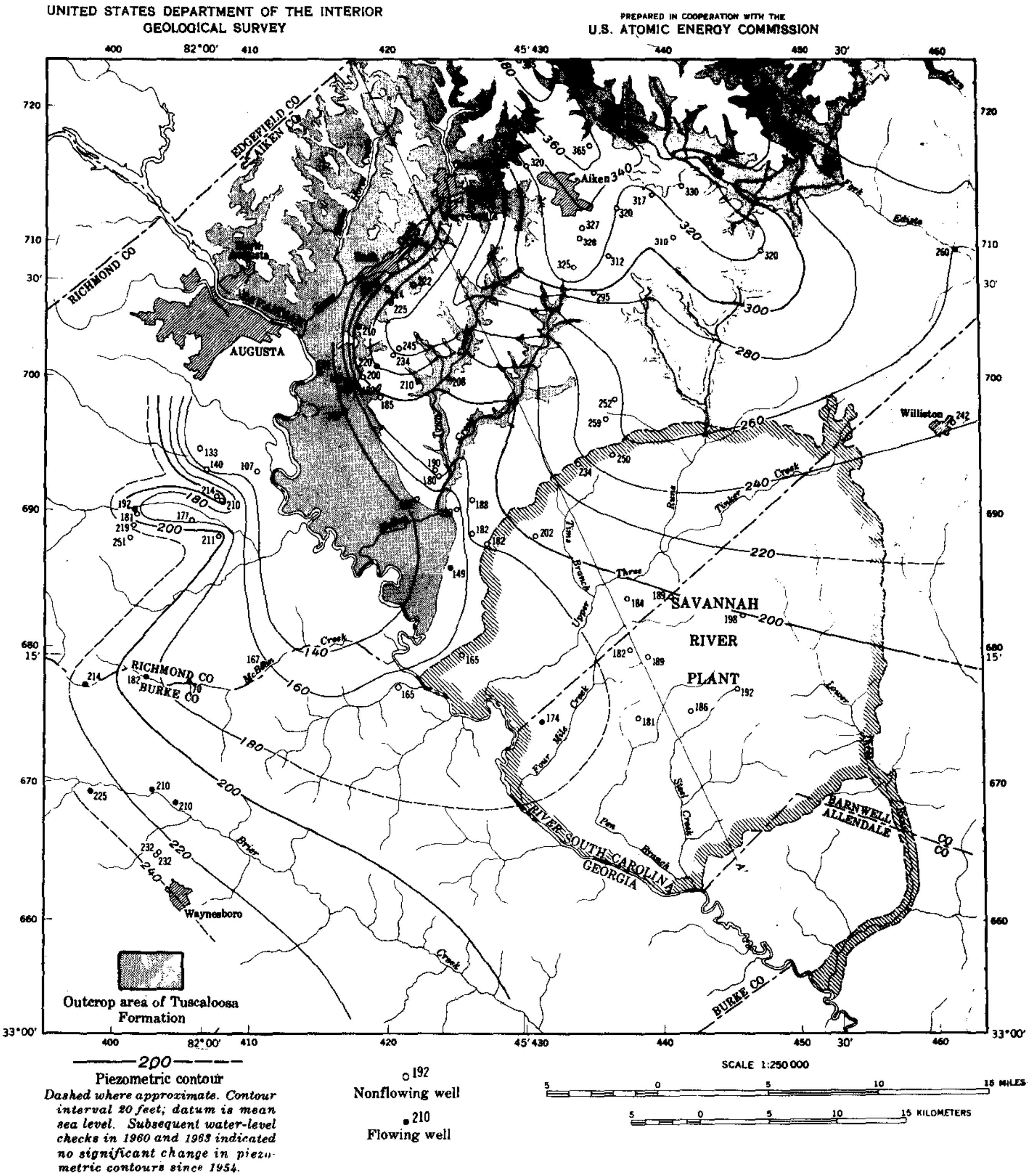


FIGURE I.5. Piezometric Map of the Tuscaloosa Aquifer piezometric pressure is usually recorded as the height above sea level to which the free water surface rises.) In a homogeneous isotropic medium the flow direction is along lines (called stream lines) drawn perpendicular to the isopiestic lines. Flow occurs from a region of high piezometric values to a region of low piezometric values.

A number of terms are used to describe hydraulic properties of geologic formations. Transmissivity is the rate at which water is transmitted through a unit width of the aquifer extending the full height of the aquifer under a unit hydraulic gradient. The coefficient of storage is the volume of water released from or taken into storage per unit surface area of the aquifer per unit change in head. Permeability is defined as the volume of water that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow.

ROCK TYPES AND THEIR PROPERTIES

Crystalline Rock

Descriptive Geology

The crystalline rock found in exploratory drilling beneath the plant site is a steeply inclined sequence of schist, gneiss, and metaquartzite (averaging 55° dip except in DRB 5 near the bottom where near vertical dip angles occur). The total depth of crystalline rock has not been explored in the vicinity of SRP but is expected to continue for a considerable distance through the earth's crust. Detailed discussions of the exploratory drilling program are presented in Appendices I-A and I-B.

Hydrology of Crystalline Rock

Evidence for two types of water-transmitting fractures in the crystalline rock is present.[4] The first type is a series of minute fractures in the rock mass through which water movement is exceedingly slow. The rock containing this type of fracture has been referred to in the literature on the bedrock concept as "virtually impermeable," and has a permeability of 0.0003 gpd/ft^2. The second type of fracture is restricted to definite zones and this type consists of larger openings that transmit water at a faster rate (permeability, approximately 1 gpd/ft^2). There are two fractured zones in the area of intensive exploration around F and H, one at the top of the crystalline rock and an inclined zone connecting DRB 5 and DRB 6. For calculation purposes of the consequences of emplacement of waste in the cavern, the permeability is assumed to range between 0.0003 and 1 gpd/ft^2, and to average 0.020 gpd/ft^2 along the 6000 ft long cavern.

Flow System and Gradient

Piezometric measurements in the crystalline rock are very limited and of insufficient number to draw an isopiestic or streamline map with any confidence although a tentative description is possible. Figure I.4 illustrates the small amount of data available on which to base any quantitative description of the assumed horizontal flow path and gradient. The regional gradient for calculation purposes is assumed to be 3 feet per mile. A possibility for flow in the vertical direction also occurs because the water pressure in the crystalline rock is greater than the water pressure in the Tuscaloosa Formation (Table I.7). The pre-construction head for the water in the crystalline rock in the vicinity of the Separations Areas is approximately 7 ft higher than for the Tuscaloosa aquifer. This average pressure drop is not large but indicates flow could occur from the crystalline rock to the Tuscaloosa aquifer and would occur most readily in regions where fractured rock is in contact with the Tuscaloosa Formation. This pressure drop occurs between the upper fracture zone in the rock and the lowest sand bed in the Tuscaloosa Formation; however, in later calculations, it will be assumed that the pressure drops linearly from the cavern to the Tuscaloosa.

TABLE I.7. Comparison of Head in the Crystalline Rock to That in the Tuscaloosa Formation Beneath the Plant Site

		Crystalline Rock		*Tuscaloosa Formation*			
Well Site	Date	Well	Head, ft[a]	Well	Location	Head, ft[a]	Δ Head, ft[b]
Deep Rock Boring (DRB)	Feb. 4, 1964	DRB Average	194.28	P1A, P2A, P3A average	Deep	181.22	13.06
H-Area, before Plant construction	Apr. 7, 1952	DRB Average	194.28	45-H	Composite	192.42	1.86
F-Area, before Plant construction	Sept. 29, 1951	DRB Average	194.28	21-F	Composite	188.7	5.6
P6	Dec. 1967 to May 1968 Average	P6R	183.50	P6 water well (screened)	Top	172.55	10.95
P8	Dec. 1967 to Dec. 1968 Average	P8R	229.82	4M	Composite	206.76	23.06
P7	Apr. 12, 1972	P7R[c]	206.32	P7A		199.07	7.25
DRB9	Apr. 12, 1972	DRB9	205.35	P10A		186.60	18.75
P5	Apr. 12, 1972	P5R	163.04	P5A		189.44	(-26.40)

a. Head on a piezometer with casing filled with fresh water, ft above sea level.

b. Amount by which head in crystalline rock is greater than head in Tuscaloosa formation, ft.

c. Well P7R located 7 miles from 200-F and 200-H Areas.

Hydraulic Constants

Knowledge of the permeability, transmissivity, and porosity of the rock was needed to permit prediction of migration rates of waste from caverns placed in the rock. Several different methods were used to determine the permeability and transmissivity of the rock. The first method isolated intervals of the exploratory wells using packers and followed the rate that water returned to the interval after it was removed by a swab, a tight fitting plunger that lifts all of the water out of the isolated interval. The calculated permeabilities ranged from 0.002 to 0.00002 gallons per day per ft^2 (Table I.8A). In the second method, a column of water was instantaneously released into the packed off interval. The rate of water level recovery was used to determine the transmissivity. The results of this test for DRB 5 and DRB 6 are shown in Figure I.6[5] and illustrate the inhomogeneity of the rock in a single hole as well as provide the basis for statements about an inclined fracture zone. The coefficient of transmissivity varied from 0 gallons per day per ft to 120 gpd/ft. Because the sections transmitting water are very likely only a small part of the packed-off intervals (15 ft), it would be meaningless to divide the coefficient of transmissivity by the thickness of the packed-off interval to obtain a value for the apparent coefficient of permeability. A third technique involved the use of pumping tests. In these tests, water was pumped from one of the drill holes and measurements of the water-level drawdown and subsequent recovery were made in other drill holes. The coefficient of transmissivity was considerably larger (Table I.8B), average 162

TABLE I.8A. Hydrologic Values of the Crystalline Rock[a]

Well	Coefficient of Transmissivity, gpd/ft	Coefficient of Permeability, gpd/ft^2
DRB 2	0.2	0.002
DRB 3	0.4	0.004
All other tests[b] (DRB 2, 3, 6, 7)		
Max.	0.09	0.0008
Avg.	0.03	0.0003
Min.	0.002	0.00002

a. Obtained by "swabbing" borings in the crystalline ("virtually impermeable") rock borings.

b. DRB's 1, 4, and 5 were not tested.

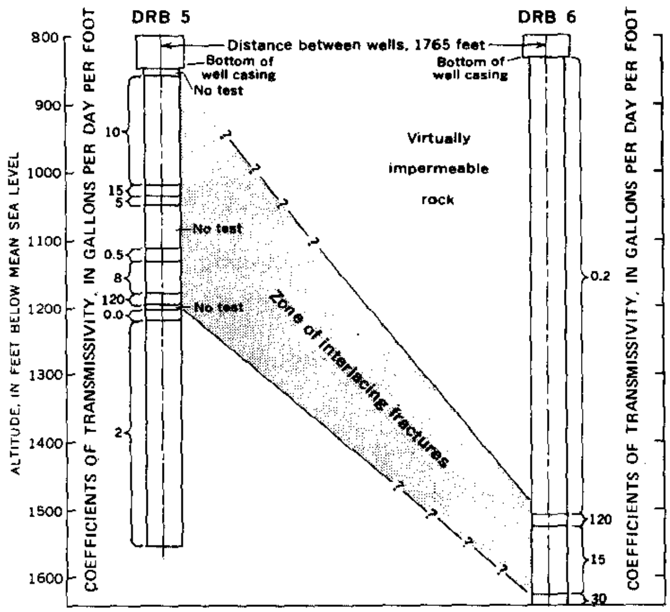


FIGURE I.6. Transmissivity vs Depth for DRB-5 and DRB-6 (An illustration of the variation in the coefficients of transmissivity for the various depths of DRB-5 and -6 from instantaneously releasing water into packed-off intervals of the wells)

TABLE I.8B. 31-Day Pumping Test on Well DRB-6 at 20.5 gpm

	Coefficient of Transmissivity, gpd/ft		Coefficient of Storage, x10[6]	
DRB Well	Drawdown	Recovery	Drawdown	Recovery
1	257	304	4.9	5.5
2	-	-	-	-
3	95	104	28	35
4P[a]	117	98	9.4	14
4C[b]	168	125	10	14
5	184	185	8.6	9.5
6	-	152	-	-
7	-	-	-	-
Average:	162		14	

a. Depth below ground surface, 1740 to 1881 ft

b. Depth below ground surface, 960 to 1076 ft gpd/ft, than observed in the swabbing tests and likely to be much closer to that observed under operating conditions. The coefficient of storage was obtained in these tests and averaged 14 x 10^{-6} (Table I.8b).

Porosity

The porosity of one sample of crystalline rock from each hole was measured by the South Atlantic Division Laboratory of the U. S. Army Corps of Engineers. The results were:

DRB Well	Total Porosity, %
1	0.08
2	0.06
3	0.13
4	0.13
5	0.12
6	0.19
7	0.19
Average	0.13

This method gives the total porosity; an effective porosity for water flow might be a factor of 10 less.

Dispersion Characteristics

Knowledge of dispersion characteristics of the crystalline rock is limited to the tritium test study[6] in which a total of 297.44 curies of tritiated water were added continuously over a 28-3/4 hour period to DRB 5 while water pumped from DRB 6 at 10 gpm was returned to DRB 5. The tritium concentration, after moving a minimum of 1765 ft from DRB 5 to DRB 6 through the inclined fracture zone, was reduced from 4750 microcuries per liter to a maximum of slightly less than 5. The time of arrival was approximately 70 days. If dispersed flow had not occurred, the arrival time would have been 440 days. This observation indicates that dispersion of the waste will occur causing arrival times to be considerably sooner down the gradient from the cavern than calculated by using mass flow measurements alone.

Nature of Crystalline Rock Water

Introduction

Analyses were made on the gas, liquid, and rock found at various depths in the crystalline rock to determine the source and age of the rock water. This information was to be used to establish the residence times and flow velocities of water in the system. Considerable data were acquired on dissolved mineral contents and isotopic ratios in the rock waters but the results were not definitive as to the age or source of water.

Chloride Content

Harshbarger[7] suspects the crystalline rock water to be marine in origin because of the chloride content. The mineralogy of the crystalline rock is such that it is not the source of the chloride. Deep crystalline rock water contains more (1400 ppm) chloride than shallow rock water (800 ppm) and both are less than ocean water (19,200 ppm) suggesting dilution by meteoric water (atmospheric precipitation) may have occurred. The amount of dilution is difficult to determine because the source of the original water (oceanic vs estuarine) is unknown. In addition, the source of the diluting water is unknown. Two possible sources of diluting water are water moving from the Tuscaloosa aquifer into the crystalline rock due to osmotic effects, or preferential flow paths along the upper portions of the rock from the recharge areas to the region beneath the plant.

Sulfur Content

Sulfur analyses indicate that the deep well water is similar to ocean water, e.g. $^{34}S/^{32}S$ = 17.5 to 21.4 parts per thousand variation from a standard (Canon Diablo troilite-FeS from Meteor Crater, Arizona) in deep well water versus 20 parts per thousand variation in ocean water, and dissimilar to rock (2.1 to 7.1 parts per thousand). This finding is additional evidence that the rock water is marine in origin.

Oxygen Content

Oxygen analyses ($^{18}O/^{16}O$) indicate that the crystalline rock water (-4.0 parts per thousand variation from standard mean ocean water) has a considerable amount of Tuscaloosa type water (-4.7 parts per thousand) when compared with ocean water (0.0 parts per thousand).

Helium Content

The high levels of helium in the rock water have suggested the possibility of calculating the age of the rock water by making various assumptions in order to calculate the rate of helium generation. If these assumptions are valid, the rock water beneath the plant site is at least 1.4 million years old and likely much older.

Physical Properties: Strength and Thermal

Physical and petrographic analyses were performed on 2 to 3 foot sections of rock core from each of seven deep rock borings. Samples were obtained at intervals ranging from 6 feet to 110 feet at depths between 1300 and 2000 feet. The physical tests, conducted to ascertain strength, elastic, and thermal properties of the core samples, were performed in accordance with standard procedures of the U. S. Army Corps of Engineers.

Compressive strength samples were examined for type of break after failure in order to correlate strengths to any structural feature which might contribute to rock weakness. Standard samples were compared with core samples treated with 1M NaOH for 30 days at a temperature of 95°C in order to determine the effect of waste on rock properties. In general, the average compressive strength of an untreated sample was larger than a sample treated with NaOH. The average compressive strengths of the rock samples after the NaOH treatment ranged from approximately 6,000 to 16,000 psi, sufficiently large enough to permit construction of a cavern.

The unit weights of the samples always exceeded 166 lb/cubic ft. The coefficient of expansion from heating was between 3 and 5×10^{-6}/°F. The specific heat of the samples ranged from 0.170 to 0.202 Btu/lb°F. The diffusivity of the samples in ft^2/hr ranged from 0.037 to 0.058, and the thermal conductivity ranged from 1.25 to 1.9 Btu/ft-hr-°F. Each of these parameters is useful in designing the final cavern. None was unexpected as far as the range normally found for crystalline rock.

Chemical Properties

The sorption of Cs, Sr, and Pu(IV) by ground rock samples from the crystalline rock wells DRB 4 and DRB 6 was measured in two ways: as ion exchange capacity, and as K_d.

$$K_d = \frac{\text{mMoles of ion adsorbed on rock}}{\text{mMoles of ion in solution}} \times \frac{\text{ml of solution}}{\text{grams of rock}}$$

The ion exchange capacity of ground rock samples (174-177 μm) was 0.45 meq/100 g of DRB 4 rock and 0.12 meq/100 g of DRB 6 rock. These values mean that 100 g of DRB 4 rock would hold 0.062 g of ^{137}Cs if no competing ions were present, while 100 g of DRB 6 rock would hold 0.016 g of ^{137}Cs.

The K_d's are listed in Table I.9. A K_d of 0, such as found with cesium and strontium when 4M NaOH is present, indicates these radioisotopes will flow at the same rate as the bulk solution. A K_d greater than 0 indicates the radioisotopes will flow at a slower rate than the solution. The K_d of 865 suggests plutonium would move extremely slowly through ground crystalline rock.

TABLE I.9. Sorption of Strontium, Cesium, and Plutonium Ions on Crystalline Rock

$NaNO_3$	Sr^{2+}, Kd		Cs^{+}, Kd		Pu^{4+}, Kd	
Moles/liter	DRB 4	DRB 6	DRB 4	DRB 6	DRB 4	DRB 6
0	62	2.5	50	21	750	400
0.001	27	2.0	190	159	-	45
0.01	23	1.8	110	111	710	390
0.1	4	0.95	-	45.5	270	450
1.0	0.45	0.11	-	1.6	-	360
4.0	∿0	0	5.9	∿0	865	680

$$K_d = \frac{\text{mMoles of ion absorbed on rock}}{\text{mMoles of ion in solution}} \cdot \frac{\text{ml of solution}}{\text{grams of rock}}$$

Model Studies

Numerous geometrical configurations and transmissivities have been used with a computer program at SRL to attempt to match the drawdowns measured in the crystalline rock at DRB 1, 2, 3, 4, 5, and 7 during the year-long pumping of DRB 6 at 14 gpm. The model that best matches the data has parallel "bands" of different transmissivities in the rock (Figure I.7). The parallel-band model is reasonable and simple but the model is not represented as being a completely accurate physical description. Its use lies in the ability to estimate the importance of various perturbations on the system and to estimate the types of transmissivities expected. For example, the model indicated (1) that off-site pumping of the crystalline rock will influence the piezometric pressures in the rock beneath the 200 Areas, (2) that transmissivities in the order of 1 gal per day per ft are the minimum to be expected, and (3) that the bulk of the area is likely to have a transmissivity around 160 gal per day per ft.

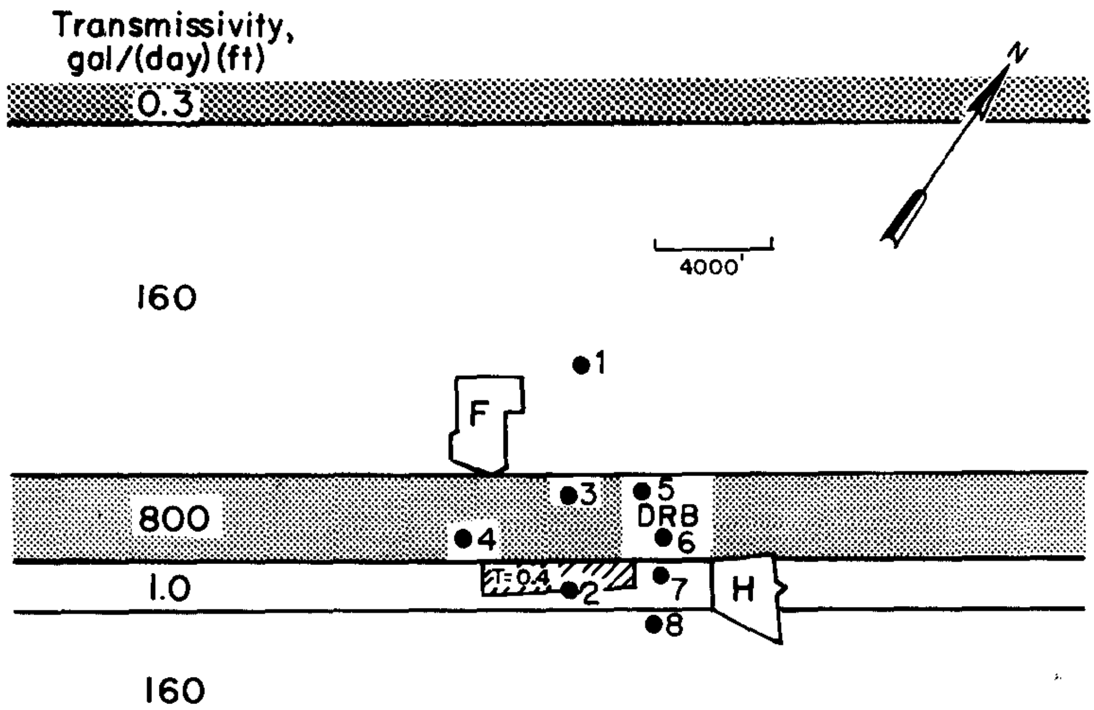


FIGURE I.7. Transmissivity Zones Calculated from the Computer Model of the Crystalline Rock System

Saprolite

Between the upper surface of the crystalline rock and the overlying sediments, there is a layer of clay. This layer is either (a) the residual weathering product of the crystalline rock formed when the rock was last exposed to the atmosphere before being covered by later sediments (perhaps 100 million years ago), or (b) has developed by weathering in place due to dissolved oxygen in the Tuscaloosa aquifer. Its mean permeability, measured on 14 core samples[8], is about 0.02 gpd/ft^2 with a mean porosity of about 35%. The continuity of this layer is questionable. It is found in the vicinity of the Separations Areas. The seismic survey data (Appendix I-C) suggest that the saprolite is no longer present in places in the region beneath the 3/700 Area. The seismic survey evidence was confirmed when the core from P9R, drilled in the vicinity of the 3/700 Area, did not contain the clayey upper part of the saprolite.

Triassic Rock

Descriptive Geology

During Triassic time the earth's crust was broken by large normal faults. These faults formed basins in which Triassic sediments accumulated. A number of Triassic basins occur in the southeast, part of one of these underlies SRP. According to aeromagnetic studies (Appendix I-C), the basin is 6 miles wide and 30 miles long. The gravity and magnetic surveys (Appendix I-C) indicate the Triassic basin to be approximately one mile deep. The basin trends NE-SW. The rock consists of a variety of cemented particles to form sandstone, siltstone, or claystone. Subsequent deposition has buried the Triassic rock 1,010 feet below sea level (P5R).

Seismic, gravity, and magnetic studies (Appendix I-C) indicated the presence of possible faults in the Triassic rock. A drilling program was conducted to evaluate the seismic findings and to determine the condition of rock at a suspected fault. Two wells, DRB 11 and P12R, were drilled in 1972. Fractured rock was found with slick surfaces in the vicinity of the suspected fault region. Inleakage into the well did not increase in the vicinity of the fault zone.

Hydrology of Triassic Rock

The permeability of Triassic rock is very low. Laboratory analyses of rock from DRB 9 and P5R indicated 6×10^{-5} to 295×10^{-5} gpd/ft^2 might be attained in the vertical direction while 1×10^{-4} gpd/ft^2 is possible in the horizontal direction (Table I.10). A field test for permeability indicated that the average permeability for the 60 ft of open hole exposed in P5R was 6×10^{-6} gpd/ft^2. A similar test at DRB 10 indicated a permeability of 1.2×10^{-6} gpd/ft^2. The value assumed as representative for the permeability of the Triassic rock in later calculations is 6×10^{-6} gpd/ft^2. The effective porosity varies with the rock type but averages 3%.

The Triassic rock system has a much higher piezometric pressure than crystalline rock. The piezometric pressure of the water in crystalline rock in the vicinity of the Separations Area is slightly greater (7 feet) than the water in the Tuscaloosa aquifer. Whereas in the Triassic system, the piezometric pressure is more than 210 ft greater than the piezometric pressure in the Tuscaloosa system directly above it. Mechanisms such as osmotic effects, compaction, and mineral alteration that could explain this observation are being evaluated. This head

TABLE I.10. Physical Properties of Triassic Rock

Well No.	Depth, ft Below Ground Surface	Physical Description	Permeability, gpd/ft² Vertical	Horizontal
P5R	1309 -1309.8	Gray-brown fine sandstone	0.6×10^{-4}	1.0×10^{-4}
DRB 9	994.9- 999.4	Gray gritty plastic clay; Tuscaloosa formation	26.0×10^{-4}	
	1004.3-1034.3	Top of Triassic rock		
	1034.3-1035.8	Red silty clay some schist particles	-	
	1047.5-1049.0	Red silty clay some schist particles	10.3×10^{-4}	
	1063.5-1067.0	Red and gray hard gritty conglomerate	29.5×10^{-4}	
	1075.0-1075.6	ditto	26.0×10^{-4}	
	1092.7-1093.3	ditto	-	
	1094.0-1095.6	ditto	1.6×10^{-4}	

difference indicates that a driving force for waste migration exists from the caverns to the Tuscaloosa aquifer, and waste could move to the biosphere should cracks develop between the cavern and the Tuscaloosa Formation following waste emplacement.

Nature of Triassic Rock Water

Isotopic analyses of DRB 10 water with regard to isotopes of hydrogen and oxygen indicated the $(^2H/^1H):(^{18}O/^{16}O)$ ratio for DRB 10 water appears significantly higher than meteoric (atmospheric precipitation) water. Iodine/chloride ratios do not correspond with those found in marine waters while sulfur isotopes closely resemble ratios from marine waters and not rock waters. The chemistry information is not sufficiently uniform to specify the origin of Triassic water at this point.

The Triassic rock water is high in dissolved salts - 12,000 ppm compared with 6000 ppm in the crystalline rock water and less than 100 in the water from the Tuscaloosa aquifer, but low compared with ocean water (35,000 ppm). The source and significance of the high salt content in Triassic water is unknown.

Sediments

Descriptive Geology

The materials overlying the rock in the vicinity of SRP are sediments transported from the region to the NW and deposited over the last 100 million years.[9] They are composed of stratified gravel, sand, silt, and clay. The structural dip of the beds is seaward, following the slope of the basement-rock surface. In general, each successively younger formation appears at the surface in a belt that lies seaward of the belt of outcrop of its predecessor, and each successively younger formation dips more gently than its predecessor.

The coastal plain sediments were deposited in the Cretaceous, Tertiary, and Quarternary Periods (Table I.6).

Cretaceous System

The non-marine Tuscaloosa Formation and the marine or estuarine Ellenton Formation comprise the Cretaceous System.

In the vicinity of the plant site, the Tuscaloosa Formation rests directly upon the basement rock and consists mainly of materials deposited by streams and in estuaries. The materials are predominately crossbedded sand and gravel with lenses of silt and clay. The Tuscaloosa Formation is exposed (Figure I.8) in the lower parts of the valleys of Horse Creek, Shaw Creek, Town Creek, Holley Creek, Savannah River, and Upper Three Runs Creek. The outcrop area is at the fall line (the area separating the Piedmont from the Coastal Plain) in a belt 10 to 30 miles wide extending northeastward across South Carolina from Augusta, Georgia. The composition and the irregularity of the sediments of the Tuscaloosa Formation suggest derivation from the disintegrated and partially weathered crystalline rocks of the nearby Piedmont and deposition in a fluvial or non-marine environment. Hence, it is assumed that the Tuscaloosa Formation was deposited by sediment-laden streams that eroded and drained the Piedmont in late Cretaceous time. Conceivably, the Tuscaloosa sediments accumulated as a series of coalescing deltas that bordered the shoreline of the late Cretaceous sea.

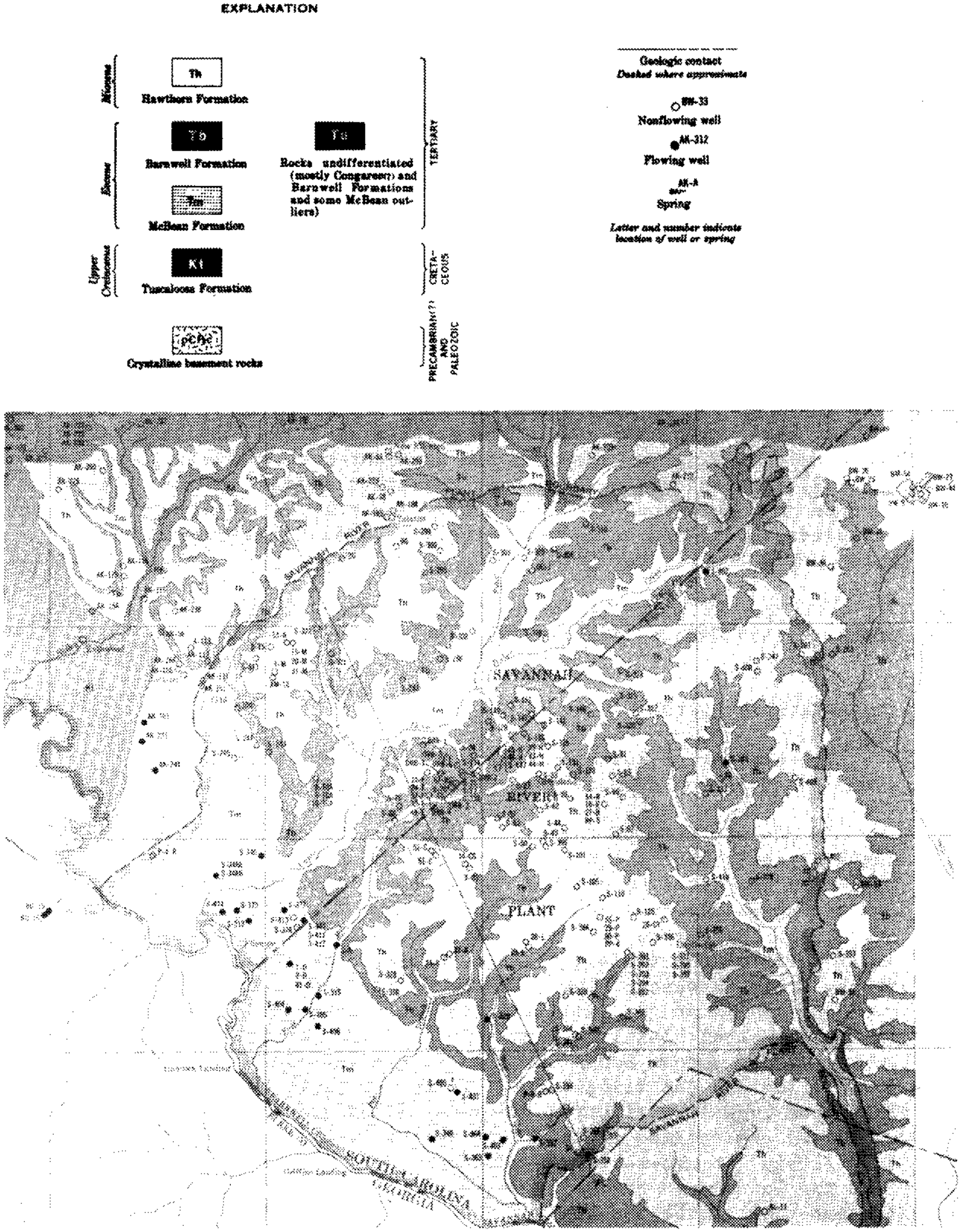


FIGURE I.8. Geologic Map of the Savannah River Plant

The Ellenton Formation was named by Siple[15] because it constitutes a separate and distinct lithologic unit. This formation lies upon the Tuscaloosa Formation in some but not all areas and consists of sandy clay interbedded with medium to coarse quartz sand.

Tertiary System

The Tertiary System consists of the Congaree, McBean, Barnwell, and Hawthorne formations.

The Congaree and McBean formations are usually combined for discussion purposes and called the McBean Formation. These formations are exposed (Figure I.8) along the major portions of the stream beds of Upper Three Runs Creek, Four Mile Creek, and Lower Three Runs Creek. In addition, they comprise all of the flood plain of the Savannah River. These formations consist of sand, marl, and clay. The marl bed has been subjected to subsurface dissolution. The Congaree and McBean formations were deposited during the period of inundation of this area by the Tertiary Sea as evidenced by the presence of numerous fossils.

At SRP, the Barnwell Formation overlies the McBean Formation and is exposed on the slopes between the stream valleys and the Aiken Plateau. The deposits are deep red, fine to coarse clayey sand and compact sandy clay. Fossils are rare in this formation. Siple[15] considers the Barnwell Formation was deposited as a limestone in a near-shore or estuarine environment during early to middle Tertiary time.

The Hawthorne Formation is the surface formation over much of the area on the plant site between the eroded stream valleys. It has numerous sediment-filled fissures crisscrossing the clayey sand.

Descriptive Hydrology

Cretaceous Sediments

The Cretaceous sediments constitute the principal source of ground water in the report area. Even though the two formations, Tuscaloosa and Ellenton, can be differentiated, they are not completely separated by an intervening confining bed, and hence are considered to constitute a single aquifer. The direction of flow (Figure I.3) is from the recharge area on the divide between Shaw Creek and Upper Three Runs Creek along an arcuate path to the Savannah River near Holley Creek. The permeability of the Tuscaloosa aquifer[10] from pumping tests is very high, ranging between 200 and 2600 gpd/ft^2. The porosity is between 25% and 40%, average for unconsolidated sediments. The hydraulic gradient is low, 3 ft/mile. The formation is 600 to 700 ft thick. The maximum velocity of water through the Tuscaloosa aquifer is approximately 1 ft per day, indicating the time for water to move from the center of the plant site to the outcrop area (20 miles) is approximately 300 years.

The McBean and Congaree formations are recharged in the topographically higher regions of the SRP Area and discharge into those tributary streams that dissect the overlying confining beds, such as Upper Three Runs Creek, Four Mile Creek, and Steel Creek. Some water is also discharged along the Savannah River, and some migrates down the dip of the beds to discharge by upward vertical leakage. Pumping tests made at three locations[9] indicate permeabilities range from 140 to 980 gpd per sq ft, adequate to supply around 1000 gpm to a pumping well.

Even though the Barnwell Formation is composed predominately of sand, it does not yield water readily to wells, partly because of the small size of the sand particles. Nevertheless, in some localities the sand of the Barnwell Formation is sufficiently coarse and free from admixtures of silt and clay as to provide moderate water yields to wells.

The Hawthorne Formation has very poor water conducting capabilities. In fact, perched ground water is frequently present.

The actual piezometer heads in the sediments are shown in Figure I.9. Piezometer levels decline with depth down to the Congaree Formation showing the downward movement of water from the water table. The piezometer level in the Ellenton Formation is about 7 feet higher than the piezometer reading in the Congaree Formation. This reading indicates that the Ellenton Formation is receiving water from a source other than vertical percolation, and, in fact, water will tend to move upward into the Congaree Formation. Water levels in the three Tuscaloosa aquifer piezometers are about the same and are lower than that in the Ellenton Formation, but they are still higher than those in the Congaree Formation. The piezometers located in the Tuscaloosa aquifer are within the influence of the cone of depression caused by pumping water from supply wells in H Area and to a lesser extent, in F Area. Under the present hydrology, the Tuscaloosa aquifer is well insulated from surface contamination because of this reversal in head.

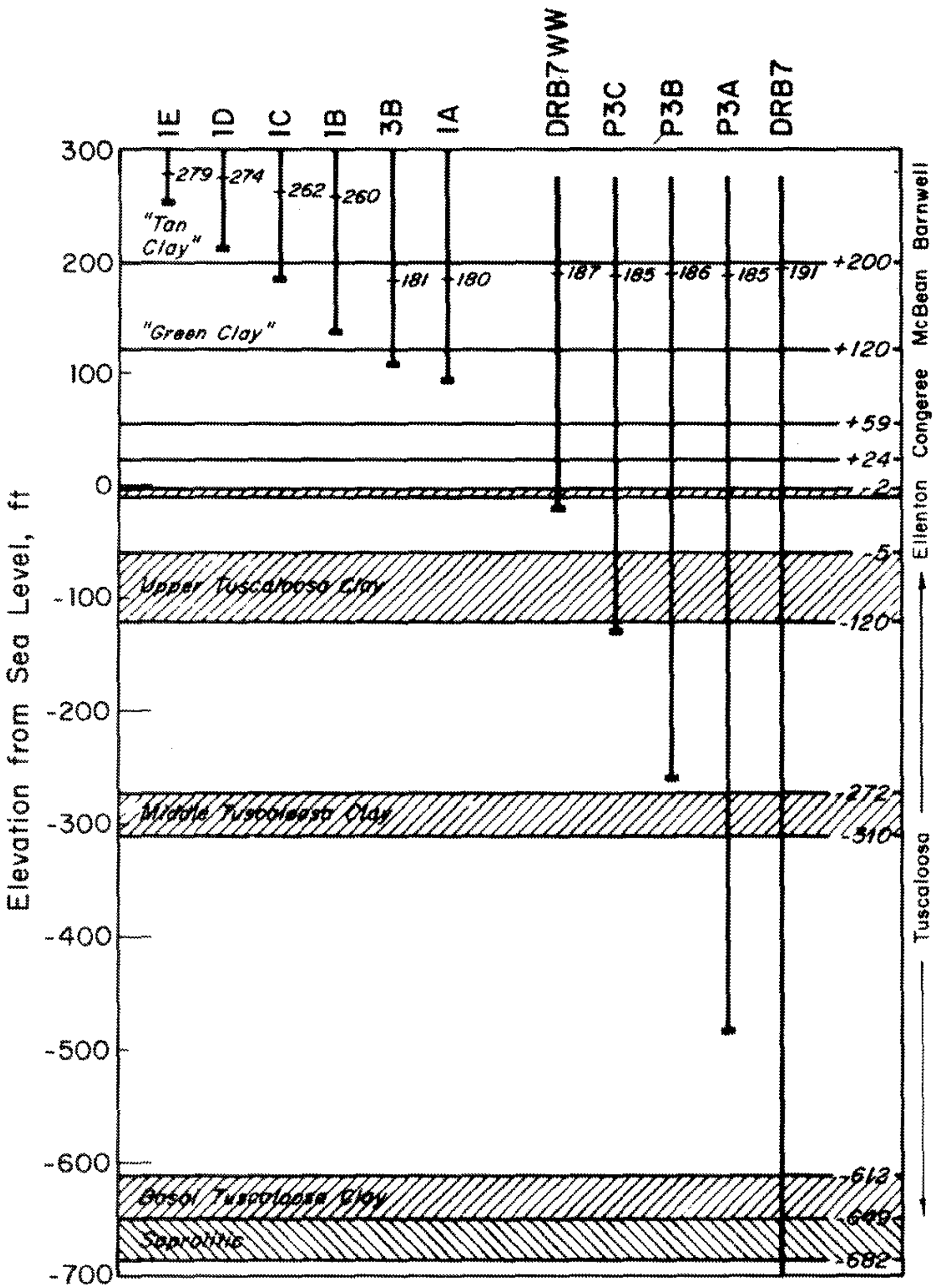


FIGURE I.9. Vertical Distribution of Well Head Pressures from the Tuscaloosa to Ground Surface at SRP

Ion Exchange Capacity

Each of the unconsolidated sediment formations has an ion exchange capacity. These capacities vary with soil texture and type of material (Figure I.10). The highest ion exchange capacities are in the clays of the McBean Formation. The average ion exchange capacity of the sediments is between 1 and 5 meq/100 g of soil. Experiments using SRP soil have shown that cesium and plutonium are generally immobile, or migrate very, very slowly. Strontium moves slightly slower than ground water, and tritium moves with the ground water.

Migration Rates

The expected rate of movement of water in the various formations beneath SRP can be estimated assuming Darcy's Law is valid:

$$V = \frac{\sigma}{\varepsilon} i \qquad (1)$$

where

V = velocity of flow, ft/unit time

σ = permeability, ft/unit time - unit gradient

ε = porosity of the rock system

i = the gradient: (difference in piezometric head, ft of water) ÷ (distance between the two piezometers, ft)

From the exploratory drilling program, extensive inhole hydrology testing, and laboratory measurements, the permeabilities and porosities required in Equation 1 were obtained for the Tuscaloosa, crystalline, and Triassic formations (Table I.11). The hydraulic gradient required in Equation 1 has 3 different values, all of which are approximate for specific cases: 3 ft of water per mile (regional gradient for Tuscaloosa and crystalline formations), 7 ft of water per 500 ft (based on piezometric head differences between crystalline and Tuscaloosa rock), and ∿250 ft of water per 500 ft (based on estimated equilibrium piezometric head difference between Triassic and Tuscaloosa rock).

Figure I.11 can be generated by substituting into Equation 1 the values for the expected gradients and values of σ/ε from Table I.11. From Figure I.11, the travel time from a cavern in

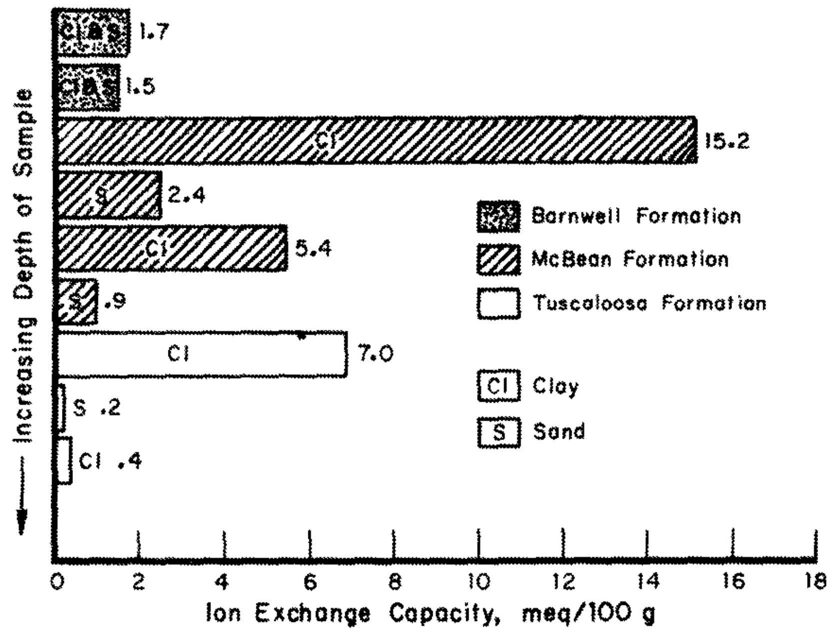


FIGURE I.10. Ion Exchange Capacities of SRP Sands and Clays

TABLE I.11. The Permeability and Porosity of Bedrock Material[a]

Strata	Permeability (σ) ft/yr	Porosity, ε	σ/ε
Crystalline Rock:			
Fractured	48	0.002	24,000
Expected	1	0.001	1,000
Unfractured	1.5×10^{-2}	0.0001	150
Triassic Basin	1.85×10^{-2} (lab)	0.03	0.62
	2.92×10^{-4} (field)	0.03	0.0098
Tuscaloosa Aquifer	2600	0.40	6,500

a. Values used to calculate the flow velocity of water through various formations.

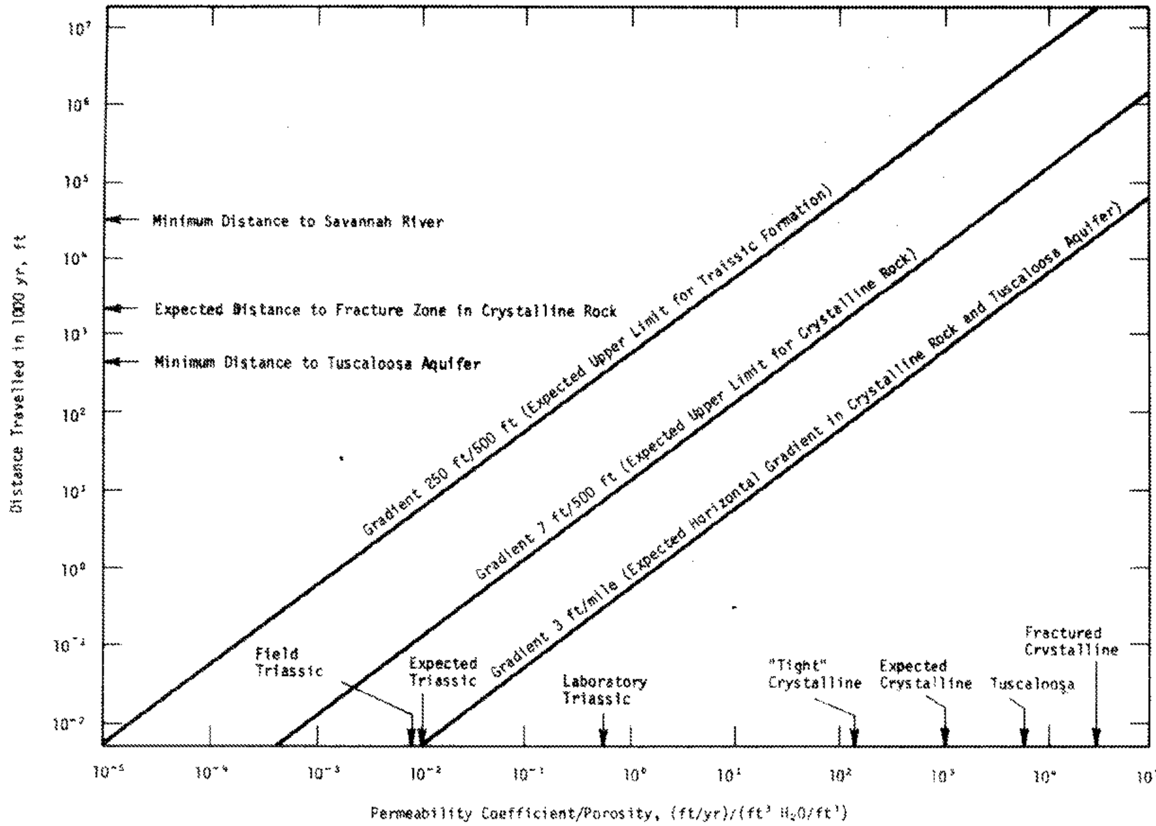


FIGURE I.11. Influence of σ/ε and Gradient on the Distance Traveled by Water Through the Bedrock

crystalline rock having expected hydrologic properties $(\sigma/\varepsilon = 10^3)$ will be 568 ft in 1000 years if a gradient of 3 ft per mile exists. If the gradient is 7 ft per 500 ft, the waste will travel around 14,000 ft in 1000 years. The expected velocity of solution through Triassic rock $(\sigma/\varepsilon = 10^{-2})$ is 5 ft/1000 years from Figure I.11 (assuming no ion exchange capacity of the Triassic rock and neglecting the time for the cavern to reach a piezometric pressure of 250 ft of water above that in the Tuscaloosa rock).

The much lower flow velocities in Triassic rock compared with crystalline rock arise because σ/ε is approximately 10^5 less for Triassic rock than for crystalline rock. An insignificant factor when compared with the effects of σ/ε between the two systems is the much larger gradient that exists between a cavern in Triassic rock and the Tuscaloosa Formation (250 ft/500 ft), than the gradient that exists between a cavern in the crystalline rock and the Tuscaloosa Formation (7 ft/500 ft).

Up to this point, some of the gradients used in the calculations have been the ones that naturally occur between the cavern and the Tuscaloosa aquifer. With increased industrial and residential growth in the area, drawdown of the Tuscaloosa through pumping is inevitable. The maximum drawdown would occur when all of the water in the Tuscaloosa aquifer is removed, in which case the vertical gradient in crystalline and Triassic systems would be approximately 2 ft of water per ft. Figure I.12 indicates that the flow time of water to the Tuscaloosa aquifer from a Triassic cavern under such a gradient would still be around 30,000 years, while water from a crystalline cavern would reach the Tuscaloosa aquifer in less than a year if we assume that the saprolite layer is absent.

The effects of ion exchange have been neglected in this section and are discussed later (Chapter III, Section 3). Because ion-exchange phenomena will reduce the velocity of radioactivity below that of water, we conclude that if water velocities are acceptable, ion exchange will only enhance the suitability of the system.

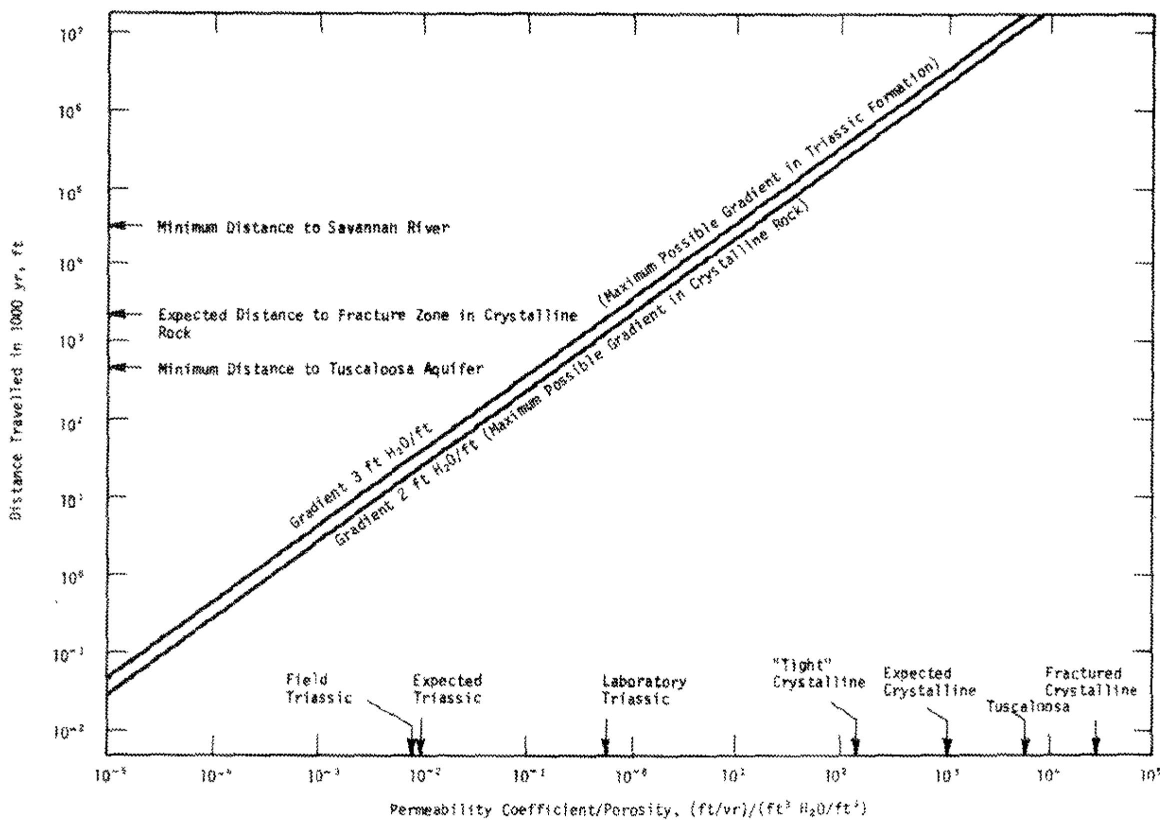


FIGURE I.12. Influence of σ/ε and a High Gradient on the Distance Traveled by Water Through the Bedrock

FUTURE NATURAL CONDITIONS

Earthquakes

The southeastern part of the United States is a region of moderate earthquake activity.[11] The only major earthquake of historic time is the Charleston earthquake of August 31, 1886, whose epicenter was 15 miles northwest of Charleston, S. C. This earthquake strongly affected an area within a radius of 100 miles, and tremors were felt within a radius of 800 miles. The intensity was X at Charleston on the Modified Mercalli scale (Appendix I-D) and probably produced accelerations of 0.15 to 0.30 g's at the ground surface at the epicenter. Since the main quake, hundreds of lesser shocks[12] have occurred in the same area. During the last 100 years, the area within a 100-mile radius of SRP has experienced 9 shocks of intensity V, 4 shocks of intensity VI, 2 of intensity VII, 1 of intensity VIII, and 1 of intensity X (through 1967). The average period between shocks of intensity V or greater has been about 5 years. The frequency of tremors with intensity IV or less has been decreasing since 1886. Between 1886 and 1897, the frequency averaged 29 per year) between 1898 and 1913, the average was 6 per year. The present rate is about 1 per year. Accelerations in the deep crystalline rock could be expected to be one-half the surface accelerations. Maximum accelerations at the ground surface from an earthquake are assumed to be around 0.2 g at SRP for design purposes.

Future seismicity is difficult to predict. Good general clues to the relative seismicity of a region are (a) surface topography, (b) geologic structures, and (c) statistical information on past earthquakes. The area surrounding SRP has low relief, usually indicative of minor seismic activity. A seismic risk map of the United States (Figure I.13) places SRP in Zone 2, moderate damage from earthquakes (corresponds to intensity VII of the modified Mercalli scale). The Zone 2 area is approximately 160,000 mi^2, while Zone 3 area (an area of major damage) is 18,000 mi^2. The crystalline rocks beneath this area and comprising the Piedmont province are tightly folded and broken by major faults. However, there is no evidence of movement along most of these faults during historic time although there is inconclusive evidence for movement along the Brevard Fault, 150 miles northwest of the plant. Statistical information on past earthquakes[12] indicates that the vicinity of the plant site is relatively stable with small tremors of low intensity relieving stresses before major tremors are required to relieve the accumulated stress.

Climatic

Any change in climatic conditions will alter the ground water region beneath the plant site. Alterations could occur from floods, glaciers, and rainfall.

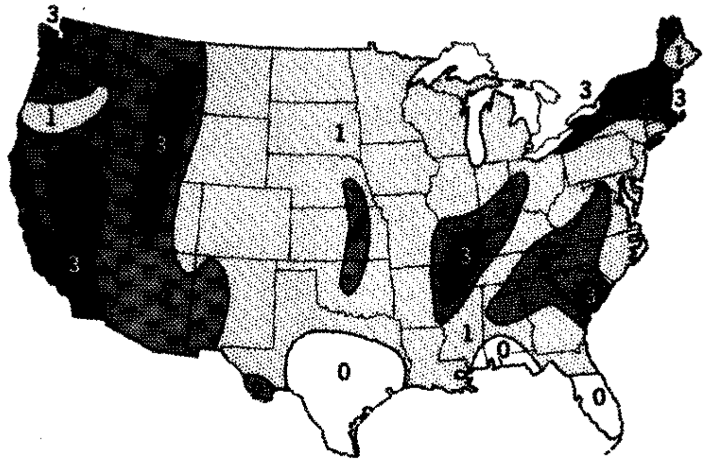


FIGURE I.13. Seismic Risk Map for Contiguous United States

- Floods are short term influences in general and are of minimal influence to flow patterns in the regional ground water patterns.

- Glaciation is unlikely to affect the waste repository. However, should an ice age occur with the appearance of glaciers in the vicinity of SRP, the ground surface could be eroded off down to and into bedrock. Ground water movement would be minimal under prolonged freezing conditions on the surface and unless bedrock was physically removed by the grinding action of glaciers, waste movement would be retarded. Ice ages on earth have occurred 18,000, 235,000,000, and 600,000,000 years ago. There is no evidence that any of the glaciations affected the topography of South Carolina.

- Increased rainfall will have minimal influence on regional aquifer water velocities because the aquifers are filled to the overflow point now. Increased rainfall will generally leave the deposition area by surface runoff rather than by increased aquifer flow.

FUTURE DEVELOPMENT

Economic Value of Regional Subsurface Water Supply

Increased pumping from the Savannah River, Tuscaloosa aquifer, and shallow ground water supplies will occur. The population in the vicinity of SRP is expected to increase and further industrial development will occur causing increased usage of the water supplies. Increased pumping from the Tuscaloosa aquifer will increase the gradient from the crystalline rock to the Tuscaloosa Formation. Detailed analyses using existing plant information could provide insight in this area, if needed.

Mineral Deposits

Coring to date in the bedrock beneath SRP has not indicated the existence of any mineral deposits of value. Comparison of the rock with similar areas elsewhere indicates that there is only a very small likelihood of mineral deposits of commercial value being found.

Gases

Although the helium content of the rock water is unusually high (0.5 cc at STP/liter of water), it is not economical to recover it. There are no other unusual gases detected to date.

Alteration of System

A number of man-made alterations to the hydrology could influence water movement. These alterations are dam construction, rock water withdrawal, injection of surface waters to the rock, and injection of surface waters into the Tuscaloosa Formation.

At the present time, no dams are planned on the Savannah River between Clark Hill and the ocean. Should a dam be placed on the Savannah River, gradients in the bedrock would be decreased, reducing flow. Gradients could be reduced from the present 4 ft per mile to 2 ft per mile but flooding of presently inhabited areas in Augusta would have to take place. Removal of dams upstream from SRP such as Clark Hill and Hartwell will not influence rock water hydrology beneath the plant.

Rock water withdrawal at any rate will alter the gradient. Similarly, rock water injection will influence gradients and alter flow paths. Neither of these factors is likely to occur because of the low yields and porosities present in the rock system; however, detailed analysis of the effects could be generated using detailed information on any proposed well.

Flow through the Tuscaloosa aquifer at the present time is calculated to range between 4 and 52 million gal/day over a 10 mile wide by 500 ft thick section depending on the assumed permeability. These values were obtained for permeabilities of 200 and 2600 gal/ft^2-day respectively, and a gradient of four feet per mile. In contrast, the current plant withdrawal is approximately 8 million gal/day. With increased industrialization in the vicinity of the site, increased pumping from the Tuscaloosa aquifer is anticipated and the piezometric pressure of the Tuscaloosa Formation will decline, enhancing the opportunities for waste migration from a cavern.

APPENDIX I-A. CHRONOLOGY OF GEOLOGIC INVESTIGATIONS OF SRP SITE FOR BEDROCK WASTE STORAGE

1951

- First suggestion that bedrock might serve as a useful waste storage site.

- An exploratory well, in the vicinity of H Area, was drilled by the U. S. Army Corps of Engineers into the crystalline rock to obtain information on the formations underlying the plant site and was abandoned.

1953

- A seismic survey from the Appalachian Mountains through the Piedmont and Coastal Plain to the Continental Shelf was conducted by the University of Wisconsin under a contract with the Office of Naval Research. One of the survey lines passed through SRP.

1958

- An airborne radiometric and airborne magnetometer survey was conducted by the U. S. Geological Survey. Du Pont made a check series in 1961 of four ground profiles with a portable magnetometer that correlated well with the previous data collected using the airborne equipment.

1961 - 1962

- Inception of the crystalline rock exploration program that would take two years to complete. The program consisted of seven deep rock boreholes (DRB 1 through DRB 7) in the vicinity of the Separations Areas.

- Three clusters of 3 piezometers each (P1A, P1B, P1C, P2A, etc.) were placed in the Tuscaloosa aquifer at various depths in the vicinity of the Separations Areas.

- Conducted a pumping test for 31 days at 20.5 gpm on DRB 6.

- Installed piezometer P4A nine miles west of the first seven DRB's and installed two rock piezometers P4R (close to P4A) and P5R (10 miles south-southeast of the Separations Areas). The latter piezometer encountered the Triassic rock formation.

1964 - 1966

- Packer tests, inhole tracer tests, and a between-wells tritium tracer test.

1967

- Three crystalline rock piezometers (P6R, P7R, and P8R) drilled approximately 200 to 300 feet into the bedrock from 4-1/2 to 6 miles north and west of the Separations Areas.

1968

- Year long pumping test of DRB 6 at 14.9 gpm begun.

1969

- Additional crystalline rock exploration with two deep rock boreholes (DRB 8 and DRB 9), one in the vicinity of the Separations Areas and the other at the discontinuity between the crystalline rock and the Triassic rock.

- First seismic survey (to define Triassic border).

1971

- Additional Triassic rock exploration with DRB 10 placed in the Triassic basin. This well was bridged shortly below the bottom of the casing sometime after completion.

- Additional piezometers were placed in both the crystalline rock and Tuscaloosa Formation. P9R and P11R were drilled near P8R. What was previously called the clayey parts of the saprolite, units 1 and 2, was totally absent. P9R was plugged from the bottom to the casing with concrete and abandoned because of major deviations from the vertical. P5A, P7A, and P10A were placed in the Tuscaloosa Formation adjacent to P5R, P7R, and DRB9, respectively.

- Two additional seismic surveys were conducted. The first survey in March, 1971 consisted of a traverse across the Triassic basin on plant grid line E 60,000, a survey line through DRB's 1-5-6-7-8, a survey line through DRB's 7-2-4, and a survey line from DRB 1 west and northwest to P8R and beyond to northern plant boundary. The second survey line in October, 1971 consisted of two traverse lines paralleling but about 3/4 of a mile on either side of the previous traverse along plant grid E 60,000, a traverse along E 80,000, one along the Seaboard Coast Line railroad, and a cross traverse connecting these four lines and the previous line along E 60,000. In addition, a seismic traverse connected well P5R into this network and a traverse was made along a road nearly paralleling E 75,000.

1972

- Ground magnetic and gravity surveys were made along plant grid E 60,000 from about 2.8 miles northwest of well DRB 9 to about 6 miles southeast of Allendale, S. C.

- A pressure gauge was installed on well DRB 10 and pressure continued to build up until it was equivalent to 90 ft above the top of the well casing; 343 ft above sea level; or about 150 ft above the water pressure in the Tuscaloosa Formation.

- Additional drilling was continued in the Triassic rock to explore a suggested fault from the seismic survey. Two wells were drilled: Hole 12 and DRB 11. DRB 11 encountered fractured rock with slick surfaces in the vicinity of the suspected fault zone.

- Program was canceled in late 1972. Reports in progress and this assessment were completed shortly thereafter in order to maximize the availability of the information from the bedrock program.

APPENDIX I-B. EXPLORATORY DRILLING PROGRAM

Introduction

To evaluate the suitability of the rock beneath SRP for storing radioactive waste, 12 deep rock borings (designated DRB 1, DRB 2, etc.) have been drilled through about 1000 ft of overburden and about 1000 ft into the basement rock. In addition, 20 piezometer wells (designated P) have been installed in both rock and sediments. Two geological formations have been the main areas of investigation for the storage of waste, crystalline rock in the vicinity of the two separations areas (designated F and H in Figure 1, Appendix I-B) and sedimentary rock underlying the southeastern section of the plant site.

Wells

Pertinent data, with respect to location and elevation of all DRB's, are shown in Table 1, Appendix I-B and Figure 1, Appendix I-B.

All borings were installed by rotary drilling methods. In general, a 6-in. pilot hole was drilled through the overburden to rock and then reamed to 10 in. diameter. In the first four borings, standard rotary rock bits were used through the overburden and into rock to refusal, which occurred at depths ranging from 10 to 36 ft below the top of the rock. Casing was set at that point, cemented in place, and pressure tested to determine if it would hold 200 psi for 1 hour. Rock corings were started from this point using a 4-in. by 5-1/2-in. double wall core barrel, 20 ft long, and the hole advanced by continuous coring to reach the total desired depth.

In DRB's 1, 3, and 4, the initial coring runs were difficult because of fractured rock and water losses. Some cementing was necessary to prevent broken rock from falling on top of the core barrel and to minimize water losses. In DRB 2, all rock cored was sound and tight.

To avoid the difficulties encountered with DRB's 1, 3, and 4 in coring the upper 200 ft of rock, DRB's 5, 6, and 7 were drilled 200, 200, and 155 ft, respectively, into the rock before the casing was set. Two borings were made at the site of DRB 6. The first of these had reached a depth of 959 ft, or 9 ft below the top of rock, when the drilling tools stuck in the hole and

TABLE I.B.1. Location, Elevation, and Depth of Deep Rock Boring (DRB) Wells

DRB No.	Plant Coordinates	Surface Elev.[a]	Depth to Rock[b]	Elev. of Top of Rock[a]	Casing Depth[b]	Elev. of Top of Casing[a]	Total Depth[b]
1	N80,000 E57,500	261.6	877	-615	890	262.86	1904
2	N72,600 E56,900	281.6	972	-690	982	282.03	1982
3	N75,500 E56,900	285.5	934	-649	951	285.20	1942
4	N73,900 E53,400	250.8	924	-673	960	252.35	1938
5	N75,600 E59.400	286.7	930	-643	1130	288.51	1838
6	N73,958 E60,005	269.1	900	-631	1100	270.50	1913
7	N72,800 E60,000	277.8	960	-682	1115	279.75	1969
8	N71,223 E59,739	262.9	954	-691	959	264.95	1959
9	N55,253 E53,964	295	1034	-739	1125	295.95	2694
10	N33,601 E60,000	250.6	1171	-920	1239	253.15	4206
11	N47,834 E60,183	274.1	1071	-797	1249	-	3320

a. ft above mean sea level.

b. ft below ground surface.

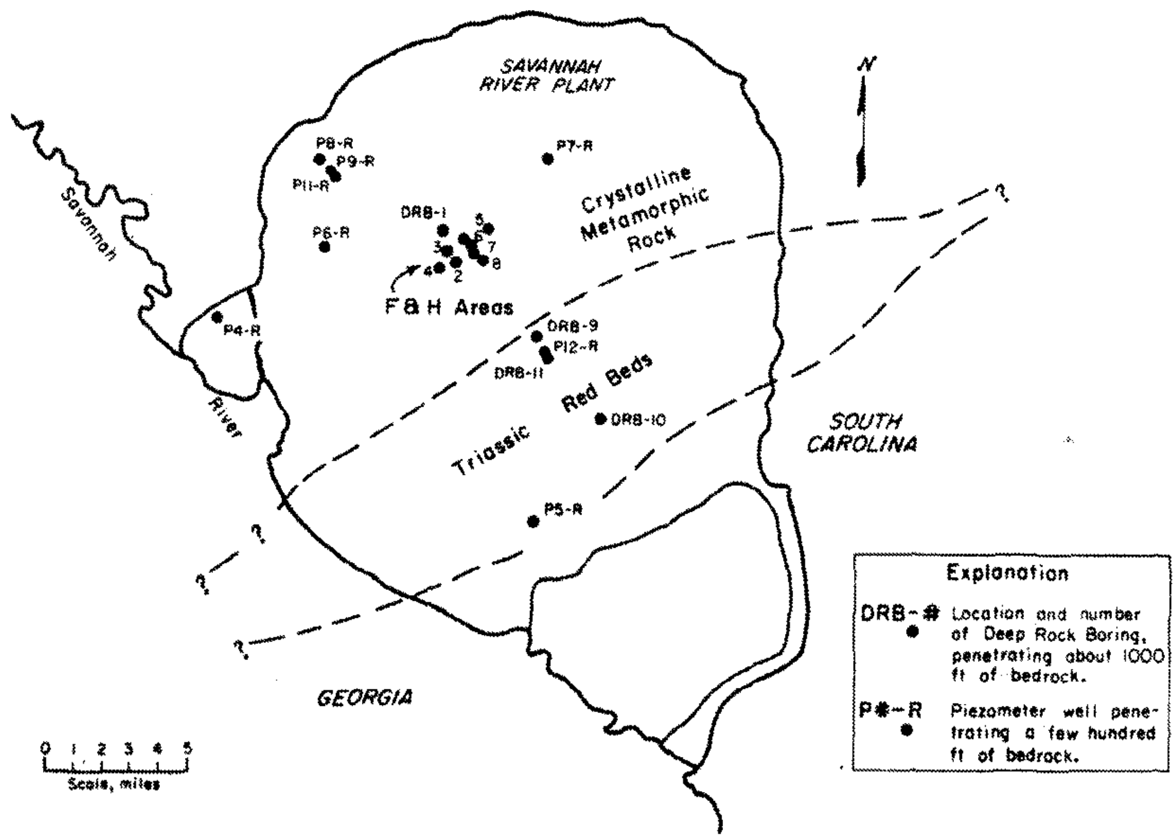


FIGURE I.B.1. Location of Deep Rock Boring Sites and Piezometers for the Bedrock Program could not be recovered. The boring was filled with cement and abandoned. DRB 6 was then relocated approximately 40 ft south-southeast of the abandoned boring site. In DRB's 5 and 7, it was decided to drill, rather than core, an additional 200 ft of rock below the casing shoe since this was a more economical means of advancing the boring. Consequently, coring was performed in DRB 5 from depths of 1330 to 1838 ft and DRB 7 from 1360 to 1969 ft. In DRB 5, severe difficulties were encountered in running the core barrel past the casing shoe. When the boring had reached a depth of approximately 900 ft into rock, with no noticeable change in the type of rock, it was decided to terminate drilling rather than risk the loss of drilling tools and abandonment of the hole.

Additional DRB's, designated DRB 8 and 9, were drilled in June, 1969. DRB 8 was drilled to explore the southeastern margin of a zone of virtually impermeable rock established by the first seven deep rock borings. DRB 9 was used to investigate the hydrologic nature of the regional discontinuity between the crystalline rock and Triassic rock.

DRB 10 was drilled to investigate the nature of the rock near the depositional center of the Triassic graben. Triassic rock was encountered in a zone of core loss at a depth of between 1168 and 1177 ft. The first Triassic material recovered was red mudstone, fairly well consolidated. The remainder of the well, to a total depth of 4212 ft, penetrated randomly occurring layers of pink to grayish sandstone (2/3 of total) and red mudstone (1/3 of total). The casing was set at about 1250 ft and the rock was drilled using only compressed air as a circulating fluid to 1600 ft. Soap was injected below 1600 ft to assist in the removal of cuttings.

DRB 11 and P12R were drilled on either side (660 ft apart) of a fault suggested by the seismic exploration program. Triassic rock was encountered in DRB 11 at -797 ft below mean sea level and in P12R at -795 ft. The almost identical depths indicate that there has been no movement on the suspected fault since the development of the erosion surface formed between 100 and 180 million years ago. Shortly after penetration of the Triassic rock began at DRB 11, the hole was deviated using retrievable steel wedges to angle northward to pass through the suspected fault. Drilling was completed in December, 1972. The final hole was 3320 ft long with a vertical depth of 3278 ft below the ground surface and a horizontal deviation of 385 ft, 55 ft beyond the midpoint of the fault zone. The material cored was predominately massive mudstone showing no bedding with occasional layers of gritty sandstone. Larger fragments consisted of schist, gneiss, and quartzite. Fractured rock with slick surfaces was encountered in the vicinity of the suspected fault region. Inleakage into the well did not increase in the vicinity of the fault zone.

Piezometers

Two basic types of piezometers, overburden and rock, were installed to study regional hydrology. Pertinent data with respect to location and elevation of all piezometers are shown in Table 2, Appendix I-B and Figure 1, Appendix I-B.

Clusters of three overburden piezometers (P1A, P1B, P1C, P2A, etc.) at each of three locations were installed between February and August, 1962. The locations were adjacent to DRB's 3, 4, and 7. At each site, the piezometers are referred to as: "A" - Deep (lower Tuscaloosa aquifer); "B" - Intermediate (bottom of upper Tuscaloosa aquifer); and "C" - Shallow (top of upper Tuscaloosa aquifer). General procedure was to drill the piezometers in the order of "A", "B", and "C" at each site.

Each piezometer designated "A" was installed in the following mannner. A 6-in. pilot hole was drilled to the clay overlying the basement rock. An electric log (to record the resistivity of the porous material and to identify the major sand aquifers of the Tuscaloosa Formation) and a caliper log (to record the diameter of the hole) were obtained. Unwashed ditch samples were taken throughout and preserved. Undisturbed samples were obtained at three locations, the clay above the Tuscaloosa Formation, the intermediate clay in the Tuscaloosa Formation, and the clay at the bottom of the Tuscaloosa Formation overlying the rock. The pilot hole was then reamed and the 6-in. casing installed and cemented to the ground surface. After the screen was installed, each piezometer was developed by surging and a short-term pumping test. Each piezometer, designated "B" and "C", respectively, was drilled to depths predetermined from the electric log of the corresponding "A" piezometer. The casing and screen were set and the piezometer developed as previously described. Formation sampling and electric logging were omitted.

A deep piezometer (P4A) was installed in the Tuscaloosa Formation to obtain a piezometric surface near the river. The formation in this location has a water pressure that is above the land surface. To avoid difficulties with this artesian pressure, alterations in piezometer design were made. The piezometer was installed by using a 4-in. screen set in the basal Tuscaloosa sand. The piezometer was capped at the ground surface and equipped with a pressure gauge.

Two piezometers (P4R and P5R) were installed in rock at remote locations from the Separations Area in order to obtain measurements. Piezometer P4R is located near the river adjacent to overburden piezometer P4A. In order to minimize the problem of artesian pressure in the overburden, a 10-in. diameter casing was set to a depth of

TABLE I.B.2. Location and Elevation of Piezometers

No.	Coordinates North - East	Elevations,[a] Surf. of Ground	Top of Casing	Casing Diam., in.	Setting in Feet Below Ground: Bottom of Casing	Well Screen From - To	Depth, Ground Surface to Rock, ft.
P1A	N75,444 E56,848	287.9	289.3	6	794.6	798.7-809.0	
P1B	N75,443 E56,818	289.1	290.2	6	539.4	545.0-555.0	
P1C	N75,465 E56,797	289.4	291.9	2	358.0	358.0-368.0	
P2A	N73,896 E53,316	249.9	250.9	6	763.1	769.0-779.0	
P2B	N73,895 E53,335	250.3	252.1	6	516.5	522.0-532.0	
P2C	N73,893 E53,281	249.0	251.6	2	340.0	340.0-350.0	
P3A	N72,800 E60,100	277.1	279.1	6	755.0	761.6-771.6	
P3B	N72,800 E60,130	277.6	278.9	6	534.1	537.5-547.5	
P3C	N72,826 E60,115	278.3	279.5	2	400.5	400.5-410.5	
P4A	N90,583 E14,957 Note: Elev. of pressure gage was 109.7 ft.	105.3	108.2	4	559.0	559.0-569.0	
P4R	N90,559 E14,902	105.3	106.6	6	708.7	Open Hole 708.7-765.0	690
P5R	N24,616 E40,685	208.4	209.5	6	1253.1	Open Hole 1253.1-1312.9	1252.8
P5A	N24,649 E40,617	206.4	208.64	7	974	973.5-983.5	
P6R	N86,227 E36,895	253.0	255.91	6	852	Open Hole 852-1042	842
P7R	N77,638 E83,253	273.0	275.99	6	900	Open Hole 900-1178 Total Depth, 1178 ft	888

a. Elevations in feet above mean sea level (MSL).

TABLE I.B.2. Location and Elevation of Piezometers (contd)

No.	Coordinates North - East	Elevations: Surf. of Ground	Elevations: Top of Casing	Diam., in.	Setting in Feet Below Ground: Bottom of Casing	Setting in Feet Below Ground: Well Screen From - To	Depth, Ground Surface to Rock, ft
P7A	N77,660 E83,309	273.5	275.49	7	703	703.5-713.5	
P8R	N102,013 E46,195	357.0	359.60	6	829	Open Hole 829-1026 Total Depth, 1026 ft	830
P9R	N97,643 E47,743	321.2	324.53	7	820	Total Depth, 1245 ft	733
P10A	N55,280 E60,049	296.7	299.74	6 5/8	821	841.3-851.3	
P11R	N97,535 E47,758	320.1	323.32	7	821	Open Hole 821-1569 Total Depth, 1569 ft	733
P12R	N48,486 E59,953	292.3	296.15	4 1/2	1222	Open Hole 1222-1272	1088

218 ft and cemented in place. The hole was then drilled to a depth of 708.7 ft and a 6-in. casing was set and cemented in place. Top of rock was encountered at a depth of 690 ft. Using carbide insert knobby bits, the rock was then drilled to a depth of 765 ft. The hole is open in crystalline rock from 708.7 to 765 ft. Piezometer P5R is located about 10 miles south-southeast of the deep rock borings. In drilling for this piezometer, weathered rock was encountered at a depth of 1218 ft and hard rock reported at 1230 ft. A 6-in. casing was set to a depth of 1253 ft and cemented in place. Using a standard rotary rock bit, the rock below the casing was drilled to 1299 ft, then cored with a double wall core barrel to 1313 ft. The 12 ft of core recovered was identified as belonging to the Triassic Red Bed group. The hole is open in rock from 1253 to 1313 ft.

Three piezometers (P6R, P7R, and P8R) were installed at distances from 4-1/2 to 6 miles from the vicinity of the Separations Areas during 1967 in order to measure piezometer heads in the surrounding area. The piezometers were rotary drilled through the overburden to the basal Tuscaloosa clay with a 9-7/8-in. diameter bit. Unwashed ditch samples were taken at 10 ft intervals and preserved. Attempts to obtain undisturbed samples of the sand, comprising the basal aquifer of the Tuscaloosa Formation, were unsuccessful, except in P8R, where three samples were obtained. The lower portion of each hole through the basal Tuscaloosa clay and the saprolite overlying the rock was cored with a 4-in. by 5-1/2-in. core barrel and the samples were preserved. The portion of the hole which was cored was enlarged by reaming with a 9-7/8-in. diameter rock bit. Each hole was extended into the rock by coring and reaming for a distance sufficient to set the casing. The 6-in. diameter casing was set, cemented in place, and pressure tested. The casing test requirement of 200 psig at the ground surface remaining constant for a period of one hour after pressurization was met for P6R but could not be met for P7R and P8R. The casing installations for P7R and P8R were accepted without location or repair of the leaks on the premise that casing leaks can be isolated from the hydraulic system of the bedrock by future installation of packers. Also, calculations indicated that the leak in each well was probably in the top casing joint. This joint was cemented by a different method than the rest of the casing. After the pressure tests of the casing, the water in the casing was blown out, and the casing shoe was drilled out using air for circulation. Air drilling in the rock was done with 5-5/8-in. or 5-7/8-in. diameter bits. In P8R, after the plug was drilled, the rock was cored for about 4.5 ft and cores recovered before drilling.

In P6R, approximately 4 ft of rock core was obtained from the bottom of the hole. When only a negligible amount of water was encountered in drilling in the rock for P7R, drilling was continued below 200 ft into the rock but was terminated when a carbide insert and pieces of two of the other inserts were lost from the bit and could not be recovered. Additional drilling attempts resulted in the loss of carbide inserts from a new bit. Attempts to recover these inserts were not successful and in the attempts a magnet and sinker bar, a 5-ft length of 1-1/2-in. pipe, were also lost. These were not recovered and remain in the bottom of the hole.

Hydrofracturing of the rock portion of P7R was attempted to increase the water flow into the hole. A Lynes inflatable packer was installed at a depth of about 994 ft, and about 5200 gallons were injected into the hole at a treating pressure of 3300 psi together with about 2000 lb of sand (propping agent). After the hydrofracturing operation, the hole was bailed and also blown out with compressed air to remove the sand and water left in the hole. The sand was removed to a depth of approximately 1170 ft (8 ft above total depth). Ultimately, about the same quantity of sand was removed as was originally injected into the hole. During the removal operation, the yield of the well continually decreased. The ultimate yield returned to the rate before hydrofracturing of the well began.

A well designated P9R was drilled 4000 ft SE of piezometer P8R. No saprolite was encountered above the crystalline rock but substantial amounts of weathering of fractured rock had occurred. The hole was cased at 825 ft and then drilling continued into rock to a measured depth of 1250 ft, where logging revealed a horizontal displacement of 104 ft N 19 1/2° W and a maximum deviation angle of 23 1/2° from vertical. The water yield was 0.06 gpm, not nearly sufficient for desired hydrologic observations. The well was plugged with concrete up to the casing rather than attempting to drill deeper or to straighten the hole. Another well, P11R, was drilled about 50 ft from P9R as a substitute well. P11R was cased at 830 ft and drilled to 1576 ft. The water yield was even lower (0.025 gpm at 1200 ft depth). This well is serving as a rock piezometer.

Three Tuscaloosa Formation piezometers (P5A, P7A, and P10A) were drilled[2] adjacent to P5R, P7R, and DRB 9. A fourth new well near P6R was abandoned because of drilling difficulties. These piezometers were screened in the lower Tuscaloosa Formation and show that the head in the Tuscaloosa aquifer is approximately 10 ft lower than the head in the rock. These wells were 6-1/2-in. in diameter. The well casing is 1/4-in.-wall mild steel.

Abandoned Well 35H

During the exploratory phase of the Savannah River Plant investigations, Dr. J. L. Gillson, Development Department, E. I. du Pont de Nemours and Co., suggested the exploration of the bedrock for its suitability for storing radioactive waste. The first well to explore the bedrock was drilled in 1952 as a continuation of a completed water well. Briefly, the well was an extension of a water well drilled to 860 ft. In order to protect the completed water well from damage due to the circulation of drilling fluids, a 5-in. I.D. casing was equipped with Hastellite slugs on its lower end and then drilled a few tenths of a foot in the concrete plug in the bottom of the well. This formed an effective seal between the subsequent drilling and the water well. The hole was advanced by fish-tailing methods, until weathered broken rock was encountered at 1001.1 ft. The hole was continued until relatively firm rock was reached at about 1200 ft below the surface. At this point, a 3-1/2-in. casing was placed inside the 5-in. casing and cemented to the weathered rock. Coring operations were then begun. Approximately 164 ft of cored hole was drilled. Packer tests revealed inflow measured 1/16th of a gallon per minute and the static level of the water in the rock at a depth of approximately 1025 ft below ground surface was found to be approximately equal to that of the Tuscaloosa Formation. At the completion of packer tests, the equipment was removed from the hole and the water well rehabilitated for use. The condition of the well in the rock is unknown. Hence, Well 35H is considered abandoned.

Abandoned Well DRB 6

The second well that has been abandoned following penetration of the crystalline bedrock is the predecessor to the present DRB 6. This well is 40 ft west of the present DRB 6. Following the removal of the first bedrock core, the drilling tools were lifted to 744 ft below the ground surface and drilling suspended for one day. The following day the tools were found to be wedged in place. Subsequent efforts freed all but the bottom 33 ft of equipment consisting of pipe and bit. The well was cemented from the bit upward but beneath the bit there may remain an open hole extending 147 ft into the Tuscaloosa aquifer, 55 ft through the saprolite, and 12 ft into the crystalline rock.

Types of Rocks

The rock core specimens encountered from DRB 1 (29 core samples) are predominately fresh, foliated, medium grained, flaser textured, quartz-feldspar gneiss, and hornblende gneiss. Subordinate rock types are fresh, fine grained, hornblende schist, and hornblende-chlorite schist. Mylonite gneiss and epidotic streaks occur locally where granulation and confining pressure were more intense. Structural features include (a) healed fractures at inclined angles to foliation containing secondary calcite, zeolite, chlorite-sericite, or a combination of these minerals, (b) local minor flexures, and (c) local shear folds with minor displacements.

The rock types from DRB 2 (13 core samples) consist of predominately dark, greenish-grey, fine grained, dense varieties of schist containing local lensoid units of quartzite and gneiss. Subordinate flaser and mylonite gneiss occur in the samples in the lower portion of the hole.

The schist varieties, in order of decreasing abundance, include hornblende, chlorite, hornblende-chlorite, chlorite-biotite, and epidotic chlorite. Gneiss varieties range from quartz-feldspar gneiss to highly granulated mylonite gneiss.

The rock samples from DRB 3 (15 core samples) are predominately greenish-grey, dense, fine grained, foliated varieties of schist containing local subordinate bands and lensoid units of quartzite and gneiss. Varieties include hornblende-chlorite, chlorite-biotite, and epidotic chlorite schists.

Calcite-healed fractures, at inclined angles to schistosity, are common occurrences; minor displacement along shear fractures and minor flexures are local occurrences.

The rock samples from DRB 4 (14 core samples) are predominately grey, fresh foliated, fine grained, intercalated mixtures of phyllite and micaceous quartzite between 1603-1903 ft, and dark greenish-grey, schist varieties at other locations. White, lensoid units of coarser grained, granoblastic textured quartzite comprise up to 20% of some of these samples. Although contorted banding and minor flexures are common, foliation and schistosity are generally parallel. Thin calcite-healed fractures occur locally, both parallel to and at inclined angles to schistosity.

The specific gravity of most of the rock core samples from DRB 4 is less than in samples from other borings because of the relatively high ratio of quartz. Rock weakness is attributed primarily to schistosity. Sericite is an important constituent of phyllite and, where abundant, imparts a satin luster to the rock.

The rock types from DRB 5 (8 core samples) are essentially greenish-grey, fine grained, epidotic chlorite schist in the upper elevations and micaceous quartzite in the lower portions of the hole. Schistosity and foliation increase from 55 degrees to essentially vertical with increasing depth. Thin fractures, essentially parallel to and at inclined angles to schistosity tend to be poorly healed with calcite; many of these fractures appear partially healed and contain ferruginous stains.

Schistosity and poorly-healed fractures contribute appreciably to rock weakness. The tendency of the rock to break along such planes of weakness limited the selection of samples to the stronger sections of the boring and compressive strength values are necessarily not representative. The lower compressive strength values are all attributed to poorly-healed fractures.

The rock core samples from DRB 6 (11 core samples) are predominately foliated, fine grained, varieties of schist and subordinate gneiss and micaceous quartzite. Varieties include hornblende, chlorite, hornblende-chlorite, and epidotic chlorite schists. Mylonite gneiss occurs in samples toward the bottom of the boring. Micaceous quartzite foliations and lensoid units of white, coarser grained, granoblastic textured quartzite occur locally in the schist varieties. Thin, generally discontinuous, calcite-healed fractures, at inclined angles of schistosity, are common occurrences.

The rock core samples from DRB 7 (12 core samples) are (a) predominately greenish-grey, foliated, fine grained varieties of schist containing local lensoid units of gneiss, and (b) subordinate micaceous quartzite. Schistosity and foliation in the rock samples are parallel. Thin, discontinuous, calcite-healed fractures at various angles to schistosity are common occurrences. Minor flexures also occur locally in the schist.

The rock core samples from DRB 8 are predominately grey quartzite hornblende gneiss but two sections (1379 to 1434 ft, and 1454 to 1554 ft below the ground surface) were almost pure white to tan quartzite.

The rock core samples from the Triassic rock in DRB 9 are predominately a red claystone and siltstone matrix containing many angular particles of gneiss and quartzite (fanglomerate). DRB 9 penetrated the contact between the Triassic and crystalline rock at a depth of 2627 ft. The crystalline rock cores consisted of pink feldspar augen of 1/4 to 1/2 inch size set in a green hornblende matrix.

The rock core samples from DRB 10 consisted of three different Triassic rock types: first, a red to maroon mudstone including clay, silt, and some fine-grained sandstone; second, a grey-brown, fine-to-medium grained sandstone including much silt and clay (this rock appears poorly sorted and well consolidated; occasionally, alternate grey and light tan thin cross beds occur in this rock type); finally, a pink to buff medium-to-coarse-grained arkosic sandstone. In the arkosic sandstone, pink weathered feldspar and subangular quartz and schist sand particles are set in a matrix of hematitic clay. Occasionally, grit and small pebbles occur. This sandstone is fragile and appears weakly cemented. Common in both types of sandstone are clasts of mudstone very similar to the mudstone found at other depths in the well.

The rock core samples from DRB 11 are predominately massive mudstone consisting of clay, silt, and fine sand with no apparent bedding. Occasionally, layers of gritty sandstone 5 to 6 ft thick occurred. The mudstone made up about 90% of the core, the gritty sandstone comprised the remainder. Larger fragments of rock in the gritty sandstone were schist, gneiss, and quartzite similar to the rock types that make up the crystalline rocks to the northeast.

APPENDIX I-C. SITE SURVEYS

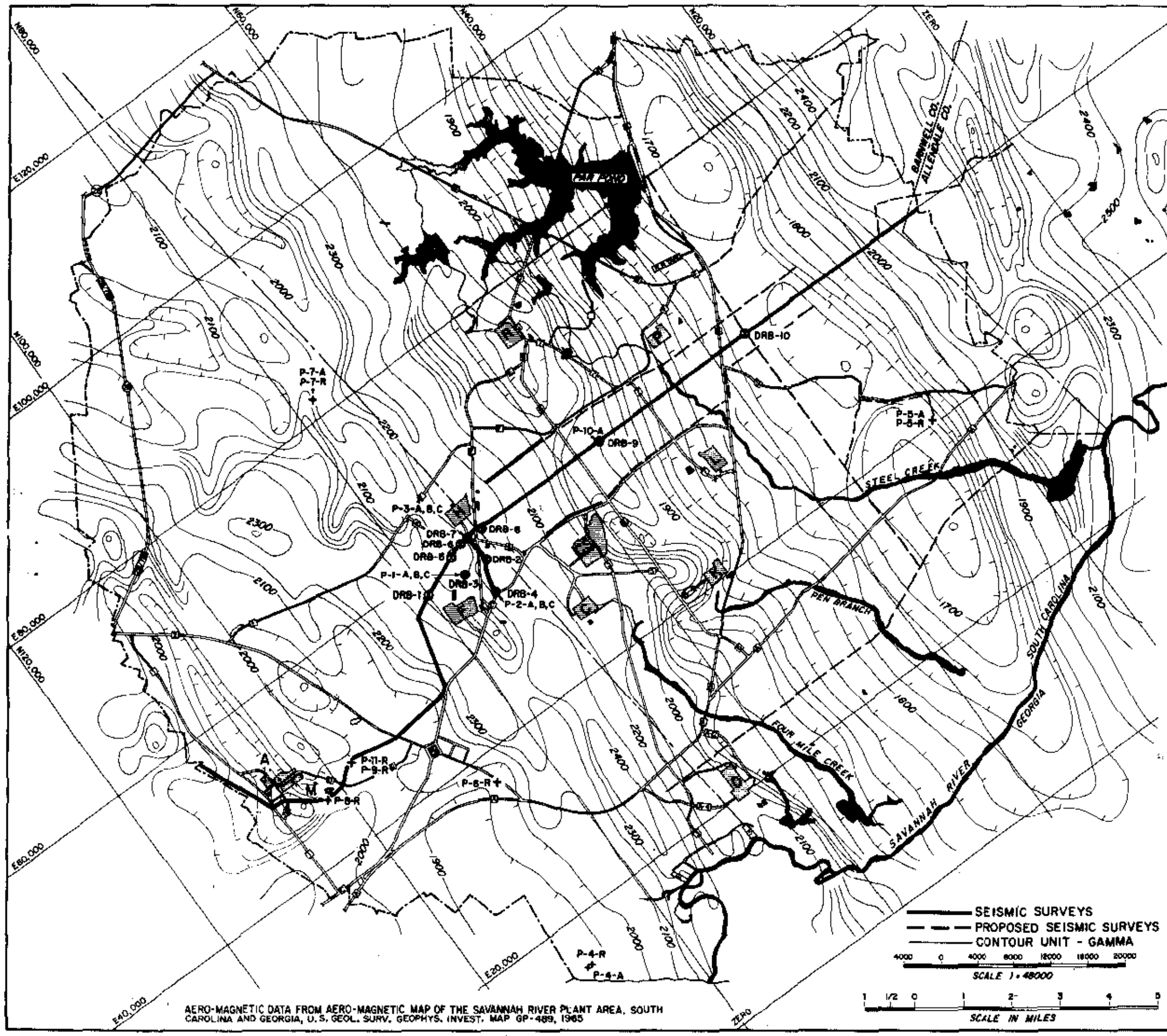
Aeromagnetic Survey

In July and August, 1958, the U. S. Geological Survey made an airborne magnetic survey of the plant site at the same time they were making an airborne radiometric survey. The flights were made in a N 40° W direction at one mile spacing and 500 ft above ground surface. In general, the data (Figure 1, Appendix I-C) show a belt five miles wide of linear highs and lows with a 400-gamma amplitude trending about N 50° E through the area, paralleled on the southeast by a 6.5-mile-wide zone of lower and relatively constant magnetic intensity. Subsequent exploration determined the magnetic highs and lows were not caused by relief variations, but magnetic variations. The magnetic low may be caused by the Triassic basin.

Seismic Surveys

Seismic surveys were conducted in May 1969, March 1971, and September-October 1971. The seismic survey lines and indicated faults are shown in Figure 2, Appendix I-C. Highlights are as follows:

Analysis of the data from the survey line across Dunbarton Triassic basin on plant grid line E 60,000 shows that a major normal fault downthrown NW is indicated 2 miles NW of the southern plant boundary. This is where the SE border of the basin is expected to be, based on the aeromagnetic survey. In addition, two intrabasin normal faults downthrown SE were indicated 1-3/4 and 4-3/4 miles NW of the SE border fault, and several displaced reflectors, possibly bedding planes in the basin, were detected. Those more than 3 miles NW of the SE border fault dip SE, and those less than 3 miles NW of the border fault dip NW. A possible additional fault located about 3000 ft inside the southern boundary of the plant and downthrown NW is suggested. Three reflectors dipping NW at depths of 3000 to 4000 ft and located just outside the plant boundary "might reflect the attitude of the crystalline rock" (underlying Triassic basin) according to the survey report. These findings do not appear to support the hypothesis, based largely on the aeromagnetic survey, that the south border of the Triassic basin is at an indicated fault about 2 miles inside the plant. Data from the survey lines through DRB's 1-5-6-7-8 and 7-2-4 indicated no faults.



⊕ DEEP ROCK BORINGS

DRB NO.	PLANT COORDS.	SURF. ELEV.	DEPTH TO ROCK	ELEV. TOP OF ROCK	CASING DEPTH FT. BELOW G.L.	ELEV. TOP OF CASING	TOTAL DEPTH
1	N80,000 E57,500	261.6	877	-615	890	262.86	1904
2	N72,600 E56,900	281.6	972	-690	982	282.03	1982
3	N75,500 E56,900	285.5	934	-649	951	285.20	1942
4	N73,900 E53,400	250.8	924	-673	960	252.35	1938
5	N75,600 E59,400	286.7	930	-643	1130	288.51	1838
6	N73,958 E60,005	269.1	940	-671	1100	270.50	1913
7	N72,800 E60,000	277.8	960	-682	1115	279.75	1969
8	N71,223 E58,739	262.5	954	-691	959	264.95	1959
9	N55,253 E59,964	295.0	1034	-739	1125	295.95	2694
10	N35,601 E60,000	250.6	1171	-920	1239	253.15	4206

+ PIEZOMETERS

PIEZ. NO.	PLANT COORDS.	SURF. ELEV.	ELEV. TOP OF CASING	CASING DIA.	BOTTOM OF CASING FT. BELOW GRD.	WELL SCREEN FROM-TO FT. BELOW GRD.	
P-1-A	N75,444 E56,848	287.9	289.3	6"	794.6	798.7 - 809.0	
P-1-B	N75,443 E56,818	289.1	290.2	6"	539.4	545.0 - 555.0	
P-1-C	N75,465 E56,797	289.4	291.9	2"	358.0	358.0 - 368.0	
P-2-A	N73,896 E56,316	249.9	250.9	6"	763.1	769.0 - 779.0	
P-2-B	N73,895 E53,335	250.3	252.1	6"	516.5	522.0 - 532.0	
P-2-C	N73,893 E53,281	249.0	251.6	2"	340.0	340.0 - 350.0	
P-3-A	N72,800 E60,100	277.1	279.1	6"	755.0	761.6 - 771.6	
P-3-B	N72,800 E60,130	277.6	278.9	6"	534.1	537.5 - 547.5	
P-3-C	N72,826 E60,115	278.3	279.5	2"	400.5	400.5 - 410.5	
P-4-A	N90,853 E14,957	105.3	108.2	4"	559.0	559.0 - 569.0	
P-4-R	N90,559 E14,902	105.3	106.6	6"	708.7	708.7 - 765.0TD	No Screen - Open Hole Depth to Top of Rock = 690 ft
P-5-R	N24,616 E40,685	208.4	209.5	6"	1253.1	1253.1 - 1312.9TD	No Screen - Open Hole Depth to Top of Rock = 1252.8 ft
P-5-A	N24,649 E40,617	206.4	208.64	7" 20 lb	974	973.5 - 983.5	
P-6-R	N86,227 E36,895	253.0	265.91	6"	852	Total Depth = 1042 ft Depth to Rock = 842 ft	
P-7-R	N77,638 E83,253	273.0	275.99	6"	900	Total Depth = 1178 ft Depth to Rock = 888 ft	
P-7-A	N77,660 E83,309	273.5	275.49	7" 20 lb	703	703.5 - 713.5	
P-8-R	N102,013 E46,198	357.0	359.60	6"	829	Total Depth = 1026 ft Depth to Rock = 830 ft	
P-9-R	N97,643 E47,743	321.2	324.53	7" 20 lb	820	Total Depth = 1245 ft Depth to Rock = 733 ft	Plugged Back into Casing
P-10-A	N55,280 E60,049	296.7	299.74	6-5/8" 20 lb	824	841.3 - 851.3	
P-11-R	N97,595 E47,758	320.1	323.32	7" 20 lb	821	Total Depth = 1569 ft Depth to Rock = 733 ft	

FIGURE I.C.1. Aero-Magnetic Survey of the Savannah River Plantsite

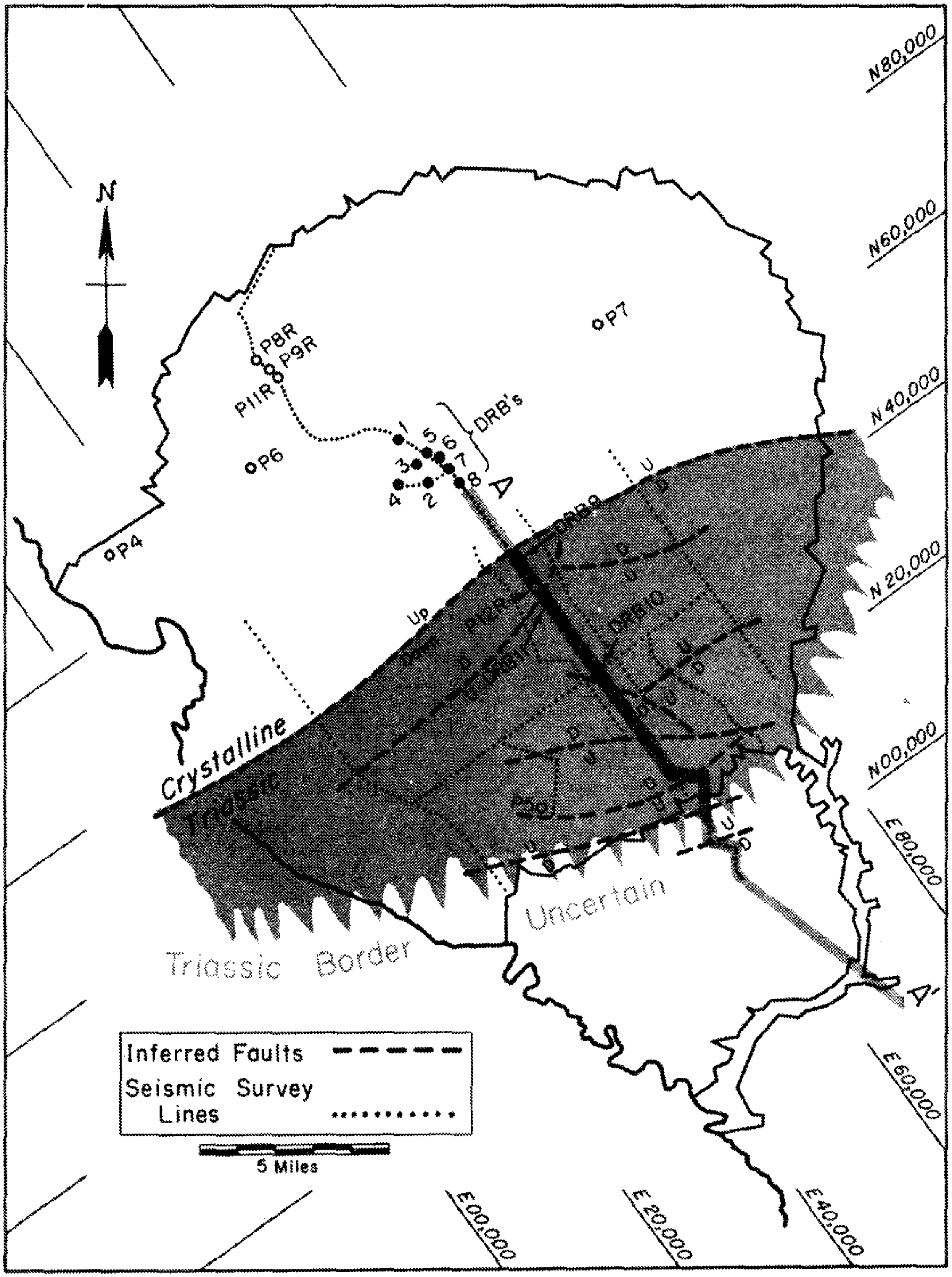


FIGURE I.C.2. Triassic Basin Fault Correlations from Seismic Surveys

Data from the survey line from DRB 1 west and northwest to P8R and beyond to the northern plant boundary indicated a fault within 250 ft of P8R, SE of the well and downthrown NW. Only one other possible fault was indicated, about 3 miles west of DRB 1 and downthrown SE. The reflection previously designated "Near Top Saprolite" about 100 ft above the reflection identified with top of crystalline rock was fairly continuous in the DRB area but continuity became questionable west of DRB 1 and this reflection was not recognizable from about 3 miles west of DRB 1 (near Road 2) to P8R (2-1/2 miles further NW) and beyond P8R about 2-3/4 miles to the plant boundary.

Magnetic and Gravity Surveys

Ground magnetic and gravity surveys were made during February 1972, along plant grid E 60,000 from about 2.8 miles northwest of well DRB 9 to about 6 miles southeast of Allendale, S. C. (Figure 2, Appendix I-C). This line coincides with seismic reflection survey line 1 but extends farther southeast. The surveys were made by Seismograph Service Corporation.

A magnetic survey, made on the ground, measures the intensity of the vertical component on the earth's magnetic field, which is influenced primarily by the depth and magnetite content of subsurface rocks. A gravity survey measures differences in the acceleration of gravity caused by differences in the depth and density of subsurface rocks. Both types of surveys are generally more responsive to metamorphic and igneous rocks than to sedimentary rocks. Thus, if the character (density, magnetic content) of the metamorphic or igneous rocks is known or assumed, these surveys permit an estimate of the configuration and depth of the base rock. When the character of the rocks is unknown, usually several assumed models will fit the observed data.

Figure 3, Appendix I-C shows two models developed by Seismograph Service Corporation that fit the magnetic and gravity observations along the traverse line. These models indicate the Triassic basin is composed of block-like units of different thicknesses. From the border fault near well DRB 9, the basin generally becomes deeper to a point 11,500 ft southeast of well DRB 10, where its depth is estimated to be 6500 ft. From that point it shallows to about 4200 ft at the southeastern plant boundary. Southeast of the plant, depths range from about 3000 to 5800 ft. These depths include the Coastal Plain sediments, which are similar to the Triassic rocks in their density and magnetic properties. However, all of these estimates are based on assumed basement rock densities and are subject to revision when the density of basement rock becomes better known.

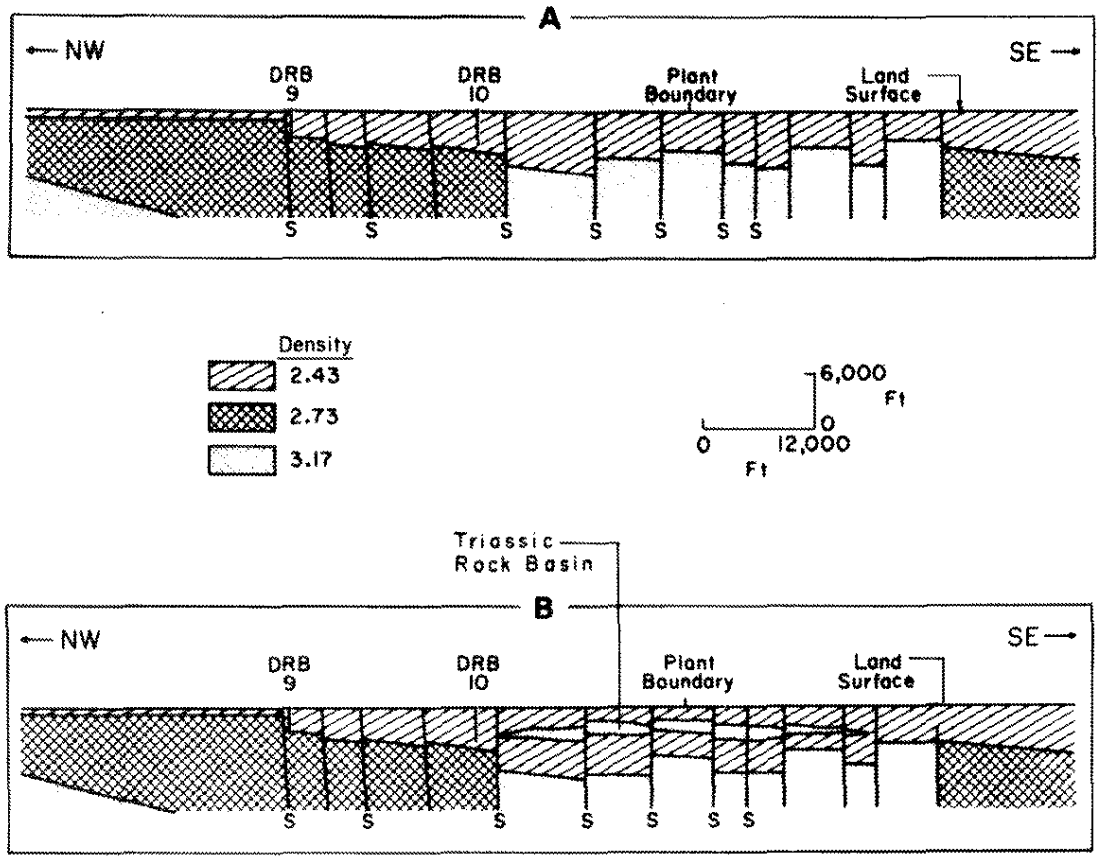


FIGURE I.C.3. Alternative Cross-Sectional Models of the Triassic Basin Based on Magnetic and Gravity Surveys (Faults marked S correlate with Triassic surface displacements found by seismic surveys: Figure A assumes dense material in the basement rock; Figure B assumes dense material present in both basement and Triassic Rock)

The surveys indicate that the faults suggested by the seismic survey as displacements on the surface of the Triassic basin correlate with displacements of the basement rock. Whereas the indicated displacements on the surface of the Triassic basin are from about 20 to 100 ft, the indicated displacements on the basement surface are from about 300 to 2500 ft. This indicates that, unless the displacements on the Triassic surface are erosional in origin, movement on the faults occurred both before and after the development of this surface.

APPENDIX I-D. EARTHQUAKE MEASUREMENTS - MODIFIED MERCALLI SCALE, 1956 VERSION[a]

Intensity	Description
I.	Not felt. Marginal and long-period effects of large earthquakes.
II.	Felt by persons at rest, on upper floors, or favorably placed. Average ground motion, 0.23% g; ground motion range, 0.1 to 0.5% g.
III.	Felt indoors. Hanging objects swing. Vibration; like passing of light trucks. Duration estimated. May not be recognized as an earthquake. Average ground motion, 0.31% g; ground motion range, 0.1 to 0.8% g.
IV.	Hanging objects swing. Vibration; like passing of heavy trucks, or sensation of a jolt like a heavy ball striking the walls. Standing motor cars rock. Windows, dishes, doors rattle. Glasses clink. Crockery clashes. In the upper range of IV, wooden walls and frame creak. Average ground motion, 0.93% g; ground motion range 0.2 to 4.6% g.
V.	Felt outdoors; direction estimated. Sleepers wakened. Liquids disturbed, some spilled. Small unstable objects displaced or upset. Doors swing, close, open. Shutters and pictures move. Pendulum clocks stop, start, change rate. Average ground motion, 1.33% g; ground motion range, 0.2 to 7.5% g.
VI.	Felt by all. Many frightened and run outdoors. Persons walk unsteadily. Windows, dishes, glassware broken. Knick-knacks, books, etc., fall off shelves. Pictures fall off walls. Furniture moved or overturned. Weak plaster and masonry D crack. Small bells ring (church, school). Trees, bushes shaken (visibly, or heard to rustle). Average ground motion, 4.0% g) ground motion range, 0.5 to 17.5% g.

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a. Ground motion accelerations were taken from: F. Neumann. *Earthquake Intensity and Related Ground Motion.* University of Washington Press, Seattle, Wash. (1954).

VII. Difficult to stand. Noticed by drivers of motor cars. Hanging objects quiver. Furniture broken. Damage to masonry D, including cracks. Weak chimneys broken at roof line. Fall of plaster, loose bricks, stones, tiles, cornices (also unbraced parapets and architectural ornaments). Some cracks in masonry C. Waves on ponds; water turbid with mud. Small slides and caving-in along sand or gravel banks. Large bells ring. Concrete irrigation ditches damaged. Average ground motion, 6.7% g; ground motion range, 1.8 to 14% g.

VIII. Steering of motor cars affected. Damage to masonry C; partial collapse. Some damage to masonry B; none to masonry A. Fall of stucco and some masonry walls. Twisting, fall of chimneys, factory stacks, monuments, towers, elevated tanks. Frame houses moved on foundations if not bolted down; loose panel walls thrown out. Decayed piling broken off. Branches broken from trees. Changes in flow or temperature of springs and wells. Cracks in wet ground and on steep slopes. Average ground motion, 17.2% g; ground motion range, 5.1 to 35% g.

IX. General panic. Masonry D destroyed; masonry C heavily damaged, sometimes with complete collapse; masonry B seriously damaged. (General damage to foundations.) Frame structures, if not bolted, shifted off foundations. Frames racked. Serious damage to reservoirs. Underground pipes broken. Conspicuous cracks in ground. In alluviated areas sand and mud ejected, earthquake fountains, sand craters.

X. Most masonry and frame structures destroyed with their foundations. Some well-built wooden structures and bridges destroyed. Serious damage to dams, dikes, embankments. Large landslides. Water thrown on banks of canals, rivers, lakes, etc. Sand and mud shifted horizontally on beaches and flat land. Rails bent slightly. Average ground motion, 25% g.

XI. Rails bent greatly. Underground pipelines completely out of service.

XII. Damage nearly total. Large rock masses displaced. Lines of sight and level distorted. Objects thrown into the air.

Masonry A - Good workmanship, mortar, and design; reinforced, especially laterally, and bound together by using steel, concrete, etc., designed to resist lateral forces.

Masonry B - Good workmanship and mortar; reinforced, but not designed in detail to resist lateral forces.

Masonry C - Ordinary workmanship and mortar; extreme weaknesses, such as failing to tie in at corners. Neither reinforced nor designed against horizontal forces.

Masonry D - Weak materials, such as adobe; poor mortar; low standards of workmanship; weak horizontally.

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CHAPTER II. EVALUATION GUIDELINES

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CHAPTER II. EVALUATION GUIDELINES

INTRODUCTION

The assessment of bedrock storage as a long-term waste management technique requires a definition of the minimum criteria that should be met. The basic purpose of bedrock storage, or any other long term waste management technique, is the protection of the health and safety of the population, and the criteria should reflect this requirement. Because of the presence of a number of extremely long-lived toxic radionuclides in the waste, the criteria should not only include limitation of the dose to any single individual in the near future, but also a limitation of the somatic and genetic damage to the population as a whole over many generations. Minimization of the risk of biomedical damage from the constituents in the waste will result in a net benefit to the population as long as the costs incurred in minimizing these risks are not excessive. The guidelines for total quantities of activity that can be released should ultimately be considered on this cost-benefit-risk basis; however, the specification for each constituent is beyond the scope of this analysis.

In this section, it is assumed that drinking water is the critical pathway for uptake by man. Design guidelines, based on the criterion of minimum dose to an individual through the drinking water pathway, are then postulated for all waste constituents. These guidelines are given in terms of the maximum allowable concentrations in public zone water and are necessary but may not be sufficient due to the possibility of critical pathways to man other than drinking water. A bedrock system would probably be designed to meet these guidelines by a wide margin.

A preliminary cost-benefit-risk analysis is also made in this section comparing the expected cost of bedrock storage, the estimated biomedical costs of releasing very long-lived isotopes such as ^{129}I, ^{135}Cs, and ^{239}Pu from a bedrock facility, and the estimated biomedical costs of abandoning the waste in its present condition.

This analysis assumes that all non-radioactive constituents of the waste, such as nitrate, nitrite, and mercury, can be safely released to the biosphere as long as they are sufficiently diluted.

SUMMARY

Two general criteria are assumed to be applicable to this analysis:

1. Radioactive and stable constituents entering the biosphere should have a negligible effect on a single individual.

2. Radioactive and stable constituents entering the biosphere should produce as low as practical effect on the population as a whole over extended time periods (many generations).

Based on the first criterion and assuming drinking water to be the critical pathway, the following upper limit design guideline was established for this analysis:

- Total concentration of all toxic constituents in public zone water will be less than 1% of presently accepted values of maximum permissible concentration (MPC).[1]

With a limitation of 1% of MPC for radioactive constituents, the yearly whole body dose to a single individual will not exceed 5 mrem (∿3% of natural background).

Although the relatively short-lived radioisotopes, such as ^{90}Sr and ^{137}Cs with ∿30 year half lives, present the greatest ingestion hazards for the first 600 years, the longer lived radioisotopes such as ^{129}I, ^{135}Cs, and ^{239}Pu and the stable chemical constituents such as nitrate, nitrite, and mercury present the greatest long term ingestion hazard to an individual through the drinking water pathway. These constituents essentially set the requirements for the bedrock storage system.

Although no guidelines were established in this analysis for acceptable total quantities of each constituent that could be released, estimates were made of the potential biomedical costs of releasing all of the very long-lived isotopes from a bedrock cavern assuming that drinking water was the only pathway to man and assuming a biomedical cost of $1000 per man-rem. The cost of abandoning waste in its present form in the existing tanks was also estimated and these costs were then compared to the expected cost of a bedrock storage facility.

This preliminary cost-benefit-risk analysis indicates that:

- The potential net biomedical cost of abandoning unaltered Savannah River radioactive waste in existing tanks is estimated to be about $300,000,000. The expected $100,000,000 cost of a bedrock storage facility for unaltered waste appears justified on this basis.

- The potential biomedical cost (at $1000/man-rem) of a bedrock storage facility that releases all of the ^{129}I and ^{135}Cs but essentially none of the ^{239}Pu may be only a few million dollars distributed over many centuries (ca. $130,000 for ^{129}I and ca. $2,200,000 for ^{135}Cs for the drinking water pathway); however, other potential pathways should be investigated.

  - Additional bedrock facility costs to prevent the entry of most of the ^{239}Pu into the biosphere are justified, if necessary, based on the estimated potential biomedical cost of ca. $66,000,000 for releasing all of the ^{239}Pu from a bedrock cavern.

The final assessment of bedrock storage will require identification and analysis of all potential exposure pathways for all of the isotopes, with special emphasis on the extremely long-lived isotopes such as ^{129}I, ^{135}Cs, and ^{239}Pu as well as the stable toxic chemical constituents such as mercury, and comparison on a cost-benefit-risk basis with alternative waste management techniques.

DISCUSSION

Criteria

Two basic criteria should be met by the bedrock storage system to minimize the effect of the high level radioactive waste placed in the facility to this and succeeding generations:

1. Radioactive and stable constituents entering the biosphere should have a negligible effect on a single individual.

2. Radioactive and stable constituents entering the biosphere should produce as low as practical effect on the population as a whole over extended time periods.

Criterion 1: Negligible Effect on a Single Individual

Analysis of the possible critical pathways to man indicates that the most important pathway leading to potential uptake by an individual is ingestion of water contaminated by activity from the bedrock cavern. This analysis assumes that ingestion of water is the critical pathway for all constituents. Since the possibility does exist that the critical pathways for certain constituents may be other than ingestion of water, the guidelines developed in this analysis must be considered necessary but not sufficient in satisfying the first criterion.

For the first criterion to be met, the net concentration of all radioactive species and toxic stable chemical species must be well below presently accepted values for MPC in public zone water (taken as MPC values given in 10CFR20[1] for the radioactive species). For this analysis, the quantitative upper limit design guideline based on the first criterion is:
Total concentration of all toxic species in public zone water will be less than 1% of MPC. If a number of species migrate through the rock together, it is necessary that each be well below 1% of MPC so that the net total of all of the species taken together does not exceed 1% of MPC. This design guideline insures that the yearly per capita dose will not exceed 5 mrem to the whole body, 30 mrem to the bone, 30 mrem to the skin and thyroid, and 15 mrem to all other soft tissues.[1] This represents a maximum dose of approximately 3% of natural background radiation.

The bedrock storage system would be designed to meet this guideline by a wide margin. For this analysis, the point of measurement is taken conservatively to be the waste as it leaves the bedrock with no credit taken for further dilution by the Savannah River or Tuscaloosa aquifer.

The relative toxicities of the waste constituents with respect to MPC are shown in Figure II-1 as a function of time assuming complete solubility (Appendix II-A). After approximately 600 years, the non-radioactive constituents nitrate, nitrite, and mercury and the relatively long-lived radioisotopes ^{239}Pu and ^{129}I represent potentially the most hazardous constituents with respect to MPC; however, almost all components are several decades above MPC.

Criterion 2: Low as Practical Effect on the Population as a Whole over Extended Time Periods

In addition to limiting the dose to a single individual, the effect of small doses of radiation to large numbers of people over extended time periods must also be considered. The second criterion requires that the total quantities of activity released should not exceed certain limits even if it can be shown that the concentration would never exceed 1% of MPC, e.g., essentially all of the waste could be pumped into the Savannah River at a rate such that the concentration would not exceed 1% of MPC.

Acceptable levels of long-term cumulative radiological effects have not yet been established nor have criteria for evaluating the biological dose potentially available from radionuclides with extremely long half-lives been developed. Inasmuch

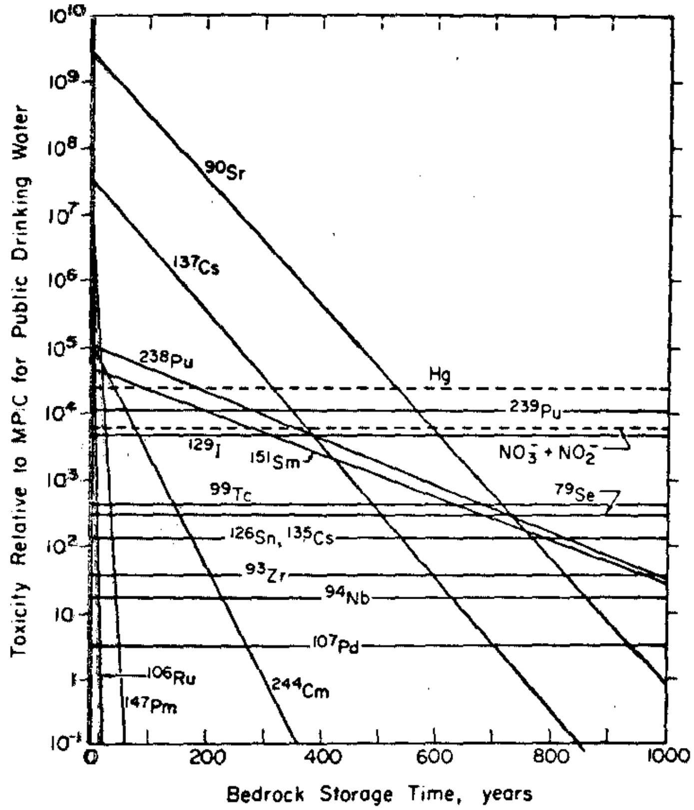

FIGURE II.1 Relative Toxicities of Waste Constituents as a Function of Time as the net effects of bedrock disposal should ultimately be compared with the effects of other waste management alternatives on a risk-benefit-cost basis, development of acceptable methods for handling the risk from long-lived radionuclides should be pursued.

Although no acceptable method for evaluating the risk of long-lived radionuclides is available, the net radiological effect of a radioisotope entering the biosphere will be a function of the amount present and the ultimate amount of uptake by man. The amount released by any confinement system can be estimated with fair accuracy; however, additional information will be required to evaluate the long term uptake and the effect of low-level radiation doses to many generations. For example, one needs to know how often and in what amounts would a release of ^{239}Pu cycle through man over a period of 100,000 years. In addition, one needs to know if there is a difference in the biomedical effects between one man receiving 1 rem in a lifetime versus man, in general, receiving a total of 1 rem over 2000 generations (ca. 40,000 years). Once this information is available, the potential biomedical costs that result from the release of radioactivity to the environment can be readily calculated and equated with the cost of reducing these releases by the use of the various alternative waste storage methods.

Assumptions

Inasmuch as the foregoing information is not available, the following conservative assumptions were made to evaluate the risks from radioactivity releases.

- There is not a threshold below which radiological damage ceases in man.
- Radiation effects are assumed to be linearly related to the dose and are independent of the dose rate.

These assumptions are routinely used by national and international bodies that set radiation protection standards and are acceptable to most people for short term exposures. Extrapolating these assumptions for use in long term exposures (many centuries) has not been done.

Hazard Index

These assumptions were used to develop a hazard index for comparing the relative long term potential ingestion hazard for the isotopes present in SRP waste. The hazard index for each isotope is simply the product of the total quantity in curies, the half life in years (as a measure of the potential time period over which the isotope might exist in the biosphere), and the integrated 70-year whole body dose in rem that would result as a consequence of each curie ingested (Appendix II-A). The absolute value of this index is meaningless except on a comparative basis between the various isotopes. The potential hazard index does not take into account differences in the rate of migration of the various radionuclides through the rock or differences in their availability in the biosphere. The use of the half life of an isotope as a measure of its biological availability tends to overestimate the relative hazard of extremely long-lived isotopes that may be converted to innocuous forms in the biosphere long before they have decayed.

Numerical values of the potential ingestion hazard index are shown in Table II-1 and Figure II-2 as a function of time. It is expected that activity would not reach the biosphere from an acceptable bedrock cavern for at least several thousand years. After ca. 10,000 years, the long term hazard indices of ^{135}Cs and ^{129}I are the largest (Table II-1). Of the remaining activity, ^{239}Pu has the greatest potential long term hazard index; however, after 100,000 years the ^{239}Pu index is only 2% of the ^{135}Cs index. When retention of ^{239}Pu in bedrock is taken into account, the potential hazard of ^{239}Pu would appear to be less than that for ^{135}Cs and ^{129}I, because ^{135}Cs (and possibly ^{129}I) are expected to be soluble in the liquid phase but much of the ^{239}Pu is presently in the sludge; also, the plutonium is more strongly adsorbed on the rock than cesium or iodine. The extremely long half lives of ^{129}I and ^{135}Cs tend to over-estimate the relative biologic hazards of these two isotopes.

The ^{129}I, ^{135}Cs, and ^{239}Pu appear to be the principal long term radiation hazards in a bedrock storage system.

Table II.1 Hazard Index for Potential Ingestion Over an Extended Time Period

Isotope	Half Life ($t_{1/2}$), yr	Initial Quantity (Qu) Ci	Integrated Whole Body Dose per Ci Ingested (D), rem/Ci	Hazard Index for Long-Term Potential Ingestion $Q(Ci) \times D \frac{rem}{Ci} \times t_{1/2}$ (yr): Initial	10^4 yr	10^5 yr
^{79}Se	6.5×10^4	5.4×10^2	5.2×10^2	1.8×10^{10}	1.6×10^{10}	4.5×10^5
^{90}Sr	28.9	2×10^8	9×10^5	5.2×10^{15}	<<1	<<1
^{93}Zr	9.5×10^5	6.7×10^3	0.9	5.7×10^9	5.7×10^9	5.3×10^9
^{99}Tc	2.1×10^5	3×10^4	50	3.1×10^{11}	3.0×10^{11}	2.2×10^{11}
^{107}Pd	7×10^6	2.6×10^1	12	2.1×10^9	2.1×10^9	2.1×10^9
^{129}I	1.6×10^7	6.2×10^1	1.3×10^4	1.3×10^{13}	1.3×10^{13}	1.3×10^{13}
^{135}Cs	2.3×10^6	2.8×10^3	4.9×10^3	3.2×10^{13}	3.2×10^{13}	3.1×10^{13}
^{137}Cs	30.2	2×10^8	4.4×10^4	2.7×10^{14}	<<1	<<1
^{151}Sm	93	4.8×10^6	2.9	1.3×10^9	<<1	<<1
^{238}Pu	87.4	1.7×10^5	2.2×10^4	3.3×10^{11}	<<1	<<1
^{239}Pu	2.4×10^4	1.7×10^4	2.6×10^4	1.1×10^{13}	8.2×10^{12}	6×10^{11}

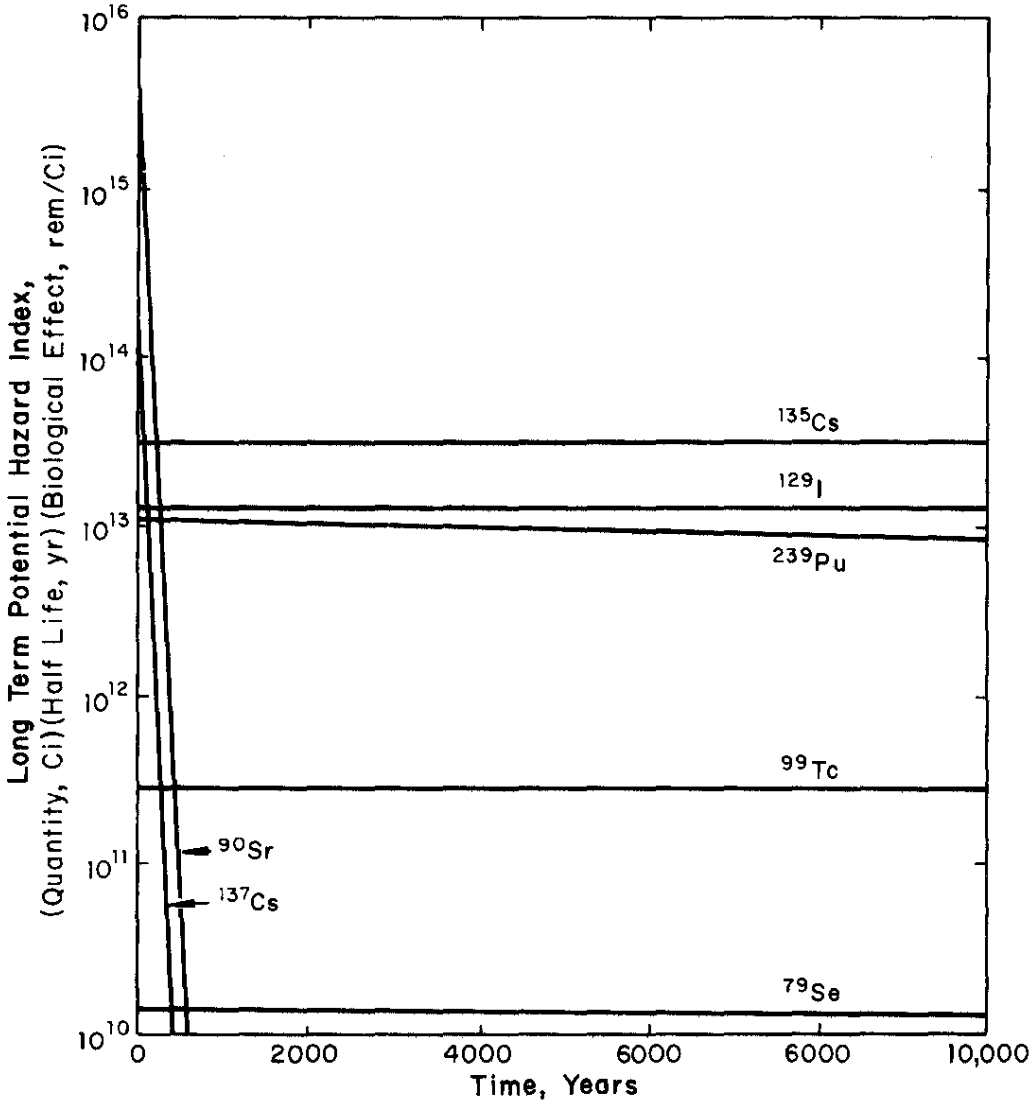

FIGURE II.2 Long-Term Potential Hazard Index for Ingestion of the Radionuclides

Biomedical Cost Estimates

For the purposes of this report, the biomedical cost per man-rem is assumed to be $1000. This value is based on social and technical judgment and is assumed to be a reasonable estimate of the biomedical costs (Appendix II-B) incurred from somatic and genetic damage due to radiation. A number of examples follow to illustrate the usefulness of a value for the biomedical cost in assessing the cost to society of various releases and in quantifying Criterion 2; radioactive and stable constituents entering the biosphere should produce as low as practical an effect on the population as a whole over extended time periods.

Example 1: Uptake of Nuclides of 1% of MPC

At the maximum concentration level of 1% of the currently accepted Maximum Permissible Concentration (MPC), the maximum yearly whole body dose per person would be 5×10^{-3} rem (assuming none of the activity is removed in any water treatment step). At an assumed biomedical cost of $1000 per man-rem, the yearly cost per capita would be a maximum of $5.00/yr. On this basis, if the number of people in the population and/or the time period over which they are exposed were large, the potential long term biomedical costs could be appreciable. For example, if a population of 10^6 people were to consume drinking water at 1% of MPC for 100 years, the total cost would be $\$500 \times 10^6$.

Example 2: Uptake of only ^{129}I, ^{135}Cs, and ^{239}Pu

For discussion purposes, order of magnitude estimates of the long term biomedical costs of ^{129}I, ^{135}Cs, and ^{239}Pu ingestion will be compared for the drinking water pathway to man. In this example, the basic assumption is that the bedrock storage facility is capable of retaining all activity with half lives in the order of ^{137}Cs and ^{90}Sr (approximately 30 years) but incapable of holding the very long-lived isotopes, and that all of the ^{129}I, ^{135}Cs, and ^{239}Pu present in the cavern enters the Savannah River. The following other assumptions are made for this case:

1. 10% of the total river flow is used for human needs.

2. Average per capita water usage for all purposes is 200 gallons per day (corresponds to present rates).

3. Average per capita drinking water consumption is 1.2 liters per day.

4. All of the activity that enters the river remains dissolved and mixed in the river.

5. None of the activity is removed in water treatment.

6. Activity that is not taken up by intake pumps of the water supply and ingested is deposited in the environment and does not again enter public zone water.

The fraction of the river used for drinking purposes would be:

$$(1.2\ \ell/\text{day})(0.264\ \text{gal}/\ell)(0.1) \div 200\ \text{gal/day} = 1.6 \times 10^{-4}$$

Based on assumptions 4, 5, and 6 the fraction of activity entering the river and being ingested would also be 1.6×10^{-4}. The net biomedical costs for this pathway (Table II-2) assuming *all* of the long lived activity initially in cavern enters the river are: $\$1.3 \times 10^5$ for ^{129}I, $\$2.2 \times 10^6$ for ^{135}Cs, and $\$66 \times 10^6$ for ^{239}Pu. If the waste were to first enter the Tuscaloosa aquifer instead of the Savannah River, the total costs would be the same as calculated for activity entering the river for assumptions equivalent to those made for the river (10% of aquifer flow used for human purposes, etc.).

Table II.2 Biomedical Costs of Releasing Long-Lived Radioactivity from the Cavern.

Radioisotope	Activity in waste, Ci[a]	Dose, rem/Ci ingested[b]	Cost, Dollars[c]
^{129}I	6.2×10^1	1.3×10^4	1.3×10^5
^{135}Cs	2.8×10^3	4.9×10^3	2.2×10^6
^{239}Pu	1.7×10^4	2.6×10^4	6.6×10^7

a. From Table II.1

b. From Chapter II, Appendix C, Table 1.

c. Cost = (activity in waste,) x (fraction of river flow used for drinking) x (Dose, rem/Ci) x ($1000/rem)

The assumption that 10% of the flow of the Savannah River or Tuscaloosa aquifer is used for human needs permits an estimate of the maximum potential uptake by drinking water. Although the total dose to the population is the same in each case, it should be noted that the number of people in the population would be different for the two water sources.

Based on the preceding assumptions and the present minimum Savannah River flow of ca. 2.5×10^6 gpm, the maximum number of people that can utilize the Savannah River as their water supply would be:

$$(0.1)(2.5 \times 10^6 \text{ gpm})(1440 \text{ min/day}) \div 200 \text{ gal/day-person} = 1.8 \times 10^6 \text{ persons}$$

Based on an estimated maximum flow of ca. 10^8 gal/day for the Tuscaloosa aquifer in the vicinity of the plant site (assumes the aquifer is 20 miles wide x 500 ft thick with a gradient of 4 feet/mile and a permeability of 2600 gal/ft^2-day), the corresponding population supported by the aquifer would be:

$$(10^8 \text{ gal/day})(0.1) \div 200 \text{ gal/day-person} = 50{,}000 \text{ persons}$$

If biomedical costs irrespective of population size are taken to be the valid criteria for use in cost-benefit-risk analysis, and if no allowance is made for the time value of money, it would appear that expenditure of additional funds above that required for a minimum bedrock facility would be justified if necessary to prevent entry of ^{239}Pu into either the Tuscaloosa aquifer or the Savannah River. Conversely, it is concluded that the potential biomedical costs of a bedrock storage facility that retains essentially all of the activity (other than extremely long-lived ^{129}I and ^{135}Cs) may be relatively small.

Example 3: Failure of Waste Tanks

The biomedical costs of alternatives to bedrock disposal have not yet been determined. For the purpose of comparison, it is useful to estimate the potential biomedical cost of abandoning the waste in its present condition, assuming the same drinking water pathway. This is not considered as an alternative to bedrock but represents an upper limit in biomedical costs. The calculation techniques and assumptions used in this estimate are equivalent to those used in evaluating the bedrock system. Only ingestion of drinking water is considered as a pathway.

It is assumed that the waste tanks would fail soon after abandonment and all of the waste would be catastrophically released as solution. Based on the expected minimum travel time of ground water to the nearest creek (200 years) and taking into account absorption of radioisotopes as they flow through the soil, it is estimated that after approximately 500 years, ca. 2000 Ci of ^{90}Sr would have entered the Savannah River. Based on the previous assumption of 1.6×10^{-4} of the activity ingested, the biomedical cost is $\$287 \times 10^{6}$ for ^{90}Sr by this pathway. The ^{239}Pu is expected to remain adsorbed in the soil. After about 60,000 years, all of the ^{135}Cs would enter the creeks and river. The total cost of the ^{135}Cs would be the same as estimated previously for use of the Savannah River for drinking water: $\$2.2 \times 10^{6}$. The total biomedical costs are approximately $\$300 \times 10^{6}$. The cost of a bedrock storage facility for unaltered waste is estimated to be approximately $\$100 \times 10^{6}$. The preceding analysis indicates expenditures of this magnitude are more than justified in terms of the potential biomedical costs associated with the shorter lived activity. Based on this preliminary analysis and the second general criterion (as low as practical effect on the population as a whole over extended time periods) the following additional guideline was established for this analysis:

- No significant quantities of ^{90}Sr, ^{137}Cs, or ^{239}Pu in the waste shall be released to the environment. This restriction requires that the ^{239}Pu must remain in the bedrock for 250,000 years or more.

Example 4: Alternative Pathways to Drinking Water

The potential biomedical costs estimated in the foregoing examples are for the drinking water pathway only. Due to the long half lives of the isotopes discussed, additional pathways that might continue to expose the population for extended time periods must be considered to assure that their net effects are acceptable. For example, if all of the ^{129}I and ^{135}Cs enter the biosphere and if a long term pathway exists such that there is a net effective uptake of each of these isotopes of 10^{-8} of the total per year during the entire effective physical lifetime of each isotope, the net biomedical costs would be about \$130,000 for ^{129}I and about \$2,200,000 for ^{135}Cs. The strong dependence of the cost estimates on the dollar cost per man-rem (\$1000/man-rem) should be noted.

Toxic Chemical Species

The foregoing discussion has dealt primarily with the biomedical costs of radionuclides in drinking water. Also present in the wastes are toxic stable chemical species, predominantly nitrate, nitrite, and mercury. Any assessment should assume that all of these stable chemicals will ultimately be released to the biosphere over millions of years. This assumption implies that Criterion 2 cannot be met; however, given a long time of release and sufficient dilution, concentrations would be below established toxic levels. A relaxation of the criteria may have to occur with stable compounds, but is not condoned and is presently accepted out of necessity.

Suitable biomedical cost estimates equivalent to the $1000/man-rem used for radioactivity are not available for stable elements. The existence of threshold values above which toxic effects become obvious and below which beneficial results are obtained for many stable compounds in the human diet, make the possibility for the development of such a relationship remote.

Somatic symptoms of excessive amounts of nitrate, nitrite, and mercury are well known. Nitrates only become toxic under conditions in which they are, or may be, reduced to nitrites. The primary hazard from aqueous sources of nitrates is to infants (less than 4 months of age) whose stomachs have microorganisms capable of reducing nitrate to nitrite. The nitrite blocks the transport ability of the blood for oxygen, resulting in asphyxia. Mercury, as methyl mercury, penetrates brain membranes to damage the brain's visual, hearing, and equilibrium centers, causing blindness, deafness, and loss of balance.

If Criterion 1 is used as the sole criterion for evaluating the effectiveness of the cavern for nitrate, nitrite, and mercury then the sum of the concentrations of these compounds present in solution should be less than 1% of MPC. The level of nitrate-nitrogen currently established by the Environmental Protection Agency (EPA) is 10 ppm. Hence, 1% of MPC is 0.1 ppm. Based on the 16,470 tons of nitrate-nitrogen present as sodium nitrate, and the flow rate of 5000 cfs in the Savannah River, the nitrate-nitrogen would need to be released over at least 30 years at 500 tons/year. Drinking water limits for mercury are not established as yet by the EPA. If the level were set at 1 part per billion, the 80 tons of mercury in the cavern could be discharged uniformly over 1600 years at 0.27 pounds/day into the Savannah River. Dilution in the rock alone (Chapter III) is unlikely to be sufficient to meet Criterion 1.

APPENDIX II-A. RELATIVE TOXICITIES OF WASTE CONSTITUENTS

Expected concentrations and relative toxicities of radionuclides and other constituents of waste as functions of bedrock storage time were calculated from physical and biological standards. Relative toxicity is defined here as the ratio of concentration to maximum permissible concentration (MPC) in public zone water. Homogeneous distribution was assumed for all constituents in the waste. ^{90}Sr and ^{137}Cs are the dominant gross activities for ca. 200 yr (Figure 1, Appendix II-A). During the first 400 years, ^{90}Sr would be at least 10 times as toxic as any other radionuclide (Figure 2, Appendix II-A). After ca. 600 yr, ^{239}Pu would be the most toxic radionuclide, but nonradioactive mercury would be at least as toxic as ^{239}Pu. Radioactive ^{129}I and nonradioactive nitrate/nitrite may be the most toxic constituents of the waste supernate after 600 years if solubility is taken into account.

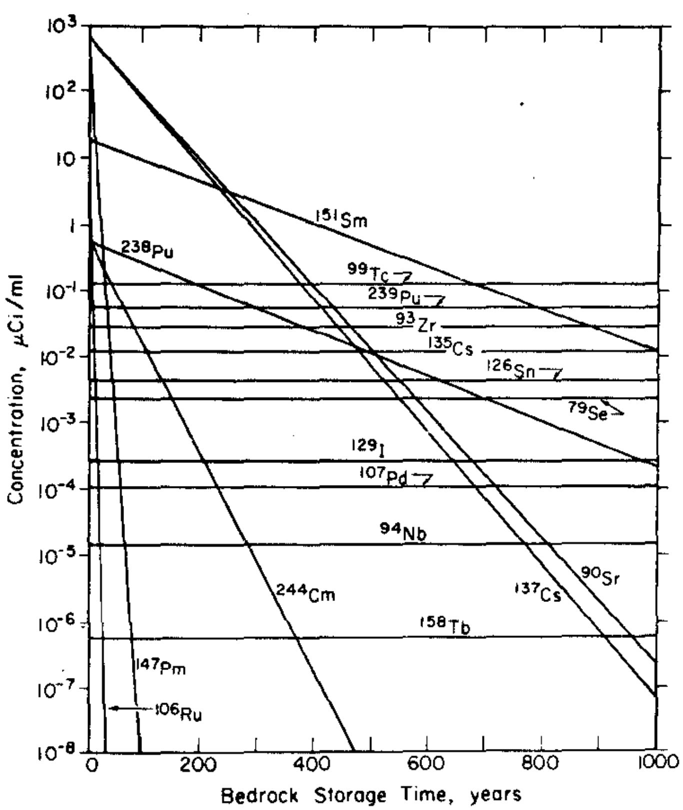

FIGURE II.A.1 Concentrations of Waste Nuclides as a Function of Time

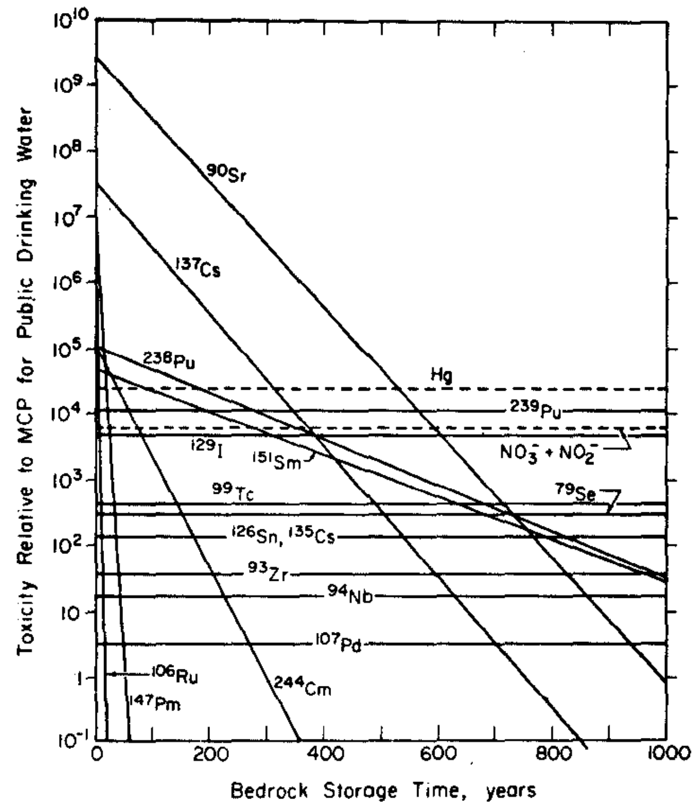

FIGURE II.A.2 Relative Toxicities of Waste Constituents as a Function of Time

Radionuclide Concentrations in Waste

The waste to be placed in the cavern is assumed to contain the entire fission product spectrum. The initial concentrations of fission products were calculated on the bedrock design basis, 660 μCi of ^{90}Sr per ml. Figure 1, Appendix II-A, shows the concentrations for fission products as a function of time, with an initial concentration above 10^{-8} μCi/ml. This concentration value eliminates nuclides with half-lives less than 1 year or greater than 10^{10} years. The values in Figure 1, Appendix II-A were adjusted for fission yield, half-life (specific activity), and decay[1] during an assumed 10-yr storage before bedrock, for each nuclide as follows:

$$C_o = 660 \times \frac{CY}{5.8} \times \frac{28.9}{t_{1/2}} \times e^{10(0.024-\lambda)}$$

where

C_o = initial concentration, μCi/ml
(660 for ^{90}Sr)

CY = chain yield from fission of ^{235}U, %
(5.8 for ^{90}Sr)

$t_{1/2}$ = half-life, yr
(28.9 for ^{90}Sr)

λ = decay constant = ln $2/t_{1/2}$
(0.024 for ^{90}Sr)

The chain yield can be used for the fission yield with negligible error for the long-lived isotopes considered here. In the cases of shielded fission products (i.e., those produced directly by fission, but not beta decay) an independent fission yield factor of 10^{-5} was also applied to the chain-yield term. Thus, the concentrations of all long-lived shielded nuclides except ^{94}Nb and ^{158}Tb are less than 10^{-8} μCi/ml.

^{239}Pu is also shown in Figure 1, Appendix II-A, at the design basis concentration of 0.056 μCi/ml. Initial concentrations of ^{238}Pu and ^{244}Cm were estimated to be about tenfold that of ^{239}Pu.

Relative Toxicity

Relative toxicity of a material is defined here as the ratio of its concentration to its current maximum permissible concentration in public zone water. This analysis assumes homogeneous distribution of every radionuclide in the waste and no dilution of the waste after placement. Figure II.A.2 shows relative toxicity as a function of time for those nuclides in Figure II.A.1 and the relative toxicity for some nonradioactive constituents. Maximum permissible concentrations and critical organs are listed in Table II.A.1.

TABLE II.A.1 MPC of Waste Constituents

	Critical Organ	MPC in Public Zone Water, μCi/ml	MPC Reference	IAEA Class for Transport[a]
^{106}Ru	GI (LLI)	1×10^{-5}	*b*	III
^{147}Pm	GI (LLI)	2×10^{-4}	*b*	IV
^{90}Sr	bone	3×10^{-7}	*b*	II
^{137}Cs	total body, spleen and liver, muscle	2×10^{-5}	*b*	IV
^{151}Sm	GI (LLI)	4×10^{-4}	*b*	IV
^{158}Tb	kidney	4×10^{-2}	*c*	-
^{94}Nb	GI(LLI)	8×10^{-7}	*c*	-
^{79}Se	spleen	8×10^{-6}	*c*	-
^{126}Sn	bone	3×10^{-5}	*c*	-
^{99}Tc	GI(LLI)	3×10^{-4}	*b*	IV
^{93}Zr	GI(LLI)	8×10^{-4}	*b*	IV
^{135}Cs	total body, spleen and liver	1×10^{-4}	*b*	IV
^{107}Pd	spleen	3×10^{-5}	*c*	-
^{129}I	thyroid	6×10^{-5}	*b*	III
^{239}Pu	bone	5×10^{-8}	*b*	I
^{244}Cm	bone	7×10^{-6}	*b*	I
$NO_3^- + NO_2^-$	-	10 mg/l(as N)	*d*	-
Hg	-	10 ppb	*e*	-

a. Regulation for the Safe Transport of Radioactive Materials, Internation Atomic Energy Agency, Safety Series 6, Vienna, 1967.

b. 10CFR20.

c. Calculated from values in Table II.A.2.

d. U.S. Public Health Service, Drinking Water Standards, November 1962.

e. Value of MPC_w for mercury not established; current estimates range from less than 1 to 10 ppb.

For those radionuclides not listed in 10 CFR 20, MPC_w was calculated from the general equation for internal dose from drinking water, using values from Table 2, Appendix II-A.

The combined concentration of nitrate and nitrite in the waste was assumed to be 4M. The concentration of mercury was assumed to be 0.002 lb/gal.

Table II.A.2. Values Used to Calculate MPC_W for Nuclides Not in 10CFR20

	^{107}Pd	^{79}Se	^{126}Sn	^{95}Nb	^{158}Tb
Critical organ	spleen	spleen	bone	GI(LLI)	kidney
Mass of organ, g	150	150	7000	150	300
Physical half-life, yr	7×10^6	6.5×10^4	10^5	2×10^4	150
Biol. half-life, days	15	18	100	1	750
$\Sigma E(RBE)_n$, Mev/d[a]	0.012	0.05	1.5	1.8	0.3
Fraction to critical organ	0.2	1.0	0.02	1.0	10^{-6}
Max rem/wk to organ	0.03	0.03	0.056	0.03	0.03

a. $\Sigma E(RBE)_n$ = avg total energy/disintegration x quality factor x linear energy transfer factor (= 1 for β,γ).

APPENDIX II-B. EVALUATION OF COST OF RADIATION DOSE IN TERMS OF DOLLARS PER MAN-REM

The ability to place a value on the biomedical cost of radiation offers the opportunity to make quantitative estimates of the effectiveness of various approaches to waste management. In order to determine this value, one needs to have an estimate of the value of human life and the effect of radiation on the productivity of the recipients and their offspring from somatic and genetic effects.

Value of Human Life

Sagan used the following assumptions, all of which we are in agreement with, to determine the value of human life.[1]

1. The loss of one day's productivity as a result of injury is assumed to be $50. This value is arrived at from the average gross weekly earnings for nonsupervisory employees and the fact that the employer bears expenses such as vacation, pension, sick leave, and other administrative costs. Government statistics for August 1971 indicate these gross weekly earnings were $173.43 for mining, $220.23 for contract construction, and $141.67 for manufacturing.

2. A fatality is the equivalent of 6000 working days. This value is used by the Department of Labor in its scale of time charges.[2]

These assumptions result in the monetary value of a fatality being $300,000.

Other estimates, in addition to Sagan's, exist for the value of human life. Jury awards for accidental deaths range from $50,000 to $500,000, with an average value near $250,000. Fromm arrived at $373,000 as the value of the life of an average individual killed in an aviation accident in 1960.[3] Carlson obtained a value for life using Air Force expenditures to develop and maintain an ejection system for the B-58. The yearly costs of this device are approximately $9 million and save an estimated 1 to 3 lives per year. The cost of life, in this context, is therefore between $3 and $9 million in Carlson's analysis.[4]

Radiation Effects

Robison and Anspaugh have calculated upper-limit risk from low levels of radiation.[5] Their values for the risk analysis are summarized in Table 1, Appendix II-B and include the risks from genetic and somatic effects from a 20 mrem exposure in one year. These values are conservative upper-limit estimates based on extrapolation from high doses and high dose rates and are the ones assumed in this report. These data, when converted to man-rem, result in a probability of death/man-rem of 10^{-3} for first generation and overall time of 10^{-2}. Values of 10^{-4} are suggested by ICRP for chronic exposure to the first generation populations and 4×10^{-3} for deaths per rem (genetic), malignancies, and life-shortening introduced into the population.

Table II.B.1 Summary of the Calculated Upper-Limit Risk per Person From Exposure to 20 mrem in One Year

	Increased Incidence per Person due to Radiation		Natural Incidence per Person
	Lower Limit	Upper Limit	
First generation			
Genetic loss[a]	0	4×10^{-6}	2×10^{-1}
Adult leukemia	0	4×10^{-7}	5×10^{-3}
Childhood leukemia	0	1×10^{-7}	2×10^{-5}
Other adult malignancy	0	8×10^{-7}	1×10^{-1}
Other childhood malignancy	0	3×10^{-7}	2×10^{-5}
Nonspecific life-shortening[b]	0	1×10^{-5}	
Total for first-generation (nonspecific life-shortening plus genetic loss)	0	$\sim 2 \times 10^{-5}$	
Over all times			
Additional genetic loss	0	1×10^{-4}	
Total detriment over all time	0	$\sim 2 \times 10^{-4}$	

a. Genetic loss refers to the eventual elimination of a deleterious gene. This would be evidenced by abortion, stillbirth, pre-reproductive death, early embryonic death, lowered fertility, or sterility.

b. Nonspecific life-shortening includes losses due to cancer, plus all other diseases and physiological processes leading to a shortened life-span.

Dollar Cost/Man-Rem

Combining the values of life and the estimated probability of death per man-rem permits one to calculate the value of a man-rem. If 10^{-3} is assumed as the risk and \$300,000 as the value of life, then \$300/man-rem is obtained. On the other hand, if 10^{-2} is assumed as the risk, then \$3000/man-rem is obtained. For the purpose of this report, a value of \$1000/man-rem was assumed as representative of the costs of radiation dose to society (corresponding to 3.3×10^{-3} deaths/man-rem). This value of \$1000/man-rem is higher than most other values in the literature. Literature values range from \$30 to \$1000. The \$30 value is presented by Sagan[1] who reached this value by assuming that 1 rem produces 100 cases of cancer per million persons exposed (that is, per million man-rems) and that the cost per life is \$300,000. Missing from his consideration are the genetic effects that might occur. (He acknowledges this omission.) A \$250 value is reached by Cohen[6] and the \$1000/man-rem value is used by Jacobsen.[7]

APPENDIX II-C. CONVERSION OF RADIOACTIVITY TO DOSE

In any assessment of the risk involving radioactivity, it is necessary to know the doses received by an individual as a consequence of ingesting specific radionuclides. Measurements or calculations of radioactivity reaching the environment are generally made in terms of curies; however, much effort over the years by health physicists and others has produced the pertinent values necessary to estimate the radiation dose produced by ingestion of radionuclides. For the purposes of this report, the commitment of an individual is defined as the lifetime dose (70 years) he receives from an integral uptake of a radionuclide. The following equation was derived (W. Marter personal communication) to calculate this dose commitment from the uptake of 1 curie of a particular radionuclide.

$$D_c = 7.38 \times 10^7 \left(\frac{f_w T \varepsilon}{m}\right) \left[1 - e\left(\frac{-1.77 \times 10^4}{T}\right)\right]$$

where

D_c = dose commitment, rem/curie

f_w = fraction of radionuclide ingested that ends up in critical organ

T = effective half-life in critical organ, days

m = mass of critical organ, g

ε = effective energy, MeV

Table 1, Appendix II-C, summarizes the values necessary in Equation 1 for calculating the whole body dose received by an individual from the ingestion of one curie of each of the radionuclides of principal concern in the bedrock concept, as well as the total whole body dose received by the individual over his life time as a consequence of the ingestion. The critical organ for these radionuclides is not always the whole body. However, the whole body dose is the appropriate value for incorporating the long term hazards associated with genetic effects and the whole body dose is the basis of the use of $1000/man-rem (Appendix II-B) as the monetary value of the risk associated with radiation.

As seen in Table 1, Appendix II-C, ^{90}Sr has the largest dose (9.5 x 10^5 rem/curie), of any of the radionuclides. Based on the assumption of $1000/man-rem, each curie of ^{90}Sr ingested has a very large biomedical cost. Large doses per curie also occur from the uptake of most of the other principal radionuclides in the waste.

Table II.C.1 Biological Hazard From Ingesting One Curie of a Nuclide[a]

Radionuclide	f_w,[b] Fraction Ingested	T, Effective Half-life, days	C, Effective Energy, MeV	Dose, rem/curie
^{90}Sr	0.15	5.7 x 10^3	1.1	9.5 x 10^5
^{137}Cs	1.0	70	0.59	4.4 x 10^4
^{239}Pu	3 x 10^{-5}	6.4 x 10^4	53.0	2.6 x 10^4
^{129}I	1.0	138	0.089	1.3 x 10^4
^{238}Pu	3 x 10^{-5}	2.2 x 10^4	57.0	2.2 x 10^4
^{151}Sm	1 x 10^{-4}	645	0.042	2.9
^{99}Tc	0.5	1	0.094	50
^{79}Se	0.9	11	0.05	5.2 x 10^2
^{135}Cs	1.0	70	0.066	4.9 x 10^3
^{107}Pd	0.2	5	0.011	12
^{93}Zr	1 x 10^{-4}	450	0.019	9.0 x 10^{-1}
^{144}Ce-Pr	1 x 10^{-4}	191	1.3	2.6 x 10^1
^{95}Zr-Nb	1 x 10^{-4}	55.5	1.1	6.4
^{89}Sr	0.15	50.3	0.55	4.4 x 10^3
^{91}Y	1 x 10^{-4}	58	0.59	3.6
^{106}Ru-Rh	0.03	7.2	1.4	3.2 x 10^2
^{147}Pm	1 x 10^{-4}	383	0.069	2.8

a. This table contains the appropriate values necessary for calculating the whole body dose received by an individual from ingesting one curie of each of the radionuclides of interest to the bedrock concept (assumes whole body mass is 7 x 10^4 g).

b. The value f_W is the fraction of radionuclide ingested that ends up in the critical organ.

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CHAPTER III. CONCEPTUAL DESIGN OF THE SRP BEDROCK WASTE STORAGE SYSTEM

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CHAPTER III. CONCEPTUAL DESIGN OF THE SRP BEDROCK WASTE STORAGE SYSTEM

INTRODUCTION

The purpose of this section is to define and evaluate the basic design features that are important in assessing the safety and performance of a bedrock storage system for SRP wastes. These features include the nature of the waste to be stored as well as the structure of the caverns. The system must retain 80 million gallons of waste containing 200 million curies each of ^{90}Sr and ^{137}Cs and 17,000 curies of ^{239}Pu.

The following factors were considered in the design of a bedrock storage system:

- General Facilities Arrangement
- Rock Mechanics
- Waste-Rock Chemistry
- Cavern Pressurization from Radiolytic Gas
- Density Gradients and Waste Migration
- Effects of Heat Generation
- Shaft Sealing Requirements

Each of these factors is discussed in a separate section of this chapter. Each section contains a separate introduction, summary, and discussion.

SUMMARY

The conceptual design for a waste storage system in crystalline rock differs significantly from a waste storage system in Triassic rock. The relatively higher permeability and lower porosity of the crystalline rock coupled with its more inhomogeneous nature makes this system more susceptible to penetration by liquid waste than a system designed for Triassic rock. Rock penetration requires that the waste charged to crystalline caverns be altered significantly. This alteration includes separation of the inert chemical constituents (such as nitrate, nitrite, etc.) from the radionuclides in order to eliminate density gradients and radiolytic gassing.

If these modifications are made, a total cavern volume in crystalline rock of approximately 100 million gallons would be acceptable, assuming that the total volume of modified waste is still approximately 80 million gallons. The technical feasibility and cost of these modifications are beyond the scope of this analysis; however, it should be emphasized that these modifications represent a major alteration of the waste.

Alteration of the waste does not appear to be necessary for storage in the Triassic formation. A total cavern volume of ca. 130 million gallons should be sufficient for a Triassic cavern located in rock equivalent to that found near the center of the Triassic basin; i.e., 80 million gallons of waste, 40 million gallons for water inleakage and radiolytic gas, and 10 million gallons for cavern volume reduction from long-term creep of the rock. The Triassic conglomerate rock at the edge of the basin is not acceptable for bedrock storage because of excessive long term reduction of the cavern volume from the rock creep phenomenon. The remaining bedrock areas appear to possess adequate strength and structural properties; they offer no particular or unusual mechanical difficulties to cavern construction.

Although alteration of the waste for storage in the Triassic formation does not appear to be necessary, it would be feasible to mix the waste with cement to form a grout that would set up in the cavern. This concept would provide some additional safety and should be considered as an alternative.

The potential for the waste to destroy grouting materials plus the extended time periods involved in bedrock storage are such that, based on existing information, no credit can be taken for engineered reduction of the permeability of the rock surrounding the caverns by grouting, although extensive grouting would still be carried out as an added measure of safety.

Effects of heat generation from decaying radionuclides in the waste should be considered in the final detailed design and arrangement of the caverns, but temperatures apparently can be kept to an acceptable level by proper sludge distribution and proper cavern size and arrangement.

Shaft sealing should be secure to afford no significant path for waste migration. Preliminary analysis indicates that such a seal can be obtained.

III-1. GENERAL FACILITIES ARRANGEMENT

Introduction

This section describes the general arrangement of the bedrock caverns as well as the associated waste handling facilities. Conceptual arrangements for waste monitoring and retrieval are discussed.

Summary

Cavern configuration and location shall be such that any portion of the cavern is an acceptable distance from either the Tuscaloosa aquifer or more permeable zones of rock. For evaluation purposes, the cavern is assumed to be located at least 1500 feet below ground level (about 500 feet into the rock).

Another important aspect of cavern design is that only air and radiolysis gases (rather than liquid waste) should be in contact with the cavern seal. This arrangement minimizes or eliminates reaction of the waste with the concrete seal and insures that if there is any slight leakage up the shaft it will consist essentially of gases. Extensive testing and monitoring of the caverns would be carried out before final cavern sealing. A long-term program for monitoring water in the rock near the Tuscaloosa aquifer could be employed.

Discussion

The bedrock concept requires an excavated region in the rock for the waste, access from ground level to the excavated region, and a connection from the source of waste to the shaft. For evaluation purposes, the cavern is assumed to be located 1500 feet below the ground surface (about 500 feet into the rock). There is considerable flexibility in the design and location of each of these areas but the resulting system should have sufficient design safeguards to prevent the loss of radioactivity during routine transfer and filling. The cavern configuration should be such that the distance from any portion of the cavern to either the Tuscaloosa aquifer or more permeable rock is acceptable. Extreme care should be devoted to the shaft sealing mechanism in order to ensure isolation of the waste from the Tuscaloosa aquifer (as discussed in Section III-7).

It is important that the tunnels be arranged so that air and radiolysis gas rather than liquid waste are in contact with the shaft seal (Figure III.1.1). This arrangement will minimize interaction of the waste with the seal and will ensure that if there is any leakage up the shaft it will consist of gases.

The total cavern is expected to be around 130,000,000 gallons (based on a Triassic cavern with 80 million gallons for liquid waste and 50 million gallons additional volume allowance for expected gas evolution, water inleakage, and long term volume reduction due to creep, Section III-4). To maintain a reasonable length (3000 ft) to the tunnels off a main connecting system (Figure III.1.1), the excavation requires six 35-ft-diameter tunnels or twelve 25-ft-diameter tunnels. Preliminary analysis suggests that 200 to 300 feet between tunnels would be adequate to maintain centerline temperatures within the caverns at or below design specifications.

At least 3 shafts will be required to connect the ground surface with the underground areas. One shaft would act as a safety escape, one for routine transfer of personnel and equipment, and the third for waste transfer. These shafts will be approximately 1500 feet deep (ca. 500 feet into rock). The total number of shafts should be kept to a minimum in order to reduce shaft sealing problems.

Waste transfer distances of up to 8 miles from the Separations Areas to the cavern may be necessary. Experience gained from the construction and operation of the SRP interarea waste transfer line will be a very useful and necessary input in designing this phase of the operation. The minimum time required to transfer 80,000,000 gallons of waste is 3.5 years if a 3-inch-diameter pipe is used with a minimum transfer velocity of 2 ft/sec (velocity required to minimize the possibility of suspended solids segregation). The high radiation rates present in the vicinity of the transfer pipe during filling will require the transfer system to be monitored remotely and to have the appropriate repair facilities available.

An extensive testing and monitoring program would be carried out on each individual cavern before it is permanently sealed. This program would probably include the following phases:

1. Test each cavern before grouting, lining, and adding wastes.
    - Water inleakage
    - Rock creep, etc.

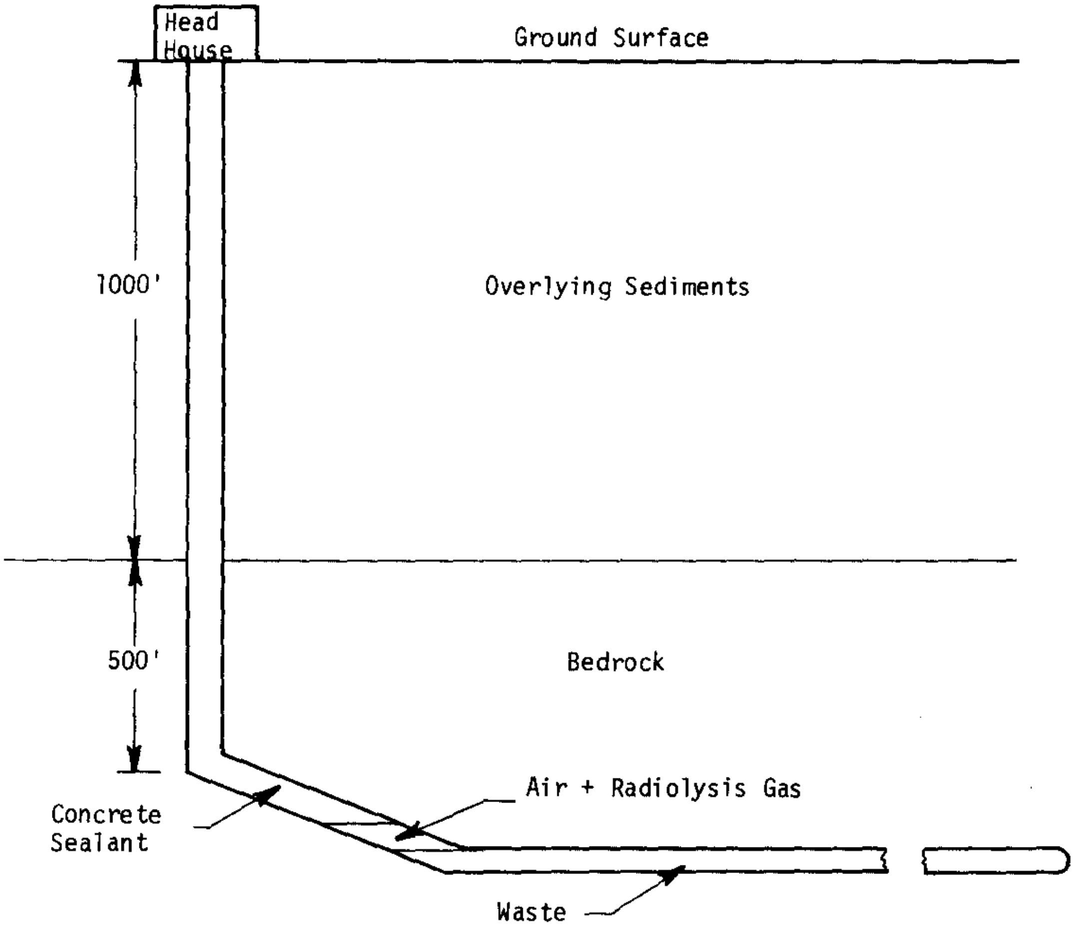

FIGURE III.1.1. Schematic Drawing of Filled Bedrock Waste System After Sealing the Shaft

2. Test each cavern again after grouting and lining.

3. Install engineered safeguards, possibly including concrete bulkheads, to separate the base of the shaft from the caverns during cavern filling.

4. Test cavern seal.

5. Fill a cavern.

6. Monitor cavern containing wastes.

   - Liquid level
   - Pressure
   - Temperature
   - Gas evolution
   - Supernate samples, etc.

7. Finally seal cavern.

8. Test final seal.

9. Seal main access shafts.

10. Test access shaft seals.

Re-entry into sealed caverns, should monitoring measurements indicate retrievability of the waste is necessary, will be a large and expensive undertaking. The cavern system is designed for ultimate storage, not simple retrievability. Means of retrieving waste following emplacement in the caverns have not been studied in detail. Recovery from storage tanks has been demonstrated to be feasible although not simple and similar techniques could be applied to retrieving wastes from the caverns. Decommissioning of the waste tanks *in situ* should not occur until testing of the shaft seal is complete, so that waste storage facilities would still be available if it proved necessary to retrieve the waste from the caverns.

After final sealing, effective monitoring of the conditions within the caverns will probably be impractical, and further monitoring would have to be well beyond the confines of the cavern.

Piezometers in the rock could be used for long term surveillance by providing periodic sampling of the water in the rock. The most effective monitoring of waste movement would be obtained by piezometers located near the caverns; however, the piezometers would provide a preferred path for waste migration were they to be abandoned by accident or improperly sealed after monitoring was terminated. If such a monitoring system were to be employed, the additional risks and costs of the monitoring system itself would have to be balanced against the benefits obtained from the information received before determining the optimum number of piezometers and their depth and location. The shafts to the caverns could be partially filled and sealed and used as piezometers for monitoring for an intermediate time period before complete sealing. A monitoring system near the interface between the rock and the Tuscaloosa aquifer would not seriously compromise the safety of the system and might be operated for several decades.

III-2. ROCK MECHANICS

Introduction

The subject of rock mechanics has broad implications in the design, construction, and long term stability of underground structures inasmuch as it may involve such critical items as the ability of the rock to support the overburden, the stress and strains that exist along the surface that can result in rock falls and cracking, and the shrinking of the tunnel volume due to creeping of the rock. These rock properties are obtained by static or dynamic tests, both in the laboratory and *in situ*. This preliminary analysis is based on short term laboratory tests of the mechanical properties of crystalline and Triassic rock [schist (crystalline rock) from DRB 7, conglomerate from DRB 9 (edge of Triassic basin), sandstone from DRB 10 (center of Triassic basin), and fine-grained sandstone from DRB 10] that have been conducted and reported by a consultant using a limited number of samples of each rock type.

Summary

All rock types tested had medium strength and appear adequate to support the overburden, although additional testing is required.

Estimates of the time dependent volume change of the waste storage tunnels due to creep, based on extrapolated values from short (21 to 30 days) laboratory studies of single samples from the various rock formations, suggest volume reductions of less than 2% for crystalline rock, of between 5 and 10% for Triassic sandstone in the center of the basin, and greater than 15% for Triassic conglomerate rock at the edge of the basin. No significant difference in the rock creep rate was observed between rock tested at 76°F and that tested at 200°F over the time span of these tests. The creep associated with the Triassic conglomerate rock from the edge of the basin, although not a problem during construction of a facility, is most undesirable for the long term storage of liquid waste.

Based on these observations, caverns constructed in either crystalline rock or Triassic sandstone in the center of the basin appear suitable with respect to rock mechanics. However, the laboratory information, obtained to date, is limited by the small number of rock samples. Further detailed experimental information from both laboratory and *in situ* experiments would be necessary before final cavern design.

Discussion

Strength

Laboratory measurements of the strength of four rock types (schist, fine-grained sandstone, medium-to-coarse grained sandstone, and conglomerate) indicated that the unconfined compressive strengths are 8000 psi or above (Table III.2.1). Rocks with compressive strengths between 8000 and 16,000 psi are considered to have medium strength, adequate for most types of tunnel construction. The tensile strength of the schist (1500 psi) is more than double that of the other three rock types (Table III.2.2).

Examination of the failed test samples together with the data from Tables III.2.1 and III.2.2 provides some insight into the engineering properties of the rocks. The schist failed in the chlorite material along the planes of schistosity indicating homogeneous and isotropic assumptions are unwarranted in this material. The fine-grained sandstone was very homogeneous as indicated by the uniformity of data obtained from the various test pieces. It had the highest unconfined compressive strength and the lowest tensile strength. The sandstone had unconfined compressive and tensile strengths similar to the fine-grained sandstone. The conglomerate was the weakest material tested. All of these rocks had sufficient strength to permit a waste storage tunnel to be safely constructed.

TABLE III.2.1. Tentative Values for Unconfined Compressive Strength of Bedrock Samples

Material	Unconfined Compressive Strength, psi
Mudstone DRB-10	11,000
Sandstone DRB-10	10,000
Conglomerate DRB-9	8,000
Schist DRB-7	8,000

TABLE III.2.2. Tentative Values for Tensile Strength of Bedrock Samples

Material	Tensile Strength, psi
Mudstone DRB 10	400
Sandstone DRB-10	400
Conglomerate DRB-9	600
Schist DRB-7	1,500

Creep

The creep properties of the various types of rock were studied using unconfined creep tests at three different axial stress levels and two temperature levels, and confined creep tests at two levels of confinement pressure. Creep is important; if unrecognized, it could create a driving force to squeeze waste out of the caverns and into the surrounding rock.

If sufficient load is applied, most rock has a creep cycle which can be broken down into four parts: instantaneous elastic strain (A-B), primary creep (B-C), secondary creep (C-F), and tertiary creep to failure (F-H) (Figure III.2.1). If the load is released at time T_1, there is an immediate elastic recovery (C-D) and a viscoelastic recovery (D-E) to the original dimensions over T_1 to T_2. If the load is maintained past time T_1, a constant strain rate (secondary creep) follows which includes some permanent deformation of the rock. After a given limit of secondary creep has occurred, the strain begins to accelerate (tertiary creep) until failure. At low stress levels, secondary and tertiary creep will not occur.

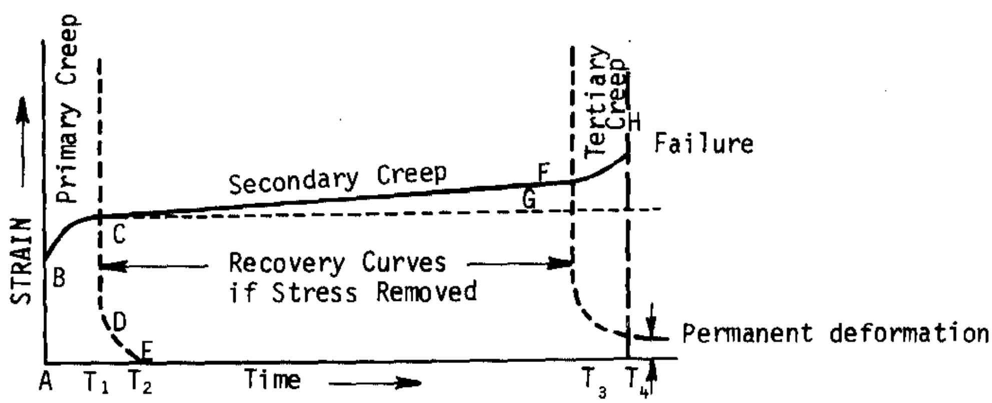

FIGURE III.2.1. Constant Stress Creep Curves

Only short term creep tests have been performed to date on the rock, and the results are only indicative of the primary creep characteristics. The relative primary creep susceptibility of the four general types of rock varies from very low for crystalline rock to quite high for Triassic conglomerate. Heating the samples to 200°F had little effect on the primary creep rates for the Triassic rock while confinement tends to decrease primary creep. To obtain realistic results on secondary creep, tests should extend for about 1 year.

To estimate the total volume reduction expected in a cavern in rock, the exponentially decreasing primary creep curves for each rock type were extrapolated from one month to one year. The results of calculations based on the extrapolated curve are:

Crystalline rock (schist) - less than 2%

Triassic sandstone - 5 to 10%

Triassic conglomerate - greater than 15%

The Triassic conglomerate's excessive creep is unsatisfactory for a cavern while the creep expected in both Triassic sandstone in the center of the basin and crystalline rock are acceptable for cavern design.

Deformation Tests

Static deformation moduli tests (tangent modulus, secant modulus, recovery modulus, and Poisson's ratio) were conducted on each of the rock types. The first three deformation moduli are shown on Figure III.2.2a. The tangent modulus of deformation is the slope of the stress-strain curve obtained between two adjacent sets of data points. It neglects the end effects of the curve and is better suited to small stress changes. The larger the value, the more resistant the rock is to deformation. The secant modulus of deformation is the slope of the stress-strain curve between zero stress and the stress in question. This modulus should be used for complete load steps from zero to the desired load. High values indicate the rock is more resistant to deformation. The initial, concave upwards, section of the stress-strain curve is often attributed to closing of microcracks and other stress-damage-type phenomena; as such, the ratio between the secant modulus and tangent modulus can be used as a means of measuring the stress damage to the material. The smaller the ratio, the greater the damage. A ratio of one indicates no microfractures. The recovery modulus of deformation is a tangent modulus on the stress releasing portion of the stress-strain curve. This modulus is generally higher than the other two moduli and is used to calculate unloading conditions. The smaller the difference between the tangent and recovery moduli, the greater is the material's capacity to regain its original shape. In a linearly elastic material, all three moduli would be identical. Figure III.2.2b shows the comparative results of the modulus tests for each of the four rock types. The schist in all cases has the highest moduli values and confinement generally increases the moduli values from 15 to 25% except for the sandstone where the values essentially doubled under confinement. These increases are indicative of increased strength under confinement.

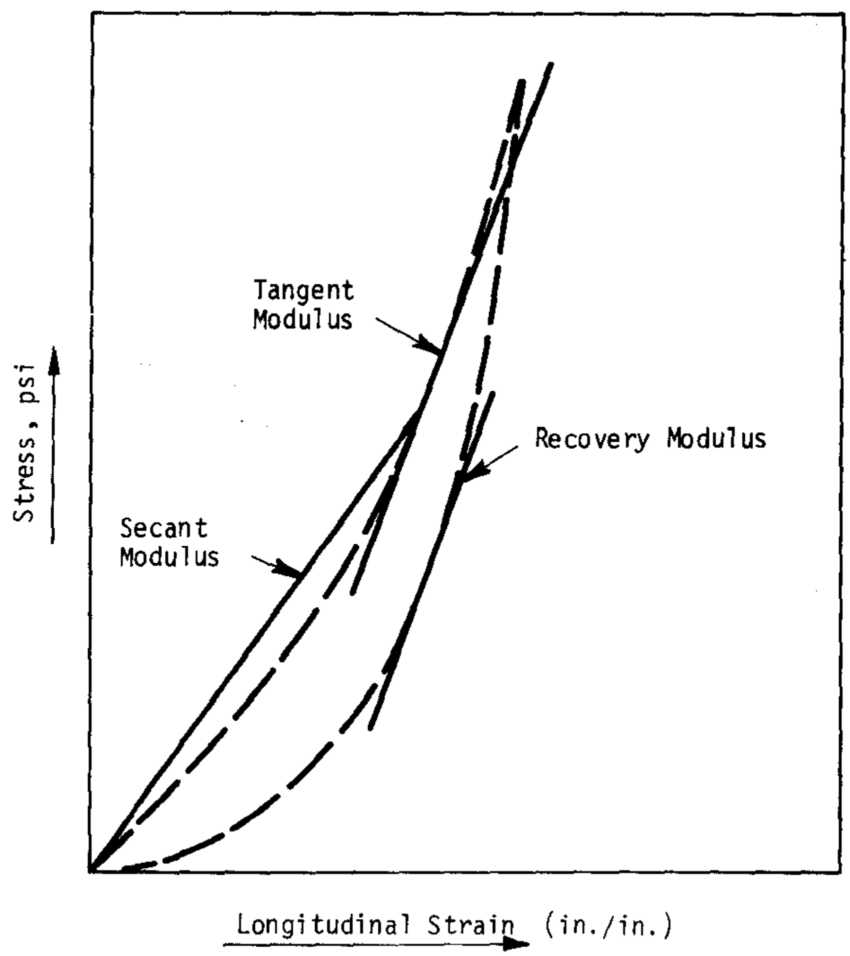

FIGURE III.2.2a. Relationship Between Tangent, Secant, and Recovery Moduli

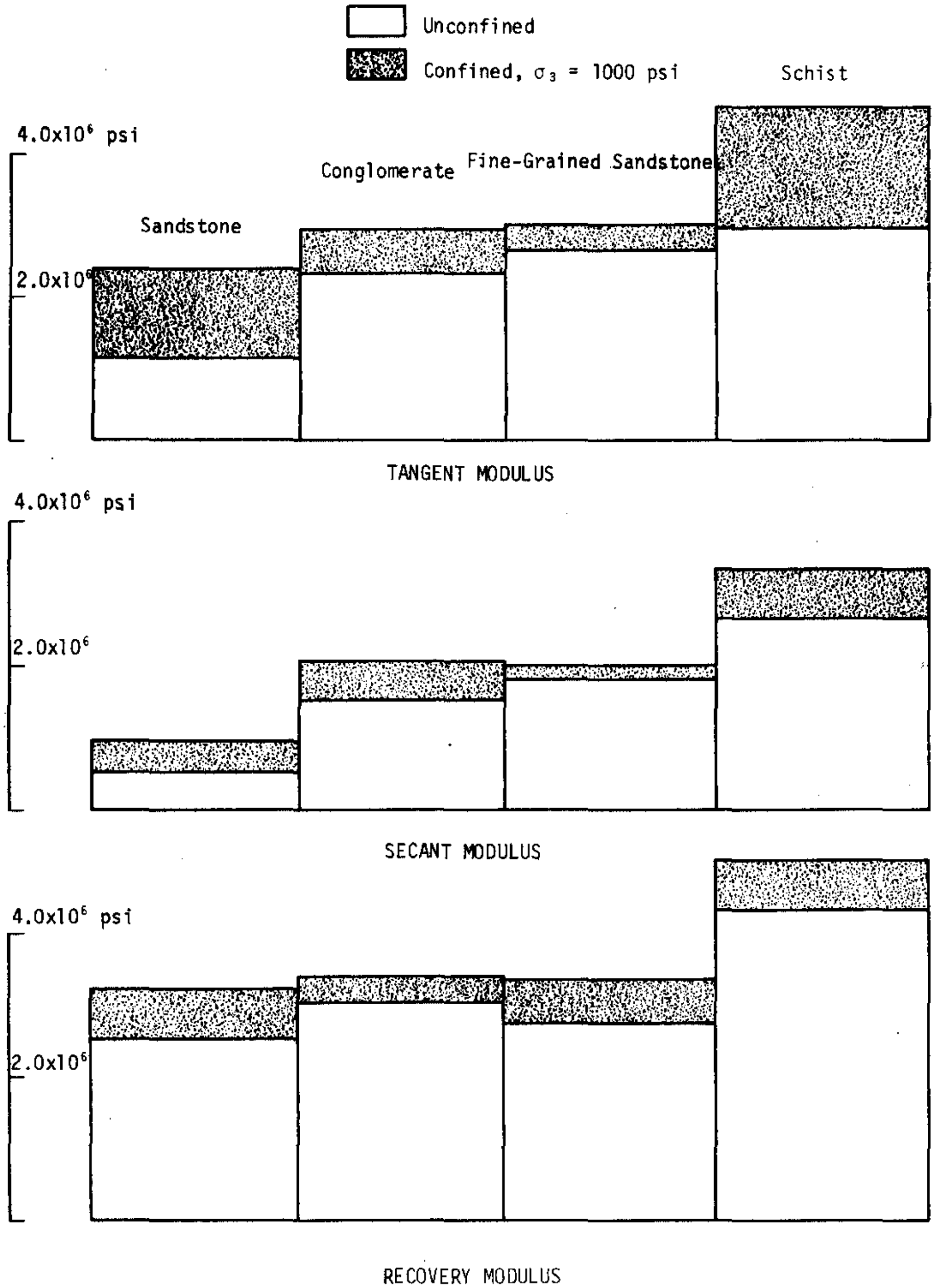

FIGURE III.2.2b. Comparison of Tangent, Secant, and Recovery Moduli

Suggested numerical values of the various moduli and Poisson's ratio for use in calculations are summarized in Table III.2.3. Poisson's ratio connects the transverse to longitudinal deformations of the rock. A small ratio indicates that the material is yielding in the direction the force is applied but not in the normal direction, and this indicates some crack closing (plastic behavior) is occurring. The fine-grained sandstone has surprisingly high tangent and secant moduli. These values are attributed to the tendency to select the stronger specimens left in the core box. The fine-grained sandstone also shows good recovery when load is removed. These two tendencies together with the moderate strength indicate the stress levels in the parent rock do not exceed the unconfined strength of the rock.

TABLE III.2.3. Suggested Values of Deformation Moduli

	Moduli, millions of psi							
	Tangent Modulus		Secant Modulus		Recovery Modulus		Poisson's Ratio	
Material Type	Conf.	Unconf.	Conf.	Unconf.	Conf.	Unconf.	Conf.	Unconf.
Fine-grained sandstone	3.0	2.6	1.8	2.0	2.8	3.4	0.15	0.20
Sandstone	2.4	1.2	1.0	0.5	3.3	2.5	0.25	0.10
Conglomerate	3.0	2.3	2.0	1.5	3.4	3.0	0.20	0.20
Schist	4.6	3.0	3.3	2.6	5.0	4.4	0.20	0.20

The sandstone had the lowest moduli. Moderate permanent set (non-elastic behavior following removal of the stress) and moderate crack damage are indicated by the data. It is unknown whether the relatively poor elastic characteristics of the material tested are because of high *in situ* stress or weathering damage in the core boxes. The data on the conglomerate indicate that crack closing occurred on initial loading.

The two schist samples showed highly elastic tendency with little energy storing and crack closing. These samples also showed a tendency for lower modulus on successive cycles, indicating some plastic deformation along the plane of schistosity.

III-3. WASTE-ROCK CHEMISTRY

Introduction

The chemistry of the waste-bedrock system is important in determining: (1) the chemical form and solubility of the hazardous species in the waste, (2) the chemical reactions between the waste, the rock, and the materials of construction in the cavern, and (3) the adsorption of the hazardous species on the rock.

Summary

Accurate values or even reasonable estimates of the solubilities and chemical forms of the various waste constituents require consideration of the complex chemical system in the caverns and the presence of a significant radiation level. Observations indicate that presently sodium nitrate, sodium nitrite, sodium sulfate, cesium, and technicium are predominately in the supernate. Manganese dioxide, ferric hydroxide, uranium, strontium, and plutonium are predominately in the sludge. The location and chemical form of mercury, iodine, and a number of trace elements have not yet been determined.

Except for plutonium, studies of the chemical form and distribution of the various radionuclides in the waste after it has reacted with the rock have not been made. Laboratory and theoretical studies using plutonium indicate its solubility may increase if carbonate is brought into solution during dissolution of the rock by the waste. Addition of cement and calcium hydroxide will remove carbonate from solution and thereby reduce plutonium mobility.

Simulated waste attacks coupons of crystalline rock, Triassic rock, chemical grout, and concrete. The attack on rock consists of dissolving silica from the rock matrix, thereby causing surface layers to lose their strength and impervious nature. Chemical grout used to seal rock fractures after or during cavern construction is reduced to a "mush" by 10^7 rads of gamma radiation. Based on these data, no credit can presently be taken for engineered reduction of the permeability of the rock around the cavern by chemical grouting due to the potential for the waste to destroy the grout. In the case of cement, chemical reactions take place forming calcium aluminosilicates from the calcium silicates in the cement. Testing to date has not delineated the effect of this reaction on the integrity of cement grout, and therefore no credit will be taken for cement grouting in this analysis.

Ion exchange properties of rocks reduce the mobility of ions present in the supernate. Because the toxicity of a radionuclide is a function of the amount present and radioactive decay is continually reducing the amount present, any reduction in flow velocity through the media tends to limit the potential effect of the nuclide. Unfortunately, in crystalline rock, flow will be through fractures and no credit can be taken for ion exchange to reduce flow rates or remove appreciable quantities of radioisotopes from solution. On the other hand, in Triassic rock, flow is through the porous material and credit can be taken for ion exchange effects. Sufficient ion exchange capacity exists in a volume of Triassic rock equivalent to 0.4% of the volume of the cavern to contain all of the plutonium and cesium in the waste. Strontium is not retained by rock when large amounts of sodium are present in solution. Adsorption effects in Triassic rock reduce the velocity of cesium to 0.1% and plutonium to 0.01% of the velocity of non-adsorbed isotopes. This reduction in velocity significantly influences the concentration and quantity of radioactivity that ultimately leaves the rock.

Discussion

Chemical and Radionuclide Composition of Stored SRP Waste

Although detailed up-to-date information on the status of the radionuclide content, chemical compounds present, and distribution of activity between supernate and the sludge in each of the tanks is lacking, isolated analyses over the years on individual tanks provide an estimate of the chemical status of the waste. The distribution of activity between the sludge and the supernate for 3 tanks was measured. ^{137}Cs, ^{60}Co, ^{90}Sr, and ^{239}Pu were detected in the supernate; ^{137}Cs, ^{125}Sb, ^{60}Co, ^{154}Eu, ^{144}Ce, ^{106}Ru, ^{65}Zn, ^{90}Sr, ^{147}Pm, ^{239}Pu, ^{241}Am, ^{237}Np, and ^{238}Pu were detected in the sludge. ^{99}Tc is shown to be present in the solution as is ruthenium and plutonium. Most of the cesium appears to be in the supernate and most of the strontium and plutonium appears to be in the sludge.[1]

The predominant cations in the sludge are iron, manganese, and uranium (Table III.3.1). The iron is expected to be in the form of ferric hydroxide; the manganese, as manganese dioxide.

The chemical form and location of iodine in the tanks is undocumented. Iodine likely resides in the sludge, precipitated with MnO_2, inasmuch as this precipitation has been shown to be successful in reducing iodine releases in dissolvers.

An estimated eighty tons of mercury have been discharged to the waste tanks; however, none is known to have been discharged to Tank 2, the source of the sludge for the analyses given in Table III.3.1.

TABLE III.3.1. Emission Spectrographic Analysis for Cations in Sludge from Tank 2

Element	Element Concentration, μg/ml of Sludge	Element	Element Concentration, μg/ml of Sludge
Iron	45,000	Bismuth	<450
Manganese	45,000	Cerium	<9,000
Uranium	16,000	Cobalt	<900
Sodium	9,000	Lanthanum	<2,200
Aluminum	5,700	Lithium	<220
Calcium	4,500	Molybdenum	<900
Magnesium	1,300	Niobium	<900
Nickel	1,300	Phosphorous	<4,500
Silicon	220	Lead	-
Copper	450	Antimony	<900
Chromium	<900	Tin	<2,200
Silver	<90	Titanium	<900
Boron	<90	Zinc	<2,200
Barium	2,200	Zirconium	<2,200
Beryllium	<22	Mercury	-

These results vary among different tanks.

Studies to determine the chemical forms present in solution and sludge after the waste is placed in the caverns have not been reported except for the fate of plutonium. The plutonium studies indicate plutonium carbonate is relatively soluble, and carbonates when present in the solution following reaction of the waste with the rock will result in concentrations of plutonium higher than the extremely low values (10^{-8} M) expected in carbonate-free solutions at pH 13.

Techniques to maintain low levels of plutonium in solution have been explored. The addition of cement to either $NaNO_3$ or Na_2CO_3 solution reduced the mobile phase of plutonium to background levels (Tables III.3.2 and III.3.3) when sufficient cement was added. These studies with cement suggested a second approach - the addition of calcium hydroxide to form calcium carbonate, on which the plutonium might sorb. Tests (Table III.3.4) indicated that when sufficient $Ca(OH)_2$ was added to the solutions to precipitate all of the carbonate as $CaCO_3$, the plutonium content of the solution was reduced below the limit of detection. Similar tests were conducted to determine if the addition of $Ca(OH)_2$ would be equally successful in reducing the strontium content of the solution. The tests (Table III.3.5) showed that strontium is removed from solution by sorbing on calcium carbonate precipitate formed by the addition of $Ca(OH)_2$ to the waste. The results show the method is successful but not to the extent achieved with plutonium.

TABLE III.3.2. Sorption of Plutonium from Sodium Nitrate Solutions by Cement[a]

Solution	Final Pu Concentration, d/(min-ml)	DF[b] (Pu)
H_2O	45 ± 21	$2.5\left\{\begin{matrix}+2.1\\-0.8\end{matrix}\right\}\times 10^3$
0.001M $NaNO_3$	Background ± 42	$\geq 2.5 \times 10^3$
0.01M $NaNO_3$	Background ± 42	$\geq 2.5 \times 10^3$
0.1M $NaNO_3$	Background ± 42	$\geq 2.5 \times 10^3$
1.0M $NaNO_3$	Background ± 21	$\geq 5.3 \times 10^3$
4.0M $NaNO_3$	Background ± 21	$\geq 5.3 \times 10^3$

a. 1 g of cement to 5 ml of solution initially containing 1.11×10^5 d/(min-ml) Pu.

b. $DF = \frac{\text{Initial concentration}}{\text{Final concentration}}$

TABLE III.3.3. Sorption of Plutonium from Sodium Carbonate Solutions[a] by Cement

Cement, g	Final Pu Concentration, d/(min-ml)	DF (Pu)
0.5	172 ± 40	$950\left\{\begin{matrix}+385\\-180\end{matrix}\right\}$
1.0	Background ± 39	$>4.2 \times 10^3$
2.0	Background	$>3.7 \times 10^3$

a. 5 ml of 0.3M Na_2CO_3, 1.63×10^5 d/(min-ml).

TABLE III.3.4. Sorption of Plutonium on Calcium Carbonate Precipitated from Simulated Waste[a]

Calcium Hydroxide, mg	Final Pu Concentration, d/(min-ml)	Carbonate Ion Remaining, mole/liter	DF (Pu)
20	2.22×10^4	0.24	12.7
40	5.36×10^3	0.19	52.6
80	3.92×10^3	0.08	71.9
200	Background ± 510	∿0	⩾553
400	Background ± 330	∿0	⩾850

a. 4.M $NaNO_3$, 0.3M NaOH, 0.3M Na_2CO_3, 0.2M Na_2SO_4, 2.82×10^5 d/(min-ml) Pu, 5 ml in each test.

TABLE III.3.5. Coprecipitation of Strontium with Calcium Carbonate from Simulated Waste[a]

Calcium Hydroxide Added, mg	^{85}Sr in Solution, c/(min-ml)	Calcium Carbonate Precipitated, g	DF[b]	K_d,[c] ml/g
20	7520	0.027	6.49	1016
40	6550	0.054	7.44	596
80	5070	0.108	9.63	399
200	3940	0.150	12.4	380
400	2750	0.150	17.7	557

a. 4M $NaNO_3$, 0.3M NaOH, 0.3M Na_2CO_3, 0.2M Na_2SO_4, 4.88×10^4 c/(min-ml) ^{85}Sr; 5 ml of sol'n req'd for each test.

b. $DF = \frac{\text{Original } ^{85}\text{Sr activity}}{^{85}\text{Sr in solution after precipitation}}$

c. $K_d = (DF-1) \frac{\text{ml solution}}{\text{grams } CaCO_3}$

An alternative method to replace direct discharge of waste to the caverns has been explored in scouting studies. In the alternative method, the waste would first be displaced through an ion exchange column containing zeolite before the discharge of the waste to the cavern. This procedure permits the bulk of the activity currently in solution to be stored as a solid. Gas production due to radiolysis would be then reduced because the nitrate and the bulk of the radiation are separated. Separation of the radioactive nuclides from the salt-bearing supernates would improve the resistance of geologic ion exchange barriers to migration, because both cesium and strontium are sorbed more strongly by rocks and clay from dilute salt solution (such as rockwater) than from the concentrated solutions that exist in the supernate.

Equilibrium studies and laboratory column runs showed[6] that cesium activity in simulated waste supernate can be reduced by a factor of at least 5×10^4 and concentrated in a volume of zeolite only about one-twentieth that of the waste solution. Further studies have indicated that significant amounts of plutonium[1] and strontium[6] if present in the supernate, would also be removed by zeolite. Desorption measurements for both cesium and strontium from zeolite using crystalline rockwater from DRB 6 showed that these nuclides will not be easily removed from zeolite by water in the cavern. No studies have been made using water of Triassic rock origin.

Resistance of Concrete and Rock to Waste Attack

A number of short term accelerated experiments conducted with construction materials and rock show untreated waste will attack these materials:

- Corrosion tests with crystalline rock coupons of quartzite previously leached and then exposed to simulated waste solutions at 200°C showed that silica was dissolved slowly, at a rate that diminished as equilibrium was apparently approached. Extrapolation of the data to infinite time suggests at equilibrium, [Si] = 0.27 M. About the same extent of dissolution was observed with 0.3M NaOH - 0.3M Na_2CO_3 solutions at 200°C, but equilibrium was attained more rapidly because no aluminum was present initially to react with the silica being dissolved. The amount of rock that must be dissolved to provide sufficient silicon to bring the silicon concentration to 0.27M is approximately 1% of the cavern volume.

- Silica was dissolved from Triassic mudstone quickly and extensively by 1M NaOH at 200°C because silica (chert), the principal substance holding mudstone together, is more soluble than quartzite. Aluminosilicates in mudstone, as in crystalline rock, did not dissolve readily when silica was present in the solution and significant quantities of aluminum were not present in the solution. After the exposure period to NaOH, the coupons were found to be cracked and swollen due to dissolving of the binding agent (chert). Exposure to sodium silicate did not affect integrity of the coupons.

- Concrete and cement coupons, when exposed to simulated waste at 100°C (reflux conditions) for 22 days, increased their densities approximately 20% due to the incorporation of aluminum within the coupon (without change in external dimensions), forming calcium aluminosilicate from calcium silicate. Exterior surfaces of concrete (but not cement) samples developed white deposits that were apparently identical to those formed by reaction with rock, and were removed before measuring coupon densities. Permeabilities of the concrete were not measured either before or after the treatment with waste so no information is available on this important parameter.

- Test coupons of a chemical grout *(Am-9 Chemical Grout* from American Cyanamid Company) were prepared according to a procedure recommended by the manufacturer. The coupons were tough and rubbery when first prepared and remained so after 4 months storage in a 100% relative humidity environment. Coupons stored in contact with simulated waste for 4 months, however, became swollen and so weak that they fell apart when moved. Samples of chemical grout exposed to 1.2×10^7 rads of gamma radiation were so severely weakened that they turned into mush without being touched. Based on these data, it is concluded that no credit can presently be taken for engineered reduction of the permeability of the rock around the cavern by chemical grouting due to the potential for the waste to destroy the organic binder in the chemical grout. Cement grouting is not altered by radiation alone, but is attacked by the liquid waste, hence it is assumed to be superior to chemical grout, but insufficient data are available to specify its suitability at this time.

Ion Exchange Properties of Rock

Ion exchange between the material in solution and the rock surface reduces the velocity of radioactively decaying material and thereby the activity reaching the biosphere. The equation describing the relative flow velocity is

$$\frac{V}{V_o} = \frac{1}{1 + \left(\frac{\rho}{\varepsilon}\right) \cdot K_d}$$

where

V = the linear velocity of radioisotope, cm/day

V_o = the linear velocity of water, cm/day

ρ = the bulk density of the rock, g/cm^3

ε = the porosity, volume of voids/volume of container

K_d = the distribution coefficient, cm^3/g

$$K_d = \frac{\text{meq of exchangeable ion adsorbed/100 g of rock}}{\text{meq of exchangeable ion in solution/100 ml of water}}$$

K_d values were obtained from laboratory experiments on crushed samples of crystalline and Triassic rocks over the expected range of sodium nitrate concentrations. The results are given in Tables III.3.6 through III.3.9. The values for crystalline rock are not appropriate for an analysis of flow because the flow is through fractures between rock masses, and the values in Tables III.3.6 through III.3.9 were obtained on

TABLE III.3.6. Sorption of Cesium on Mudstone from DRB-10 as Function of Particle Size and Sodium Nitrate Concentration

Sodium Nitrate	Cs K_d		
moles/liter	<45 μm	45-74 μm	74-177 μm
0	72[a]	52[a]	262[a]
0.001	693[a]	570[a]	563[a]
0.01	598	670	743
0.1	274	219	301
1.0	66	58	80
4.0[b]	18	11	21

a. Solutions contained suspended colloidal matter.

b. Initial (tank) sodium nitrate concentration.

TABLE III.3.7. Sorption of Cesium on Rocks from Various Wells as Function of Sodium Nitrate Concentration[a]

Sodium Nitrate moles/liter	Cs K_d DRB-4	DRB-6	DRB-10 Sandstone
0	50	21	103
0.001	190	159	223
0.01	110	111	295
0.1	-	45.5	102
1.0	-	1.6	25
4.0	5.9	~0	2

a. Particle size distribution 74-177 μm.

TABLE III.3.8. Sorption of Strontium on Rocks from Various Wells[a]

Sodium Nitrate moles/liter	Sr^{2+} K_d DRB-10 Mudstone	DRB-10 Sandstone	DRB-4	DRB-6
0	100[b]	12.6	62	2.5
0.001	66[b]	9.3	27	2.0
0.01	18	8.3	23	1.8
0.1	6.8	2.0	4.0	0.95
1.0	2.0	0.28	0.45	0.11
4.0	~0	~0	~0	~0

a. All samples had the particle size distribution 74-177 μm.

b. Solution contained suspended colloidal matter.

TABLE III.3.9. Sorption of Pu(IV) on Rocks from Various Wells[a]

Sodium Nitrate moles/liter	Pu(IV) K_d DRB-10 Mudstone	DRB-10 Sandstone	DRB-4	DRB-6
0	2230	60	750	400
0.001	3650	-	-	450
0.01	2230	170	710	390
0.1	5700	53	270	450
1.0	4100	-	-	360
4.0	2200	630	865	680

a. Particle size distribution 74-177 μm.

crushed rock. The greater the value of K_d, the slower the waste will move in relation to the velocity of water through the rock. K_d values of 0 are assumed for Cs, Sr, and Pu in crystalline rock. The minimum values for K_d in Triassic rock from these tables, 2(Cs), 0(Sr), and 53(Pu), are the most appropriate for a conservative analysis of Triassic rock. The rapid increase in K_d, with decreasing concentrations of sodium, illustrates the extreme conservatism of this assumption.

Equation 1 was used with K_d's (from Tables III.3.6 through III.3.9) with appropriate values for rock density (2.65 g/cm^3) and porosity (0.03), to calculate the relative velocity of Cs, Sr, and Pu through Triassic rock compared with water (Table III.3.10). The relative cesium velocity is greatest at the highest sodium nitrate concentrations, approximately 10^{-3} that of water, but could be several orders of magnitude slower as the waste dilutes due to mixing with rock water. Strontium travels at the same velocity as water in 4M sodium nitrate, but rapidly slows down with dilution of the waste. Plutonium travels 10^{-4} times as fast as water, independent of the sodium nitrate concentration.

Ion exchange capacities (Table III.3.11) were determined by equilibrating ground rock samples with solutions containing ^{137}Cs tracer and an excess of stable Cs. Using these ion exchange capacities, one can calculate for crystalline rock the surface area required to adsorb the activity present in the waste: 2.8×10^5 g of ^{239}Pu, 2.3×10^6 g of ^{137}Cs, and 1.4×10^6 of ^{90}Sr. The areas are listed in Table III.3.12 and indicate at least 10^9 ft^2 is necessary to satisfy the ion exchange capacity requirements of ^{239}Pu, ^{137}Cs, or ^{90}Sr alone. Most conceivable flow paths are likely to have a smaller exposed area, hence ion exchange in crystalline rock cannot be relied upon to remove radionuclides from solution.

Using the ion exchange capacities for Triassic rock, one can calculate the volume of rock required to satisfy the exchange capacity requirements of Pu, Cs, and Sr. The volumes are listed in Table III.3.13 and indicate that a rock volume less than 1% of the cavern volume is required to provide sufficient cation exchange capacity to hold the plutonium and cesium. This small volume of rock is readily encountered many times over by the expected flow path through Triassic rock to the biosphere.

TABLE III.3.10. Relative Velocity of Cesium, Strontium, and Plutonium through Sandstone (DRB 10) to that of Water as a Function of Sodium Nitrate Concentration[a]

Sodium Nitrate, moles/liter	Cs	Sr	Pu
0	1.1×10^{-4}	9.0×10^{-4}	1.9×10^{-4}
0.001	5.1×10^{-5}	1.2×10^{-3}	-
0.01	3.8×10^{-5}	1.4×10^{-3}	6.7×10^{-5}
0.1	1.1×10^{-4}	5.6×10^{-3}	2.1×10^{-4}
1.0	4.5×10^{-4}	3.8×10^{-2}	-
4.0	5.6×10^{-3}	1	1.8×10^{-5}

a. Particle size distribution of sandstone was 74 to 177 μm.

TABLE III.3.11. Ion Exchange Capacity of Rock Samples for Cesium

Sample	Capacity, meq/g
DRB-10 mudstone[a]	0.043 ± 0.002
DRB-10 mudstone[b]	0.044 ± 0.004
DRB-10 sandstone[b]	0.0056 ± 0.0008
DRB-4[b]	0.0045 ± 0.0010
DRB-6[b]	0.0012 ± 0.0003

a. Particle size distribution was 45-74 μm.

b. Particle size distribution was 74-177 μm.

TABLE III.3.12. Surface Area of Crystalline Rock Required to Satisfy the Ion Exchange Capacity Requirements of Pu, Cs, and Sr Present in the Waste

	Surface Area Required, ft^2		
Rock Source	Pu	Cs	Sr
DRB-4	3.4×10^{8}	1.2×10^{9}	2.2×10^{9}
DRB-6	1.3×10^{9}	4.7×10^{9}	8.2×10^{9}

TABLE III.3.13. Volume of Triassic Rock Required to Satisfy the Ion Exchange Capacity Requirements of Pu, Cs, and Sr Present in the Waste[a]

Element	Volume, cm^3	% of 80,000,000 gallons
Pu	3.12×10^8	0.083
Cs	1.15×10^9	0.304
Sr	2.0×10^9[b]	0.529[b]

a. Assumes no effects from competing ions.

b. Unrealistically small, because strontium is unable to compete with sodium for exchange sites (K_d = 0 with concentrated waste).

III-4. CAVERN PRESSURIZATION FROM RADIOLYTIC GAS

The following outline of the Discussion Section is provided to assist the reader.

A. Flow of Gas and Liquid Through Low Permeability Media

B. Mathematical Models of Pressure Increases from Radiolysis:

1. Design Parameters and Assumptions
2. Radiolytic Gas Production
3. Water Inleakage Rate
4. Initial Total Gas Volume
5. Cavern Pressure

C. System Behavior

1. Parameters of Gas Behavior
2. Case A: Resistance to Gas Flow From the Cavern is Negligible
    a. Effect of initial water inleakage rate
    b. Effect of initial gas volume
    c. Effect of quantity of radiolytic gas produced
3. Case B: All Gas Trapped in Cavern
    a. Effect of initial water inleakage rate
    b. Effect of initial gas volume
    c. Effect of quantity of radiolytic gas produced

D. Design Criteria (Case B Conditions)

1. Time to Reach Hydrostatic Equilibrium
2. Excess Cavern Pressure
3. Meeting Design Criteria by Eliminating Radiolytic Gassing

Introduction

Considerable quantities of non-toxic gases (oxygen, hydrogen, nitrogen and its oxides) will be produced during storage by irradiation of the waste by the ^{90}Sr and ^{137}Cs (Appendix III-4.A). Radiolytic gas production is of concern because it represents a potential force on the liquid waste acting in all directions radially about the cavern, and could result in direct vertical movement of the waste toward the overlying Tuscaloosa aquifer. Conditions are defined in this section that assure that the pressure of the radiolytic gas in the cavern will not exceed the hydrostatic pressure in the surrounding rock by a significant amount and, therefore, will not represent a significant driving force in the system.

Summary

It is expected that a bedrock cavern with the properties required for a safe waste storage system will be located in rock having very low permeability. This low permeability rock requires large gas pressures before the gas will displace the water from the small pores in the rock (or a cement liner and grouted rock if they are still intact). As a consequence, the radiolytic gas could be trapped in the cavern at pressures up to several hundred feet of water in excess of the surrounding hydrostatic pressure.

Because cavern gas phase pressures in excess of the surrounding hydrostatic pressure could potentially force waste from the caverns in all directions (including the relatively short distance up to the Tuscaloosa aquifer), the pressure should not ultimately exceed the surrounding hydrostatic pressure by more than a few feet of water. Under these conditions the driving force due to the radiolytic gases would be small compared to the natural hydraulic gradients existing in the system.

To maintain a low cavern gas phase pressure, the cavern should have sufficient freeboard to provide the necessary volume to prevent a rapid buildup of pressure in the cavern to levels that can exceed hydrostatic pressure. This buildup occurs from water leaking into the cavern and gas production by radiolysis.

Long term cavern volume reduction due to creep must also be considered. Based on the estimated initial water inleakage rate in a crystalline cavern of approximately one gallon per minute (gpm) to 30 gpm (taking no credit for artificial reduction in the permeability by grouting), the initial volume required for a crystalline cavern is estimated to be several hundred million gallons; far in excess of the 80 million gallons required for the liquid waste alone. This calculation indicates an alternative solution for reducing the gas pressure will be necessary to achieve the goal of a small excess pressure buildup. A practical approach for eliminating the gas drive in a crystalline cavern would involve removing about 99% of the ^{90}Sr and ^{137}Cs from the waste and storing it in a separate cavern in a form that produces no gas.

Based on estimated initial water inleakage rates in a Triassic cavern of approximately 10^{-3} gpm to 0.3 gpm, much less initial space is needed to accomodate the expected gas volume. For a Triassic cavern with a 0.1 gpm initial water inleakage rate, a total cavern volume of 130 million gallons should be sufficient; 80 million gallons for liquid waste, 40 million gallons for water inleakage and radiolytic gas, and 10 million gallons for cavern volume reduction due to creep.

Discussion

A. Flow of Gas and Liquid Through Low Permeability Media

In evaluating the significance of the radiolytic gas as a potential driving force on the liquid waste it is necessary to consider the flow behavior of the gas and liquid waste through the surrounding media after hydrostatic equilibrium is reached. This analysis assumes that the liquid waste has the same density as the surrounding rock water. If the liquid waste density were greater, it would begin to flow from the bottom of the cavern before the gas pressure in the cavern equalled the surrounding hydrostatic pressure, as discussed in Section III-5.

If the resistance to gas flow from the cavern were negligible compared to the resistance to liquid waste flow, the gas would begin to escape from the cavern as soon as hydrostatic equilibrium was reached and the pressure would not increase significantly above the surrounding hydrostatic pressure. However, if the resistance to gas flow were significant compared to that for the liquid, the radiolytic gases generated after the system has reached the surrounding hydrostatic pressure would represent a driving force on the liquid waste acting in all directions radially about the cavern.

Because molecular diffusion of the gas through the rock is negligible (Appendix III-4-B), appreciable amounts of gas will not begin to flow from the cavern until the difference between the cavern gas pressure and the surrounding hydrostatic pressure is in excess of the capillary entrance pressure. The capillary entrance pressure is the pressure required for the gas to overcome the surface tension forces that exist at the interface between the gas in the cavern and the water in the rock at the rock surface (Appendix III-4.C). The capillary entrance pressure is inversely proportional to the effective size of the openings in the rock through which flow takes place and for effective pore sizes in the rock of ca. 1 μm or less, it is greater than 48 ft_{H_2O} (Figure III.4.1 and Appendix III-4.D).

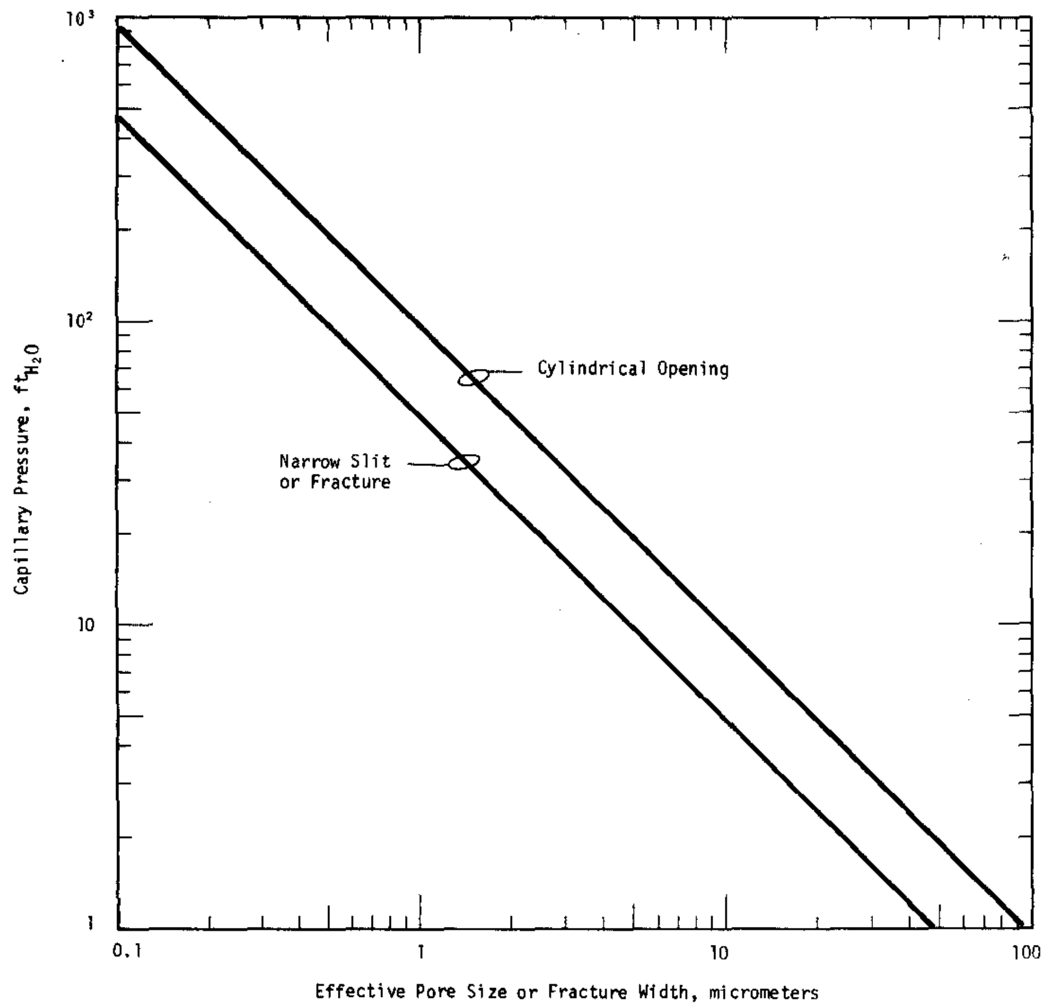

FIGURE III.4.1 Capillary Entrance Pressure

For a storage site in either the crystalline or Triassic rock with the necessarily low permeability required for successful bedrock storage, the effective pore size should be approximately less than 1 μm. If this is the case, the gas will be essentially trapped in the cavern. Published capillary entrance pressures for several different sandstones with permeabilities as low as that measured for SRP Triassic rock are on the order of several hundred ft_{H_2O} while published values for samples of concrete[1] give capillary entrance pressures of about 40 to 80 ft_{H_2O}. No credit is taken in this analysis for a cement liner or grouted areas in the rock as a means of reducing the permeability of the media due to the possibility that the liquid waste would attack the cement or other grouting materials over a period of decades and destroy the integrity of such an engineered barrier. However, if such a barrier were to be included, the attack would be expected on the area in contact with liquid waste while the area still in contact with the gas phase would not be expected to deteriorate nearly as rapidly. This effect would increase the probability that the resistance to gas flow from the cavern would be large compared to the resistance to liquid waste flow.

Even if gas does overcome the capillary entrance pressure, the rate at which it flows from the cavern will still be determined by the nature of the rock and the subsequent two-phase flow system that would result as the gas penetrated through the rock and mixed with the water in the rock. In a media such as a relatively impermeable rock, the resistance to the flow of a two-phase mixture of gas and water would be expected to be much greater than the resistance to either phase alone. This phenomenon is dependent upon the size and shape of the pores. Measurements of this effect in sandstones[2] have shown that the permeability of the media to gas flow is negligible until approximately 10% or more of the pore space becomes filled with gas. The permeability to gas flow still may be less than 10% of the permeability for gas alone after 30 to 40% of the pore space is filled with gas. Therefore, even if the gas is not completely trapped in the cavern by capillary forces, the volumetric flow rate of gas from the cavern still may be small compared to the volumetric flow of liquid waste from the cavern.

It should be noted that since the liquid waste phase is completely miscible with the water in the rock, it would not have to overcome the surface tension forces that the gas would have to overcome. If the gases dissolved in the liquid waste were to be evolved as this waste migrated upward toward the Tuscaloosa, the resulting two phase system would have a greater flow resistance than the liquid alone, however, no credit is taken for this effect due to the possibility that the gases might remain super-saturated in the liquid waste.

Based on the preceding considerations, it is expected that a bedrock cavern with the low permeability that will be required to prevent extensive liquid waste migration will trap all of the radiolytically produced gas at pressures up to several hundred feet of water in excess of the surrounding hydrostatic pressure. The actual behavior of gases in the rock media must be determined by *in-situ* tests.

B. Mathematical Models of Pressure Increases From Radiolysis

1. Design Parameters and Assumptions

The pressure of the gas phase in the cavern is mainly dependent upon three parameters:

1. The total quantity of radiolytic gases produced in a cavern.

2. The water inleakage rate to a cavern when it is sealed.

3. The gas volume in a cavern when it is sealed.

These three parameters can be estimated by direct measurements on the waste and the caverns before sealing. Mathematical models are derived in this section to predict upper limit values of the pressure in the gas phase, the quantity of water that has entered the cavern, or the quantity of waste that has been forced from the cavern at any time as a function of these three parameters. Conservative design criteria that will assure negligible waste migration from radiolytic gas evolution are then specified in terms of these parameters.

The following basic assumptions are made:

1. The cavern is at atmospheric pressure when sealed.

2. No credit is taken for engineered techniques of reducing the permeability of the rock by grouting because of the potential for the waste to attack the grout.

3. The water inleakage rate is assumed to be at the "steady-state" value measured just before sealing the cavern.

4. The waste is treated as if it were evenly divided throughout all of the caverns (both with respect to volume and activity) and each cavern is assumed to have the same initial gas volume. (This is equivalent to assuming that all of the waste is in a single large cavern.)

5. The waste flowing from the cavern is assumed to have the same properties (viscosity, density, etc.) as the rock water flowing into the cavern.

6. The total cavern volume is assumed to be constant. (The effects of total volume reduction due to creep are discussed separately in Section III-2 and at the end of this section.)

2. Radiolytic Gas Production

The rate at which gas is evolved is essentially controlled by the rate at which the waste is being irradiated by ^{90}Sr and ^{137}Cs. The integrated quantity of gas evolved at any time after sealing is described by the following equation:

$$N = N_T \, (1 - e^{-\lambda t}) \qquad (1)$$

where

t = time since sealing, years

N_T = total quantity of radiolytic gas produced ($t = 0$ to $t = \infty$), moles

N = quantity of gas evolved after sealing ($t = 0$ to t), moles

λ = effective average decay constant for ^{90}Sr and ^{137}Cs, 0.024 yr^{-1}

This equation assumes that the yield of gas (molecules produced per unit of energy absorbed by the waste) is constant. [The yield is expected to decrease by a maximum of ca. 15% for untreated waste as the nitrate concentration decreases (Appendix III-4A)]. The total volume of radiolytic gas produced is basically a parameter characteristic of the waste itself because the interaction of the waste with the bedrock environment is not expected to significantly affect radiolytic gassing.[3] For untreated waste, a total of ∿700 million gallons of gas (at 0°C and 1 atm pressure) are expected. The total quantity to be produced could be significantly decreased by alteration of the waste to reduce gassing, and therefore it is introduced as a variable to be evaluated.

3. Water Inleakage Rate

The water inleakage rate to the cavern is expected to decrease over the first several years after the tunnel has been excavated, and then begin to level out at a relatively constant or "steady state" value. It is assumed that the cavern will be located in a zone of relatively tight rock surrounded by zones of rock with much higher permeabilities. All of the resistance to water inleakage is assumed to occur across the relatively impermeable zone of rock surrounding the cavern. The rate of water inleakage to the cavern is expressed by the following equation:

$$W = C\ (P_{rock} - P_{cavern}) \qquad (2)$$

where

W = water inleakage rate, gal/yr

P_{rock} = hydrostatic pressure in the surrounding rock, ft_{H_2O} gauge

P_{cavern} = pressure of gas in the cavern, ft_{H_2O} gauge

C = a constant equal to the product of the area and the effective permeability across the relatively impermeable layer divided by effective thickness, gal/yr-ft_{H_2O}

This equation predicts that if the cavern remains vented (P_{cavern} = 0) the water inleakage rate will be a constant. In an actual cavern maintained at atmospheric pressure, this will occur when the cavern system reaches the point where the system is being recharged at a rate equal to the water inleakage rate. Even for the hypothetical case of a system extending an infinite distance, the inleakage rate approaches a relatively constant value for times of the order of that of concern for this analysis (ca. 100 to 200 years) as shown in Figure 4 of Appendix III-4.D.

Equation 2 takes into account the reduction in the rate of water inleakage as the cavern pressure increases. The pressure difference driving force term in Equation 2 goes to zero as the cavern gas pressure approaches the hydrostatic pressure in the surrounding rock. If the pressure of the gas in the cavern exceeds the hydrostatic pressure in the surrounding rock, the direction of flow is reversed and waste then flows from the cavern into the rock. Because the waste flowing from the cavern is assumed to have the same properties as the water in the rock, Equation 2 applies for flow into and out of the cavern.

The water inleakage rate to the caverns when they are charged and sealed is taken as the single parameter reflecting the hydrology of the system. This will be referred to as the initial water inleakage rate, W_i. The hydrostatic pressure in the rock is taken to be 1500 ft_{H_2O} for this study. The constant, C, associated with this rate of water inleakage is evaluated by setting P_{cavern} in Equation 2 equal to zero. The initial water inleakage rate is a characteristic of the particular location of the cavern and the type of rock. The minimum expected initial water inleakage rate for a crystalline rock cavern just before sealing would be approximately 1 to 10 gpm. A more likely rate of inleakage assuming that only 90% of a crystalline cavern is located in the least permeable zone is about 30 gpm. The inleakage rate for Triassic rock is expected to be about 0.1 gpm (Table 1, Appendix III-4.D).

4. Initial Total Gas Volume

The initial total gas volume or "freeboard", V_i, in the caverns is also an important parameter in determining the potential for the cavern pressure to exceed the surrounding hydrostatic pressure. Sufficient initial gas volume should be provided for the water that will leak into the caverns, as well as for the radiolytic gases generated in the waste. There are practical limits on the volume of freeboard allowed, due to the added cost of this space. It is assumed that added gas volume would be obtained by increasing the diameter of the tunnels rather than the length in order to minimize the probability of intersecting zones of high permeability.[4]

5. Cavern Pressure

The absolute pressure in the cavern at any time was calculated by:

$$P_{cavern} = \phi \left[\frac{N_{Radiolytic} + N_i}{N_i}\right] \left[\frac{V_i}{V_{gas}}\right] \left[\frac{T}{T_i}\right] \qquad (3)$$

P_{cavern} = absolute pressure in the cavern at any time t, ft_{H_2O} or psi

where

ϕ = atmosphere pressure, 33.9 ft_{H_2O} or 14.7 psi

N_i = initial quantity of gas present in the cavern when sealed, moles (t = 0)

$N_{Radiolytic}$ = total accumulated moles of gas produced by radiolysis at time t (Equation 1)

V_i = freeboard, initial gas volume in the cavern when sealed, (t = 0), millions of gallons

V_{gas} = gas volume in the cavern at time t, millions of gallons; V_i minus accumulated water inleakage (Equation 2)

T_i = initial temperature of gas in the cavern, °K

T = temperature of gas in the cavern at any time, t, °K

Equation 3 is derived from the ideal gas law and simply relates the pressure, volume, temperature, and moles of gas at two different times.

Equations 1, 2, and 3 were solved by computer (Appendix III-4.E) to obtain the cavern gas pressure at any time and the total quantity of waste forced from the cavern (when this pressure exceeded the surrounding hydrostatic pressure) for combinations of the three controlling parameters; initial water inleakage, initial gas volume, and total quantity of gas evolved as discussed below.

C. System Behavior

1. Parameters of Gas Behavior

In order to evaluate the significance of radiolytic gas evolution, two limiting cases are considered:

- Case A: The resistance to gas flow from the cavern is negligible.
- Case B: All of the gas remains trapped in the cavern.

As discussed previously, Case A is a limiting case that probably would not be approached in an actual bedrock storage system. Case A is presented here for discussion purposes only, as one of the limiting cases with respect to gas drive. For this limiting case, the radiolytic gases do not present a potential drive on the waste. Case B is expected to be a reasonable approximation to actual behavior in a bedrock waste storage system.

The effects of each of the three main parameters, (1) initial water inleakage rate, (2) initial gas volume, and (3) total quantity of radiolytic gases, were evaluated for Cases A and B by assuming expected values for two of the parameters and varying the third. The behavior of the system is identical for Cases A and B during the period when the cavern pressure is not in excess of the surrounding hydrostatic pressure.

For Case B, the radiolytic gases represent a potential drive on the system. For this case, conservative design criteria were formulated that assure negligible consequences from radiolytic gas evolution. The combinations of the main variables that met these requirements were determined for water inleakage rates expected for crystalline and Triassic caverns, respectively.

2. Case A: Resistance to Gas Flow From the Cavern is Negligible

For this case, the radiolytic gases do not represent a potential drive on the liquid waste. In order for this case to be approached in an actual bedrock storage system, it would be necessary that the flow of gas from the rock be through a small number of vertical (greater than 50 micrometer cracks, Appendix III-6.A). For this situation, the capillary entrance pressure would be small and the mixing of gas with water in the rock would be minimized so that the two-phase flow resistance of the gas in the rock would be essentially that of the gas alone (the viscosity of the gas is approximately 3% of the viscosity of the liquid). This system would effectively be a series of small vent pipes to remove gas from the cavern. As discussed in Sections III-5 and III-7, such a rock hydrology system would not be acceptable due to the route it would present for vertical waste movement by other drives on the waste, however, Case A is presented here as a limiting case with respect to the radiolytic gas drive.

a. Effect of Initial Water Inleakage Rate

The pressure in the cavern is shown as a function of time in Figure III.4.2 for the case where the resistance to gas flow from the cavern is negligible. The calculations assume 700 million gallons (at atmospheric pressure) of radiolytic gas, an initial gas volume of 60 million gallons (this corresponds to a 140 million gallon cavern containing 80 million gallons of liquid waste) and initial water inleakage rates of 1, 2, and 3 gallons per minute (gpm). The cavern gas pressure does not reach the surrounding hydrostatic pressure for at least 200 years when the water inleakage rate is 1 gpm, however, for an initial water inleakage rate of 3 gpm the cavern reaches hydrostatic equilibrium in approximately 40 years. The effect of temperature was included in Equation 3 using the cavern temperature model described in Section III-6 assuming an effective cavern radius of 14 feet, an effective thermal conductivity of rock of 1.6 Btu/(hr-ft-°F) and an initial cavern temperature of 90°F. The result of including the temperature effect is an approximately 15% higher cavern pressure at about 20 years. For systems reaching equilibrium at times in excess of 100 years, the net effect of the temperature increase is a slight reduction in the amount of water flowing into the cavern during the first 50 years. In subsequent calculations for Case B, the term T/T_i in Equation 3 was assumed to be unity.

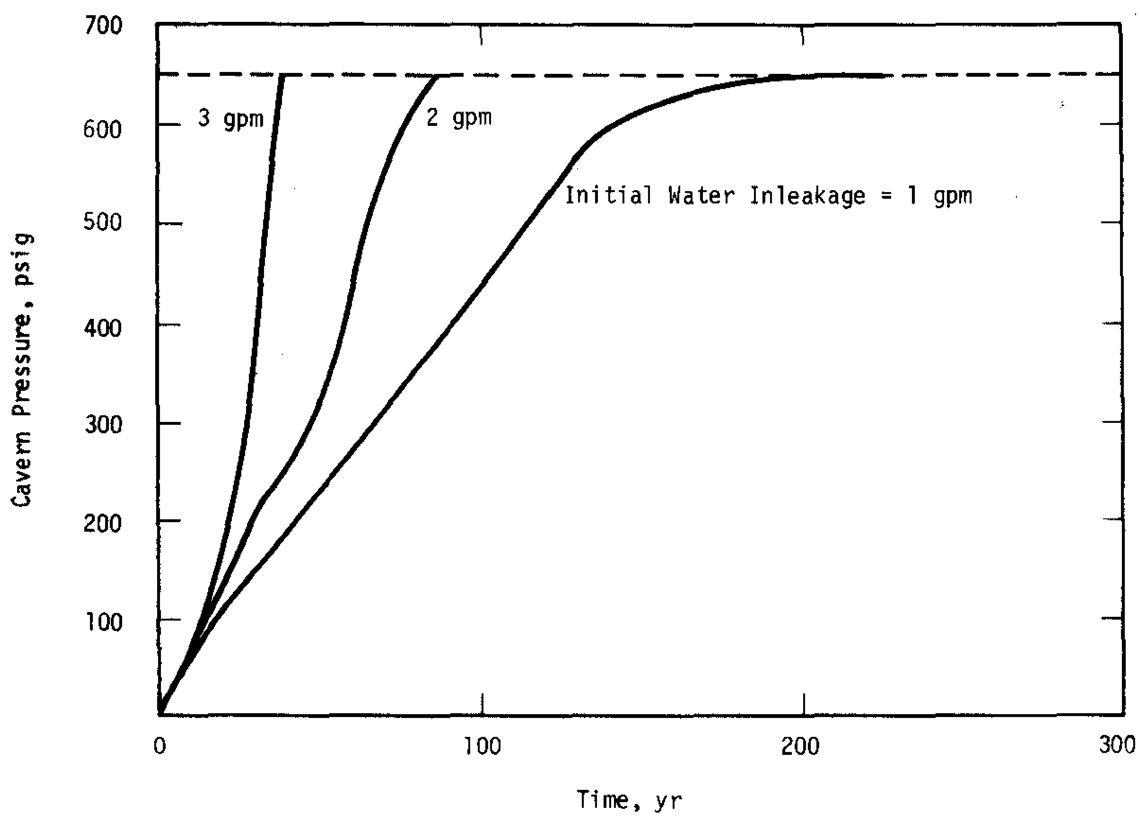

FIGURE III.4.2 Effect of Initial Water Inleakage Rate on Cavern Pressure When the Initial Gas Volume is 60 x 10^6 Gallons and the Total Quantity of Radiolytic Gas Produced is 700 x 10^6 Gallons (90°F, 14.7 psia)

b. Effect of Initial Gas Volume

The effect of initial gas volume is shown in Figure III.4.3 for an assumed initial water inleakage rate of 1 gpm and an expected total quantity of radiolytic gas of 700 million gallons (at 1 atm) at initial cavern volumes of 20, 40, and 60 million gallons. For an initial cavern volume of 60 million gallons the system does not reach hydrostatic equilibrium for at least 200 years. For an initial cavern volume of 20 million gallons the cavern reaches hydrostatic equilibrium in approximately 30 years (this behavior is very similar to that shown in Figure III.4.2 for an initial gas volume of 60 million gallons and an initial water inleakage rate of 3 gpm).

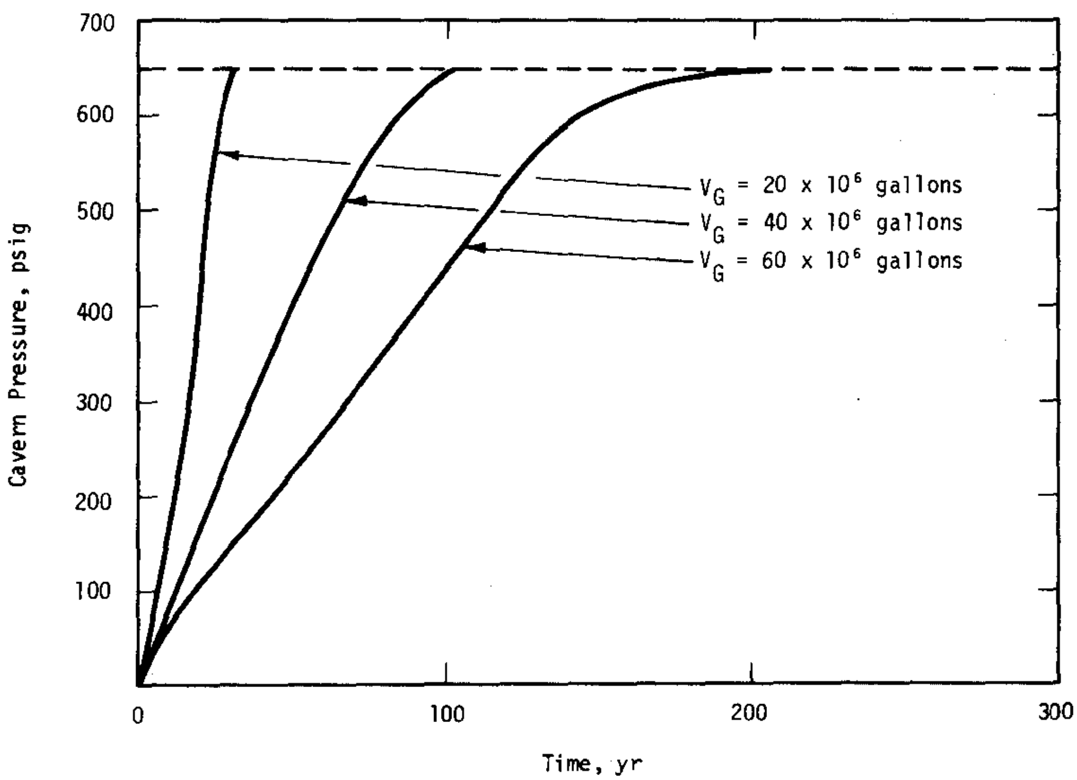

FIGURE III.4.3. Cavern Pressure Increase; Effect of Initial Gas Volume

Initial Water Inleakage Rate = 1 gpm
Total Quantity of Radiolytic Gas = 700 x 10^6 gal.
(90°F, 1 atm)

Figures III.4.2 and III.4.3 show clearly that the time to reach hydrostatic equilibrium can be maximized by providing a system with large initial gas volumes and low initial water inleakage rates when the resistance to gas flow from the caverns is negligible.

c. Effect of Quantity of Radiolytic Gas Produced

The maximum quantity of radiolytic gas evolved from untreated waste is expected to be approximately 700 million gallons at one atmosphere pressure at the expected rock temperature of 90°F. However, this total quantity could be reduced appreciably by altering the waste to reduce the radiolytic gas yield (Appendix III-4.A). The total quantity of radiolytic gas is taken to be a variable and its effect is evaluated for an initial water inleakage rate of 1 gpm and initial gas volumes of 20, 40, and 60 million gallons. The most unfavorable case considered a 20 million gallon initial gas volume (shown in Figure III.4.4) for assumed total quantities of radiolytic gas (V_{gt}) of 0, 70, and 700 million gallons. For this case, when the resistance to gas flow from the cavern is negligible, the system reaches hydrostatic equilibrium in about 30 years for 700 million gallons of radiolytic gas and about 40 years for 70 million and 0 gallons. For the intermediate case of 40 million gallons of initial gas volume (Figure III.4.5) the system reaches equilibrium in about 80 years for either 0, 70, or 700 million gallons of radiolytic gas evolved.

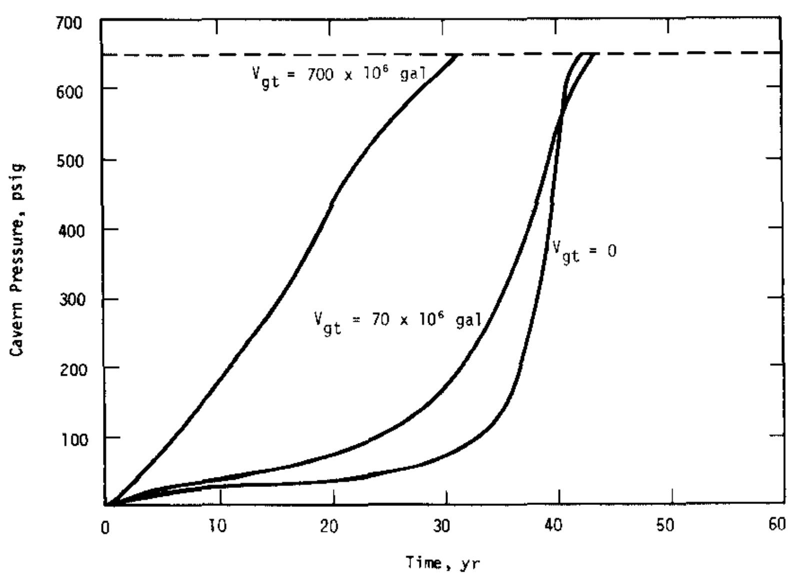

FIGURE III.4.4. Cavern Pressure Increase; Effect of Quantity of Radiolytic Gas Produced (Initial 20 Million Gallon Volume)

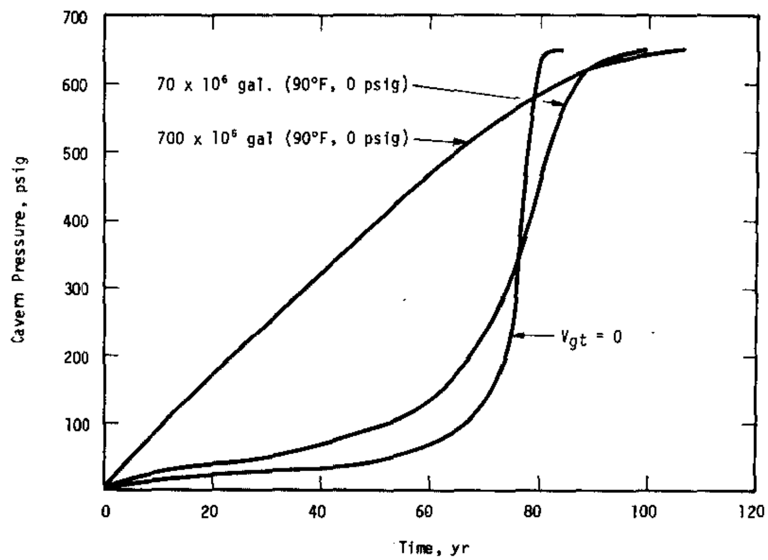

FIGURE III.4.5. Cavern Pressure Increase; Effect of Quantity of Radiolytic Gas Produced (Initial 40 Million Gallon Volume)

Figure III.4.6 illustrates the effect of designing a cavern with a large volume of space for subsequent gas production. In this case (60 million gallons of initial cavern gas volume), the cavern reaches hydrostatic equilibrium sooner (approximately 125 years) for small amounts of radiolytic gas (0 and 70 million gallons) than for large amounts (700 million gallons) of gas (more than 200 years) when the resistance to gas flow from the cavern is negligible.

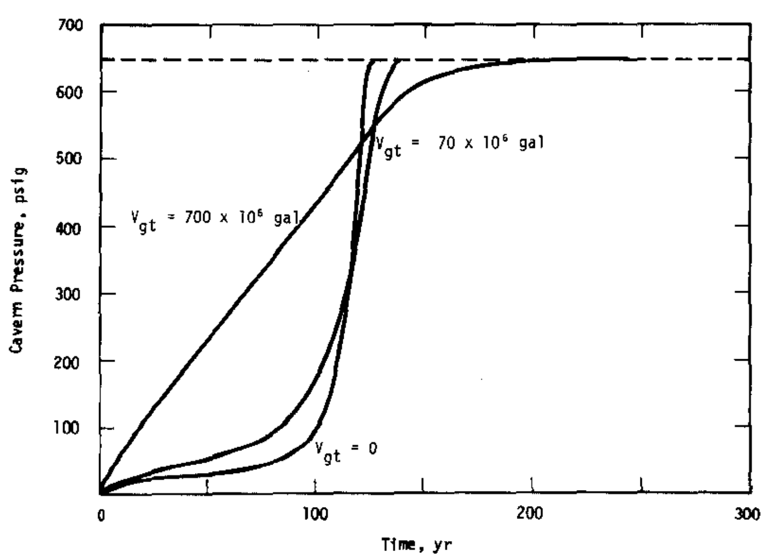

FIGURE III.4.6. Cavern Pressure Increase; Effect of Quantity of Radiolytic Gas Produced (Initial 60 Million Gallon Volume)

In summary, for a cavern storage system designed to maximize the time period required to reach hydrostatic equilibrium (large initial cavern gas volume, low initial water inleakage rate, and negligible resistance to gas flow from the cavern), the production of radiolytic gas is an advantage, because it increases this time even further by resisting water inleakage to the cavern during the early period.

3. Case B: All Gas Trapped in Cavern

The assumption that the gas is trapped by capillary forces in tight rock is a more reasonable approximation to expected behavior in a bedrock storage system. For this case the potential pressurization of the cavern above the surrounding hydrostatic equilibrium pressure must be considered. This pressurization is especially important because this force will act in all directions radially about the cavern and represents a potential drive for direct vertical movement of the waste through the relatively short distances (500 to 1000 ft) expected between the cavern and the overlying Tuscaloosa aquifer. Natural horizontal gradients are expected to be on the order of 3 to 4 ft_{H_2O} per mile in the crystalline rock (Chapter I), therefore, excess cavern pressures (cavern pressure minus surrounding hydrostatic pressure) of 1 ft_{H_2O} represent vertical hydraulic gradients in excess of existing horizontal gradients for this rock. Excess cavern pressures of as little as 7 ft_{H_2O} represent unacceptably large driving forces in the vertical direction for a cavern with the properties expected for crystalline rock if it is assumed that this pressure is exerted in the vertical direction and the density of the waste is assumed equal to that of the rock water (Figure I.11). An excess cavern pressure of 7 ft_{H_2O} could be tolerated in the expected Triassic system.

If dispersion and dilution of waste as it flows through the rock is assumed to be zero, the density of the liquid waste flowing from the cavern represents an upper limit to the vertical distance that the waste can travel. A cavern pressure of 50 ft H_2O above hydrostatic pressure would be sufficient to lift waste with a specific gravity of 1.1 to a height of 500 ft above the cavern. However, dispersion and dilution of waste for migration distances of several hundred feet could be appreciable and much lower excess pressures would be sufficient to overcome the density of more dilute waste.

Based on these considerations, it is evident that the excess cavern pressure should not exceed a few feet of water in a crystalline cavern in order to eliminate this driving force as a means of forcing large quantities of waste from the cavern or forcing waste up to the Tuscaloosa aquifer. An arbitrary upper limit of approximately 1 ft_{H_2O} of head difference will be applied to both the crystalline and Triassic systems; however, it should be noted that the higher permeability and lower porosity expected for the crystalline rock make it more critical that the crystalline system meet these criteria.

a. Effect of Initial Water Inleakage Rate

The pressure in the cavern is shown as a function of time in Figure III.4.7 for the expected total quantity of radiolytic gas of 700 million gallons (at 1 atm) and an initial gas volume of 60 million gallons at initial water inleakage rates of 1, 2, and 3 gpm. The desired system behavior is obtained at the 1 gpm initial water inleakage rate. For this condition, the pressure in the cavern approaches the surrounding hydrostatic pressure asymptotically after 200 years. Because the amount of gas remaining

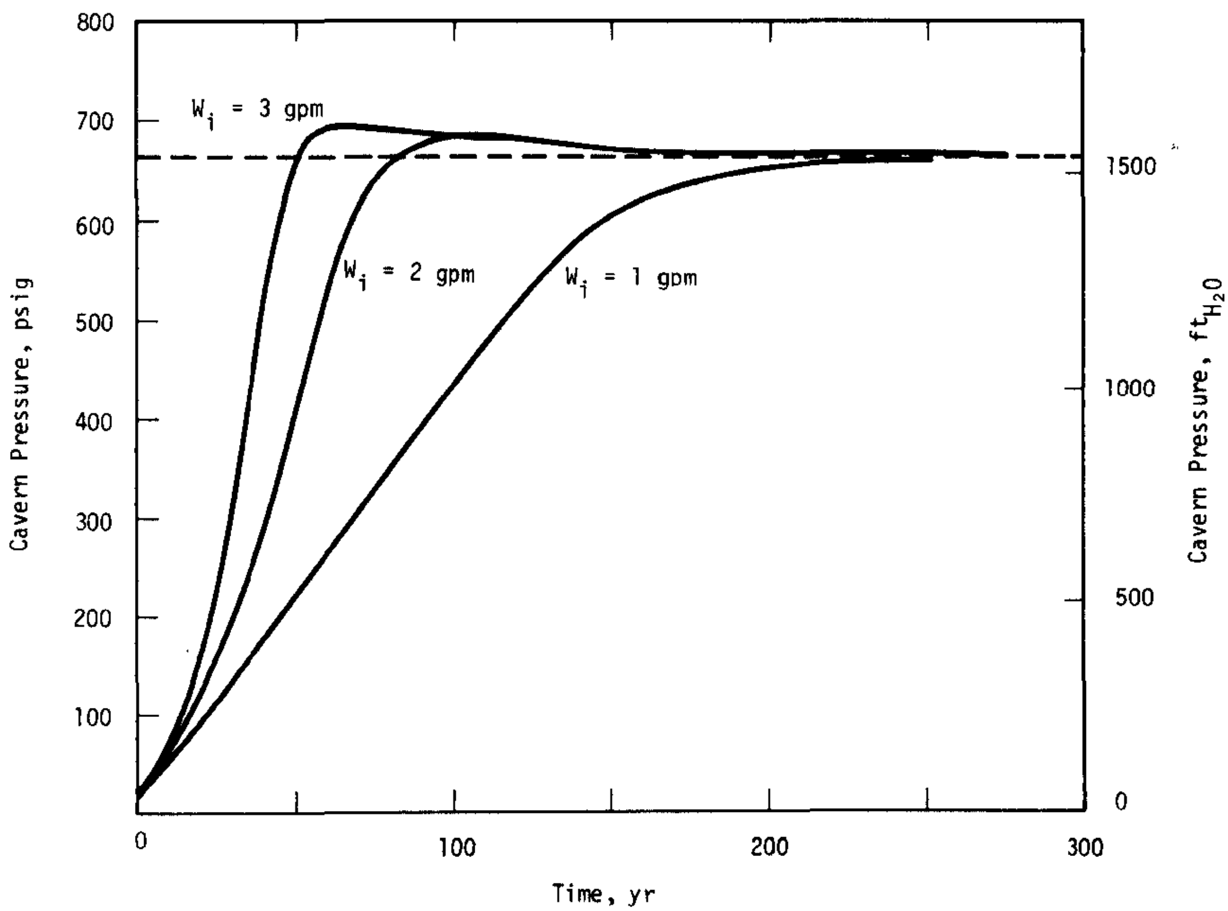

FIGURE III.4.7. Cavern Pressure Increase; Effect of Initial Water Inleakage Rate to be produced is small compared to the remaining gas volume at this time, the system pressure never exceeds the surrounding hydrostatic pressure by more than 1 ft_{H_2O}. However, for the case of a 3 gpm initial water inleakage rate the excess cavern pressure reaches about 30 psi (ca. 70 ft_{H_2O}) and a relatively large quantity of waste (about 4.5 million gallons) is forced from the system by the radiolytic gas. The volume of liquid waste forced from the system is equal to the volume of radiolytic gas (measured at the surrounding hydrostatic pressure of approximately 1500 ft_{H_2O}) which is evolved after the system reaches hydrostatic equilibrium. Because the excess cavern pressure is large compared to the pressure required to force the waste up to the Tuscaloosa aquifer, it is possible that some portion of this waste would enter the aquifer.

b. Effect of Initial Gas Volume

The effect of initial gas volume is shown in Figure III.4.8 for an assumed initial water inleakage rate of 1 gpm and an expected total quantity of radiolytic gas of 700 million gallons (at 1 atm) at initial cavern volumes of 20, 40, and 60 million gallons. The results for a 20 million gallon initial gas volume at 1 gpm are an excess cavern pressure reaching a maximum of about 95 psi (ca. 220 ft_{H_2O}).

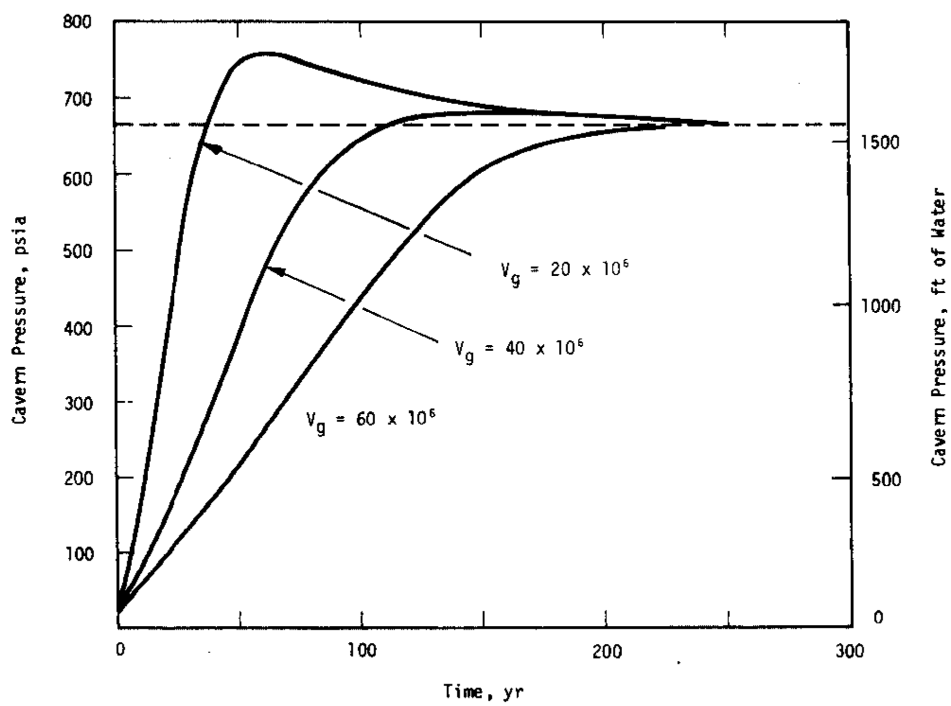

FIGURE III.4.8. Cavern Pressure Increase; Effect of Initial Gas Volume

c. Effect of Quantity of Radiolytic Gas Produced

As was shown in Figure III.4.6, reduction of the quantity of radiolytic gas produced does not necessarily result in an increase in the time required for a vented system to reach hydrostatic equilibrium. The effect of the total quantity of gas evolved is dependent upon the initial water inleakage rate and the initial gas volume. The relationship of these three principal parameters are discussed in the following section, "Design Criteria".

D. Design Criteria (Case B Conditions)

To develop design criteria for cavern storage, the effect of various combinations of the three main parameters (initial water inleakage rate, initial gas volume, and total volume radiolytic gas produced) was studied. The criteria assumed conservatively that all gas was trapped in the cavern (Case B). For each combination of these three parameters the time to reach hydrostatic equilibrium, the peak cavern excess pressure, and the total quantity of waste forced from the cavern were calculated. These results are plotted as a function of the total quantity of gas evolved for an assumed initial gas volume and several assumed values of initial water inleakage rate (Figure III.4.9 through III.4.15). Principal emphasis was on the limitation of the driving force (in terms of the excess cavern pressure) as the basis for establishing requirements.

1. Time to Reach Hydrostatic Equilibrium

It is desirable to maximize the time required for the system to reach hydrostatic equilibrium. The importance of this effect can be determined from the mathematical models that are presented in Chapter IV. The concentration and quantity of a particular radioisotope entering the biosphere is a function of the time required to reach hydrostatic equilibrium. Maximizing this time period will reduce the concentration and quantity of radioisotopes with relatively short half lives. However, the time periods required for decay of the very long lived radioisotopes will probably be large compared to the time periods expected for the cavern to reach hydrostatic equilibrium. Figure III.4.9 gives the time required to reach hydrostatic equilibrium for an initial gas volume of 60 million gallons at initial water inleakage rates of 1 and 2 gpm. At 2 gpm, the time is relatively independent of the total quantity of gas produced, however, at 1 gpm, the time to reach hydrostatic equilibrium is a maximum for about 900 million gallons of gas evolved.

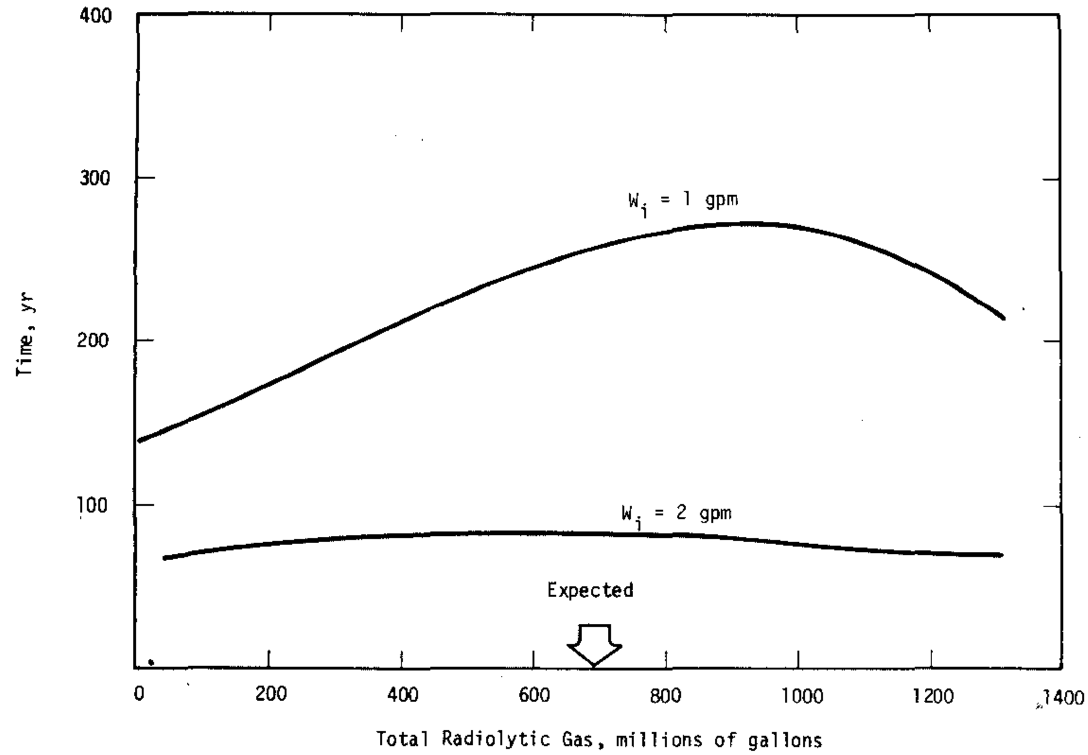

FIGURE III.4.9. Time to Reach Hydrostatic Equilibrium with 60 Million Gallon Freeboard

Figure III.4.10 shows the effect at 120 million gallons of freeboard and initial water inleakage rates of 1, 2, 3, and 4 gpm. At 3 and 4 gpm, the time is essentially independent of the total quantity of gas produced. At 2 gpm, the time required to reach hydrostatic equilibrium increases steadily with the total amount of gas evolved. At 1 gpm, the time to reach hydrostatic equilibrium becomes large for all values of total quantity of gas evolved.

Although the time required to reach hydrostatic equilibrium should be maximized for both Case A and Case B, for Case B the criterion for acceptable storage conditions is the limitation of excess cavern pressure as discussed below. The time to reach hydrostatic equilibrium is not as important as maintaining cavern pressure below the hydrostatic pressure. Long times are only a means to this desired end, but are not the end, *per se*.

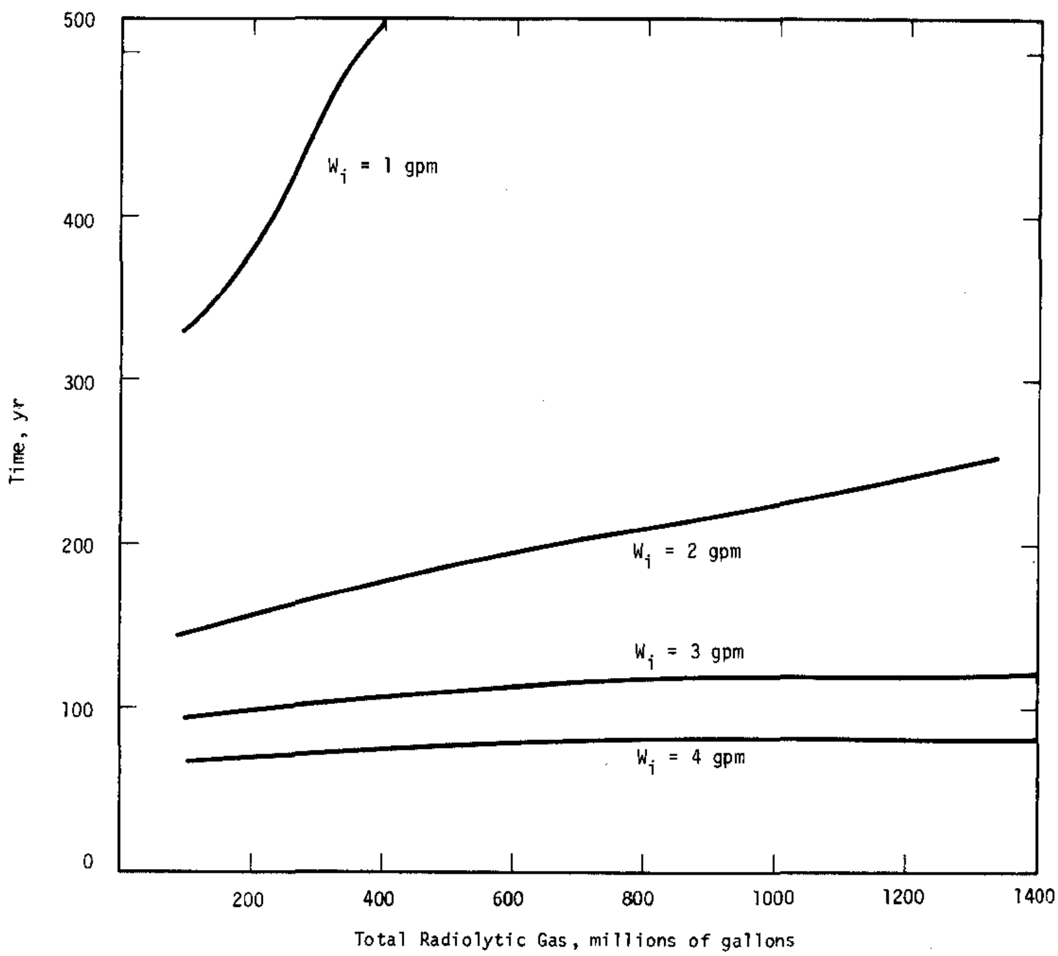

FIGURE III.4.10. Time to Reach Hydrostatic Equilibrium with 120 Million Gallon Freeboard

2. Excess Cavern Pressure

For a maximum acceptable pressure drop between the cavern and the overlying sediments of approximately one ft_{H_2O}, the resulting local pressure gradients in the system would be similar to the natural horizontal gradients in the crystalline system (ca. 3 to 4 ft_{H_2O} per mile) or the vertical gradient of a more dense waste phase (equivalent to about 6 ft_{H_2O} excess pressure in a 30-ft-diameter cavern containing waste with a specific gravity of 1.2).

Based on about 1 ft_{H_2O} as an upper limit for the excess cavern pressure, the waste storage system must be designed such that the excess cavern pressure will be well below this value and will not be overly sensitive to the controlling parameters over the expected range of variation of these parameters.

Figures III.4.11 through III.4.15 show the maximum values of the excess cavern pressure for several combinations of the parameters and indicate the relative sensitivity of pressure to these parameters.

Figure III.4.11 shows that for an initial gas volume of 60 million gallons the system performance with respect to excess pressure is borderline for a 1 gpm initial water inleakage rate and is definitely unacceptable at 2 gpm. At 1 gpm inleakage, the curve shows a maximum at ca. 200 million gallons of total radiolytic gas produced and a minimum at ca. 900 million gallons.

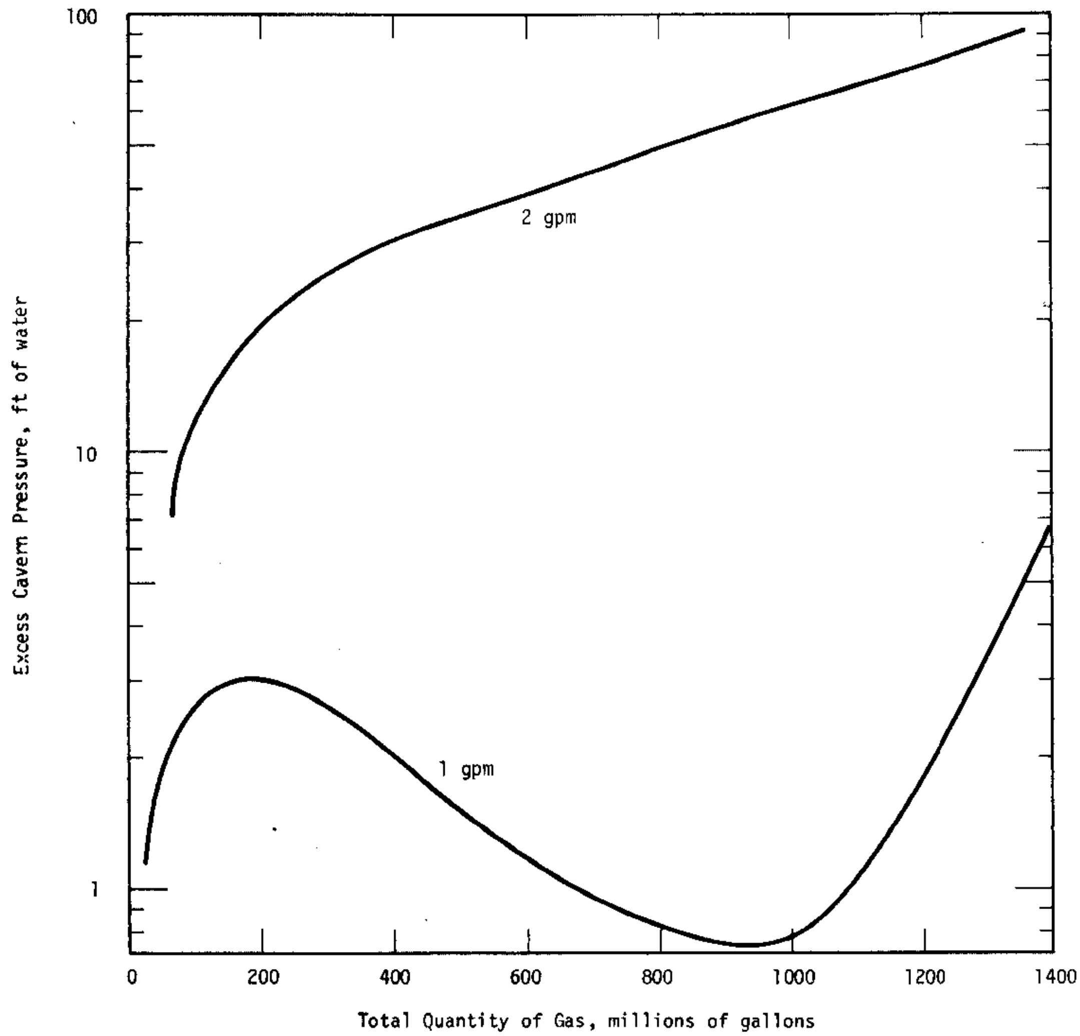

FIGURE III.4.11. Potential Cavern Pressure Increases with 60 Million Gallon Freeboard

Figure III.4.12 shows that for a cavern with an initial gas volume of 120 million gallons, the system is borderline at about 3 gpm and unacceptable at about 4 gpm. The total volumes of liquid waste that would be forced from the cavern would be as much as several million gallons at a 4 gpm initial water inleakage rate. (Figure III.4.13). Because the inleakage rates investigated in these two figures are in the range of the lowest that could be expected for crystalline rock, and because water inleakage rates much higher than this are likely, it is expected that unacceptably large initial cavern gas volumes (several hundred million gallons) would be necessary for the required system behavior in a crystalline cavern in which the gas did not escape.

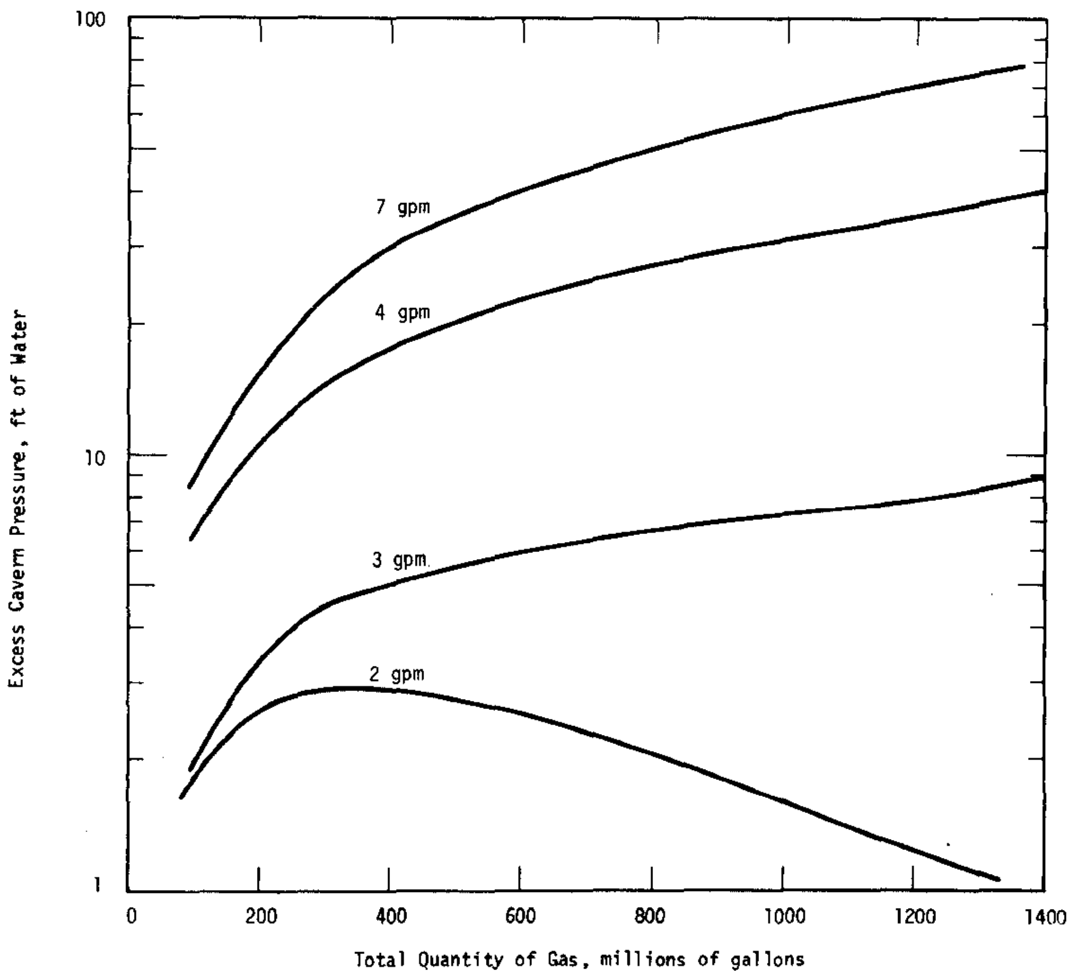

FIGURE III.4.12. Potential Cavern Pressure Increases with 120 Million Gallon Freeboard

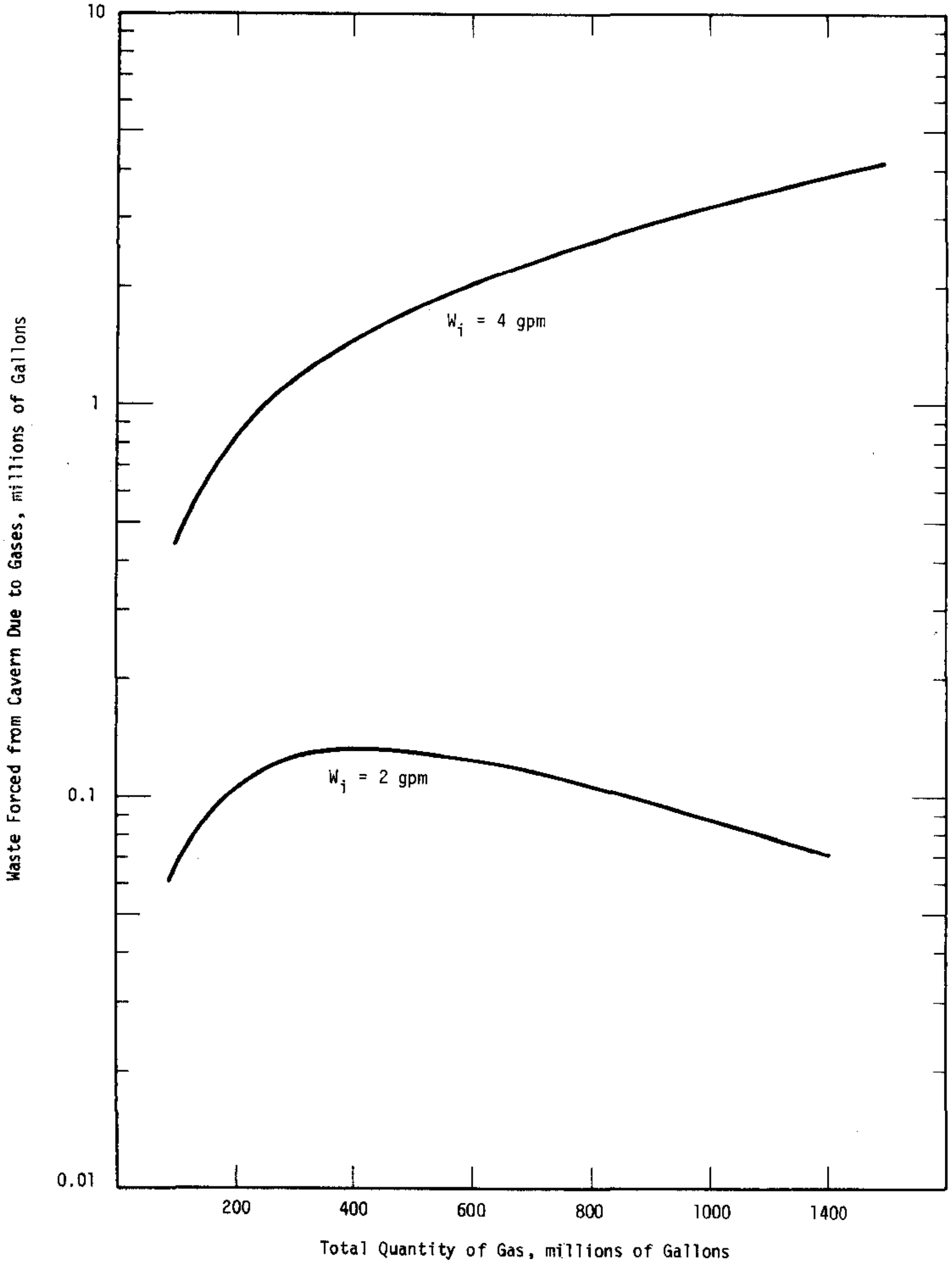

FIGURE III.4.13. Flow of Waste from Cavern with 120 Million Gallon Freeboard

A Triassic cavern should require much less initial cavern gas volume for water inleakage. At a water inleakage rate of 0.1 gpm in a cavern with a 40 million gallon gas volume, the system would require more than 1000 years to reach hydrostatic equilibrium and would never exceed it for the range of total radiolytic gas volumes considered (0 to 1400 million gallons). Even at 0.5 gpm the system would not over pressurize unless the total quantity of radiolytic gas produced were in excess of about 1100 million gallons (Figure III.4.14). A cavern with only 20 million gallons of initial gas volume would be sensitive to the water inleakage rate even in the 0.1 gpm range (Figure III.4.15). Under these conditions, the expected volume of radiolytic gases at the pressure of the cavern is close to the initial gas volume in the cavern, and the system is overly sensitive to the quantity of gas produced and the water inleakage rate.

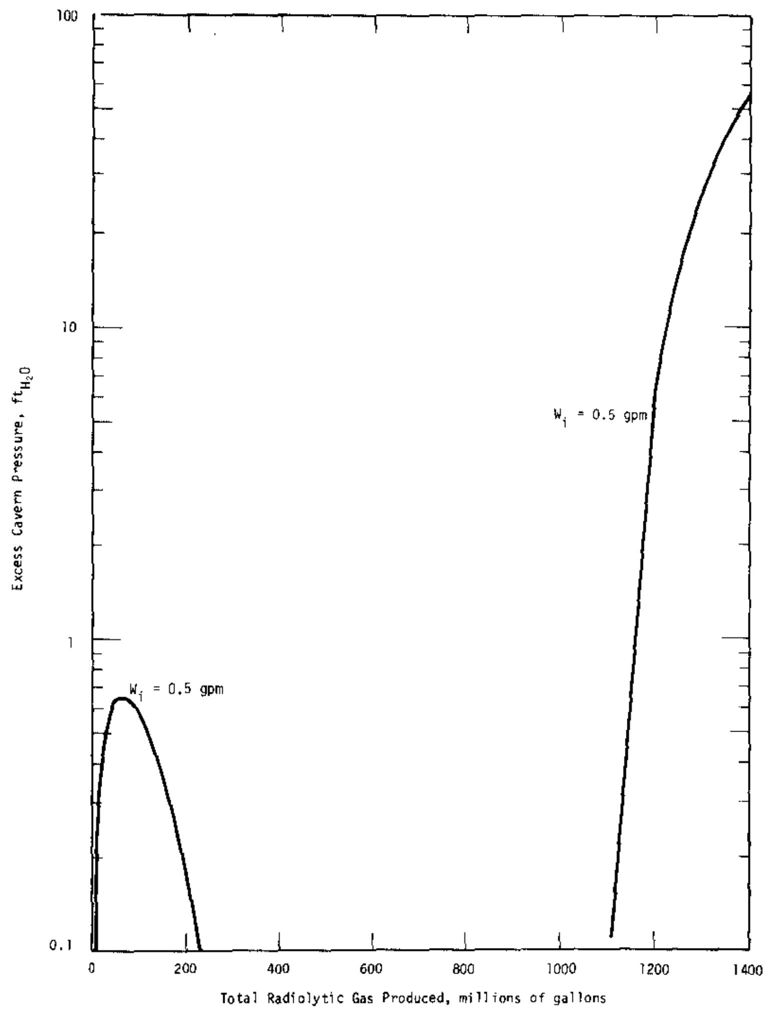

FIGURE III.4.14. Potential Cavern Pressure Increases above Hydrostatic Pressure (Initial 40 Million Gallon Volume)

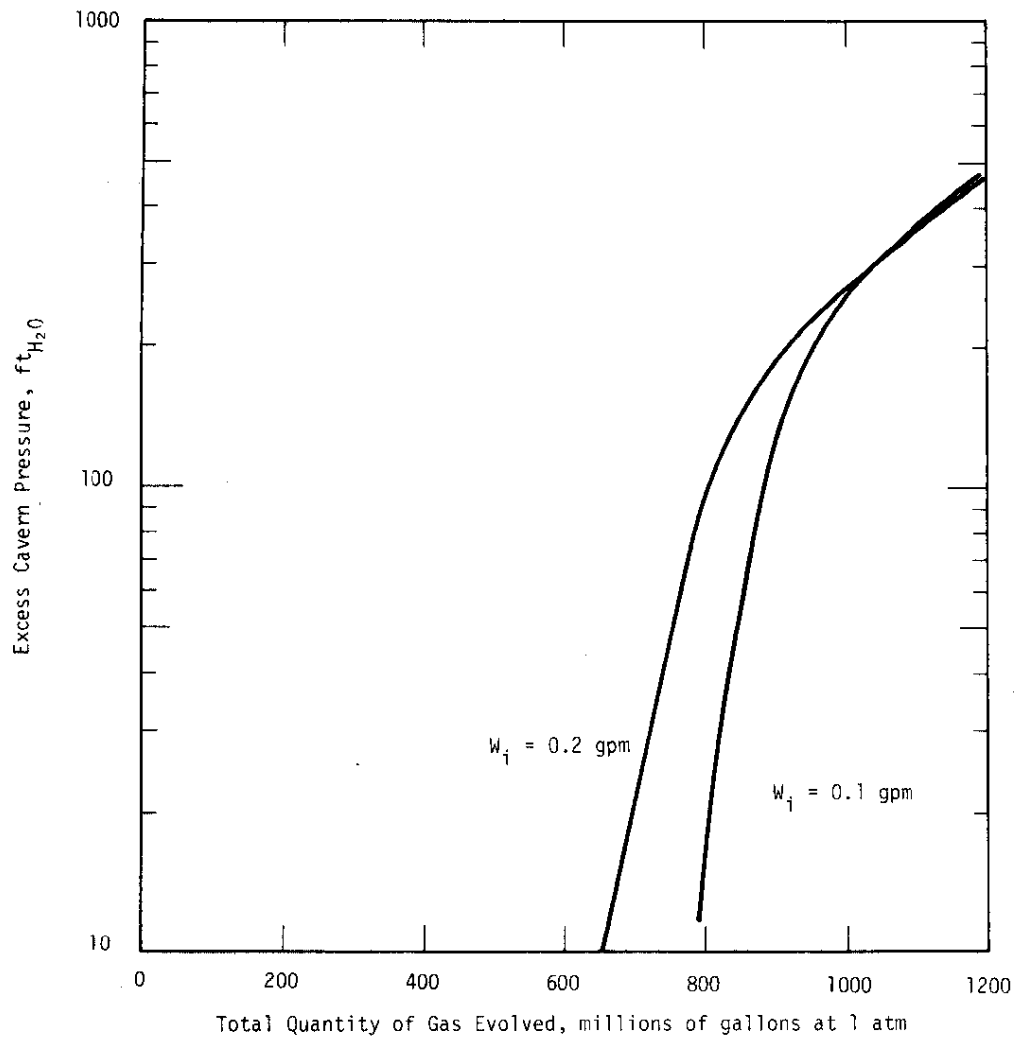

FIGURE III.4.15. Potential Cavern Pressure Increases above Hydrostatic Pressure (Initial 20 Million Gallon Volume)

Based on these calculations, a Triassic cavern with a 0.1 gpm water inleakage rate and an initial gas volume of approximately 40 million gallons would be adequate assuming no reduction in the total volume of the cavern.

The volume reduction due to creep was not included in this analysis. Based on an upper limit estimate of 5 to 10% cavern volume reduction due to creep in Triassic rock (Section III-2), this effect could be allowed for by providing additional initial cavern volume equal to this maximum expected volume reduction due to creep, ca. 10 million gallons. This would increase the total volume necessary for a Triassic cavern with a 0.1 gpm inleakage rate to 130 million gallons; 80 million gallons of waste, 40 million gallons for water inleakage and gas, and 10 million gallons for long term creep.

3. Meeting Design Criteria by Eliminating Radiolytic Gassing

An alternative approach to the gas drive problem would be to reduce the amount of radiolytic gas produced to an insignificant level. Figures III.4.11 through III.4.13 show that the total gas evolved should be reduced to well under 100 million gallons in order to eliminate this drive. It is estimated that approximately 10 million gallons of gas would be dissolved in the waste itself at a cavern pressure of 1500 ft_{H_2O}. Therefore, the removal of about 99% of the ^{90}Sr and ^{137}Cs from the waste would eliminate the gas drive on the remaining waste. The separated ^{90}Sr and ^{137}Cs would have to be contained in a form which would not give off radiolytic gases. Adsorption of the activity on zeolite and burial in a separate cavern should meet this requirement. Essentially all of the chemicals present in the waste (including the sludge) would have to be separated from the radioactivity because the presence of even small concentrations of many of these chemicals give rise to radiolytic gassing (Appendix III-4.A and Reference III-4.3). An alternative to removing all activity from the sludge would be to mix the sludge with a quantity of cement sufficient to absorb all of the radiation. This would require a quantity of cement equivalent to several times the weight of the sludge ($\sim$24,000 tons).

Venting the cavern to reduce the total quantity of gas that would be evolved after sealing does not appear to be practical. Over 100 years of venting would be required before the gas evolution would be reduced to the point that well under 100 million gallons remained to be evolved.

Based on the preceding analysis, the water inleakage rate to the cavern is the most important parameter in evaluating cavern freeboard requirements for eliminating the radiolytic gas drive. The cavern should be located in a region of rock in which the water inleakage rate is a minimum, preferably less than one gallon per minute. Based on existing data, the Triassic rock appears to satisfy this criterion. The water inleakage rate could be estimated with even greater accuracy if additional information on the hydrology of the Triassic basin were to be obtained by additional rock borings; however, existing data were sufficient for this preliminary analysis. The water inleakage rate can ultimately be confirmed by direct measurement after the rock has been excavated for the cavern.

The excess cavern pressure is much less sensitive to the total quantity of radiolytic gas produced than it is to the inleakage rate. Previous laboratory measurements of the radiolytic gas yield were sufficient for this analysis.

APPENDIX III-4.A. RADIOLYSIS OF WASTE

This appendix summarizes the data on radiolytic gas evolution based on laboratory studies with synthetic waste in a radiation field equivalent to that present in the waste. Data on the rate of hydrogen evolution in the waste tanks agree with results of laboratory tests. Due to the large air sweep in the tanks, data are not available on oxygen evolution. However, the conversion of nitrate to nitrite is observed in the liquid.

A maximum of 9 volumes of gas (STP) per volume of waste will be produced. This value has been experimentally determined with simulated waste and with cobalt-60 as a source of radiation, and is based on 200 x 10^6 Ci each of strontium-90 and cesium-137 in 80 x 10^6 gallons of waste.

The quantity of gas generated is independent of temperature (40 to 120°C), pressure (0 to 1000 psig), alkalinity [neutral-1M (OH^-)], and dose rate (1 x 10^6 to 20 x 10^6 rads/hr). The yield is also unaffected by reaction with crushed rock.

The total quantity of gas produced would be about 700 x 10^6 gallons (STP). The gas volume would be about 16 x 10^6 gallons when the pressure in the cavern reached hydrostatic equilibrium with the surrounding rock (650 psig).

The exact composition of the gas depends on the phase in which the Sr and Cs are present (Table 1, Appendix III-4.A).

The gas generation rate was found to be directly proportional to the rate at which radiation is absorbed. The rates given in Table 2, Appendix III-4.A are based on the dose rates in the waste at various times. The rate of gas generation decreases as the radiation source decays exponentially.

Because O_2 and H_2 recombine in the gas phase in the presence of β and γ radiation, the magnitude of this recombination was measured. It was determined that less than 3% of the total amount of H_2 released would recombine. The rate of thermal recombination of oxygen and nitrate was experimentally determined to be negligible.

TABLE III.4.A1. Gas Composition

Gas	Sr and Cs in Supernate	Sr in Sludge, Cs in Supernate[a]	Sr and Cs in Sludge
O_2[b]	80%	86%	90%
H_2	18%	12%	8%
$N_2 + NO_2$	2%	2%	2%

a. Initial distribution.

b. The gas is rich in O_2 because the principal source is the conversion of nitrate to nitrite.

TABLE III.4.A2. Maximum Gas Generation Rate

Time, yr	Absorbed Dose, % of total	Yield, molecules/100 eV	Maximum Gas Generation Rate, millions of gallons (STP) per year
0	0	0.40	17
29	50	0.37	8
100	91	0.34	1
200	99	0.34	0.1

Solubility of the gas in the waste was small but was not measured. Based on data on the solubility of O_2, H_2, and N_2 in solutions of $NaNO_3$, Na_2SO_4, and NaOH, the solubility of the gases is approximately 0.2 volumes of gas (STP) per volume of waste. This represents approximately 2% of the total gas evolved.

Preliminary tests have been carried out to determine alterations of the waste necessary to reduce or eliminate gassing. One approach is the addition of chemicals to the supernate to remove O_2 as it forms. The most effective inorganic additive found to date is Na_2SO_3 and the most effective organic additive is tributylphosphate (Table 3, Appendix III-4.A).

Solidification of the waste in cement and clay reduces the gas yield (Table 4, Appendix III-4.A). The reduction in gas yield is attributed to the absorption of a large fraction of the radiation by the clay and cement and the immobilization of reactive species that form gases.

TABLE III.4.A3. Radiolysis of Liquid Waste Containing Additives

Additive	Radiolytic Gas Yield, molecules/100 eV	Gas Composition, %		
		O_2	H_2	N_2+NO_x
None	0.38	80	18	2
Saturated with Na_2SO_3	0.10	46	39	15
2.5 vol. % TBP	0.06	5	90	5

TABLE III.4.A4. Radiolysis of Cement-Waste Mixes

Grams Cement + Clay per cc of Waste	Gas Yield, molecules/100 eV	Gas Composition, %		
		O_2	H_2	N_2
0	0.38	80	18	2
0.90	0.157	92	5	3
1.125	0.122	86	9	5
1.63	0.089	80	11	9
2.25	0.051	72	14	14
2.50	<0.02	-	-	-

APPENDIX III-4.B. DIFFUSION OF GAS THROUGH ROCK

Although the pore space in the rock is small (ca. 3% for Triassic rock and ca. 0.01% for crystalline rock) essentially all of the diffusion would take place through the water in the rock due to the much higher diffusion rates of gases in water as compared to solid rock.

An upper limit estimate of the relative rate of diffusion of gas through rock will be made by assuming that the cavern wall is suddenly subjected to a gas pressure of approximately 1500 ft_{H_2O}. It is assumed that initially there is no gas in the rock. Actual gas diffusion rates would be at least 100 times lower because gas would be present in the rock near the cavern wall before the cavern reached this pressure.

The rate of diffusion of gas from the cavern for these conditions is given by:

$$N_G = A \cdot C_o \sqrt{D/t}$$

where

N_G = gas transport from cavern by diffusion, cm^3 (STP)/yr

A = diffusion area, cm^2

C_o = equilibrium concentration of gas in rock water, cc gas/cc rock water

D = diffusivity of gas in rock water, cm^2/yr

t = time, years

The diffusion area is taken to be surface area of the cavern wall (ca. 10^6 ft^2) times the estimated void fraction. This would be a maximum for Triassic rock:

$$A = (10^6 \text{ ft}^2)(0.03) = 3 \times 10^4 \text{ ft}^2 = \text{ca. } 3 \times 10^7 \text{ cm}^2$$

The equilibrium concentration of oxygen (the principal radiolytic gas) in water at 1500 ft_{H_2O} pressure is on the order of 1 cm^3 gas/cm^3 water.[5] The liquid phase diffusivity is estimated[6] to be approximately 10^{-5} cm^2/sec = 320 cm^2/yr. This assumes that eddy diffusion in the very small pores is negligible compared to molecular diffusion.

The estimated upper limit rate of diffusion of oxygen through the Triassic rock for t = 1 year is then:

$$N_{O_2} = \left(3 \times 10^7 \text{ cm}^2\right)\left(1 \frac{\text{cm}^3}{\text{cm}^3}\right)\sqrt{\frac{320 \frac{\text{cm}^2}{\text{yr}}}{1 \text{ yr}}}$$

$$N_{O_2} = 5.4 \times 10_8 \frac{\text{cm}^3}{\text{yr}} = 1.4 \times 10^5 \text{ gallons/yr (STP)}$$

The upper limit rate of diffusion of oxygen for crystalline rock would be ca. 470 gal/yr (STP) because the porosity is only 0.01%.

The initial rate of gas evolution is ca. 17 x 10^6 gal/yr (STP). After 200 years, the gas evolution rate is expected to be ca. 10^5 gal/yr. Even based on the upper limit calculation for gas removal by diffusion, the rate of removal by diffusion is small compared to the rate of generation.

It is estimated that after 1000 years, less than 30% of the hydrogen and less than 2% of the oxygen would have diffused from a Triassic cavern and less than 1% of the hydrogen and oxygen would have diffused from a crystalline cavern.

APPENDIX III-4.C. CAPILLARY ENTRANCE PRESSURE

The gas pressure necessary to overcome the surface tension forces between the gas and a liquid phase (water) that wets the rock is called the capillary entrance pressure. The exact value of the capillary entrance pressure will depend upon the geometry of the openings in the rock; however, it would be expected to lie between the two extremes of a cylindrical opening and a long narrow slit or fracture (no curvature). For the cylindrical opening the capillary pressure is given by the following equation:

$$P_C = \frac{4\gamma}{D} \qquad (1)$$

where

P_C = capillary entrance pressure, dynes/cm²

γ = surface tension, dynes/cm

D = diameter of cylindrical opening, cm

For an opening in the form of a long narrow slit P_C is given by:

$$P_C = \frac{2\gamma}{B} \qquad (2)$$

where

B = width of slit

The shape of the openings in either crystalline or Triassic rock would be expected to be somewhere between these two extremes. In either case the capillary entrance pressure is approximately the same when the largest dimension of the opening is considered as the effective pore size. Estimates of capillary entrance pressures for various effective pore sizes were obtained based on the surface tension of the air-water system (72 dynes/cm) and Equations 1 and 2. These results are shown in Figure III.4.1, and indicate relatively high pressures are required before gas flow through rock will occur. These pressures exceed the 1 ft_{H_2O} pressure indicated earlier as one design criterion and indicate water flow out of the cavern will occur prior to gas movement.

APPENDIX III-4.D. ESTIMATION OF WATER INLEAKAGE RATES BEFORE CAVERN SEALING

The initial water inleakage rate before cavern sealing is the single most important parameter in determining the size of freeboard in the cavern. Freeboard is defined as the excess volume necessary to contain both the inleakage of water and the gas produced by radiolysis of the waste solutions following sealing of the cavern. Should inleakage rates be too high, the freeboard required to prevent pressurizing the cavern above the surrounding hydrostatic pressure during gas production is prohibitive.

Three different techniques (Theis, Darcy's Law, and line sink) were used to estimate the inleakage rates to the cavern before sealing. These rates are summarized in Table 1, Appendix III-4.D. The calculated values indicate that inleakage rates of less than 0.3 gallon per minute are highly possible for a cavern constructed in Triassic rock; however, inleakage rates of at least 3 gpm are likely in "tight" crystalline rock. It appears that these low inleakage rates can be measured directly in an actual cavern using dew point measurements.

TABLE III.4.D1. Inleakage Rates into the Cavern by Three Approximate Methods[a,b]

Rock Type	Theis 5 Years	Theis 10 Years	Theis 100 Years	Darcy's Law, Steady State	Line Sink, Steady State
Average crystalline	480	440	360	416	197
"Tight" crystalline	7.6	6.6	4.0	4.16	1.2
Triassic	0.3	0.2	0.07	0.003	0.001

a. In gallons per minute (gpm).
b. Not directly comparable; rates based on slightly different assumptions.

Theis Method

The Theis method for the computation of drawdowns in the vicinity of a vertically discharging well[7] has the following assumptions:

1. A homogeneous geological formation of infinite extent is assumed. This is not a good assumption and may or may not be conservative depending upon the nearby geological formations. The assumption is conservative if less transmissive regions exist at some distance from the cavern than those used in the calculations, inasmuch as these less transmissive regions will act as partial dams and water will not flow through these regions to the cavern as rapidly as predicted. The assumption will not be conservative if more permeable formations exist at some distance from the cavern than formations adjacent to the cavern. The numerical model and well tests suggest that more permeable rock can exist within 1000 ft of the center of the tight rock.

2. Assume that the cavern is replaced by a series of wells that fully penetrate the rock. This assumption in the calculation is conservative because the cavern does not fully penetrate the rock.

3. Assume transmissivity is a constant. This assumption is conservative because the effect of drawdown will be to decrease transmissivity and some partial healing of fractures may occur during excavation of the cavern due the expansion of the rock.

In using Theis's method, we are assuming the 6000-ft-long cavern can be replaced by a series of wells. The method requires values for transmissivity and storage coefficient. Appropriate values for the transmissivity are 160 gpd/ft as an average for crystalline rock, 1 gpd/ft as an expected value for crystalline rock, and 0.003 gpd/ft for Triassic rock. The storage coefficient for crystalline rock is 14×10^{-6}, for Triassic it is 2.2×10^{-4}. The time of pumping, the pumping rate, and the distance from the pumping well, are the variables.

Figures 1, 2, and 3 of Appendix III-4.D illustrate the type of information obtained using Theis's method. For example, for average crystalline rock (Figure 1, Appendix III-4.D) the drawdown at 1000 ft from the pumping well increases from approximately 10 feet for a pumping rate of 2.5 gpm after 100 days to 350 feet after the same length of time of pumping at 80 gpm. The time dependent nature of water inleakage to a single well maintained at a constant drawdown was approximated by this series of steady-state curves by assuming that the drawdown is maintained at 1500 feet (the depth of the cavern) and that water is being removed at the same rate that water enters the cavern. Under these conditions, the drawdown would remain at 1500 feet of water if the pumping rate at the end of 100, 1000, 10,000, and 100,000 days averaged 350, 265, 197, and 155 gpm for average crystalline rock.

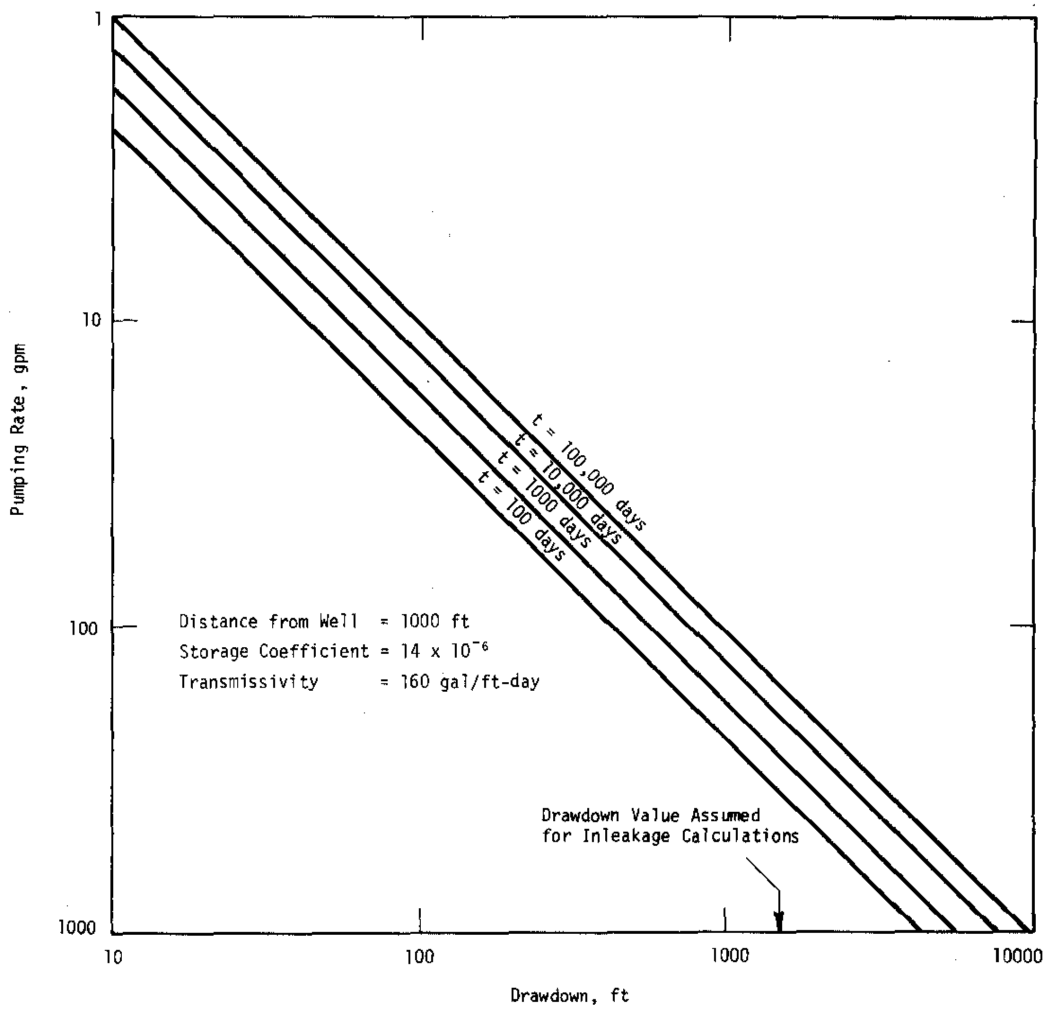

FIGURE III.4.D1. Pumping Rates versus Drawdown in Average Crystalline Rock

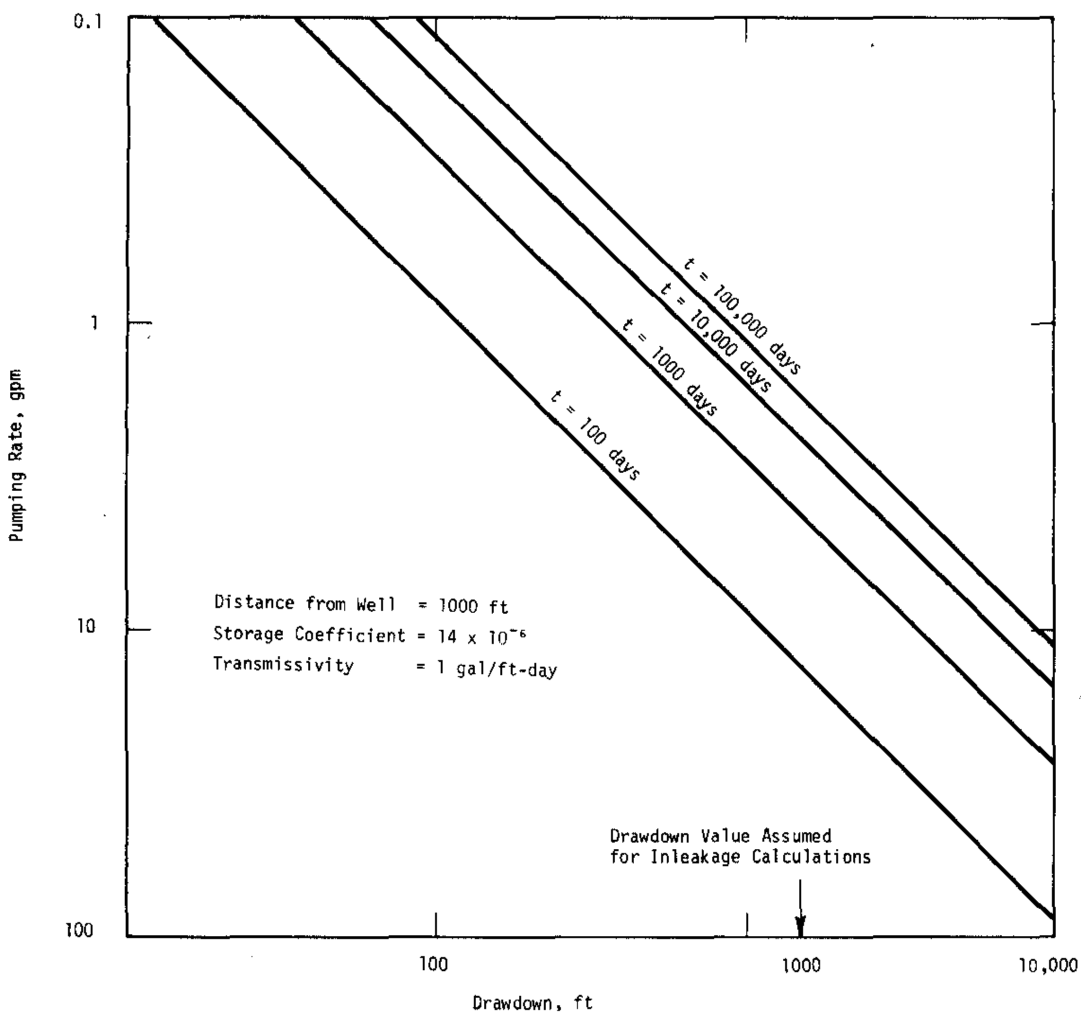

FIGURE III.4.D2. Pumping Rates versus Drawdown in "Tight" Crystalline Rock

In order to represent the horizontal cavern, a variable number of vertical wells is required. The number of wells required to represent 6000 ft of cavern was calculated[a] by determining the radial distance out from the well that produces a drawdown of 750 feet. Wells would need to be spaced on centers located at twice this radial distance because the adjacent well also contributes 750 feet to the drawdown at the midpoint, thereby producing a total of 1500 feet of drawdown at the midpoint. The number of wells required at 1000 days for average crystalline, "tight" crystalline, and Triassic rocks is 1, 1.4, and 286, respectively.

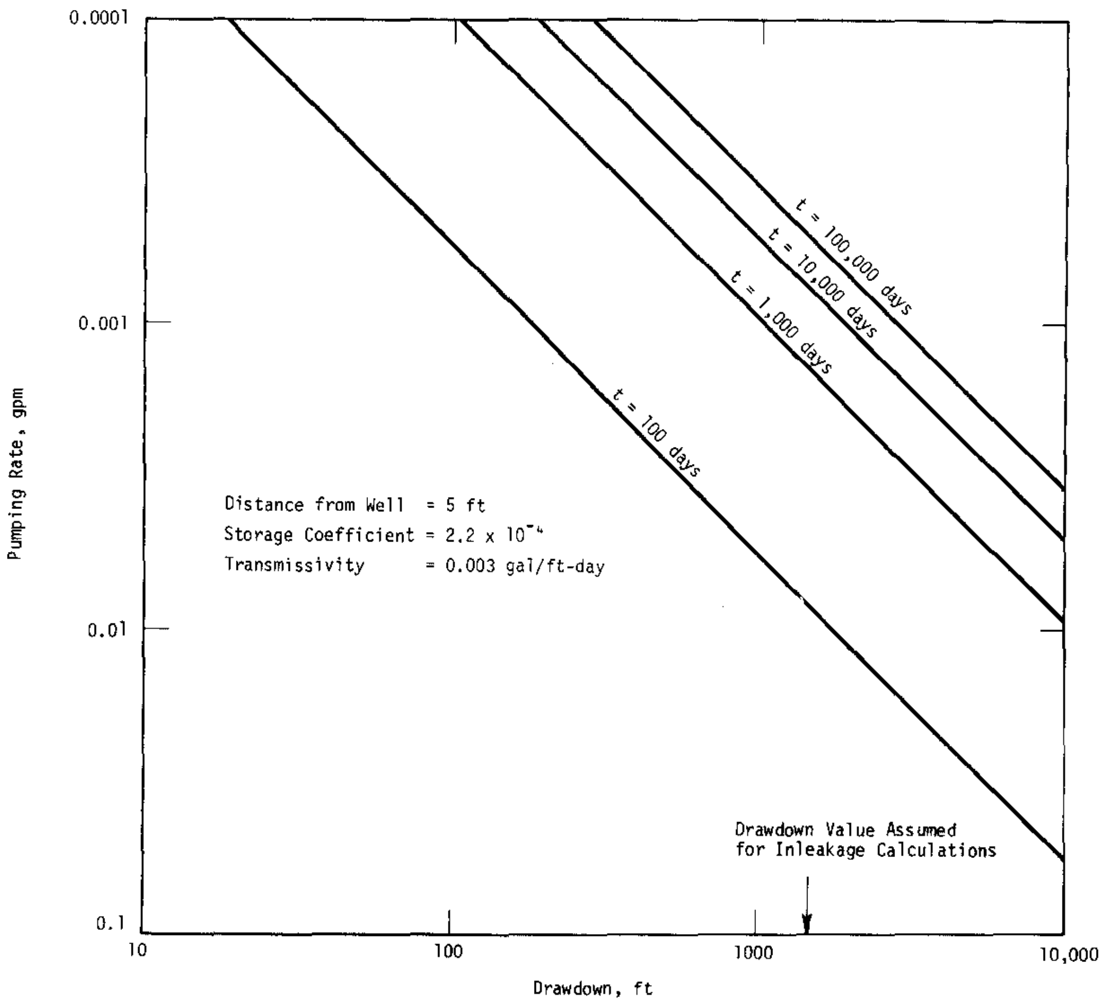

FIGURE III.4.D3. Pumping Rates versus Drawdown in Triassic Rock

The data in Figure 4, Appendix III-4.D, give the expected inflow to the cavern at any time following construction but before sealing. The curves are the product of the inleakage to a single well and the number of wells needed to represent the cavern at each particular time. The data show that inleakage into a cavern constructed in "tight" crystalline rock will approximate 4 gpm in 2000 days, while inleakage to a cavern constructed in average crystalline rock will approximate 240 gpm in 2000 days. The inleakage rates to a Triassic cavern will be less than 1 gpm (and should be approximately 0.3 gpm) 2000 days after completion of the cavern.

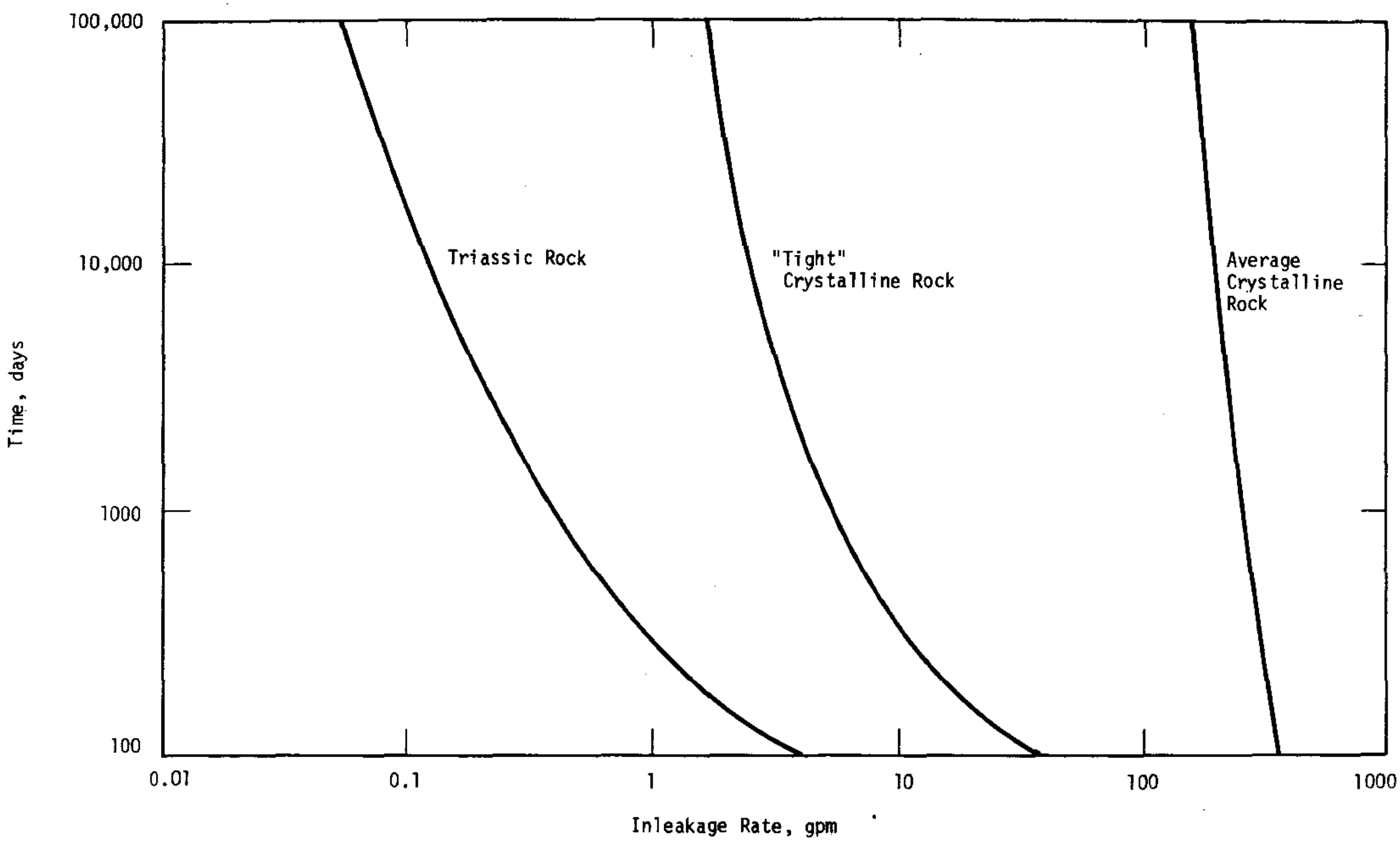

FIGURE III.4.D4. Estimated Cavern Inleakage Rates in Average Crystalline, "Tight" Crystalline, and Triassic Rock versus Time

Darcy's Law

An alternative method of calculating inflow to the caverns is to use Darcy's Law

$$Q = A\ K\left(\frac{I_2 - I_1}{L}\right)$$

where

Q = the quantity of inleakage, gal/min

A = the cross sectional area of the cavern through which flow may occur, ft^2

K = the permeability, $(gal\text{-}ft)/(min\text{-}ft^2\text{-}ft_{H_2O})$

$\frac{I_2 - I_1}{L}$ = the gradient, I_2 is the head in ft_{H_2O} at some distance L, ft, from the cavern and I_1 is the head in ft_{H_2O} at the cavern

The assumptions in this approach are:

1. There is a readily available supply of water (Tuscaloosa aquifer, fractured rock, etc.) 500 ft from the cavern. If it is assumed that this supply of water is infinite, the head (I_2) of this supply remains constant and the rate of water inleakage calculated by Darcy's Law is independent of time. This is a reasonable assumption when the Tuscaloosa aquifer is considered as this source of water.

2. The cross sectional area is constant. In the calculations, this area is considered to be the product of the cavern height and cavern length. This is too small but is not off by more than a factor of ten.

Equation 1 gives inflow values when used with L = 1000 ft, A = 6000-ft-long by 25-ft-high by 2 (for symmetry as flow is assumed to enter simultaneously from left and right). The permeability, K, equals 1 (for fractured rock), 0.02 (expected crystalline rock), and 0.0000062 gpd/ft^2 (expected Triassic rock). The results are summarized in Table 2, Appendix III-4.D. The results are less in each case than those calculated by Theis's formula. The results again indicate that Triassic rock is the superior location from an inleakage standpoint, and inleakage into a crystalline cavern is likely to exceed the criteria of 1 gpm.

TABLE III.4.D2. Calculated Inleakage to a Waste Cavern

Permeability of Rock, gal/day/ft^2	Gallons Entering Cavern,[a,b] gal/min
1	416
0.01	4.16
0.0000062	0.003

a. Cavern dimensions: 6000-ft long, 25-ft high.

b. Flow from both sides into cavern (Equation 1).

Line Sink

A third method of calculating inleakage to the cavern is outlined by Stallman.[9] The assumptions of this approach are:

1. The aquifer is homogeneous, isotropic, and of semi-infinite (bounded on one side only by an infinite supply of water) areal extent, The assumption that the rock is homogeneous and isotropic has been discussed in the first method. It is not a good assumption, particularly in crystalline rock, and may be conservative or non-conservative, depending on the assumed transmissivity.

2. The discharging drain completely penetrates the aquifer. The cavern does not fully penetrate the aquifer, so this assumption is not fulfilled.

3. The aquifer is bounded by impermeable strata above and below. The validity of this assumption is unknown.

4. The flow is laminar and unidimensional. The flow will be laminar but the second assumption is not fulfilled due to the partial penetration of the cavern.

5. The release of water from storage is instantaneous and in proportion to the decline in head. This is a reasonable assumption.

6. The drain discharges water at a constant rate. This could be a reasonable assumption but, in general, discharge will be greater at first, therefore conservative in nature.

The results of this approach are given in Table 3, Appendix III-4.D. The results are similar to those obtained by the other methods and indicate inleakage rates of less than 1 gpm are definitely possible in Triassic rock and of borderline possibility in some of crystalline rock.

TABLE III.4.D3. Calculated Inleakage to a Waste Cavern by Line Sink Method

Rock Type	Transmissivity of Rock, gal/(day-ft)	Water Entering Cavern,[a] gpm
Average crystalline	160	197
Exceptionally tight crystalline	1	1.2
Triassic	0.0003	0.001

a. Calculated for a 6000-ft-long cavern.

Measurement of Inleakage Rates

The inleakage rate will ultimately be measured directly in the cavern after construction. One way to monitor inleakage of water into a cavern during testing is to stop circulating fresh air into the cavern and monitor changes in the dew point of the air in the cavern. This type of calculation is outlined in the *Handbook of Physics and Chemistry*.[10] If the air temperature is 20°C, the barometric pressure is 760 mm, and the dew point changes from 10 to 11°C, then 76 gallons of water have entered the air in a 100,000,000 gallon cavern. Knowledge of the time for the dew point to change 1°C allows inleakage rates to be readily measured to very low values (0.04 gpm for a 32-hour test). This method is equally applicable for smaller sections of the cavern, e.g., if a single cavern was 1,000,000 gallons in size, the inleakage could be measured at 0.0004 gpm under the same experimental situation as described earlier in the paragraph. The technique requires all water inleakage to evaporate or it underestimates the inleakage rates.

APPENDIX III-4.E. COMPUTER PROGRAM TO CALCULATE RADIOLYTIC GAS PRODUCED, WATER INLEAKAGE, CAVERN FREEBOARD, AND CAVERN PRESSURE AS FUNCTIONS OF TIME

Definition of Terms

A = Initial absolute cavern pressure before sealing, psi

VO = Initial cavern freeboard, millions of gallons

GX = Incremental radiolytic gas volume, millions of gallons (STP)

HP = Surrounding hydrostatic pressure at cavern depth, psi

WI = Initial total water inleakage rate before cavern is sealed, gallons per minute

DK = Effective decay constant for ^{90}Sr and ^{137}Cs, 0.024 yr^{-1}

YRS = Time increment, years

C = 8.08×10^{-4} WI = Water inleakage rate coefficient, gallons/year

DW = Water inleakage, gallons

VR = Cavern freeboard after sealing, gallons

T = Time after cavern sealing, years

GT = Total radiolytic gas to be evolved, gallons

V = Total radiolytic gas evolved up to time T, gallons

P = Cavern pressure, psig

W = Accumulated water inleakage, gallons

```
              C  PROGRAM TO COMPUTE BEDROCK PRESSURES
              C
              C
ISN 0002            DIMENSION TITLE(20)
              C
ISN 0003            A=14.7
ISN 0004            READ(5,100) TITLE
ISN 0005            WRITE(6,200)TITLE
ISN 0006            READ(5,101) VO,GX,HP,WI,DK,YRS
ISN 0007            READ(5,102) NTIM
ISN 0008            DO 10 J=1,15
ISN 0009            GT=GX*J
ISN 0010            C=8.08E-4*WI
ISN 0011            W=0.
ISN 0012            P=A
ISN 0013            WRITE(6,203) VO,GT,HP,WI,DK,YRS
ISN 0014            WRITE(6,201)
ISN 0015            DO 10 I=1,NTIM
ISN 0016            DW=C*(HP-P)
ISN 0017            W=W+DW
ISN 0018            VR=VO-W
ISN 0019            IF(VR.LE.0.) GO TO 20
ISN 0021            T=I*YRS
ISN 0022            V=GT*(1.-EXP(-DK*T))
ISN 0023            P=A*((VO+V)/VO*(VO/VR))
ISN 0024            WRITE(6,202) P,VR,W,V,T
ISN 0025         10 CONTINUE
ISN 0026            GO TO 30
ISN 0027        100 FORMAT(20A4)
ISN 0028        101 FORMAT(8E10.4)
ISN 0029        102 FORMAT(20I4)
              C
ISN 0030        200 FORMAT('1',20X,20A4,//)
ISN 0031        203 FORMAT(' VO =',1PE12.4/,' GT =',E12.4/,' HP =',E12.4/,' WI =',
                   1       E12.4/,' DK =',E12.4/,' YRS =',E12.4//)
ISN 0032        202 FORMAT(1P5E16.4)
ISN 0033        201 FORMAT('         PRESSURE            FREEBOARD           LEAKAGE               RA
                   1O GAS          TIME',/)
ISN 0034         20 WRITE(6,204)
ISN 0035        204 FORMAT(//,' NEGATIVE VOLUME IN CAVERN')
ISN 0036         30 STOP
ISN 0037            END
```

III-5. DENSITY GRADIENTS AND WASTE MIGRATION

Introduction

The density of the liquid waste phase is expected to be approximately 1.2 gm/cm^3 after emplacement in the cavern and subsequent dilution by water inleakage (assuming that the nitrate and other dissolved solids are not removed). Because the density of the water in the rock is approximately 1.01 gm/cm^3, there is a net gravitational driving force acting on the denser liquid waste. It is assumed in this chapter that sufficient freeboard has been allowed for radiolytic gases so that the gas drive is a negligible force. Under these circumstances, the gravitational forces on the denser liquid waste and the existing regional hydraulic gradients in the system represent the greatest forces acting on the waste when it begins to migrate from the cavern. The migration of waste due to the density influence is discussed in this section.

Summary

Estimates of the rates and extent of migration of dense liquid waste through rock with properties expected for the crystalline and Triassic rock, respectively, are given in Table III.5.1. The migration pattern and cavern arrangement assumed for this analysis are given in Figure III.5.1.

TABLE III.5.1. Migration of Dense Waste Phase from Caverns

Crystalline Cavern: $\sigma = 1 \frac{ft/yr}{ft_{H_2O}/ft}$; $\varepsilon = 0.1\%$

Downward Migration, ft	Lateral Migration, ft	Gradient, ft_{H_2O}/mile	Downward Velocity, ft/yr	Elapsed Time, yr
0	0	530	100	0
500	250	480	90	5
1,000	500	410	80	12
5,000	2,500	170	30	155
10,000	5,000	20	4	910
30,000	15,000	2	0.5	22,000
70,000	35,000	1	0.25	275,000

Triassic Cavern: $\sigma = 3 \times 10^{-4} \frac{ft/yr}{ft_{H_2O}/ft}$; $\varepsilon = 3\%$

Downward Migration, ft	Lateral Migration, ft	Gradient, ft_{H_2O}/mile	Downward Velocity, ft/yr	Elapsed Time, yr
0	0	530	10^{-3}	0
100	50	530	10^{-3}	15
500	250	185	3.5×10^{-4}	8×10^5
2,000	1,000	18	3.3×10^{-5}	2×10^7

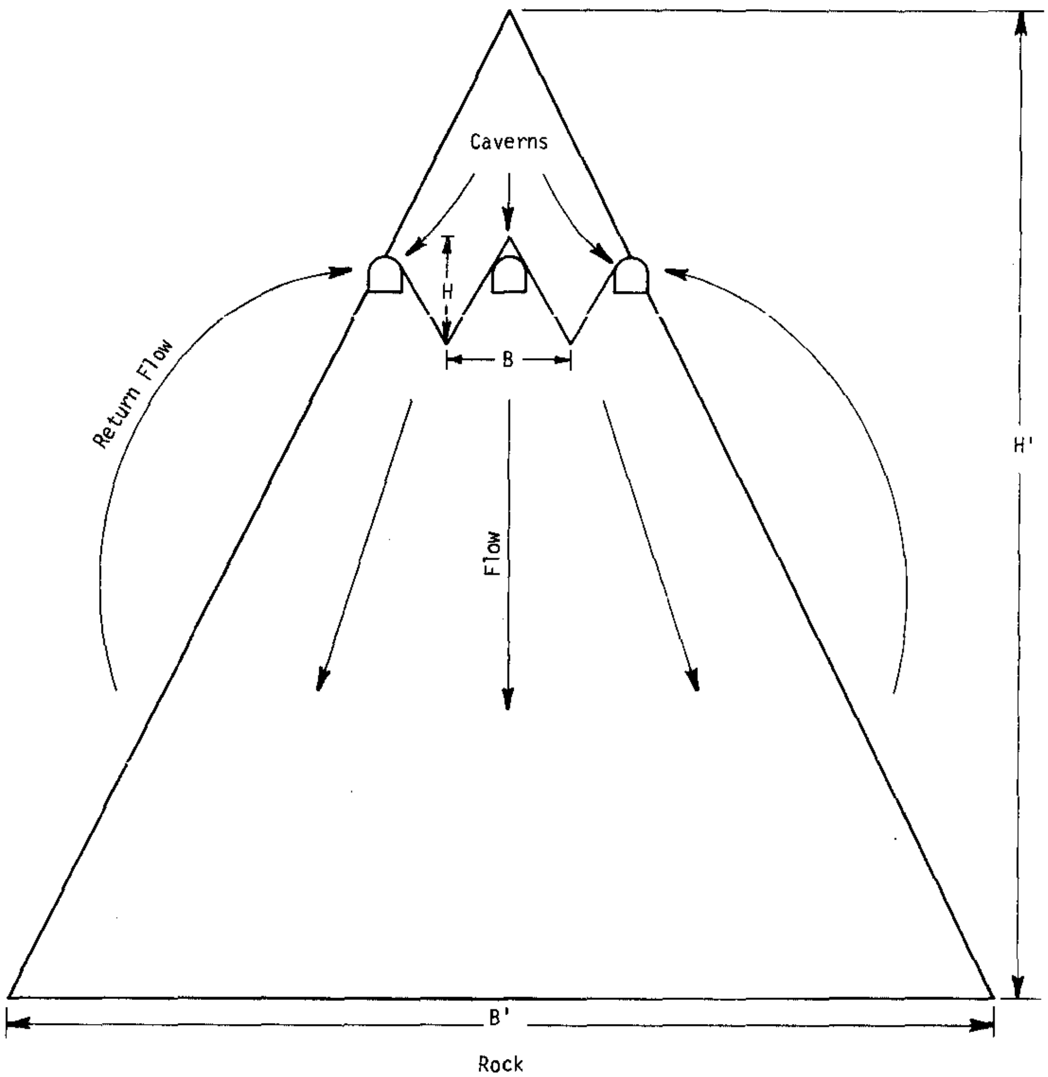

FIGURE III.5.1. Assumed Migration Pattern of Dense Waste

Migration of a dense liquid waste phase would be much more rapid and extensive for a crystalline cavern because of the higher permeability and lower porosity expected for such a cavern. Downward and lateral movement of waste from a crystalline cavern (greater than 10,000 feet down and greater than 5000 feet laterally in 1000 years) creates a potential for the waste to move into zones of higher permeability outside of the region in which the cavern would be located in a much shorter time period than would occur for movement under the existing natural gradients alone (ca. 1000 feet in 2000 years due to the regional gradient of 3 ft_{H_2O}/mile).

In a Triassic cavern, the downward migration probably would be of greater importance than lateral migration because the waste could enter the crystalline rock below the Triassic basin. Downward migration probably represents the critical path from a Triassic cavern. However, for a Triassic cavern located at least 2000 feet above the underlying crystalline rock, the time required for the waste to migrate down to this formation would be great, more than 10^7 years, and the waste would still have to migrate through the crystalline rock to reach the biosphere. Also, because of the more homogeneous nature of the Triassic rock and the shorter migration distances involved, the migration is more easily predicted.

Discussion

A cross section of a hypothetical cavern is shown in Figure III.5.2. After all of the radiolytic gas has been evolved, water will continue to flow slowly into the cavern. Based on a waste density of 1.2 gm/cm^3, the pressure on the waste at the bottom of the cavern (P_3) will be (1.2 x 30) = 36 ft_{H_2O} greater than the pressure in the gas phase (P_1). The cavern gas phase will be assumed to be at a depth such that the pressure on the water in the rock at this level (P_2) is 1500 ft_{H_2O}. The pressure in the rock at the same level as the bottom of the cavern (P_4) would be 1500 ft_{H_2O} plus 30 x 1.01 = 1530 ft_{H_2O}. As soon as the gas pressure in the cavern exceeds 1494 ft_{H_2O} the waste will begin to flow from the bottom of the cavern because the pressure acting on this waste will be in excess of the surrounding 1530 ft_{H_2O}. Waste will continue to flow from the lower section of the cavern and an equal amount of water will flow into the upper section of the cavern. The gas pressure in the cavern (P_1) will be less than the pressure in the rock at that level (P_2) as long as this flow continues. The expected overall movement of waste and rock water under these conditions is as shown in Figure III.5.1. This movement is essentially a gravitational convection cell.

An estimate of the rate of flow of waste under these conditions is made based on the following assumptions:

1. Dilution of the migrating waste as it mixes with water in rock is equal to dilution of waste remaining in the cavern as it mixes with rock water flowing into the cavern.

2. The net driving force is equal to the effective excess density of the waste column times its effective height (H in Figure III.5.1).

3. The net flow path for waste and rock water is equal to twice the effective height of the column of waste in the rock.

4. The permeability of the rock is constant and equal in all directions.

5. The force on an element of waste at the leading edge of the migrating waste is directly proportional to the height of the waste column above the element and equal in the horizontal and vertically downward directions.

Assumptions 4 and 5 suggest a simplified waste migration pattern in which the waste moves initially from a single cavern at the same rate in the horizontal and vertical directions (Figure III.5.2). The resulting pattern for a single cavern would initially be a triangle in the plane normal to the cavern length with a base equal to approximately twice the height. As the waste continues to spread laterally, the height of the waste column above the waste that is no longer directly under the caverns is not as great as that directly under the caverns, and

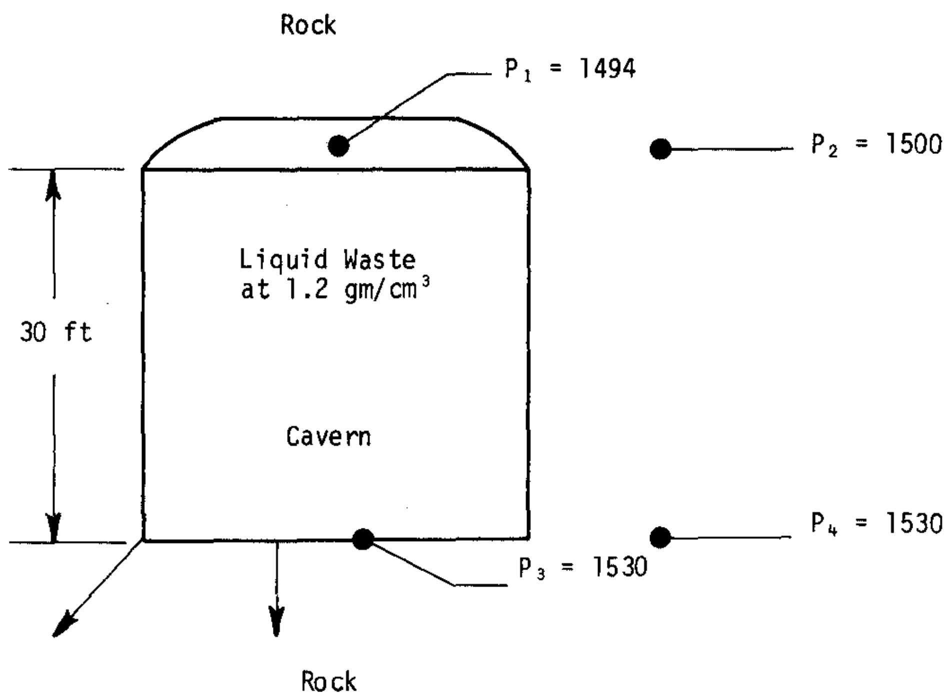

FIGURE III.5.2. Pressures in System When Waste Begins its Downward Migration the rate of lateral migration decreases to some fraction of the downward migration rate. Waste is assumed to migrate laterally from the individual caverns at a rate equal to 1/2 the rate of downward migration, forming a triangular cross section in the rock below the cavern with a base equal to the height, and waste from the individual caverns is assumed to merge into a larger triangular cross section of the same geometry (Figure III.5.1).

Based on assumptions 2 and 3, the rate at which the waste travels through the rock is approximated by:

$$V = \frac{\sigma}{\varepsilon} \cdot \frac{\Delta P}{2H} \qquad (1)$$

where

V = downward and lateral velocity of waste, ft/yr

σ = permeability of rock, ft/yr-ft_{H_2O}-ft

ΔP = net driving force, ft_{H_2O}

$2H$ = net flow path, ft

ε = porosity of rock

The net driving force based on assumption 2 would be:

$$\Delta P = \left(S_pG_{waste} - S_pG_{rock\ water}\right) \cdot H \qquad (2)$$

where

S_pG = specific gravity, weight of solution/weight of equal volume of water

H = height of triangle, ft_{H_2O}

Assumption 1 allows estimation of the term S_pG waste in terms of the initial specific gravity, the initial waste volume (ca. 1.3×10^7 ft^3), and the volume included by the triangular waste-rock water system ($\varepsilon BHL/2$, where ε = porosity, B = base of triangle, H = height of triangle, and L = length of caverns). This volume is equivalent to $\varepsilon H^2L/2$ when B = H, hence:

$$S_pG_{waste} = \frac{(1.2)(1.3 \times 10^7) + \frac{\varepsilon H^2L}{2}}{1.3 \times 10^7 + \frac{\varepsilon H^2L}{2}} \qquad (3)$$

When Equations 2 and 3 are substituted into Equation 1 it becomes

$$V = \frac{dH}{dt} = \left[\frac{\sigma}{\varepsilon}\right] \left[\frac{1.25 \times 10^6}{1.3 \times 10^7 + \frac{\varepsilon H^2 L}{2}}\right] \qquad (4)$$

Estimates of the rates of vertical and horizontal migration based on Equation 4 are given in Table III.5.1. The media is assumed to be homogeneous and isotropic and the length of cavern is taken to be 6000 feet. The waste is assumed to continue its downward migration until the vertical gradient is small compared to the existing lateral gradient (taken as approximately 3 ft/mile for this discussion). This occurs after the waste has travelled down more than 70,000 feet in over 275,000 years for a system with a value of σ/ε of 10^3 expected for the crystalline system.

For the value of σ/ε of about 10^{-2} expected for the Triassic system, the waste would be expected to migrate down only ca. 2000 feet in a time period of more than 10^7 years. It is expected that a Triassic cavern would be located at least 2000 feet above the interface between the Triassic basin and the crystalline rock underlying it.

The assumption of a homogeneous isotropic media (σ/ε constant and equal in all directions) is expected to be reasonable in the Triassic system due to the nature of this basin. However, the nature of the fractured crystalline rock is such that the assumption of homogeneity is much more questionable. The existence of a highly transmissive zone a few thousand feet beneath the crystalline cavern would represent a preferred path for the waste. This situation would be unacceptable if such a zone extended for a large distance since lateral waste migration would be accelerated not only by the higher permeability but also the additional driving force of the denser column of waste. The existence of an extensive impermeable zone a few thousand feet below a crystalline cavern would not greatly accelerate lateral migration due to density effects because the height of the waste column would no longer be increasing.

Separation of most of the hazardous radionuclides from the dense liquid waste phase and storage of the separated materials in a separate cavern would prevent most of the activity from migrating along with the denser liquid waste phase.

III-6. THERMAL EFFECTS OF HEAT GENERATION

Introduction

The heat generated by radioactive decay of ^{90}Sr and ^{137}Cs in the waste solution results in increased temperatures and temperature gradients in the cavern and the rock surrounding the cavern. Maximum temperature limits are expected to depend upon vault construction materials and have not yet been specified; however, heat generation by Savannah River waste is not excessive and it is expected that any temperature limits can be met by proper cavern design.

In this section the effects of heat generation are estimated and the parameters controlling these effects are identified. Potential for waste migration due to thermal influences is also discussed.

Summary

The principal parameters controlling the temperatures and temperature gradients in a bedrock system are:

1. The thermal conductivity of the rock.
2. The heat output per linear foot of cavern.
3. The form of the waste (solid or liquid, thermal conductivity, etc.)

Based on the expected thermal conductivity of the rock and assuming that the waste is not solidified for cavern storage, preliminary calculations indicate that maximum system temperatures can be kept at less than 200°F by ensuring that the heat emitting activity is evenly distributed throughout the caverns and by limiting the size of the caverns to an effective radius of 10 to 20 feet.

The potential for migration of the water in the rock away from the cavern due to the thermal gradient appears to be small. The temperature gradients in the rock would be negligible once the cavern reaches hydrostatic equilibrium. During the time period in which rock temperatures and temperature gradients are significantly higher than ambient, all rock water flow is expected to be into the cavern.

Discussion

The effects of heat generation in a bedrock cavern were based on calculation techniques and assumptions: a thermal conductivity of 1.6 Btu/hr-ft-°F (the average thermal conductivity measured for crystalline rock), an effective cavern radius of 14 feet, and a uniformly distributed heat load in the caverns. These calculations showed that:

1. The maximum wall temperature increase of about 75°F above the initial rock temperature of about 100°F would occur 15 to 20 years after filling of the vaults began with most of the increase occurring during the first 5 years.

2. The liquid waste would be only about 1°F warmer than the wall (due to convection) and the center of the sludge would be about 6°F warmer than the wall.

3. After 100 to 200 years, temperatures and temperature gradients would be small.

4. If sludge is not evenly distributed, considerably higher temperatures could be produced locally (if the quantity of sludge in a cavern is 3 times the average for uniform distribution, temperatures in the sludge would be 330°F and at the wall approximately 260°F).

5. Thermal convection of water in the rock surrounding the cavern would be significant only in fractures greater than 0.1 mm in width.

6. A 300-foot separation distance between parallel caverns would be sufficient to eliminate additional temperature increases in one cavern from the heat produced in an adjacent cavern.

Although maximum permissible temperatures and temperature gradients will probably be set to minimize effects upon vault construction materials and deformation of the rock in which the cavern is located, it is expected that temperatures less than approximately 200°F would be acceptable. A maximum upper limit temperature based on the vapor pressure of the solution would be about 500°F for a cavern located approximately 1500 feet below ground level. At higher temperatures, the vapor pressure would exceed the surrounding hydrostatic pressure and represent a potential driving force on the liquid waste.

The effective thermal conductivity of the rock in which a cavern is finally located may not be equal to the average value for crystalline rock that was used in the calculations in Appendix III-6 (1.6 Btu/hr-ft-°F). The measured[1] thermal conductivities of crystalline rock samples have varied from 1.3 to 1.9 Btu/hr-ft-°F. Thermal conductivities for the Triassic rock have not yet been measured. However, based on measurements for other sandstones, thermal conductivities would not be expected to fall outside of the range of 0.5 to 2.0 Btu/hr-ft-°F. The change in thermal conductivity with temperature must also be considered. A temperature increase of 100°F might be expected[2] to result in a decrease in thermal conductivity of about 10%. The effect of thermal conductivity is such that for a system equivalent to that evaluated in Appendix III-6 (effective radius = 14 ft) but with the lowest value of thermal conductivity considered (0.5 Btu/hr-ft-°F) the cavern wall temperature reaches approximately 345°F (Figure III.6.1).

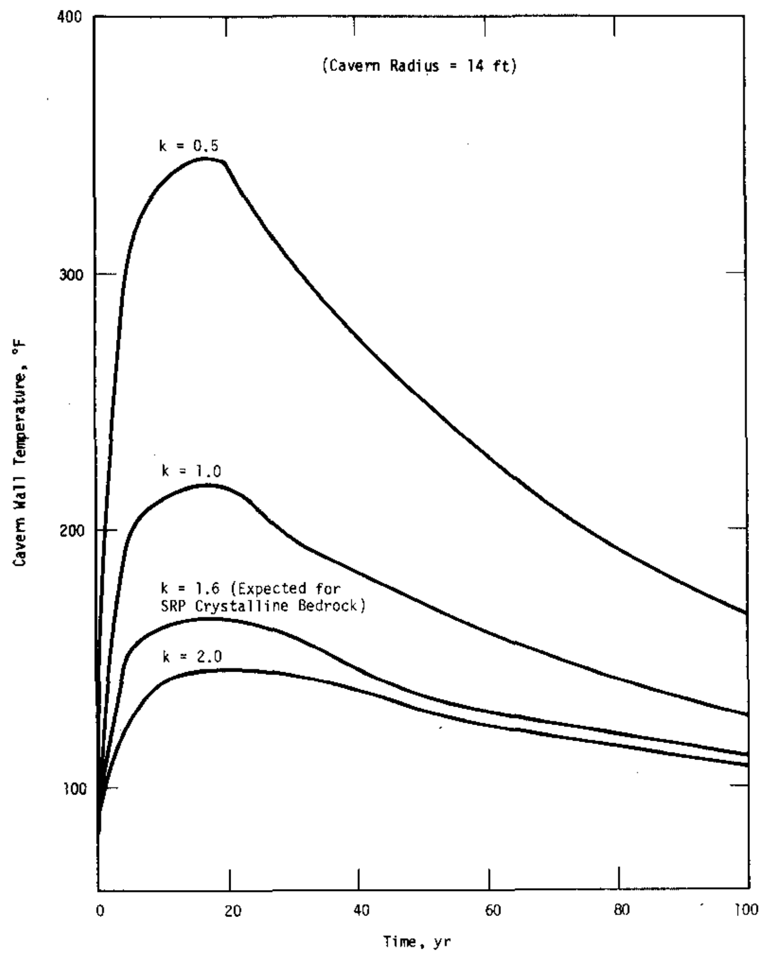

FIGURE III.6.1. Effect of Thermal Conductivity of Rock

If necessary, cavern temperatures can be reduced by reducing the size of the caverns and thus limiting the heat output per linear foot of cavern. When the effective cavern radius is reduced from 14 feet to 10 feet the maximum temperature increase is reduced by about 40% (Figure III.6.2).

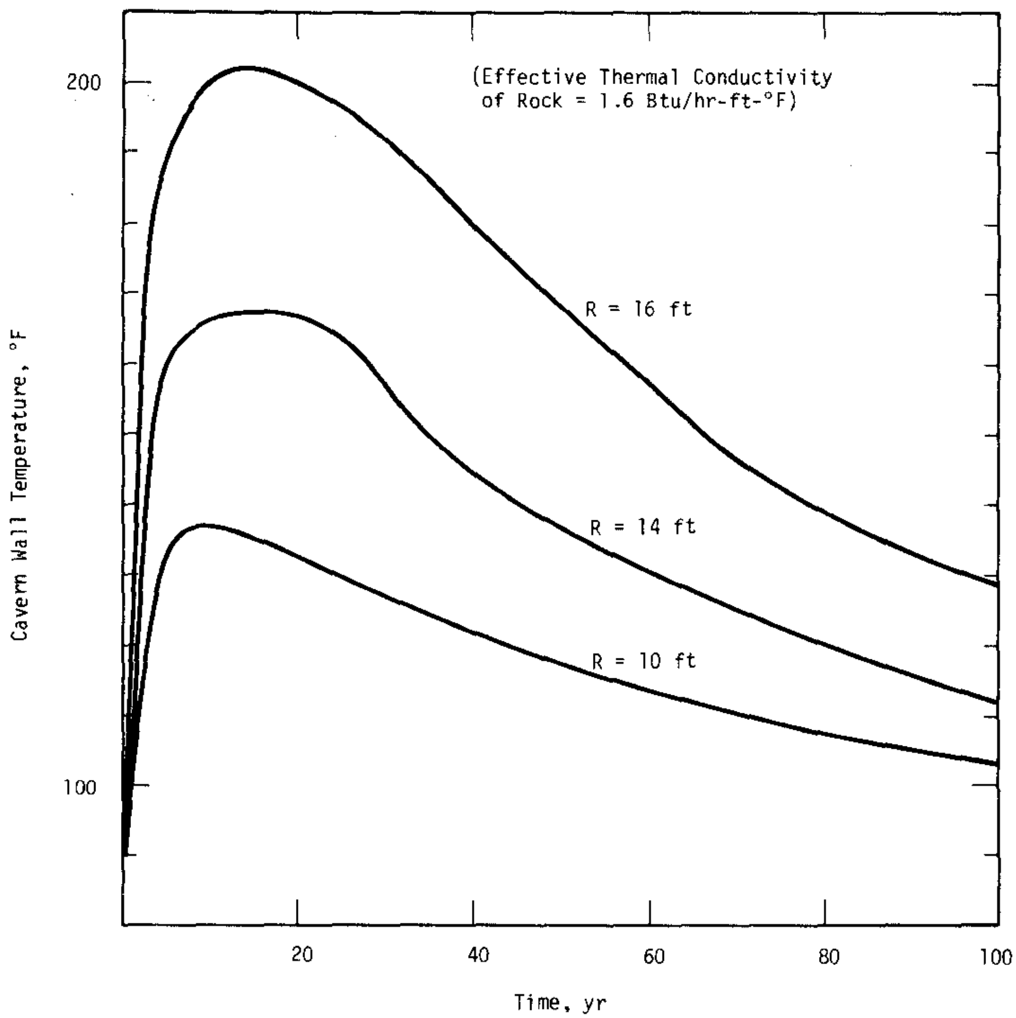

FIGURE III.6.2. Cavern Temperatures versus Time for Caverns of Various Radii

The existence of a temperature gradient gives rise to a potential for fluid movement in the surrounding rock. The most directly related effect would be thermal convection and this appears to be insignificant (Appendix III-6). Other coupled phenomena that represent a potential for causing rock water to migrate away from the caverns (such as thermo-osmosis and electro-osmosis) would be expected[3] to have even less effect.

Based on the estimates made in this section indicating that temperatures and temperature gradients would return to normal in the rock in approximately 200 years and earlier calculations that suggest time periods in excess of 200 years to reach hydrostatic equilibrium for a properly designed cavern (Section III-4), migration of water would be controlled by the large pressure gradient acting to force water into the cavern and thermal effects should be negligible.

If all of the waste were to be incorporated in a single solid waste phase (such as cement, etc.), there would be no heat transfer by convection in the cavern, and additional consideration would have to be given to reduce the effective cavern radius to keep temperatures within acceptable limits.

APPENDIX III-6. EFFECTS OF HEAT GENERATION[4]

Effects of nuclear heat emitted by waste solution in a prospective bedrock storage vault were calculated. Maximum permissible temperatures and temperature gradients will depend on vault construction materials and have not yet been determined for the bedrock storage system.

Preliminary calculations for a vault with an effective radius of 14 ft indicate that if strontium-90 and cesium-137 were uniformly distributed longitudinally, the maximum wall temperature would be about 75°F above the initial rock temperature. This maximum would occur 15 to 20 years after the filling of the vault begins, with most of the increase occurring during the first 5 years. The liquid waste would be less than 1°F warmer than the wall; the center of the sludge, about 6°F warmer. With an initial rock temperature about 90°F, this means that the maximum temperature in the vault would be approximately 170°F. If the sludge were not uniformly distributed in the vault, considerably higher temperatures could be produced locally.

Thermal convection of water is calculated to be negligible in both transmissive and nontransmissive rock adjacent to the vaults; convection in large vertical fractures would be significant only in fractures wider than 0.1 mm.

Temperature Gradient in Bedrock

The following equation[5] was derived for heat transfer from a long cylindrical source with exponentially decreasing heat output:

$$\Delta T = \frac{Q_0}{2\pi k} \int_{\beta_o}^{\infty} e^{-0.024\tau} \left(\frac{e^{-\beta^2}}{\beta}\right) d\beta \qquad (1)$$

where

T = temperature of rock above initial temperature, °F

Q_0 = initial heat output per linear foot of cavern (Btu/hr-ft)

k = thermal conductivity of rock,[6] 1.6 Btu/hr-ft-°F

τ = integration variable (0 to t)

$= t - \frac{R^2}{4\gamma\beta^2}$

$\beta = \frac{R}{2\sqrt{\gamma(t-\tau)}}$; $\beta_0 = \frac{R}{2\sqrt{\gamma t}}$

R = distance from center of vault (radius), ft

γ = thermal diffusivity of rock, 0.048 ft^2/hr

t = time, hr

Equation 1 was integrated for various combinations of R and t, with the following assumptions:

1. Effective radius of vault is 14 ft.

2. Initial heat output is 0.72 Btu/hr-ft^3. This corresponds to 200,000,000 Ci each of strontium-90 and cesium-137 in 80,000,000 gallons of waste. Initial heat output per linear foot is 470 Btu/hr-ft, for a circular cross section.

3. Heat transfer is uniform at the wall. This assumption neglects the filling time and is conservative in that calculated temperature increases are maxima. However, during filling, although heat output per foot is less than maximum, only a proportional fraction of wall is in contact with the waste.

4. The length/diameter ratio of the vault is large enough to neglect end-effects because this ratio is greater than 120 in prospective configurations.

5. Thermal capacity of the waste is assumed to be zero (with a resulting error of about 3%).

6. Waste is in direct contact with rock (no lining).

Results are shown in Figures 1 and 2, Appendix III-6. The wall reaches maximum temperature in 15 to 20 years at a ΔT of approximately 75°F; most of this increase occurs within 5 years. At distant positions in the rock, maximum ΔT is much smaller and occurs later. Because ΔT is only about 7°F in 15 to 20 years at 140 ft from the center of the vault, distances of about 280 ft or more between vaults ensure little if any thermal interaction. Separations of less than 280 ft in the same horizontal plane would distort the single-vault temperature distribution by increasing heat flux in the vertical direction to compensate for decreased heat flux between the vaults. For the uniform heat fluxes assumed in this analysis, interaction between vaults does not appear to be a serious problem. In the limiting case of two coaxial vaults (zero separation), the resulting single vault has double heat flux, and maximum ΔT at the wall is also doubled, to approximately 150°F. With initial rock temperature at 90°F, maximum rock temperature would then be 240°F. In the clay layer above the bedrock (R about 500 ft), temperature would increase by only a few degrees.

After 200 to 300 years, the vertical temperature gradients due to the nuclear heat flux would be less than the existing geothermal gradient (ca. 0.8°F/100 ft). After about 300 years, the rock would cool to within a few degrees of original temperature; although ΔT is small, the amount of rock with temperatures above ambient is large. Temperature gradients in the rock for various times are shown in Figure 2, Appendix III-6. Maximum temperature gradient is calculated to be about 3°F/ft. In a concrete liner, maximum temperature gradient is approximately 10°F/ft.

Convection Heat Transfer in Liquid Waste

Convection heat transfer in the liquid waste was estimated from standard design equations.[7] The initial convection heat transfer coefficient is estimated to be about 16 Btu/hr-ft^2-°F. Temperature difference would be less than 1°F between the bulk of the liquid and the wall. A number of convection cells would be set up in the liquid. During 100 years this number would be about halved. Convection is estimated to continue in the liquid waste for several hundred years.

Distribution of Sludge

The sludge sediment is expected to contain all of the strontium-90 and will constitute 5 to 10% of the total waste volume. If the sludge is approximately 10% of the waste volume and is distributed evenly throughout the vaults, it would be about 2 ft thick and would contact about one fourth of the wall

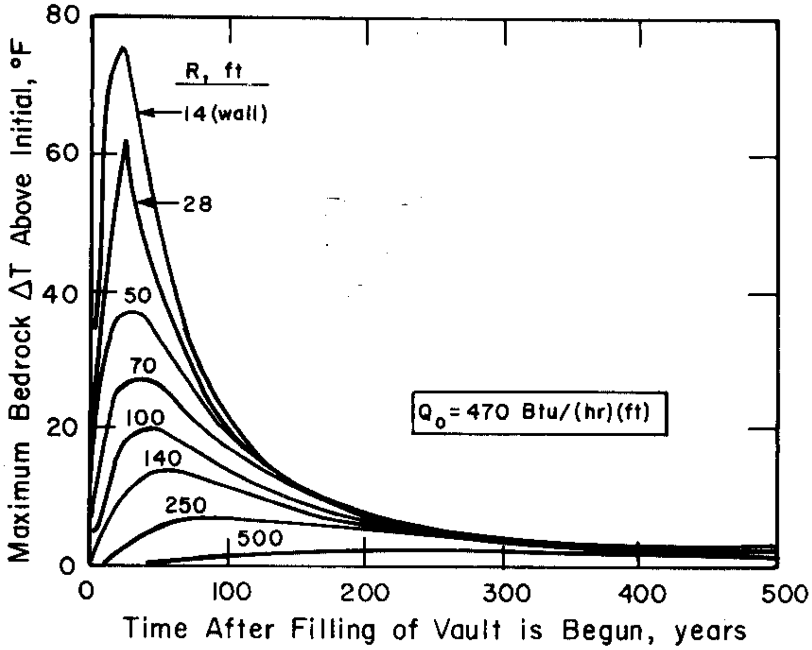

FIGURE III.6.A1. Temperature Versus Time in Bedrock

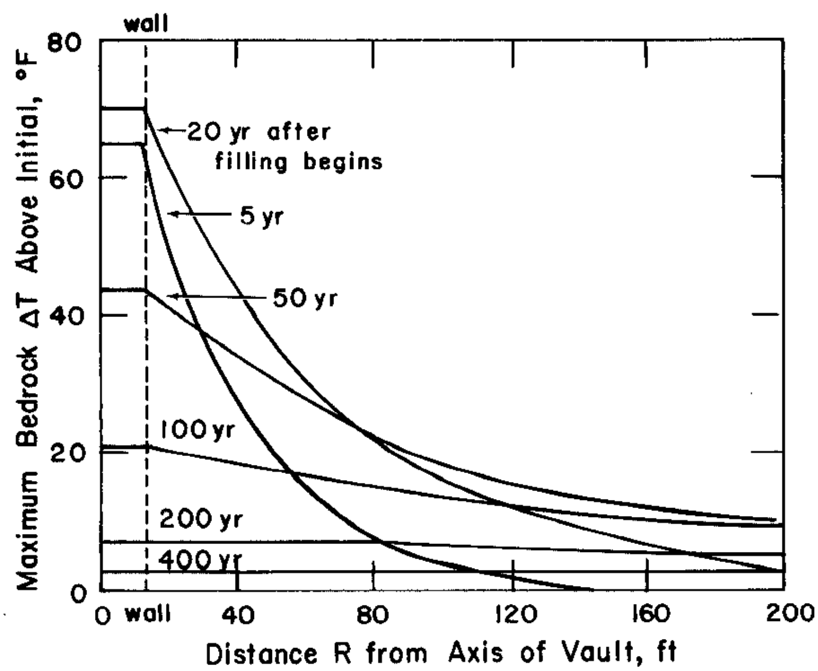

FIGURE III.6.A2. Temperature Gradients Versus Time in Bedrock surface. If all of the strontium-90 (which develops about one half of the total heat output) were in the sludge, about one half of the heat would flow from the sludge to the liquid, and the heat flux at the wall would be the same from the sludge as from the liquid. Under these circumstances, the assumption of uniform heat flux remains valid.

Uneven thickness of sludge in the vaults would result in higher local heat transfer and local temperature at the wall. If nonuniform distribution of the sludge is so extensive in the longitudinal direction that axial heat transfer can be neglected, but radial conduction and convection can be assumed sufficient to maintain homogeneous radial heat transfer rates, the results can be evaluated by Equation 1 and appropriate equations developed to determine conduction heat transfer in the sludge. Table 1, Appendix III-6 gives maximum expected temperatures based on sludge representing 5 and 10%, respectively, of the waste volume.

TABLE III.6.A1. Effect of Nonuniform Sludge Distribution on Temperature

Overall Sludge Volume, % of Total Waste	Nonuniform Sludge Volume, % of Section	Wall Temp., °F	Sludge Centerline Temp., °F
5	5 avg	165	168
	10	241	254
	20	312	363
10	10 avg	165	171
	30	232	260
	30	263	330

Thermal Convection in Adjacent Rock Water

Heating of the water in the bedrock adjacent to the vaults can potentially cause thermal convection cells in the rock. Such convection is analyzed separately as summarized in the following sections for vertical and horizontal temperature gradients.

The potential for convection cells due to the vertical temperature gradient is evaluated by stability analysis in which the vault system is modeled as a horizontal grid that represents a flat heating plate and the rock above the vault is considered as a porous medium heated from below, so that rock water is more buoyant near the vaults than near the surface.

Thermal convection due to a horizontal temperature gradient from the vault is modeled by vertical columns of rock in which the rock water is more buoyant than at the same depth in columns farther from the vaults. This convection was evaluated for both fractured and nonfractured rock adjacent to the vault. Local convection was also considered with individual large vertical fractures adjacent to a vault.

Thermal Convection Due to Vertical Temperature Gradient

Fluid in a homogeneous porous medium with a vertical gradient of temperature becomes unstable when the gradient exceeds the critical value λ:[8]

$$\lambda = (4\pi^2 \gamma v)/(h^2 a g \sigma) \qquad (2)$$

where

γ = thermal diffusivity of rock, 0.048 ft^2/hr

v = kinetic viscosity, 0.0138 ft^2/hr (based on H_2O at 180°F)

h = thickness of heated layer, ft

a = volumetric thermal expansion of liquid, 2.6×10^{-4}/°F

g = acceleration of gravity, 1.15×10^5 ft/hr^2

σ = permeability, 3.6×10^{-16} ft^2 for nonfractured rock

Thus, convection is favored (λ decreased) by a thick heated layer h and high permeability σ in the medium; these conditions do not exist in the metamorphic or Triassic rocks.

The permeability of the rock was determined from previous measurements of water flow in the rock.[9] Conditions for convection are most favorable after approximately 20 to 50 years, when the heated layer is thick. Equation 2 predicts that the temperature gradient over a thickness of 500 ft would have to be about 30,000°F/ft to initiate homogeneous convection in nonfractured rock, and about 60°F/ft for fractured rock. Actually, the maximum gradient at any time is about 3°F/ft, and only at the wall of the vault. To permit convection due to the heating from below, permeability would have to be approximately 10^7 times as high as that for nonfractured rock and higher than is estimated for fractured rock or for the Tuscaloosa aquifer.

Thermal Convection Due to Horizontal Temperature Gradient

The buoyant force on heated water in rock adjacent to a vault, relative to cooler water farther from the vault at the same depth, is determined by the temperature and height of the heated column. Data in Figures 1 and 2, Appendix III-6, can be used to estimate the maximum values of temperature and height of these heated sections.

If the horizontal thermal gradients are approximated as linear, the maximum velocity of a convection cell can be estimated by:

$$V_{max} = \frac{\text{(Permeability Coefficient)(Gradient)}}{\text{(Porosity)}}$$

$$= \frac{\sigma[cgh(\Delta T/2)\rho_o a]/L}{\varepsilon} \qquad (3)$$

where

V_{max} = maximum vertical velocity, ft/hr

σ = permeability coefficient, (ft/yr) ÷ (ft_{H_2O}/ft)

c = conversion factor = 5×10^{-4} ft sec^2 ft_{H_2O}/ft

g = acceleration of gravity, 1.15×10^5 ft/hr^2

h = effective height of heated column of water, ft
≃ (first approximation) distance from center of cavern to boundary of heated rock

ΔT = difference between cavern wall temperature and original rock temperature, °F

ρ_o = density of water at 25°C, lb_M/ft^3

a = volumetric thermal expansion of liquid, 2.6×10^{-4}/°F

L = distance through which water flows in convection cell, ft

ε = porosity or void fraction

For a postulated large convection cell that would circulate the fluid up to the clay layer and back to the cavern region (L ≳1,000 ft), the calculated order of magnitude of the maximum velocity at various times for a cavern located in fractured rock and in nonfractured rock is given in Table 2, Appendix III-6.

TABLE III.6.A2. Maximum Velocities in Large Bedrock Convection Cells[a]

Time, yr	Maximum Velocity,[b] ft/yr — Nonfractured Rock, $\sigma = 0.1 \frac{ft/yr}{ft_{H_2O}/ft}$, $\varepsilon = 10^{-4}$	Fractured Rock, $\sigma = 49 \frac{ft/yr}{ft_{H_2O}/ft}$, $\varepsilon = 10^{-2}$
5	0.3	1.5
20	0.6	3
50	0.5	2.5
100	0.2	1
200	10^{-2}	5×10^{-2}
400	0	0

a. Assumed flow path ~1000 ft.

b. All thermal convection velocities are maxima at steady state and do not account for the time required to accelerate the fluid.

The maximum vertical movement of water would be approximately 50 to 100 ft in a zone of nonfractured rock and approximately 300 ft in a zone of fractured rock. Velocities would remain at their maxima during the period from 20 to 50 years after filling of the vaults is begun. Before 20 years, the heated columns would have little height; beyond 50 years, horizontal temperature gradients would become negligible.

Because the stored solution is about 30% more dense than rock water, the heated solution must be diluted below 6% of original concentration by dispersion before it would be more buoyant than unheated rock water, and below 1% of original concentration before the mixture could reach the tabulated convection velocities.

In similar analysis for a large individual fracture, exposed to horizontal heat flux from the vault, the velocity gradient in the fracture is obtained by simultaneous solution of equations of heat and momentum transfer:

$$V = \left(\frac{\rho a g Q b^3}{6k\mu}\right) [N^3 - N] \qquad (4)$$

where

V = vertical convection velocity, ft/hr

ρ = density of water at 25°C, lb_m/ft^3

a = volumetric thermal expansion of liquid, 2.6×10^{-4}/°F

g = acceleration of gravity, 1.15×10^5 ft/hr^2

Q = heat flux, Btu/hr-ft^2

b = half width of fracture, ft

k = thermal conductivity of rock water, 0.386 Btu/hr-ft-°F

μ = viscosity of water, 0.968 lb/(hr-ft)

N = distance from centerline of fracture, half-widths

An equation for the maximum velocity was derived from Equation 4, and maximum velocity at 0 and 100 years was computed for various fracture widths close to the vault, with heat flux the same as that at the vault wall. The calculations show that convection in vertical fractures would be significant only for fractures wider than 0.1 mm. Maximum velocity occurs promptly and decreases rapidly (Table 3, Appendix III-6).

All thermal convection velocities in the two foregoing tables are maxima at steady state and do not account for the time required to accelerate the fluid.

TABLE III.6.A3. Convection Within a Vertical Fracture

Time, yr	Fracture Width, mm	Maximum Velocity, ft/yr[a]
0	0.1	0.1
	1.0	100.0
100	0.1	0.01
	1.0	10.0

a. All thermal convection velocities are maxima at steady state and do not account for the time required to accelerate the fluid.

III-7. SHAFT SEALING REQUIREMENTS

Introduction

All access shafts and nearby deep rock borings must be sealed so that they do not provide a high conductance path for the waste to flow into the Tuscaloosa aquifer. The requirements for this sealing step are discussed in this section.

Summary

The permeability of concrete used to seal the shaft should be as low as the surrounding rock so that the sealed shaft does not represent the path of least resistance for the waste. A crack as large as 10 μm extending all the way from the waste to the Tuscaloosa aquifer and located at the circumference of a 15-ft-diameter shaft (the largest crack expected in such a system) does not appear to pose a serious problem. If special care is taken in the choice of concretes used to seal the shaft and the choice of shaft sealing techniques, a seal of sufficient integrity can be obtained.

Discussion

After the cavern is constructed, evaluated, and charged with waste, the shafts to the cavern must be sealed. These shafts can be the critical pathway to the biosphere if they are not properly sealed to the surrounding rock matrix or if the permeability of the seal is significantly higher than the surrounding rock. A variety of materials could be used to seal the shafts, however concrete is likely to be the main one used. Although structures built of concrete are known to have survived in good condition since Roman times (the Pantheon in Rome is constructed of concrete), the history of concrete structure is short compared to the requirements of the shaft.

There are many types of concrete, but all types fall into one of the two general categories, shrinking or swelling. Generally, concrete shrinks around 0.1% during drying. Specially prepared concrete, known as swelling concretes (contain $4CaO.SO_3$, CaO, and $CaSO_4$) will expand from 0.2 to 6% depending on the mix. As long as a swelling concrete is confined, it maintains its strength. Inasmuch as the concrete used in the shaft will likely be in contact with water or a saturated relative humidity, shrinkage is unlikely to be a serious problem if a proper seal can be attained following curing in a low relative humidity atmosphere because dried concrete may swell 0.01 to 0.02% when placed in contact with water.

Several means exist to improve the seal between concrete and rock. One approach is to use a polymer concrete (aggregate plus an organic polymerizing compound in place of concrete) containing a bonding agent, e.g., polymethylsiloxane, which increases the amount of bonding between the rock and the concrete from only a small percentage attained by normal concrete to approximately 100%. Another approach might be to space epoxy plugs at regular intervals up the shaft. Epoxy plugs are used to prevent venting of underground nuclear explosions but have not been evaluated for use in the bedrock concept.

The consequences of inadequate bonding between the rock and the shaft sealant are examined in detail in Appendix III-7 and shown to be of minor importance if reasonable care during construction is exercised in workmanship and materials. Waste will not enter the Tuscaloosa aquifer from a 10 μm crack (a maximum-sized crack) around the concrete used to seal the 15-ft-diameter shaft in a crystalline cavern for 30,000 years, and then at the rate of only 1 gal/year. Waste will not enter the Tuscaloosa aquifer from the same size crack around the shaft plug in Triassic rock for 15,000 years and then at the rate of about 50 gal/year. In either case, if all the activity was collected in a well penetrating the Tuscaloosa aquifer and pumped at 30 gpm, the concentration of activity would be less than 1% of MPC.

The permeability of the concrete itself can be of concern if sufficiently more than the surrounding rock. The permeability of concrete is a function of the type of aggregate used in the mix and of the method of preparing the concrete. Various authors quote different ranges of concrete permeabilities to water. The lowest concrete permeabilities reported[1-3] by three different sources are 10^{-8}, 10^{-6}, and 10^{-2} gal/day/ft^2. The first two numbers are equal to or better than Triassic rock, the latter is much worse and concrete of this permeability would act as the critical pathway. This wide range of permeabilities indicates extreme care must be exercised during construction to obtain minimum permeabilities of concrete. An alternative to the use of normal concrete is the use of polymer concrete, mentioned earlier, which has a permeability several orders of magnitude lower than normal concrete.

Concrete is susceptible to chemical attack. Sodium hydroxide in the waste dissolves the silica matrix, destroying the integrity of the concrete with time. Either sufficient concrete must be present to prevent this effect from being important in reducing the total path length, or additives put in the waste to eliminate this effect, e.g., increasing the silicon ion concentration or adding a silicon-based thixotropic agent. The presence of a gas pocket above the waste that effectively isolates the concrete is expected to be very effective also.

The importance of the final condition of the shaft after sealing to the over-all safety of the cavern concept indicates considerable effort should be expended in evaluating alternate sealing materials with regard to their bonding properties to the rock, their permeabilities, and their resistance to attack. Equal care needs to be applied to the development of techniques for sealing exploratory borings in the vicinity of the cavern, otherwise these borings may provide the path of least resistance for the waste.

APPENDIX III-7. EFFECT OF A CRACK IN THE SHAFT SEAL

A crack, if it exists between the material (assumed to be concrete) used to seal the shaft and the rock wall of the shaft, will provide the preferred pathway for material to leave the cavern. An upper limit estimate of the size of such a crack can be obtained by assuming a 15-ft-diameter shaft filled with concrete that contracts 0.15% on setting, then grouting the crack with the same material and assuming it also shrinks by the same percentage. The resulting crack is roughly 10 μm all the way around the shaft. This crack size is the estimated upper limit because expanding cements, bonding agents, and other materials properly applied should produce no separation between the rock and the sealing material.

Existing equations can be used to calculate flow velocities and quantities through these cracks. Bird[4] states that the maximum velocity of a fluid during laminar flow in a narrow slit is described by

$$V_2 = \frac{(P_o - P_L) \quad B^2}{2 \nu L} \left[1 - \left(\frac{X^2}{B} \right) \right] \tag{1}$$

where

V_2 = the velocity, cm/sec^2

P_o = the pressure at the inlet, gm/cm sec^2

P_L = the pressure at the outlet, gm/cm sec^2

B = the half-width, cm

ν = the viscosity of the solution, gm/cm sec

L = the length of the slit, cm

X = the distance from the center line, cm

The total quantity of material (Q, cm^3/sec) moving through the slit is

$$Q = \frac{2/3\ (P_o - P_L)\ B^3\ W}{\nu L} \qquad (2)$$

where W is the length of the crack intersecting the cavern wall. Equations 1 and 2 can be used to obtain the distance fluid will move through a crack and the quantity of fluid that will be discharged for various sizes of slits. Figure III.7.1 illustrates the importance of the slit width and the gradient $[(P_o - P_L)/L]$ on the flow velocity of air and waste from the cavern. From Figure III.7.1, the velocity of liquid in a crack 10 μm thick is such that waste will travel 6600 ft/yr when the gradient is 0.5 ft_{H_2O}/ft, a gradient that might occur between the cavern in the Triassic formation and the overlying Tuscaloosa aquifer. For a gradient of 0.0014 ft_{H_2O}/ft that might be likely for crystalline rock, the flow rate would be 170 ft/yr. The volume of solution leaving the crack can be obtained from Figure III.7.2,if we assume the crack extends all the way around the perimeter of a 15-ft-diameter shaft. The appropriate gradients are marked on the figure for the following situations: the gradient that would exist between the cavern and the Tuscaloosa aquifer immediately following sealing of the cavern, the natural gradient for the formation, and gradients to the Tuscaloosa aquifer under presently existing conditions for both the Triassic and the crystalline systems. If a crack equivalent to 1 μm and a pressure gradient of 0.5 ft_{H_2O}/ft are assumed, then approximately 50 gallons of waste or 900 gallons of air will leave the cavern in 1000 years.

The effect a 10 μm crack between the concrete filling and the rock will have on the release of activity from the caverns depends on the rock type chosen. In the crystalline cavern, waste would need to be deposited in a solidified state to reduce gas evolution problems, as discussed in Section III-4. At the time of cavern sealing, there are expected to be 20,000,000 gallons of air at atmospheric pressure. Inleakage to the cavern will begin; and the gas phase volume will be reduced due to increased pressures. The rate of inleakage through a 10 μm crack (Figure III.7.2) is insignificant (6×10^{-6} gallons/min) compared with that entering through the rock. Air flow out of the crack will begin in about 50 years, the time at which the piezometric pressure is 5 feet greater than the Tuscaloosa aquifer (at this pressure the air entry value of the crack is exceeded, see Section III-4). The air will leave at 30 gallons/year (Figure III.7.2). The gas at cavern pressure (approximately 50 atmospheres) is 400,000 gallons, hence, gas will bleed out for 13,000 years. Thereafter, liquid will leave at the rate of 1 gallon/year (Figure III.7.2).

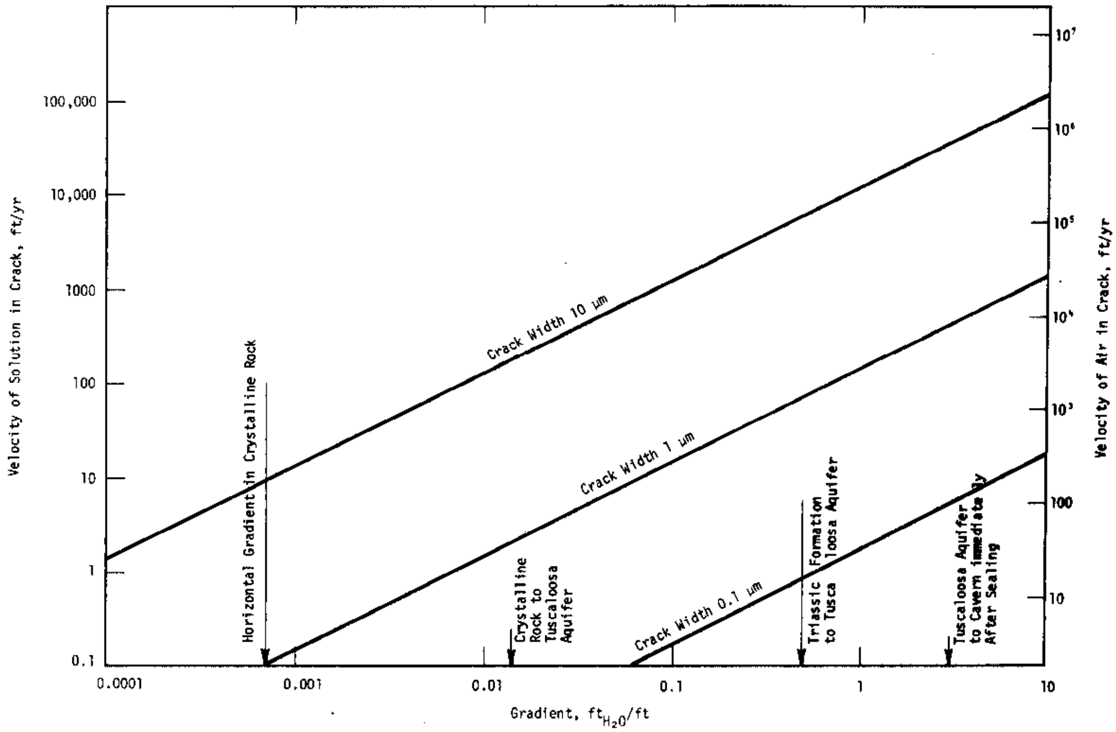

FIGURE III.7.1. Influence of Crack Widths and Pressure Gradients on Flow of Waste Solution and Air through Cracks in the Rock

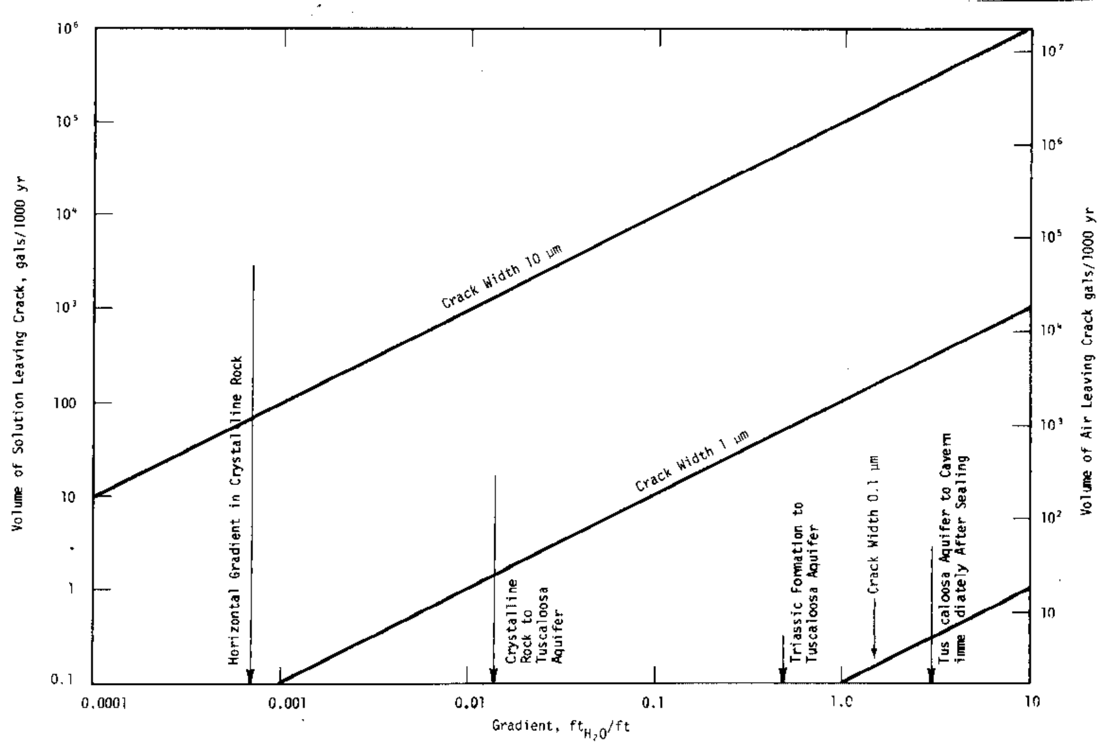

FIGURE III.7.2. Influence of Crack Widths and Pressure Gradients on Flow of Waste Solution and Air through Perimeter Crack in Shaft Seal

In the Triassic cavern, waste would be deposited as the liquid. At the time of cavern sealing there are expected to be 50,000,000 gallons of air at atmospheric pressure in the cavern. In addition, while the waste is decaying approximately 700,000,000 gallons of gas will evolve. The total amount of gas at 50 atmospheres will be 14,000,000 gallons. After approximately 1000 years, hydrostatic pressure will be reached. Before reaching hydrostatic pressure, the dense waste will begin to leave the cavern. Pressure will continue to build up in the cavern, but very slowly because of loss of waste from the cavern, the low permeability and low hydraulic gradients in the rock, and the loss of gas through cracks. The gas loss will approximate 1000 gallons/year through a 10 μm crack after the presently existing piezometric pressure in the Triassic is reached, requiring at least 14,000 years for gas evolution to be completed. At the end of this time, waste will move through the crack at 50 gallons per year.

If a well used for domestic water supply was located directly above the interface between a crack in crystalline rock and the Tuscaloosa aquifer, and was pumped at 30 gpm, the dilution factor would be 6×10^{-8}, sufficient to decrease the toxicity level of all components remaining after 13,000 years to well below the maximum permissible concentration (MPC). A similar well in Triassic rock will result in a dilution factor of 3×10^{-6}, also sufficient to reduce the concentration to below MPC after a period of 15,000 years.

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CHAPTER IV. MATHEMATICAL MODELS OF BEDROCK PERFORMANCE

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CHAPTER IV. MATHEMATICAL MODELS OF BEDROCK PERFORMANCE

INTRODUCTION

Mathematical models were derived to predict the concentrations and quantities of various waste constituents migrating from a bedrock cavern to the biosphere. These models are written in terms of the chemical characteristics of the waste (distribution of various isotopes between the solid and liquid waste phases, dissolution rate of solid waste, etc.) and the chemistry and hydrology of the rock in which the cavern is located. The models permit the parameters of greatest significance to be determined, allow estimates of the approximate magnitude of these parameters required to meet design guidelines, and permit comparisons among different potential storage locations. When used with conservative assumptions for the values of the various parameters, they give upper limit estimates of the concentrations and quantities of the various radionuclides entering the biosphere.

These models are used specifically to compare the systems having characteristics expected for crystalline and Triassic rock as potential cavern sites, and to determine whether these systems could meet the design guideline that concentrations of all toxic materials must be less than 1% of MPC upon entering the biosphere.

The system is assumed to have a negligible radiolytic gas driving force and the cavern shafts are assumed to be well-sealed and do not represent critical flow paths. Requirements necessary to meet these criteria are discussed in Chapter III.

SUMMARY

The mathematical models presented in this section give concentrations and quantities of various isotopes leaving the various rock systems as a function of several parameters that are characteristic of the waste to be stored as well as the rock formation in which the cavern is located. Important parameters are the travel time required for non-adsorbed waste to reach the biosphere along the principal flow path, the adsorption capacity and coefficients for the various isotopes in the rock, time required to reach hydrostatic equilibrium in the cavern, the volumetric flow rate of waste from the cavern, and the solubility of various isotopes in the liquid waste phase. The solubility of an isotope in the liquid waste is of secondary importance for a particular isotope as long as the time required for that isotope to reach the biosphere is large compared to the time required for it to decay to negligible levels. However, marginal systems will be improved if the isotopes can be guaranteed to remain in a stable solid phase in the cavern.

When evaluated by the mathematical models, Triassic rock appears to be well suited for bedrock storage of radioactive waste. The relatively homogeneous character of Triassic rock and infrequent fractures and fracture zones permit tentative identification of the critical flow path of the waste from such a cavern and the corresponding travel time. The low permeability and moderate porosity result in low rates of flow (Chapter III). The favorable ion exchange properties significantly reduce the rate of migration of many of the radionuclides. The expected low permeability of the Triassic rock suggests low inleakage rates (less than 1 gpm) and a long time period (about 1000 years) to reach hydrostatic equilibrium. Subsequent volumetric flow rate of waste out of the cavern would be low. However, the high piezometric head in the Triassic rock compared to that in the overlying Tuscaloosa aquifer (ΔP greater than 200 ft H_2O) should be demonstrated not to force waste rapidly through the Triassic rock into the Tuscaloosa aquifer.

Flow in crystalline rock is through fractures and fracture zones making the critical flow path difficult to predict. The higher permeability, low porosity, and low ion exchange capacity result in much higher rates of migration through crystalline rock than through Triassic rock.

The mathematical models determined whether the evaluation guideline of total radioactivity entering the biosphere at less than 1% MPC could be met with expected values of the parameters for crystalline and Triassic rock with no credit taken for dilution in the biosphere. A variety of flow paths for the following waste components were considered:

- ^{135}Cs and ^{137}Cs as examples of radioisotopes with relatively long and short half-lives (2×10^6 for ^{135}Cs and 30 yr for ^{137}Cs, respectively) but with identical chemical properties.
- ^{239}Pu as an example of a radioisotope with an intermediate half-life (2.4×10^4 yr).
- Nitrate-nitrite as an example of a stable toxic chemical.

The calculations showed that:

1. Assuming all of the constituents are soluble in the liquid phase of the waste (System I), then for the crystalline system both ^{135}Cs and ^{239}Pu would be greater than MPC when leaving the bedrock. For the expected Triassic system, both of these isotopes would be well below 1% MPC.

2. Storage of unaltered waste in a Triassic cavern with the properties assumed for this analysis would meet the evaluation guidelines for all radionuclides considered in this section, providing the principal driving force controlling the direction and rate of migration was the density of the liquid waste.

3. In either the crystalline or Triassic systems, nitrate-nitrite represents the most difficult constituent to reduce below 1% MPC. Only the more porous Triassic rock would dilute this constituent to concentrations less than MPC upon leaving the rock. Even for the Triassic system, the evaluation guideline of less than 1% MPC is not met at the point where the salts leave the rock (maximum concentration of nitrate-nitrite leaving the rock from a Triassic cavern is estimated to be approximately 8% of MPC), however, mixing of the waste emerging from the rock with as little as 0.2 gpm of water would be sufficient to reduce the nitrate-nitrite concentration below 1% MPC.

4. Modification of the waste would probably be required to maintain releases from a crystalline cavern within design specifications. This modification would require three steps. The first step would be to remove all dissolved solids from the supernate to reduce the drive from the specific gravity of the waste. The second step would be to remove toxic nitrate-nitrites. The final step would involve treating the waste to assure that all of the hazardous long-lived isotopes (especially ^{239}Pu) remain in a stable solid waste phase.

DISCUSSION

Development of Models

Three waste systems are considered in this analysis:

I. All radioactivity is in a liquid waste phase.

II. Most radioactivity is sorbed on a stable solid waste phase.

III. All radioactivity is initially in a solid waste phase that dissolves very slowly.

The first system (I) is the simplest of the three and takes no credit for containment of the waste by a solid waste phase. The second system (II) assumes that a large fraction of the radioactivity is distributed in a stable solid waste phase that remains in equilibrium with the liquid phase at all times. The term stable in this context refers to a solid with a very low equilibrium solubility in the liquid waste phase. An example would be the sludge that exists at present in the caustic waste. Other potential "additives" to remove activity such as zeolites, might also fit this definition. For both systems (I and II) radioactivity is present in the liquid phase initially, but in system II there are thermodynamic limits to the concentrations of the radionuclides.

The third system (III) assumes that all of the radioactivity in the waste is initially incorporated into a solid. The radioactivity is assumed to be transported from this solid to the liquid phase at a very low rate and equilibrium is assumed never to be reached. This transport could take place by simple dissolution of the bulk of the solid or diffusion of activity from the solid matrix into the liquid phase. Regardless of the exact mechanism, this system is such that the concentration of activity in the liquid phase is controlled by a kinetic rather than a thermodynamic limit.

A mathematical model was developed for each of the three systems. The detailed derivations of these models including all assumptions are presented in Appendix IV-A. The basic approach to the derivation of these models is outlined below:

- The models are based on material balances taking the cavern (defined as including the waste but none of the rock) as the system. This material balance gives the relationship for the concentration of any isotope leaving the cavern and entering the rock.

- The relationship for the concentration of an isotope leaving the rock and entering the biosphere was then determined by assuming that the rock behaves as a large uni-directional ion exchange column. The length of the column is essentially the length of the critical path which the waste would take from the cavern to the biosphere. The critical path would not necessarily be the shortest straight line distance from the cavern to the biosphere. The exact path of the waste from a particular cavern would depend upon the forces tending to drive the waste and the resistance of the various sections of rock to that flow. The residence time of liquid waste in bedrock is taken as the average time required for water to travel from the cavern to the biosphere along the critical path. The waste is conservatively assumed to follow this critical path. No credit is taken for dilution of waste in the biosphere.

- Although plug flow (no dispersion) is assumed along the critical path, dispersion would be expected from diffusion, velocity gradients in fractures or intersticies between particles, and macroscopic channeling effects on a scale that is small compared to the size of the critical path. The plug flow assumption is generally conservative because it takes no credit for dilution by the water in the rock from dispersion.

  In addition to dilution, dispersion causes some of the activity to arrive in the biosphere far ahead of the main body of waste. In some cases, the dilution of this activity does not completely compensate for the reduction in the amount of decay, and the concentrations entering the biosphere can exceed estimates based on the plug flow assumption. This effect is discussed further in Appendix IV-B and is taken into account in all cases where it is significant. Dispersion along the critical path would not have a strong effect on the total quantity of activity entering the biosphere because the additional curies entering the biosphere ahead of the main body of waste would be approximately counter-balanced by the additional decay of activity reaching the biosphere behind the main body of waste.

- The effect of adsorption is evaluated by assuming that the waste migration through the rock is equivalent to flow through an ion exchange column composed of this rock at a rate slow enough for equilibrium to be attained at all times. The time required for a particular radioisotope to travel through the rock can then be related with standard equations to the adsorption properties of the rock and the average residence time of water flowing through the rock (Appendix IV-B).

The mathematical models that are derived on the basis of these assumptions are sufficient to determine which parameters are of greatest significance and give estimates of the approximate magnitude of these parameters that would be required for acceptable performance. They also allow a direct comparison of the relative importance of alterations of the waste to reduce the mobility and solubility of the activity (such as solidification, etc.) as compared to the isolation from the biosphere provided by the bedrock storage system. When these equations are used with conservative assumptions for the values of the various parameters, they give upper-limit estimates of the concentrations and quantities of the various isotopes entering the biosphere from the bedrock system. The mathematical models for System I (all activity is in the liquid phase), System II (all activity sorbed on the solid waste) and System III (all activity initially in the solid waste, which later slowly dissolves) are given in Table IV-1. The symbols used in this table are:

γ = time required to reach hydrostatic equilibrium after filling, yr

ε = void fraction of rock

θ = minimum residence time of liquid waste in bedrock, yr

λ = decay constant for a radioisotope, yr^{-1}

ρ = bulk density of rock, gm/cm^3

C = concentration of a radioisotope entering biosphere, Ci/gal

C_{max} = maximum concentration of a radioisotope entering biosphere, Ci/gal

K = effective equilibrium distribution coefficient between solid waste phase and liquid waste phase; conc. in solid/conc. in liquid

K_d = equilibrium distribution coefficient for a radioisotope between waste and bedrock;

$$\frac{\text{fraction of radioisotope in rock/mass of rock}}{\text{fraction of radioisotope in liquid/volume of liquid}}$$

k = effective mass transfer coefficient for transport of isotope from solid by diffusion and convection defined by: flux from solid = $k'A\ (C_S - C_L) = k\ (C_S - C_L)$ where A = surface area of solid and k' = mass transfer coefficient based on unit surface area), gal/yr

Q = total integrated quantity of a radioisotope that has entered biosphere ($t = o$ to $t = \infty$), Ci

Q_o = initial quantity of radioactivity present when cavern is sealed, Ci

s = effective solid dissolution rate, defined by: rate of dissolution = s'A = s (where s' = dissolution rate based on unit surface area), gal/yr

t = time, yr

V_L = liquid waste volume in cavern, gal

V_S = solid waste volume in cavern, gal

W = steady-state water flow rate through cavern after reaching hydrostatic equilibrium, gal/yr

Application of Models to Bedrock Systems

These equations can be used to determine the behavior of the waste in crystalline and Triassic rock systems with expected characteristics (cases designated as A), as well as characteristics that are considered less likely but which cannot presently be ruled out (cases designated as B and C). For each case, the time to reach hydrostatic equilibrium is assumed to be 50 years for the crystalline cavern and 1000 years for the Triassic cavern.

In order to use the equations outlined in Table IV-1, appropriate values for each of the parameters are required. The properties of the rock are taken to be those expected for each system (Chapter III). A summary of the assumed conditions and corresponding residence times are given in Table IV-2. For each system, the conditions assumed for Case A represent the most probable behavior; however, the conditions given for the other cases cannot presently be ruled out.

TABLE IV-1. Mathematical Models Summary

System	Concentration Entering Biosphere	Quantity Entering Biosphere
I All activity in liquid waste phase	Equation I-a $C = 0$ when $t < \frac{K_d \rho \theta}{\varepsilon} + \theta$ $C = \frac{Q_o}{V_L} \exp\left[-\frac{W}{V_L}\left(t - \frac{K_d \rho \theta}{\varepsilon} - \theta\right)\right] \exp\left[-\lambda(\gamma + t)\right]$ when $t \geq \frac{K_d \rho \theta}{\varepsilon} + \theta$ $C = C_{max}$ when $t = \frac{K_d \rho \theta}{\varepsilon} + \theta$	Equation I-b $Q = Q_o\left(\frac{W/V_L}{W/V_L + \lambda}\right) \exp\left[-\lambda\left(\gamma + \frac{K_d \rho \theta}{\varepsilon} + \theta\right)\right]$
II Activity sorbed on stable solid waste phase	Equation II-a $C = 0$ when $t < \frac{K_d \rho \theta}{\varepsilon} + \theta$ $C = \left(\frac{Q_o}{KV_s + V_L}\right) \exp\left[-\left(\frac{W}{KV_s + V_L}\right)\left(t - \frac{K_d \rho \theta}{\varepsilon} - \theta\right)\right] \exp\left[-\lambda(t + \gamma)\right]$ when $t \geq \frac{K_d \rho \theta}{\varepsilon} + \theta$ $C = C_{max}$ when $t = \frac{K_d \rho \theta}{\varepsilon} + \theta$	Equation II-b $Q = Q_o\left(\frac{W/V_L}{W/V_L + \lambda + \lambda K\ V_s/V_L}\right) e^x$ $e^x = \exp\left[-\lambda\left(\gamma + \frac{K_d \rho \theta}{\varepsilon} + \theta\right)\right]$
III All activity initially in solid waste phase that dissolves slowly	Equation III-a $C = 0$ when $t < \frac{K_d \rho \theta}{\varepsilon} + \theta$ $C = \frac{Q_o\ (k+s)}{V_s\ W}\left\{1 - \exp\left[-\left(\frac{W}{V_L}\right)\left(t - \left(\frac{K_d \rho \theta}{\varepsilon}\right) - \theta\right)\right]\right\} e^{-\lambda t}$ when $t \geq \frac{K_d \rho \theta}{\varepsilon} + \theta$ $C = C_{max}$ when $t = \frac{K_d \rho \theta}{\varepsilon} + \theta$	Equation III-b $Q = Q_o\left(\frac{k+s}{V_s \lambda}\right) \exp\left[-\lambda\left(\frac{K_d \rho \theta}{\varepsilon} + \theta\right)\right]$ applies when $\left(\lambda V_s >> k+s \text{ and } \frac{1}{\lambda^2} >> 1\right)$

TABLE IV-2. Resident Times for Wastes in Crystalline and Triassic Rock for Various Conditions

	Crystalline Rock			Triassic Rock	
	A	B	C	A	B
Residence Time in rock, yr	6×10^4	10^2	40	2×10^7	10^5
Conditions Assumed:					
Waste Density, gm/cm^3	1.2	1.2	1.0	1.2	1.2
Permeability, ft/yr	1	1	1	3×10^{-4}	3×10^{-4}
Porosity	10^{-3}	10^{-3}	10^{-3}	0.03	0.03
Time to Reach Hydrostatic Equilibrium, yr	50	200	50	1000	1000
Regional Gradient	3 ft_{H_2O}/mi	3 ft_{H_2O}/mi	7 ft_{H_2O}/500 ft	3 ft_{H_2O}/mi	250 ft_{H_2O}/500 ft
Critical Path Distance, ft	35,000 (to Savannah River)	700 (fracture zone to Tuscaloosa aquifer)	500 (cavern up to Tuscaloosa aquifer)	2000 (down to crystalline rock)	500 (up to Tuscaloosa aquifer)

Crystalline Rock System

Crystalline System, Case A

The critical path is assumed to be the lateral distance to the river (about 35,000 ft) through rock having an average permeability of 1 foot/year, and the regional hydraulic gradient is taken to be 3 ft_{H_2O}/mile.

Crystalline System, Case B

The critical path is assumed to be the downward flow of waste to a fracture zone located approximately 700 ft beneath the caverns. This depth is arrived at by assuming that the caverns are located near DRB 7 and the fracture zone identified between DRB 5 and DRB 6 extends down under DRB 7 at a constant angle. After reaching the fracture zone, the waste is assumed to flow up to the Tuscaloosa aquifer through the fracture zone. For this case, migration to the biosphere is estimated to take place in only 100 years, an unacceptable situation because no appreciable decay of ^{90}Sr and ^{137}Cs would occur before the waste reached the biosphere. This case will not be explored further.

Crystalline System, Case C

The critical path is the distance from the caverns to the Tuscaloosa aquifer. Flow may occur in this direction because the pressure in the crystalline rock is approximately 7 ft_{H_2O} greater than the pressure in the Tuscaloosa Formation. This pressure is assumed to be linearly distributed across the roughly 500 ft path up to the Tuscaloosa aquifer. The density of the waste is assumed to be equal to that of the rock water. For this case, migration to the biosphere is estimated to take place in only 40 years, an unacceptable situation because no appreciable decay of ^{90}Sr and ^{137}Cs would occur before the waste reached the biosphere. The case will not be explored further.

Triassic Rock System

Two cases are considered for Triassic rock. For both of these cases, waste density is assumed to be 1.2 g/cm^3 and the time to reach hydrostatic equilibrium is taken to be 1000 years.

Triassic System, Case A

Lacking definitive information on the regional hydraulic gradient in Triassic rock, it is assumed to be 3 ft_{H_2O}/mile. The critical path is the minimum expected distance down to crystalline rock underlying the Triassic cavern (2000 ft). Waste migration is controlled by the waste density effect. The equations predict a residence time for the waste of 2×10^7 years prior to entering the biosphere.

Triassic System, Case B

The final pressure in the Triassic cavern is assumed to be 250 ft_{H_2O} above the pressure in the Tuscaloosa aquifer and this pressure difference is assumed to be linearly distributed across the minimum expected distance to the Tuscaloosa Formation (500 ft). The critical path is then the distance from the cavern up to the Tuscaloosa aquifer. The equations predict a residence time for the waste of 10^6 years before entering the biosphere.

In addition to the preceding parameters, a number of assumptions are necessary to use the equations in Table IV-1. These assumptions are:

- The radiolytic gas drive is assumed to be negligible.
- The water flow rate (W) to the cavern after hydrostatic equilibrium is reached is required for use in the models and is estimated by assuming that W is equal to the rate at which water would flow through an area of solid rock equal to three times the projected area of the caverns ($\sim 10^6$ ft^2). The water flow rate is then given by:

$$W = A \sigma \left(\frac{\Delta h}{\Delta x}\right) \tag{1}$$

where

W = water flow rate, gal/yr

A = three times the projected area of caverns ($\sim 10^6$ ft^2)

σ = permeability, (gal/yr ft^2) $\div$ (ft$_{H_2O}$/ft)

$\left(\frac{\Delta h}{\Delta x}\right)$ = hydraulic gradient, ft$_{H_2O}$/ft

- The following additional assumptions will be made:

  1. Liquid waste volume = 10^8 gal.

  2. Solid waste sludge volume = 10^7 gal.

  3. Adsorption on crystalline rock is negligible.

  4. Adsorption on Triassic rock is included for certain isotopes, including cesium and plutonium.

The use of these equations is illustrated for the following waste constituents:

1. ^{135}Cs and ^{137}Cs as examples of isotopes with relatively long and short half-lives; respectively, 2 x 10^6 yr for ^{135}Cs, and 30 yr for ^{137}Cs, but with identical chemical properties.

2. ^{239}Pu as an example of an isotope with an intermediate half-life, 2.4 x 10^4 yr.

3. Nitrate-nitrite as an example of a stable toxic chemical species.

Waste Dispersion in Bedrock Systems

Cesium (^{135}Cs and ^{137}Cs)

Crystalline Rock: Case A

The cesium is first assumed to be completely soluble in the liquid phase (System I of the mathematical models). Under these conditions, the maximum concentration of ^{137}Cs and the total quantity entering the biosphere would be essentially negligible (10^{-100} of original). However, the maximum concentration of ^{135}Cs entering the biosphere is estimated by System I of the mathematical models to be approximately 100 MPC (the same as that initially in the liquid waste) and the total quantity of ^{135}Cs entering the biosphere is estimated to be approximately equal to the original amount of ^{135}Cs in the waste (2800 Ci). The estimates are based on the extremely long half-life of the ^{135}Cs as compared to the predicted residence time in the crystalline rock for Case A and the assumption that crystalline rock has a negligible K_d.

Assuming that the cesium is adsorbed on a stable solid waste phase (System II of the mathematical models) with a distribution coefficient (K) of 10^3, the maximum concentration of ^{135}Cs entering the biosphere is estimated to be approximately equal to MPC. The total quantity of ^{135}Cs entering the biosphere is estimated to be approximately 2000 Ci or about 75% of the original quantity of ^{135}Cs in the waste. This calculation illustrates that the reduction of the concentration of extremely long-lived (2×10^6 yr half-life) isotopes to concentrations less than MPC entering the biosphere does not necessarily reduce significantly the total integrated quantity entering the biosphere.

Triassic Rock: Case A

For ^{135}Cs and ^{137}Cs in the Triassic rock system, the minimum expected distribution coefficient (K_d of 2) between the liquid phase and the Triassic rock is conservatively used in these calculations. Assuming the cesium is dissolved in the liquid, the maximum concentration and total quantity of ^{137}Cs entering the biosphere are essentially negligible. The maximum concentration of ^{135}Cs entering the biosphere would also be negligible (less than 10^{-100} x MPC) as would the total integrated quantity (much less than 1 μCi).

Triassic Rock: Case B

Case B assumes the Triassic system residence time (θ) would be much shorter. This assumption results in the concentration of ^{135}Cs entering the biosphere remaining the same as that in the cavern (100 x MPC). The total quantity entering the biosphere would therefore be the same as the initial quantity in the waste.

The preceding comparison of the crystalline and Triassic rock systems for the retention of ^{135}Cs and ^{137}Cs isotopes illustrates the following points:

1. Based on the admittedly limited data presently available for the Triassic rock, the Triassic Formation nonetheless appears to be superior to the crystalline rock as a potential storage site. For expected conditions in Triassic rock (Case A), both ^{135}Cs and ^{137}Cs would decay to negligible quantities before entering the environment.

2. Assuming plug flow in either geological formation, the twin guidelines of concentrations of material entering the biosphere totaling less than 1% of MPC, and negligible total quantities released will be difficult to meet. This difficulty arises because of the presence of relatively long-lived radioisotopes (half-life greater than 2×10^6 years).

3. Successful storage of ^{135}Cs in a crystalline cavern would require alteration of the waste and adsorption of long-lived activity on a stable solid waste phase.

Plutonium (^{239}Pu)

Crystalline Rock: Case A

The plutonium will first be assumed to be soluble in the liquid phase of the waste. For Case A in the crystalline rock, the maximum concentration entering the biosphere is estimated to be about 2000 x MPC and the total quantity entering the biosphere is estimated to be about 3005 Ci (ca. 18% of the initial quantity of ^{239}Pu).

If the ^{239}Pu is assumed to exist in a stable solid phase (System II) with an effective distribution coefficient (K) of 10^5, the estimated concentration entering the biosphere is about 0.2 × MPC and the total quantity entering the biosphere is estimated to be 0.5 Ci.

If the waste is in the form of a solid that dissolves slowly (System III) with an effective k + s of 10^{-1} gal/yr for ^{239}Pu (equivalent to 10^{-8} of the total ^{239}Pu dissolved per year), the maximum concentration entering the biosphere is estimated to be 0.4 x MPC and the total quantity entering the biosphere is estimated to be approximately 1 Ci. Even glasses would be expected to leach at a rate greater than 0.1% per year in a bedrock cavern. No demonstrated process exists to convert Savannah River waste to a form with a rate as low as 10^{-8} per year. For System III, the water inleakage rate (W) as well as the leach rate must be known to estimate maximum concentrations entering the biosphere.

Triassic Rock: Case A

The minimum expected distribution coefficient for ^{239}Pu in Triassic rock is 53. Using this value, the estimated maximum concentration of ^{239}Pu entering the biosphere is less than 10^{-100} x MPC and the total quantity is much less than 1 μCi.

Triassic Rock: Case B

The maximum concentration of ^{239}Pu entering the biosphere would still be less than 10^{-100} x MPC and the total quantity much less than 1 μCi.

The preceding calculations show that:

1. It would be necessary to assure that essentially all of the ^{239}Pu would remain in a stable solid phase in a crystalline cavern in order to meet conservative guidelines for concentrations and total quantities of material entering the biosphere.

2. Conversion of the waste to a solid that dissolves very slowly but continuously would not cause a significant reduction in the concentration of ^{239}Pu entering the biosphere from a cavern in crystalline rock. This conclusion is based on measured initial leach rates for glasses and other demonstrated waste forms.

3. A cavern in the Triassic Formation would be expected to meet the most conservative design criteria for ^{239}Pu assuming all ^{239}Pu is soluble in the liquid phase of the waste.

Nitrate-Nitrite

The waste volume, as presently constituted, consists primarily of stable toxic chemicals dissolved in the supernate. The compounds do not decay; rather, all of the stable compounds added to the cavern will ultimately enter the biosphere.

In this section, an estimate is made of the amount of dilution that will occur as nitrate-nitrite migrates through the rock and is diluted by the water flowing into the cavern and the water in the rock along the critical path. This dilution is controlled by the total amount of water in the rock through which the waste flows and the dispersion characteristics of the rock. This realistic approach of assuming dilution can occur as the waste migrates from the cavern to the biosphere is in contrast to the plug flow models used in the preceding sections to calculate the concentration of radioisotopes present as the solution enters the biosphere. The plug flow models conservatively took no credit for dilution of the waste during movement from the cavern to the biosphere but depended solely upon decay to reduce the radioactivity. If a similar approach were used here, no reduction of the concentrations would occur and nitrate-nitrite would enter the biosphere at 8000 MPC.

Only the first guideline (less than 1% of MPC) is used in assessing the impact of stable releases on the populace. The second guideline was not considered to be applicable in the case of stable releases because the total quantities of stable compounds in the waste are small compared to the quantities of the material presently being accommodated by the environment. Furthermore, it was assumed that these chemicals have no adverse somatic or genetic long-term effects as long as they are diluted below MPC.

The same cases with their attendant properties as considered for the radionuclide portion of the waste are used to evaluate discharges of the stable compounds. Cases B and C for crystalline rock are neglected because the short flow paths made their radionuclide discharges unacceptable.

Crystalline Rock: Case A

For the cavern constructed in the crystalline rock formation, the total volume of water in the critical path is estimated assuming a total path length of 35,000 feet. A transmissive zone with a thickness of about 200 ft has already been identified in the crystalline rock. Even if the waste channels through such a zone for some fraction of its path length to the river, it would spread out as it entered the more extensive impermeable zones that would lie along the path. The cross sectional area of the critical path in crystalline rock is taken to be approximately 3×10^6 ft^2 (6000 ft x 500 ft). The total volume of the rock in the critical path would then be $(3 \times 10^6 \text{ ft}^2)(3.5 \times 10^4) = 10^{11} \text{ ft}^3$. Assuming 0.1% porosity (the maximum expected value), the amount of water contained in the rock along this path is estimated to be 10^8 ft^3. Taking into account the degree of dispersion expected for crystalline rock (Appendix IV-C), it is estimated that the maximum concentration of nitrate-nitrite entering the biosphere would be approximately 50% of the original concentration in the cavern and would be about 4000 x MPC. Assuming that most of the mercury and ^{239}Pu remain in a stable solid waste phase, the nitrate-nitrite would represent the greatest potential drinking water hazard and the most difficult constitutent to reduce below MPC. Based on the assumed area of the critical path of 3×10^6 ft^2 and the other parameters assumed for Case A (Table IV-1), the estimated volume rate of flow of the resulting waste-rock water mixture entering the environment is estimated to be about 0.024 gpm (Equation 1). The mixture would have to be diluted in the biosphere by a flow of approximately 9600 gpm to reduce the nitrate-nitrite concentration to 0.01 x MPC. Assuming that the waste enters the Savannah River and mixes completely with the minimum flow of the river (2×10^6 gpm) the concentration of the nitrate-nitrite in the river would be 5×10^{-5} x MPC. It should be noted that for these same assumptions for flow parameters, all activity initially present in the waste except ^{90}Sr (if assumed to be soluble) could be diluted below MPC.

Triassic Rock: Case A

If the main flow of waste from a Triassic rock cavern is due to the density of the waste, the volume of the rock through which the waste would be expected to flow would be approximately 10^{10} ft^3 (a triangular element with a base and height of 2000 ft and a length of 6000 ft, Chapter III). For the expected porosity of 3% (Table IV-2), this volume of rock would contain about 3×10^8 ft^3 of water. Taking into account the degree of dispersion expected in the Triassic rock (Appendix IV-C), the maximum concentration of nitrate-nitrite entering the crystalline rock below the cavern would be 3.2×10^{-3} of the original concentration in the caverns and would be about 20 x MPC. Based on the estimates of the effect of waste density on flow (Chapter III), the estimated flow rate of the resulting waste-rock water mixture entering crystalline rock is roughly 10^{-4} gpm. Taking into account the subsequent dilution from mixing with the crystalline rock water between the Triassic-crystalline interface and the Savannah River, the estimated concentration of nitrate-nitrite entering the biosphere is reduced to 10% MPC. The waste stream entering the biosphere would have to be mixed with only a 0.2 gpm flow to reduce the concentration to 1% MPC.

Triassic Rock: Case B

For Case B in the Triassic Formation, the area of the critical flow path directly up to the Tuscaloosa aquifer is taken to be the vertical projected area of the caverns 4×10^6 ft^2 (6000 ft x 700 ft). The total volume of rock included in this critical path would be (500 ft) (4×10^6 ft^2) = 20×10^8 ft^3 and the volume of water in this rock would be 6.0×10^7 ft^3. For this case, the volume of water in the rock is not large compared to the volume of waste in the cavern. Dispersion would also be less than Case A because of the shorter travel path and higher rate of travel. The concentration of nitrate-nitrite entering the biosphere (Tuscaloosa aquifer) for these conditions is estimated to be about 0.1 of the initial concentration (Appendix IV-C) or about 800 x MPC. The estimated flow rate of the waste-rock water stream entering the Tuscaloosa aquifer would be approximately 0.01 gpm. The waste stream entering the Tuscaloosa aquifer would have to be mixed with an 800 gpm flow to reduce the nitrate-nitrite concentration to 1% MPC. This flow is readily available in the Tuscaloosa aquifer if the 6000-ft dimension is oriented in a direction perpendicular to the flow of the incoming stream.

The preceding calculations show that:

1. The soluble, non-radioactive but toxic nitrate-nitrite waste component represents the constituent which will be the most difficult to reduce below MPC on entering the biosphere. Reducing the nitrate-nitrite concentration below MPC for either rock system can only be achieved by dilution.

2. Dilution of the nitrate-nitrite in the crystalline rock will not be sufficient to reduce the concentration below MPC before the material enters the biosphere.

3. Dilution of the nitrate-nitrite from a cavern in the Triassic formation along the expected downward flow path would be sufficient to reduce the concentration to less than 10% of MPC. Appreciable further reduction in the biosphere would be expected.

CONCLUSION

A summary of the results of calculations on the amount of ^{137}Cs, ^{135}Cs, ^{239}Pu, and nitrate-nitrite are given in Table IV-3 assuming that all of the constituents considered are soluble in the waste phase (System I). The release of an intermediate- (^{239}Pu) and a long-lived (^{135}Cs) radioisotope as well as stable elements does not meet the very stringent guidelines for any of the assumed cases in crystalline rock for System I. Case A of the Triassic system met the first guideline (concentrations entering the biosphere should be less than 1% of MPC) for all radioactive constituents considered but not for the nitrate-nitrite. Case B of the Triassic system did not meet the guidelines for ^{135}Cs but it does meet it for ^{239}Pu and is superior to Case A for crystalline rock.

TABLE IV-3. Estimates of Waste Concentrations Entering Biosphere, MPC, When All Constituents Are Assumed Soluble in Liquid Waste (System I)

	Crystalline Rock			Triassic Rock	
Constituent	A	B	C	A	B
^{137}Cs	<<0.01	>>1	>>1	<<0.01	<<0.01
^{135}Cs	10^2	10^2	10^2	<<0.01	10^2
^{239}Pu	2×10^3	10^4	10^4	<<0.01	<<0.01
NO_3^--NO_2^- [a]	4×10^3	>>1	7×10^3	0.1	800

a. Takes credit for dilution of waste by rock water.

APPENDIX IV-A: DERIVATION OF MATHEMATICAL MODELS

System I: All Activity in Liquid Waste Phase

Notation:

γ = Time to reach hydrostatic equilibrium after sealing cavern

λ = Decay constant of the radioisotope

C_L = Concentration of isotope in liquid waste in cavern

C_{Lo} = Concentration of isotope in liquid waste in cavern at $t = 0$

Q = Total quantity of activity entering biosphere

Q_o = Quantity of activity present when cavern is sealed

Q'_o = Quantity of activity present when cavern reaches hydrostatic equilibrium ($Q'_o = Q_o e^{-\lambda\gamma}$)

Q_t = Total quantity of activity leaving cavern, limited by $t = \infty$

t = Time elapsed after cavern reaches hydrostatic equilibrium

V_L = Liquid waste volume

W = Steady state water flow rate into caverns after hydrostatic equilibrium has been reached

Assumptions: Perfect mixing of waste in cavern (Figure IV.A.1).

Cavern Material Balance For An Isotope

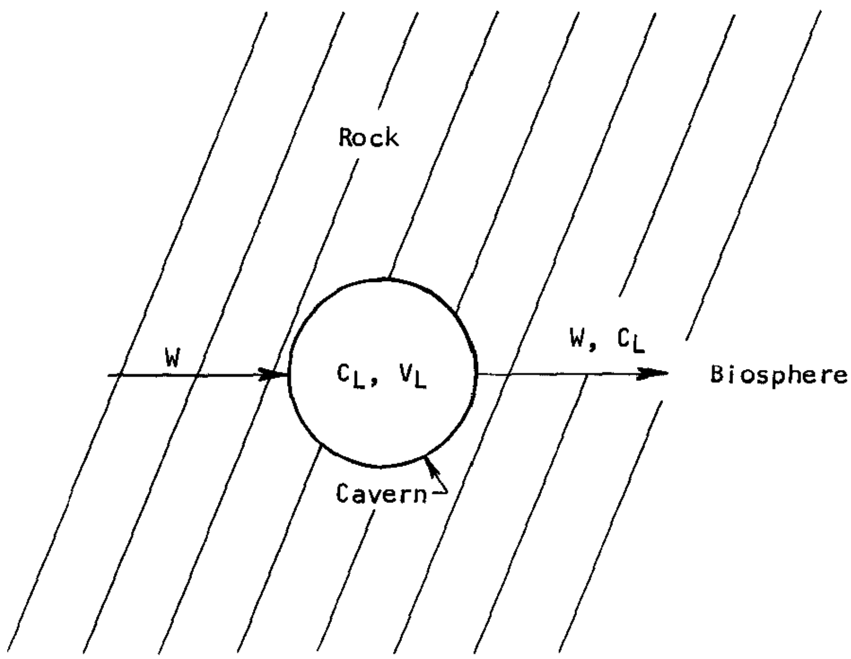

FIGURE IV.A.1 Schematic Drawing of System With Dispersed Sludge

Input = Output + Accumulation

$$0 = W\ C_L + \lambda\ V_L C_L + V_L \frac{dC_L}{dt}$$

$$-\ (W + \lambda V_L)\ C_L = V_L \frac{dC_L}{dt}$$

$$C_L = C_{Lo}\ \exp -[(W/V_L) + \lambda]\ t$$

$$= \left(Q_o{}'/V_L\right) \exp -[(W/V_L) + \lambda]\ t \qquad (1)$$

Total Integrated Quantity of Activity Leaving Cavern

$$Q_t = \int_o^\infty C_L\ W\ dt = W \frac{Q_o{}'}{V_L} \int_o^\infty \exp\left[\left(\frac{W}{V_L} + \lambda\right) t\right] dt$$

$$Q_t = \left(\frac{W/V_L}{W/V_L + \lambda}\right) Q_o{}' \qquad (2)$$

Effect of Time to Reach Hydrostatic Equilibrium

$$Q_o{}' = Q_o\ \exp -(\lambda\gamma)$$

Equation 1 then becomes:

$$C_L = \left(\frac{Q_o}{V_L}\right)\left[\exp -(\lambda\gamma)\right] \cdot \left[\exp -\left(\frac{W}{V_L} + \lambda\right)\right] t \qquad (3)$$

Equation 2 becomes:

$$Q_t = Q_o\ \exp -(\lambda\gamma) \left[\frac{W/V_L}{(W/V_L) + \lambda}\right] \qquad (4)$$

Concentration of Activity Leaving Bedrock and Entering Biosphere:

Notation:

β = Residence time of activity in bedrock

ε = Bedrock void fraction

θ = Minimum residence time of liquid waste in bedrock

ρ = Bulk density of bedrock

C = Concentration of activity entering biosphere

K_d = Equilibrium distribution coefficient for isotopes between waste and bedrock

$$K_d = \frac{\text{fraction of isotope in rock/mass of rock}}{\text{fraction of isotope in liquid/volume of liquid}}$$

Q = Quantity of activity entering biosphere

Assumptions:

- Movement of waste band is sufficiently slow that equilibrium is attained.
- Bedrock behaves as a large unidirectional ion exchange column.
- Neglect dilution by dispersion.

- K_d is independent of exposed rock surface (for a system in which adsorption is only on the exposed surface; a similar K_d can be defined which is proportional to the exposed area).

- The residence time of activity in the rock is related to K_d, ρ, ε, and θ by the following equation (Prout, 1958).

$$\beta = \left(\frac{K_d \rho}{\varepsilon} + 1\right) \theta$$

Equation 3 can be written as:

$$C_L = \left(\frac{Q_o}{V_L}\right)\left[\exp\ (-W/V_L)\,t\right]\left[\exp\ -\ \lambda(\gamma+t)\right]$$

The effect of a holdup in bedrock is such that the concentration of activity entering the biosphere is:

$$C = 0 \quad \text{at} \quad t < \beta$$

$$C = \left(\frac{Q_o}{V_L}\right)\left[\exp\ (-W/V_L)(t - \beta)\right]\left[\exp\ -\ \lambda(\gamma + t)\right]$$

or

$$C = \left(\frac{Q_o}{V_L}\right)\left[\exp\ (-W/V_L)(t - K_d\ \rho\ \theta/\varepsilon)\right]\left[\exp\ -\ \lambda(\gamma + t)\right] \tag{5}$$

when $t \geqslant \beta$

Total Integrated Quantity of Isotope Entering Biosphere

$$Q = \int_{\beta}^{\infty} C\ W\ dt = Q_o \frac{W}{V_L} \left[\exp - \lambda\gamma\right] \int_{\beta}^{\infty} \left[\exp\ (-Wt/V_L)\right] \left[\exp\ (W\beta/V_L)\right]$$

$$\cdot \left[\ \exp - \lambda t\ \right] dt$$

$$Q = Q_o \frac{W}{V_L} \left[\exp - \lambda\gamma\right] \left[\exp \frac{W}{V_L}\beta\right] \int_{\beta}^{\infty} \left[\exp - (W/V_L + \lambda)\,t\right] dt$$

$$Q = Q_o \left[\frac{W/V_L}{W/V_L + \lambda}\right] \left[\exp\left\{- \lambda(\gamma + \beta)\right\}\right]$$

$$Q = Q_o \left[\frac{W/V_L}{W/V_L + \lambda}\right] \left[\exp\left\{- \lambda(\gamma + K_d\ \rho\ \theta/\varepsilon + \theta)\right\}\right] \qquad (6)$$

System II: Activity Sorbed on Stable Solid Waste Phase

Notation:

ε = Void fraction in solid waste phase

ρ' = Bulk density of solid waste phase

C_s = Concentration of isotope in solid phase

C_{so} = Concentration of isotope in solid phase at t = 0

K_d' = Equilibrium distribution coefficient for isotope between liquid waste phase and solid waste phase

$\overline{C}_L$ = Average concentration of isotope in liquid waste in cavern

V_L = Liquid waste volume

V_S = Solid waste volume

Assumptions:

- Equilibrium solubility of bulk solid waste phase in liquid waste and rock water is negligible.
- Equilibrium between solid and liquid waste is maintained at all times (Figure IV.A.2).
- Perfect "mixing" in liquid and solid phases.

Cavern Material Balance

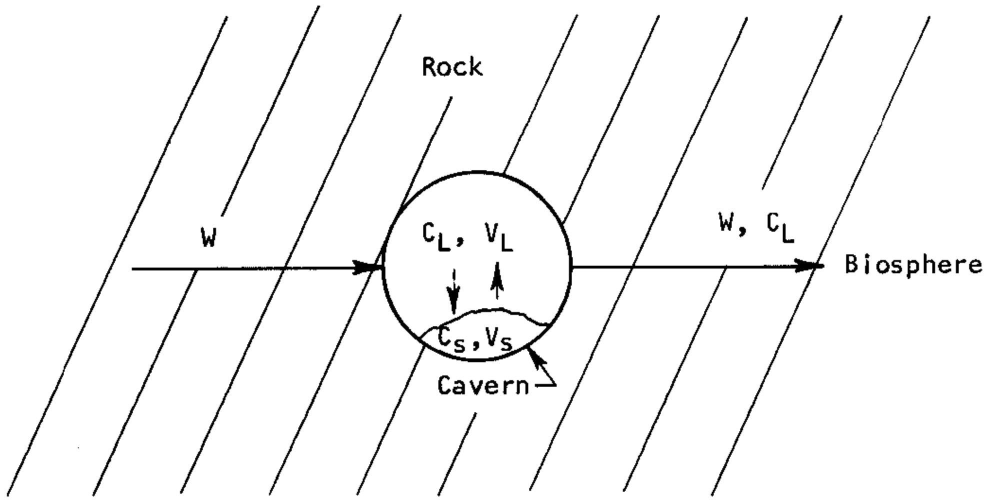

FIGURE IV.A.2 Schematic Drawing of System With Settled Sludge

Input = Output + Accumulation

$$0 = W\ C_L + \lambda\ C_L\ V_L + \lambda\ C_s\ V_s + V_s \frac{dC_s}{dt} + V_L \frac{dC_L}{dt}$$

$$C_s = C_L\ (K_d'\ \rho') = C_L\ K$$

$$0 = W\ C_L + \lambda\ V_L\ C_L + \lambda\ V_s\ K\ C_L + V_s\ K \frac{dC_L}{dt} + V_L \frac{dC_L}{dt}$$

$$\frac{dC_L}{C_L} = -\left[(W + \lambda V_L + \lambda K\ V_s)\Big/(V_s\ K + V_L)\right] dt$$

$$C_L = C_{Lo}\ \exp - \left[(W + \lambda V_L + \lambda K\ V_s)\Big/(K\ V_s + V_L)\right] t$$

$$C_L = C_{Lo}\ \exp - \left[W\Big/(K\ V_s + V_L) + \lambda\right] t \qquad (7)$$

Total Integrated Quantity of Activity Leaving Cavern

$$Q_t = \int_0^\infty (C_L\ W)\, dt = \int_0^\infty (W\ C_{Lo})\ \exp - \left[(W + \lambda V_L + \lambda K\ V_s)\Big/(K\ V_s + V_L)\right] t\ dt$$

$$Q_t = W\ C_{Lo} \left[(K\ V_s + V_L)\Big/(W + \lambda V_L + \lambda K\ V_s)\right] \qquad (8)$$

When K = 0, Equations 7 and 8 reduce to Equations 1 and 2 for an all liquid system.

When time to reach hydrostatic equilibrium is taken into account, Equations 7 and 8 become:

$$C_L = C_{Lo}\ \exp - \left[Wt\Big/(K\ V_s + V_L)\right]\left[(\exp - \lambda t)(\exp - \lambda \gamma)\right] \qquad (9)$$

$$Q_t = W\ C_{Lo}\ \left[(K\ V_s) + V_L\right] \Big/ \left[W + \lambda V_L + K\ V_s \lambda\right]\ \exp -\lambda\gamma \qquad (10)$$

Concentration of Activity Entering Biosphere

Effect of bedrock holdup is such that the concentration of activity entering the biosphere becomes:

$$C = 0;\ t < \beta$$

$$C = C_{Lo}\ \exp -\left\{\left[W\big/(K\ V_s + V_L)\right]\left[(t - \beta)\right]\right\} \exp -\lambda(t + \gamma)$$

or

$$C = C_{Lo}\ \exp -\left\{\left[W\big/(K\ V_s + V_L)\right]\left[t - \left(\frac{K_d\ \rho\ \theta}{\varepsilon}\right) - \theta\right]\right\} \exp -\lambda(t + \gamma)$$

when $t \geqslant \beta$ (11)

Total Quantity Entering Biosphere:

$$Q = \int_\beta^\infty C\ W\ dt = W\ C_{Lo}\ \exp -\lambda\gamma \int_\beta^\infty \exp -\left\{W\Big/\left[(K\ V_s) + V_L\right]\right\} t$$

$$\cdot \left\{\exp\ W\Big/\left[(K\ V_s) + V_L\right]\ \beta\ \exp -\lambda t\right\} dt$$

$$Q = \left[W\ C_{Lo}\ \exp -\lambda\gamma\ \exp\left\{W\Big/\left[(K\ V_s) + V_L\right]\right\}\beta\ \cdot\right.$$

$$\int_\beta^\infty \exp -\left[\left[W\big/\left(K\ V_s + V_L\right) + \lambda\right] t\right] dt$$

$$Q = W\ C_{Lo}\ \exp -\lambda\gamma\ \frac{1}{\left[W/(K\ V_s + V_L)\right] + \lambda} \cdot \exp -\lambda\beta$$

$$Q = W\ C_{Lo} \left[(K\ V_s) + V_L\right] \Big/ \left[W + (\lambda K\ V_s) + \lambda V_L\right] \bullet \exp -\lambda\left(\gamma + \frac{K_d\ \rho\ \theta}{\varepsilon} + \theta\right) \tag{12}$$

$$Q_o = C_{Lo}\ V_L + C_{so}\ V_s$$

$$Q_o = C_{Lo}\ V_L + K\ (C_{Lo}\ V_s)$$

or

$$C_{Lo} = \frac{Q_o}{V_L + K\ V_s}$$

Therefore Equations 11 and 12 become:

$$C = \left[\frac{Q_o}{V_L + (K\ V_s)}\right] \exp\left[-\left(\frac{W}{(K\ V_s) + V_L}\right) \bullet \left(t - \frac{K_d\ \rho\ \theta}{\varepsilon} - \theta\right)\right] \exp\left[-\lambda(t + \gamma)\right]$$

$$\text{when } t \geqslant \frac{K_d\ \rho\ \theta}{\varepsilon} + \theta \tag{13}$$

and

$$Q = \left[\frac{W\ Q_o}{V_L + (K\ V_s)}\right] \left[\frac{(K\ V_s) + V_L}{W + (K\lambda V_s) + \lambda V_L}\right] \exp - \left[\lambda\left(\frac{(\gamma + K_d\ \rho\ \theta)}{\varepsilon} + \theta\right)\right]$$

(14)

$$Q = Q_o \left[\frac{W/V_L}{(W/V_L) + \lambda\ K\ (V_s/V_L) + \lambda}\right] \exp\left[-\lambda\left(\frac{\gamma + K_d\ \rho\ \theta}{\varepsilon} + \theta\right)\right]$$

Equation 14 gives the criteria for effective reduction of the quantity of activity reaching the biosphere by adsorption on a solid waste phase. These criteria are:

$\lambda\ K\ V_s$ is of the same magnitude as $W + \lambda\ V_L$; or K is significant compared to

$$\frac{W + (\lambda\ V_L)}{V_s} = \frac{W}{\lambda\ V_s} + \frac{V_L}{V_s}$$

System III: All Activity Initially in Solid Waste Phase that Dissolves Slowly

Notation:

k = Mass transfer coefficient for transport of isotope from solid diffusion and convection, defined by:
Flux from solid = $k'A\ (C_s - C_L) = k\ (C_s - C_L)$

A = Surface area of solid

s = Solid dissolution rate, defined by:
Rate of dissolution = $s'A = s$

Assumptions:

- Neglect concentration of isotope in liquid phase in determining flux; flux = $k\ C_s$.
- k and s are constant.
- Solid is completely soluble in waste or rock water.
- Loss of activity in solid by radioactive decay is large compared to loss by diffusion and dissolution, i.e.,

$$\lambda\ V_s C_{so} e^{-\lambda t} >> (k+s) C_{so} e^{-\lambda t}$$

or:

$\lambda V_s >> (k+s)$.

- Neglect time required to reach hydrostatic equilibrium.

Material Balance on Liquid Phase in Cavern

Input = Output + Accumulation

$$(k+s)\ C_s = W\ C_L + \lambda\ C_L V_L + V_L \frac{dC_L}{dt}$$

$$(k+s)\ C_{so}\ e^{-\lambda t} = W\ C_L + \lambda\ C_L V_L + V_L \frac{dC_L}{dt}$$

$$\frac{dC_L}{dt} + \left(\frac{W + \lambda V_L}{V_L}\right) C_L = \frac{(k+s)\ C_{so}\ e^{-\lambda t}}{V_L}$$

$$\text{Integrating factor} = \exp \int \left(\frac{W}{V_L} + \lambda\right) dt \ \text{-exp} \left(\frac{W}{V_L} + \lambda\right) t$$

$$C_L = \left[\exp -\left(\frac{W}{V_L} + \lambda\right) t\right] \int_o \left[\frac{(k+s)C_{so}}{V_L} \exp -\lambda t \cdot \exp\left(\frac{W}{V_L} + \lambda\right) t\right] dt$$

$$+ \bar{C}_1 \exp -\left(\frac{W}{V_L} + \lambda\right) t$$

$$C_L = \left[\exp -\left(\frac{W}{V_L} + \lambda\right) t\right] \int_o \frac{(k+s)C_{so}}{V_L} \left[\exp \left(\frac{W}{V_L}\right) t\right] dt + \bar{C}_1 \exp -\left(\frac{W}{V_L} + \lambda\right) t$$

$$C_L = \left[\exp -\left(\frac{W}{V_L} + \lambda\right) t\right] \left(\frac{(k+s)C_{so}}{(W/V_L)(V_L)} \cdot \exp(W/V_L)t\right) + \bar{C}_1 \exp -\left(\frac{W}{V_L} + \lambda\right) t + \bar{C}_2$$

$$C_L = \left[\exp -\lambda t\right] \left(\frac{(k+s)(C_{so})}{W}\right) + \bar{C}_1 \exp -\left(\frac{W}{V_L} + \lambda\right) t + \bar{C}_2$$

Boundary Condition No. 1: $C_L = 0$ when $t = 0$

$$C_L = 0 = \left[\frac{(k+s)\,C_{so}}{W} \right] + \bar{C}_1 + \bar{C}_2$$

Boundary Condition No. 2: $C_L = 0$ when $t = \infty$

$$C_L = 0 = \bar{C}_2 \; ; \; \bar{C}_2 = 0$$

and

$$\bar{C}_1 = - \left[\frac{(k+s)\,(C_{so})}{W} \right]$$

$$C_L = \frac{Q_o \; (k+s) \; e^{-\lambda t}}{V_s \; (W)} \cdot \left[1 - \exp - \left(\frac{W}{V_L} \right) t \right] \tag{15}$$

Concentration of Activity Entering Biosphere

Equation 15 becomes:

$$C = \frac{Q_o \; (k+s)}{V_s \; W} \exp - (\lambda t) \left[1 - \exp - \left(\frac{W}{V_L} \right) \left(t - \frac{K_d \; \rho \; \theta}{\varepsilon} - \theta \right) \right]$$

$$\text{when } t \geqslant \left[\frac{K_d \; \rho \; \theta}{\varepsilon} \right] + \theta$$

and

$$C = 0 \text{ when } t < \left[\frac{K_d \; \rho \; \theta}{\varepsilon} \right] + \theta \tag{16}$$

Total Integrated Quantity Entering Biosphere

$$Q = \frac{W\ Q_o (k+s)}{V_s\ W} \left[\int_{\beta}^{\infty} e^{-\lambda t}\, dt - \int_{\beta}^{\infty} e^{-\lambda t}\, e^{-\left(\frac{W}{V_L}\right) t} \cdot e^{\beta\left(\frac{W}{V_L}\right)}\, dt \right]$$

$$Q = \frac{Q_o (k+s)}{V_s} \left\{ \frac{1}{\lambda} e^{-\lambda\beta} - e^{\beta\left(\frac{W}{V_L}\right)} \left[\frac{1}{\lambda + W/V_L} \right] e^{-\lambda\beta} \cdot e^{-\frac{W}{V_L}\beta} \right\}$$

$$Q = \frac{Q_o (k+s)}{V_s} \left[\frac{1}{\lambda} - \left(\frac{1}{\lambda + W/V_L} \right) \right] e^{-\lambda\beta}$$

$$Q = \frac{Q_o (k+s)}{V_s} \left[\frac{1/\lambda^2 + W/\lambda V_L - 1}{1/\lambda + W/V_L} \right] e^{-\lambda\beta}$$

assume $1/\lambda^2 \gg 1 \quad |\lambda| \ll 1$

$$Q = \frac{Q_o\ (k+s)\, e^{-\lambda\beta}}{V_s\ \lambda} = \frac{Q_o\ (k+s)}{V_s\ \lambda} \exp -\left(\frac{K_d\ \rho}{\varepsilon} + 1 \right) \theta \qquad (17)$$

$$\lambda\ V_s \gg k+s \text{ and } \frac{1}{\lambda^2} \gg 1$$

The above information is summarized in Table IV-1.

APPENDIX IV-B: DISPERSION EFFECTS IN BEDROCK

Introduction

When solution from the cavern enters either the crystalline or Triassic rock formations, flow through the rock does not result in a sharp interface between the cavern water and the rock water. Rather, dispersion creates a diffuse region where the two solutions are intermingled. The net result is some activity from the cavern reaches a given distance sooner than it would under plug flow conditions. The concentration conservatism of plug flow models for predicting radionuclide concentrations in rock is examined here for the flow velocities, rock types, and distances traveled in the bedrock.

When radioactive decay, coupled with reduction in velocity due to adsorption and exchange is accounted for, neither ^{239}Pu nor ^{135}Cs enter the biosphere from a Triassic cavern. Only a small reduction in the concentration in ^{239}Pu and no reduction in ^{135}Cs concentration occur during movement of waste from a crystalline cavern to the Savannah River because no exchange is assumed to occur between the waste and crystalline rock.

Discussion

The concentration change with time at some point downstream from a constant source, as predicted both by the plug flow model and by a dispersion model for a non-exchanging contaminant, is schematically shown in Figure IV.B.1. The more skewed (the greater the dispersion) the arrival curve of the actual contaminant becomes, the greater is the time between the predicted arrival using plug flow models and the actual arrival times. The maximum concentration in the solution and its relation to MPC is of concern in determining if the guidelines are reached. Examination of Figure IV.B.1 indicates that the maximum concentration is the same for the plug flow model and the dispersed flow model for a constant concentration source with no radioactive decay.

The comparison of plug flow with predicted behavior for various degrees of dispersion has been quantified as shown in Figure IV.B.2 (Levenspiel).[1] To use this figure, reliable measurements or estimates of the dispersion coefficient (D, cm^2/sec), the flow velocity (u, cm/sec) and the length of the flow path (L, cm) are required. By curve fitting the experimental data of the *in-situ* tritium tracer test in crystalline rock, Webster, et al. (1970)[2] found the value of D/uL to be 0.25. Using Figure IV.B.2 (Reference 3) and the conditions from the tritium tracer test (u = 1.415×10^{-3} cm/sec, L = 5.38×10^{4} cm), an approximate value for the particle radius (A_p) can be obtained if the value for the diffusion coefficient (K) is assumed to be 2×10^{-5} cm^2/sec. The resulting radius is 282 cm. With this radius and estimating expected gradients and rock water velocities (Table IV.B.1), the appropriate dispersion coefficient can be obtained from the ordinate value that corresponds to the intersection of the curve and a line from the abscissa at the value corresponding to the velocity of interest. Similar calculations for the Triassic rock system, assuming a particle radius of 0.1 cm (personal judgment), can be made. The values for the dispersion coefficients as well as D/uL are summarized in Table IV.B.2 for both crystalline and Triassic rock.

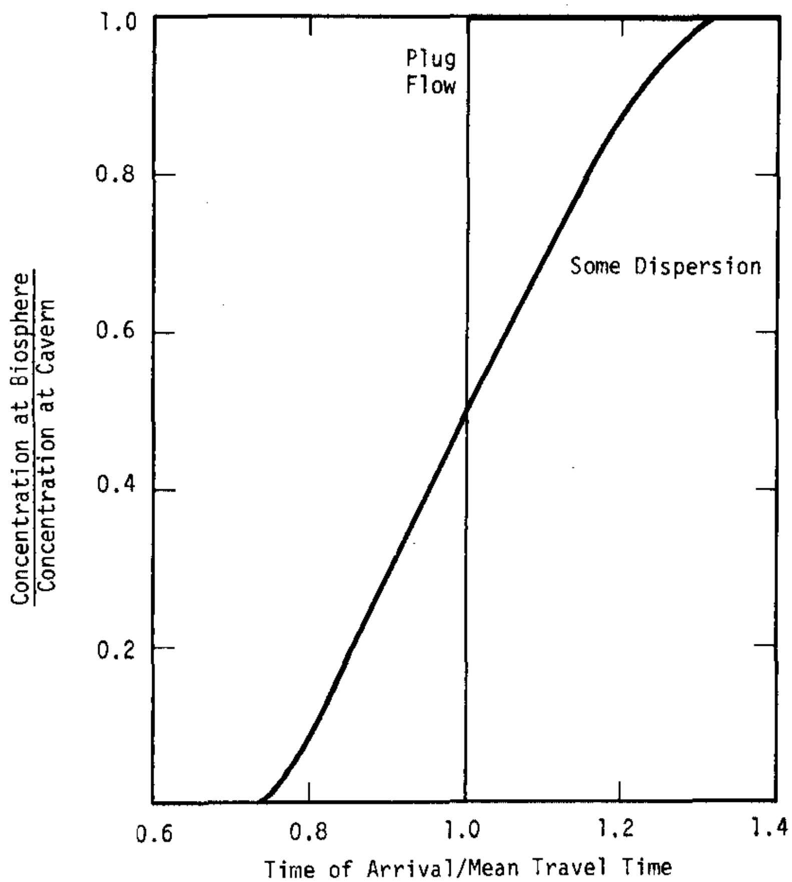

FIGURE IV-B.1. Concentration Differences of Plug Flow and Dispersion Flow

TABLE IV.B.1. Summary of Cavern Rock Parameters and Hydrologic Flow Conditions

	Cavern Rock Parameters	
	Crystalline Rock	Triassic Rock
Permeability, ft/yr	1	3×10^{-4}
Porosity	0.001	0.03
Particle diameter, cm	564	0.2
K_d, Pu	0	50
K_d, Cs	0	2

	Hydrologic Flow Conditions			
	Crystalline Rock Cavern to		Triassic Rock Cavern to	
	Savannah River	Tuscaloosa	Crystalline	Tuscaloosa
Gradient, ft_{H_2O}/ft	5.7×10^{-4}	1.4×10^{-2}	See gravity drive section	0.5
Flow path, ft	35,000	500	2,000	500
Velocity, ft/yr	5.7×10^{-1}	14	1×10^{-4}	5×10^{-3}
Flow time, yrs	6.1×10^{4}	35.7	2×10^{7}	1×10^{5}
$A_p \cdot u/K_\tau$	7.8	190	4.8×10^{-7}	2.4×10^{-5}

where:

A_p = particle radius, cm
u = velocity, cm/sec
K_τ = diffusion coefficient, 2×10^{-5} cm^2/sec

TABLE IV.B.2. Summary of the Dispersion Coefficients and the Value of D/uL for Crystalline and Triassic Rock

	Flow from Crystalline Rock to		Flow from Triassic Rock to	
	Savannah River	Tuscaloosa Aquifer	Crystalline Rock	Tuscaloosa Aquifer
Dispersion coefficient, cm^2/sec	0.002	0.1	1.34×10^{-5}	1.34×10^{-5}
D/uL	3.4×10^{-3}	0.485	2.2	0.18

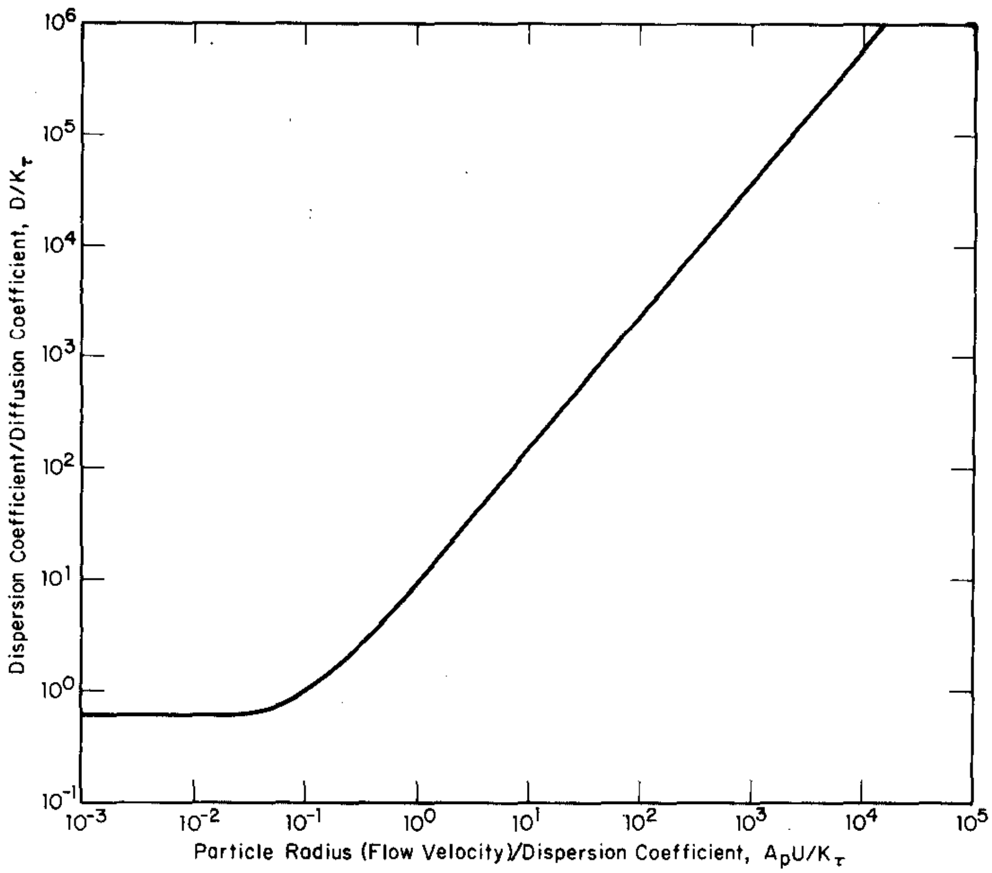

FIGURE IV-B.2. Curves in Closed Vessels for Various Extents of Back-mixing as Predicted by the Dispersion Model

Figure IV.B.3 illustrates the expected curves obtained for a continuous source using a dispersion model and assuming a non-adsorbing solution.[1] For crystalline rock, the curve labeled "small amount of dispersion" (D/uL = 0.002) approximates the expected situation for flow from the cavern to the Savannah River. For Triassic rock, the curve labeled "large amount of dispersion" (D/uL = 0.2) approximates flow from the cavern to the Tuscaloosa aquifer. Large amounts of dispersion promote mixing of the radioactive waste with the rock water and result in decreased concentrations and early arrival times.

The assumption of a uniform concentration at the source is conservative for bedrock studies because the cavern has a finite volume, hence a decreasing concentration with time, and the predicted concentrations indicated in Figure IV.B.2 are the maximum potential hazards calculable.

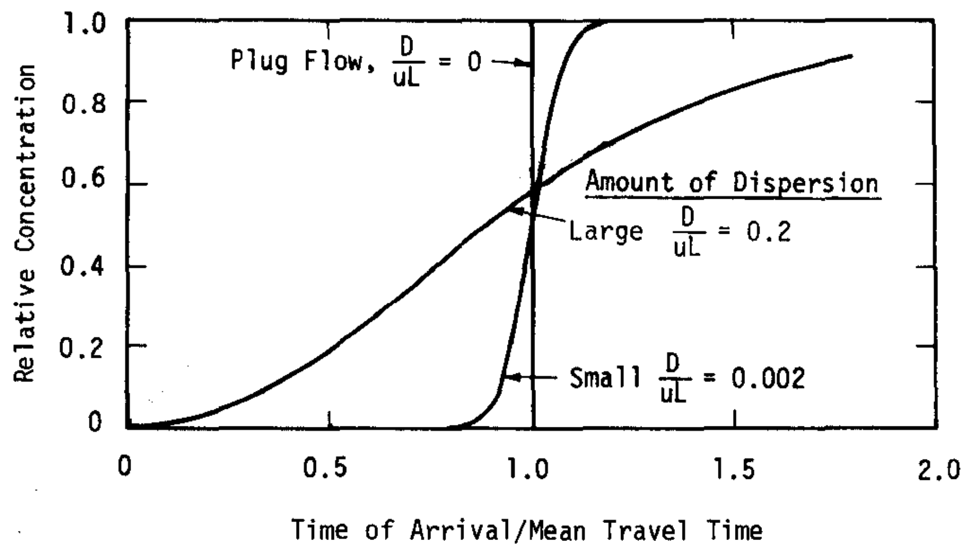

FIGURE IV-B.3. Effect of Dispersion on Aqueous Waste Transport

In any system with radioactive material, the amount of material calculated to reach the biosphere must be reduced by the fraction decayed during the time for passage through the rock to the biosphere. Under the expected conditions in Triassic rock, exchange phenomena will be operating to retard the velocity of flow while in crystalline rock, this effect will be negligible. The importance of exchange in conjunction with D/uL is illustrated by comparison of Figure IV.B.4 with Figure IV.B.5. Figure IV.B.4 shows predicted arrival curves in the vicinity of the river (35,000 ft away) of nitrate, plutonium-239, and cesium-135 after travel through crystalline rock from a continuous source in the vicinity of the Separations Areas. Figure IV.B.5 illustrates predicted arrival curves at the Tuscaloosa aquifer of the same materials after travel through Triassic rock from a continuous source 500 feet directly below the aquifer. Retardation of flow from exchange in Triassic rock is sufficient to decay the ^{239}Pu and ^{135}Cs below meaningful levels in the shortest path from a cavern in the Triassic system to the biosphere. The longest flow path possible in crystalline rock, because no credit can be taken for exchange, produces no reduction of ^{135}Cs concentration from decay; approximately a factor of 10 can be assumed for plutonium. The approximation of the plug flow model to the predicted maximum concentration is very good. The predicted concentrations from waste disposal in a crystalline cavern show that modification of the waste is necessary to increase retention time in the cavern if a crystalline rock cavern is contemplated.

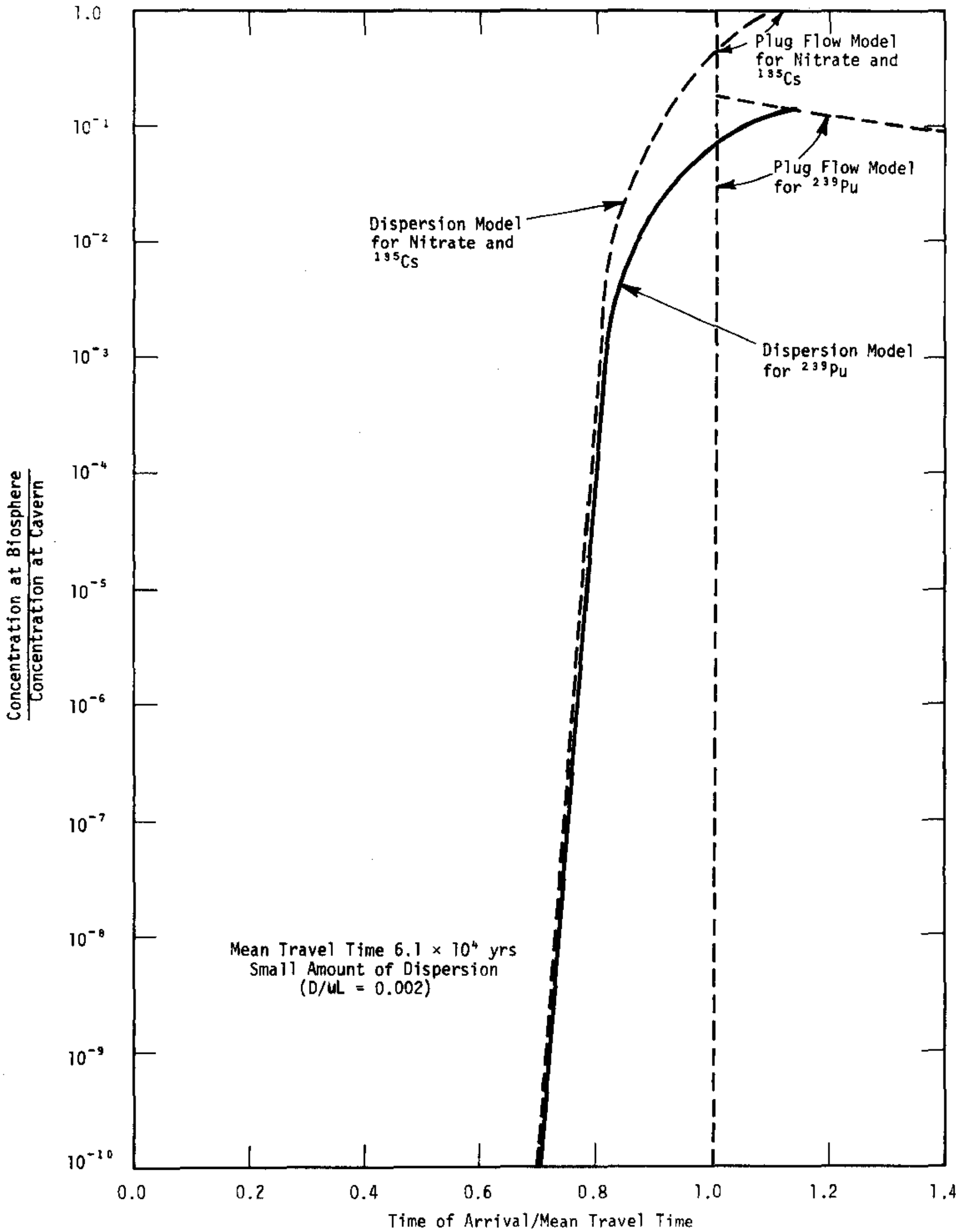

FIGURE IV.B.4. Predicted Arrival of Radionuclides at the Savannah River (after waste has moved through crystalline rock from a cavern in the vicinity of the Separations Areas)

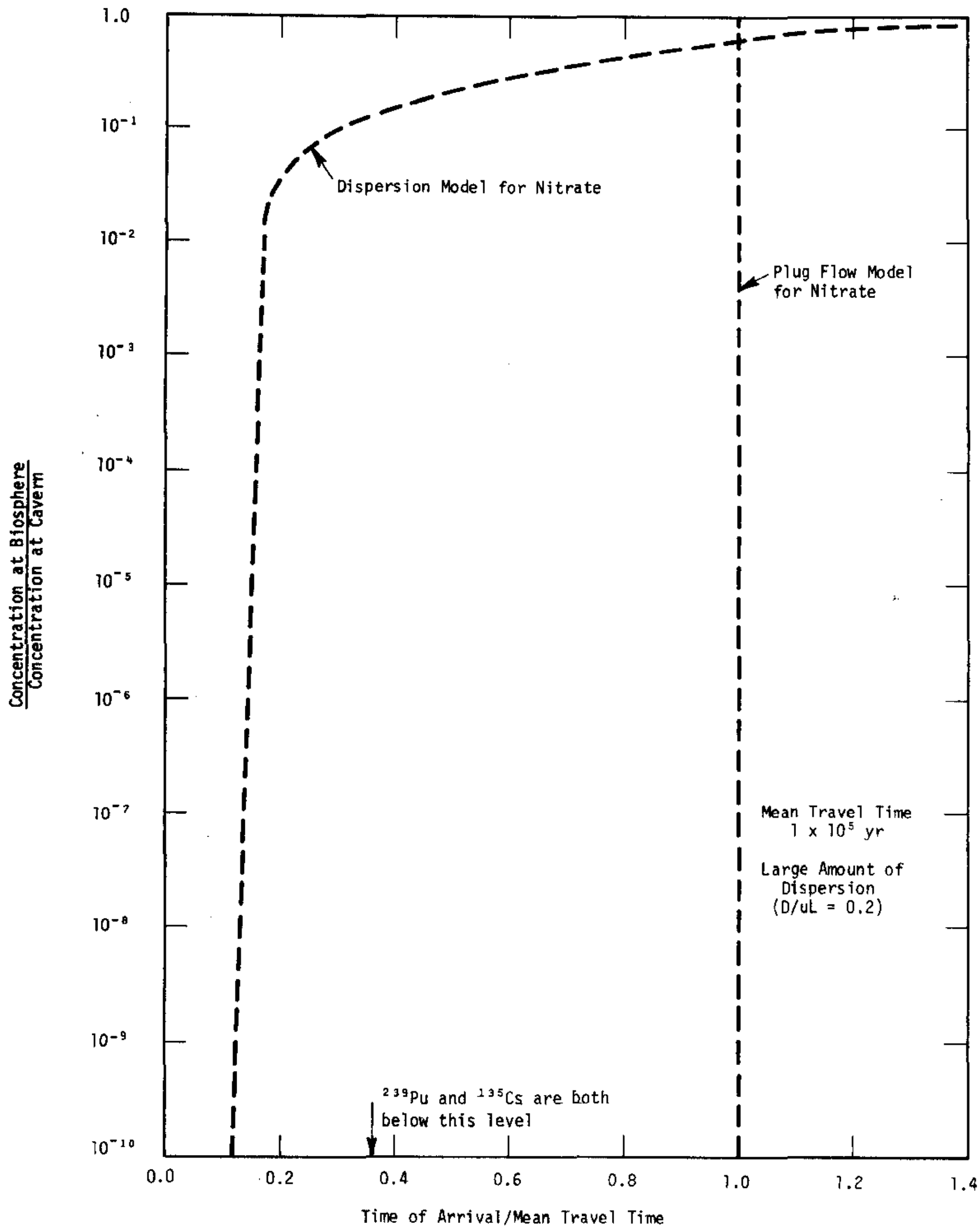

FIGURE IV.B.5. Predicted Arrival of Radionuclides at the Tuscaloosa Aquifer (after waste has moved through Triassic rock from a source 500 ft below the aquifer)

APPENDIX IV-C: MATHEMATICAL MODEL TO CALCULATE MAXIMUM WASTE CONCENTRATIONS ENTERING THE BIOSPHERE

The maximum concentration of any waste component leaving a bedrock cavern can be obtained by assuming a normal distribution curve describes the arrival of the waste solution at the biosphere. Inherent in this assumption is the fact that all of the waste leaves the cavern in the same instance. The normal distribution curve is shown schematically in Figure IV.C.1. The maximum value (C_{max}) on the normal distribution curve (Snedecor, p. 202)[1] is

$$C_{max} = \frac{A}{\sigma \sqrt{2\pi}} \qquad (1)$$

where

A = area under initial concentration versus distance curve in path lengths

$\sigma = \sqrt{2\,(D/uL) + 3(D/uL)^2}$ = standard deviation in path lengths (Levenspiel, p. 265)[2]

The area, A, is obtained by multiplying the ratio of the volume of solution in the caverns to the volume of water present in the flow path by the concentration of material in the cavern.

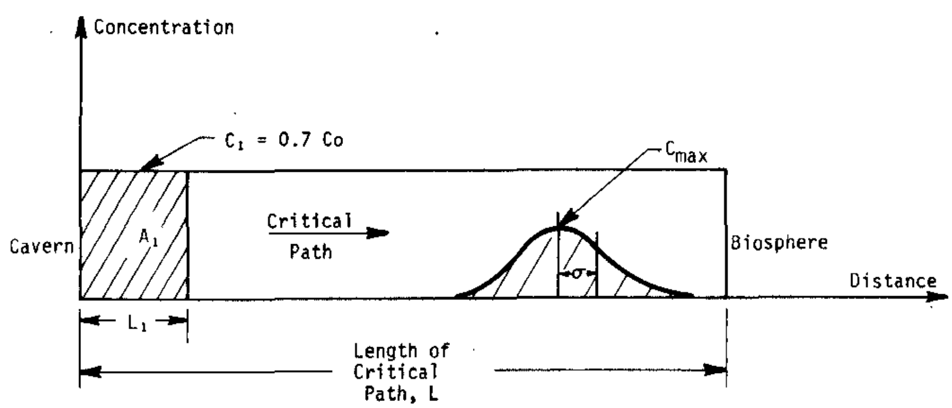

FIGURE IV-C.1. Flow of Stored Wastes from Cavern

Table IV.C.1 summarizes the pertinent values necessary for calculating C_{max} using Equation 1 for the cases discussed in the text.

TABLE IV.C.1. Pertinent Values Necessary to Calculate C_{max} as Nitrate-Nitrite Enters the Biosphere

	Cavern Waste Values		
Rock Formation →	Crystalline, Case A	Triassic, Case A (Triassic to crystalline rock only)	Triassic, Case B (Triassic to crystalline rock only)
Volume of waste in caverns, gallons	1.3×10^7	1.7×10^7	1.7×10^7
Volume of water in rock, gallons	10^8	3×10^8	6×10^7
Concentration of waste in cavern	$0.8\ C_o$	$0.6\ C_o$	$0.6\ C_o$
D/uL	3.4×10^{-3}	2.2	0.18
σ	8.2×10^{-2} L	4.3 L	0.676 L
C_{max}	$0.49\ C_o$	$3.2 \times 10^{-3}\ C_o$	$0.10\ C_o$

Triassic: Case A

There is additional dilution to that shown in Table IV.C.1 because of mixing in the crystalline rock from the Triassic-crystalline interface to the Savannah River. This dilution is approximated as follows:

- The estimated flow rate of waste entering the crystalline rock is 10^{-4} gpm.
- The same flow path and dilution is assumed as found for crystalline; Case A (p. IV-22).
- The flow rate through the crystalline rock is 0.024 gpm.

Hence, the additional dilution from mixing with water in the crystalline rock is 2.4×10^2 $(0.024/10^{-4})$. Therefore, the maximum concentration of any constituent entering the biosphere is $1.3 \times 10^{-5}\ C_o$ $(3.2 \times 10^{-3}\ C_o/2.4 \times 10^2)$ or 0.1 MPC $(1.3 \times 10^{-5}\ C_o \times 8000\ MPC/C_o)$ for nitrate-nitrite.

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APPENDIX IV-B. Dispersion Effects in Bedrock

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APPENDIX IV-C. Mathematical Model to Calculate Maximum Waste Concentrations Entering the Biosphere

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2. O. Levenspiel, *op. cit.*

CHAPTER V. PRELIMINARY SAFETY ANALYSIS

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CHAPTER V. PRELIMINARY SAFETY ANALYSIS

INTRODUCTION

A preliminary analysis of the risks associated with bedrock storage is presented in this chapter. The analysis is divided into two periods:

1. The cavern-filling period.

2. The period after the cavern is sealed.

The cavern-filling period includes removing waste from the tanks and charging it to a bedrock cavern. Risks involved in the construction of the bedrock cavern are not included. The risk of waste migration into the biosphere after the cavern is sealed is considered separately.

The mathematical models described in Chapter IV were applied to estimate the quantities of activity released for various assumed conditions. Consequences were generally expressed in terms of the potential dose to man for the drinking water pathway, assuming as in previous sections that 1.6×10^{-4} of the released activity is ingested; however, additional consideration was given to the potential for recovery of released activity for accidents postulated to occur during cavern filling, at which time monitoring would be expected and the occurrence of the accident would be known.

For both periods, three general modes of operation are considered:

1. Normal Operation. Operation that meets the design guidelines.

2. Abnormal Operation. Operation of the system outside of the normal range of operating conditions but within a range of operating conditions that were anticipated as being possible. The systems were assumed to be designed so that they will still meet design guidelines for abnormal operating conditions.

3. Accidents. Relatively low probability events that are not expected to occur but which cannot presently be ruled out. These accidents must create significant consequences to represent a risk comparable to that

associated with normal and abnormal operating conditions.

A complete quantitative risk analysis was not attempted. However, estimates were made of the consequences of operation under various conditions, and judgments were made as to the possible range of probabilities of these accidents. This analysis assumed that the risk is measured by the product of the consequences times the probability of the occurrence of these consequences. Based on these assumptions, a comparative assessment of bedrock storage risks was made for expected normal and abnormal operating conditions as well as for several postulated accidents.

For these safety analyses, the waste form placed in the crystalline rock differs from the waste placed in the Triassic system. To meet earlier guidelines, the waste buried in a crystalline cavern would have to be free of all stable constituents such as nitrate-nitrite ions, there would be essentially no radiolytic gassing, and most of the activity would be in a stable solid phase. These modifications were discussed in detail in Chapter III. The technology required to obtain these conditions has not yet been demonstrated and would be expected to add significantly to the cost of bedrock storage. In a Triassic rock cavern, the waste is assumed to be unaltered between removal from the tanks and final storage.

SUMMARY

Analysis of the consequences of bedrock storage and preliminary assessment of the associated range of probabilities of these consequences indicate that:

- The greatest risk appears to be during cavern filling.
- For normal and abnormal operating conditions, the greatest risk will be to the personnel removing waste from the tanks and decontaminating the tanks. A dose estimated to be at least 1000 man-rem will result from this activity. This risk would occur for any long term waste management alternative that involved removing the waste from the tanks and decontaminating the tanks.
- The potential accident during cavern filling that offers the greatest risk is an earthquake or other catastrophe that results in the destruction of some portion of the shaft in the Tuscaloosa aquifer and the engineered safeguards separating the base of the shaft from the caverns containing the waste. The consequences would depend strongly upon the form of the waste being charged, the engineering designs utilized to mitigate the effect, and the ability either to seal the shaft in the rock rapidly or to recover essentially all of

the waste from the cavern before the waste leaked into the aquifer. The loss of even a small fraction of the waste might result in the loss of the use of the Tuscaloosa aquifer at the present plant site for centuries.

- After the cavern is sealed, the risk of bedrock storage is reduced considerably. The potential accident presenting the greatest risk after cavern sealing is the withdrawal of essentially all of the water from the Tuscaloosa aquifer. The potential consequences are much higher for a crystalline cavern (5,500,000 man-rem) than a Triassic cavern (760 man-rem). Based on the magnitude of the estimated consequences of significant withdrawal of water from the Tuscaloosa aquifer for a crystalline cavern, and the relatively high probability that, although not all of the water would be withdrawn, a large withdrawal might occur within a few centuries after cavern sealing, it appears that the risk of a crystalline cavern as presently envisioned is unacceptable unless drawdown of the Tuscaloosa aquifer on the present plant site can be prohibited for several centuries, an unlikely occurrence.

- Further refinement of the risk estimates will depend upon more accurate estimates of the probability of postulated accidents that have significant potential consequences.

CAVERN-FILLING PERIOD

Removal of the waste from the tanks for bedrock storage will involve:

1. Dissolution of all salts in water and removal from tanks.

2. Slurrying over 90% of all insoluble sludge in water using high pressure jets and removal from tanks.

3. Blending sludge and salt and transfer to bedrock cavern (possibly 5 to 8 miles away).

4. Chemical removal of most of the remaining activity from the tanks and transfer to cavern.

5. Final treatment of tanks to ensure that any small quantity of remaining activity is immobilized or removed.

NORMAL AND ABNORMAL OPERATIONS

Safe handling of the waste during the removal and transfer operation will require close attention to ensure adequate shielding protection for workers and adequate protection against leaks, spills, etc. Design of such a system will draw heavily from previous experience at SRP in the handling and transport of waste from one area to another. A detailed analysis of the risks of this phase of the operation is beyond the scope of this analysis. It is assumed that proper design of the system will reduce the risk of uptake or exposure during normal and abnormal conditions to an acceptable level and that only major accidents would have a potential for appreciable consequences for persons either onsite or offsite.

This analysis assumes that the routine exposure of plant personnel as a direct consequence of removing the waste from the tanks and charging a bedrock cavern is the same as for normal waste tank operation at present. Based on operating experience in the Savannah River tank farm it is estimated that the total exposure to operating personnel for normal operating conditions will be about 200 man-rem during the period required for removal of waste and transfer to a cavern (3 to 4 years). The additional exposure from unanticipated problems, equipment removal, leaks, etc. is estimated to be about another 200 man-rem. The exposure from final tank decontamination operations will depend strongly upon the degree of decontamination that is required. Even a modest program of final decontamination might add an additional 600 man-rem for a total of about 1,000 man-rem for all phases of the operation. This 1,000 man-rem exposure for plant personnel is taken as the expected dose to man for both normal and abnormal operating conditions.

ACCIDENTS DURING CAVERN FILLING

The potential consequences of several accidents are evaluated below.

Destruction of Shaft

If a major catastrophic accident, such as an earthquake of unanticipated intensity or an explosion, were to destroy a portion of the shaft in the Tuscaloosa and the engineered safeguards separating the base of the shaft from the caverns containing the waste after much of the waste had been added to the cavern (but before any of the shaft had been sealed), immediate sealing of the portion of the shaft in the rock might be impossible. Water from Tuscaloosa could begin to flow into the cavern through the unsealed shaft, filling the cavern with water in less than one year, and re-establishing the pressure gradient that existed between the rock and the Tuscaloosa aquifer before the cavern was constructed. Waste that had been charged to the cavern could then begin to migrate up through the shaft into the Tuscaloosa aquifer. The rate of migration would be controlled by the rate at which water flowed into the cavern from the surrounding rock, the rate of transport of activity up through the shaft, by diffusion and convection, the solubility of the activity in the liquid phase, and/or the rate of dissolution of a solid waste phase if the activity were incorporated in a solid. If no remedial action were taken, water would be flowing into the cavern from the surrounding rock and up through the open shaft into the Tuscaloosa formation at an estimated rate of about 5,000 gallons per year in either crystalline or Triassic rock for the first 50 years. The rate of transport of activity up through the shaft by diffusion is estimated to be less than 1% of the rate of transport by bulk flow.

It will first be assumed that convection in the shaft is negligible, and essentially all of the bulk flow from the system is due to the estimated 5,000 gallons/year from water inleakage through the rock. The estimates of activity released to the Tuscaloosa aquifer based on these assumptions cannot presently be shown to represent maximum values because of the possibility of a significant bulk flow of waste from thermal convection. It will also be assumed for the following analyses that 25% of the waste was in the cavern before the accident occurred and that this waste has direct access to the open shaft.

If all of the activity is in the liquid phase and it is assumed that no further efforts are made to recover the waste or to repair and seal the shaft, 100,000 curies each of ^{137}Cs and ^{90}Sr, 2,700 curies of ^{239}Pu and 700 curies of ^{135}Cs is estimated to enter the Tuscaloosa aquifer.

The ^{90}Sr and ^{137}Cs would be the principal long term hazards. Based on the expected minimum distribution coefficient ($K_d = 10$) for adsorption between cesium or strontium and the Tuscaloosa sediments, and the estimated flow velocity in the Tuscaloosa toward the Savannah River of $\sim$1 ft/day, the ^{137}Cs and ^{90}Sr activity is estimated to be confined to the present plant site for several thousand years, at which time the total quantity remaining would be negligible.

If the aquifer on the plant site were to be used for drinking water 100 years after the accident occurred, the estimated dose to man for the drinking water pathway would be about 2,700,000 man-rem. This dose would occur mainly from ^{90}Sr ingestion.

Assuming next that 99.9% of the activity is present in a stable solid phase, 400 curies each of ^{90}Sr and ^{137}Cs, 30 curies of ^{239}Pu and 500 curies of ^{135}Cs is estimated to migrate into the Tuscaloosa aquifer following destruction of the shaft. If then the aquifer were used for drinking water 100 years after the accident, the estimated dose to man for the drinking water pathway would be 11,000 man-rem (mainly from ^{90}Sr).

In any case, the potential consequences of such an accident would be loss of the Tuscaloosa aquifer below the plant site for an extensive period, unless provisions were made for rapidly sealing the open shaft in the rock or completely removing the waste from the cavern.

If the liquid waste phase contained all of the nitrate and nitrite, it would be more dense than the water in the shaft even though the waste would be at a higher temperature. The density difference would tend to reduce large scale convection in the open shaft. However, even small temperature differences between one side of the shaft and the other at the same elevation could set up convection cells in an open shaft. An upper limit estimate of potential convection velocities in an open shaft with a net flux of heat from one side to the other can be obtained by neglecting curvature and assuming the shaft to be a large fracture with a fracture width equal to the diameter of the shaft with some small fraction of the maximum heat flux in the system passing from one side of the shaft to the other. Convection velocities resulting from the horizontal temperature gradients in the shaft can then be estimated by the same equation used to evaluate small fractures as described in Chapter III, Section 6, Appendix 1 (Equation 4). For such a large fracture width, the velocities are estimated to be on the order of several feet per hour even if the net heat flux is as little as $\sim 10^{-8}$ of the maximum system heat flux. The extent that this convection brought fresh water into the shaft and forced contaminated water out into the Tuscaloosa aquifer would represent an additional transport of activity into the Tuscaloosa aquifer by bulk flow.

If thermal convection in the open shaft in the rock were very large, the maximum quantities of activity could be released. The upper limit in the potential dose to man for the drinking water pathway 100 years after the accident can be obtained by assuming that all of the activity in the cavern migrates into the biosphere by convection within 100 years. Under these conditions, about 5×10^6 curies each of ^{90}Sr and ^{137}Cs would be in the aquifer after 100 years and the potential dose for the drinking water pathway would be about 5×10^8 man-rem. This activity would require many centuries to decay to an acceptable level.

Sludge-Water Slurry Spill

The spill resulting in the greatest potential for either an offsite uptake by an individual or a long term hazard due to the release of activity to the biosphere is a spill of the sludge-water slurry as it is being pumped from one of the waste tanks. The estimated rate of removal from the waste tank is roughly 1,000 gpm. The estimated ^{90}Sr concentration in the slurry is about 3 Ci/gal and the estimated ^{239}Pu concentration is approximately 3×10^{-4} Ci/gal (obtained by assuming all of the strontium and plutonium are evenly distributed in the 57 million gallons of water added to slurry out the sludge.

Assuming an above ground spill occurs in the doubly contained system in the vicinity of the waste tanks, and that the spill continues for 5 minutes before instruments alarm and personnel respond, about 5,000 gallons would escape. Ten percent of this spill (500 gallons) is assumed to reach a nearby creek and 4500 gallons is assumed to seep into the ground between the site of the spill and the creek before the monitoring and diversion system diverts and collects the remainder of the spill. Further, if all of the ^{90}Sr and ^{239}Pu present in the 500 gallons that escapes to the creek washes into the Savannah River, a total of about 1,600 Ci of ^{90}Sr would be released. If this activity were to remain suspended in the creek, and then dissolve as soon as it reached the river, a maximum concentration of 0.005 µCi/ml ^{90}Sr would occur at a point in the river about 24 hours after the spill and would persist at any point along the river for about 5 minutes. If an individual were to drink 1200 ml of this water (the average amount of water consumed in one day by an individual), the integrated whole body dose to that individual over the following 70 years as a result of that single ingesion would be about 11 rem and the dose to the critical organ (bone) would be about 76 rem.

Assuming the spill would be prevented from entering the intake pumps of water supply systems on the river near Savannah, Georgia, and extensive measures would be taken after the spill to eliminate any further uptake, then the whole body dose of 11 rem to a single individual is taken to be the biomedical consequence of this spill.

Supernate Spill

The flow rate of supernate being removed from the tanks after dissolving the salts is estimated to be 100 gpm. The expected concentration of ^{137}Cs in the supernate is 3 Ci/gal. As in the preceding case of a sludge spill, an above ground spill occurring in the vicinity of the waste tanks and continuing for 5 minutes before monitors or instruments alarm and personnel respond, would allow an estimated 500 gallons to escape. If 10% of this quantity (50 gallons) reaches a nearby creek through storm sewers before the monitoring and diversion system diverts and collects the remainder of the spill, and if all of the ^{137}Cs initially present in the 50 gallons that escapes to the creek (150 Ci) washes into the Savannah River, a concentration of approximately 5×10^{-4} μCi/ml of ^{137}Cs would occur in the river about 24 hours after the spill and would persist for about 5 minutes at any one point along the river. If an individual were to drink 1200 ml of this water, the integrated whole body dose to that individual over the following 70 years as a result of that single ingestion would be about 27 mrem.

ACCIDENTS AFTER CAVERN SEALING

Normal Operation

Normal operation is taken to be an operation that meets by a wide margin the guidelines given in Chapter II. Assuming that essentially all of the short-lived activity as well as the ^{239}Pu and ^{135}Cs remain in the cavern and the rock until the activity has decayed, the principal radiological consequence of bedrock storage is the release of the extremely long lived ^{129}I (1.6×10^7 yr half-life). Based on estimates for the drinking water pathway, the dose due to release of all of the ^{129}I would be approximately 130 man-rem and this radiation dose is taken to be the consequence of bedrock under normal operating conditions.

Abnormal Operation

Abnormal conditions after sealing are taken to be conditions that were anticipated as being possible although not likely. A bedrock storage system would be designed with a wide margin for safety, so that even if several of the parameters were to have less favorable values than had been expected, the system would still meet the design criteria by a wide margin. In effect, the conservatism of the design would eliminate additional releases to the biosphere from anticipated variation of parameters outside of normal limits, just as double containment for a pipe at the surface eliminates a release to the biosphere from a spill. Variation of parameters far beyond the range considered probable will be considered as major accidents in this analysis and are treated below. The consequences of abnormal operation are taken to be the same as for normal operation.

Unexpectedly Large Withdrawal of Water From the Tuscaloosa Aquifer

Usage of the Tuscaloosa aquifer at the present plant site for public drinking water at some time in the future is assumed. The consequences of an unexpectedly large and extensive drawdown of this aquifer are evaluated as an accident. It is further assumed (as an extreme condition) that the pressure at the base of the Tuscaloosa aquifer is reduced to atmospheric after the cavern reaches equilibrium with the hydrostatic pressure in the rock. Atmospheric pressure represents the lowest possible pressure in the Tuscaloosa aquifer and such a situation is not expected to occur, although some drawdown of this aquifer in the future is likely. Under these conditions, the maximum driving force on a crystalline cavern would be 1000 ft_{H_2O} + 7 ft_{H_2O} (present head at the base of the Tuscaloosa plus the present pressure difference between the crystalline rock and the Tuscaloosa). Similarly, the driving force on a Triassic cavern would be 1000 ft_{H_2O} + $\sim$250 ft_{H_2O} = 1250 ft_{H_2O}. The consequences of such a pressure differential for each system acting over the expected distance from the cavern up to the Tuscaloosa aquifer (about 500 feet) for an infinite time period is evaluated below for each system.

Effect on a Cavern in Crystalline Rock

The following assumptions and information are used in order to calculate the significance of this accident in crystalline rock:

1. The pressure gradient for the crystalline system after drawdown of the Tuscaloosa aquifer is complete would be 1007/500 = 2 ft_{H_2O}/ft acting to force waste up to the Tuscaloosa aquifer.

2. 99.9% of all activity is sorbed on a stable solid waste phase.

3. Resistance to air flow is nil as it flows from the cavern (radiolytic gassing is assumed to be eliminated).

4. Drawdown from the Tuscaloosa aquifer occurs 50 years after the cavern is sealed. This is the expected time required for the cavern pressure to reach hydrostatic equilibrium.

5. For the expected permeability and porosity of crystalline rock (σ = 1 ft/yr, $\varepsilon = 10^{-3}$), the average residence time of activity in the rock would be less than one year.

Using these assumptions, the mathematical models predict that a total of about 3.8×10^5 Ci of ^{90}Sr would flow into the

Tuscaloosa aquifer. The potential dose to man for the assumed drinking water pathway (1.6×10^{-4} ingested) would be 5×10^7 man-rem.

The sensitivity of the crystalline rock to withdrawal from the Tuscaloosa aquifer indicates that acceptable storage of waste in crystalline rock would require either (1) proof that drawdown of the Tuscaloosa aquifer would not result in a driving force on the crystalline rock (this would require an essentially impermeable layer between the crystalline rock and the Tuscaloosa aquifer), or (2) the assurance that much more than 99.9% of the activity would be in a stable solid phase at equilibrium or that all of the waste could be incorporated in an "insoluble" solid, or (3) assurance that such withdrawal of water from the Tuscaloosa aquifer can be prohibited for the next several centuries. None of these alternatives can be assumed to be possible based on present information.

Effect of a Cavern in Triassic Rock

A similar evaluation of the above accident for the Triassic system uses the following assumptions and information:

1. The corresponding pressure gradient in the Triassic system after drawdown of the Tuscaloosa aquifer has occurred is 1250/500 = 2.5 ft_{H_2O}/ft and remains constant with time.

2. All activity is in liquid phase.

3. Resistance of radiolytic gases as they flow from the cavern is insignificant.

4. Drawdown from the Tuscaloosa aquifer occurs 1000 years after the cavern is sealed. This is the expected time required for the cavern pressure to reach hydrostatic equilibrium.

5. For the expected Triassic rock ($\sigma = 3 \times 10^{-4}$ ft/yr, $\varepsilon = 0.03$) the average residence time of non-adsorbed activity in the rock would be approximately 20,000 years.

From these assumptions and the mathematical models, it appears that ^{135}Cs would be the principal hazard. It is estimated that about 35% of the ^{135}Cs or, roughly, 1000 Ci would enter the Tuscaloosa aquifer if this gradient were maintained over a million years. The potential dose to man through the drinking water pathway for this activity is estimated to be 760 man-rem.

Unexpectedly High Migration Rates Through Bedrock

The hydrological conditions expected for bedrock caverns were given in Chapter I. The expected conditions were listed as Case A in Table 1 of that section. The expected average residence time in the crystalline rock for non-adsorbed activity was 6×10^4 years, and for Triassic rock, 2×10^7 years. For each system, additional cases that cannot presently be completely ruled out were also considered. The average residence times for these cases were as low as 40 years for crystalline (Case C, Table 1, Chapter I), and 10^5 years for Triassic (Case B, Chapter I). These lower residence times were assumed as the appropriate values to use for the case of unexpectedly high migration rates through the rock for "accident" conditions (Table V.1). Significant modification of the waste was assumed to be necessary for crystalline storage as described below but only small modifications were made for Triassic storage.

Table V.1. Consequences of Unexpectedly High Migration Rates Through Crystalline Rock

Isotope	Quantity Released to Biosphere, Ci	Potential Dose to Man, man-rem
^{90}Sr	100	15,000
^{137}Cs	100	710
^{135}Cs	24	110
^{239}Pu	370	270

Each rock system is considered separately.

Crystalline Rock

Assumptions:

1. Nitrate-nitrite removed by previous treatment before storage.

2. All radionuclides adsorbed on a stable solid phase so that at equilibrium 99.9% of any radionuclide is in the solid phase, and 0.1% is in the liquid.

3. Time to reach hydrostatic equilibrium is 50 years (based on an initial water inleakage rate of 2 gpm to a cavern with approximately 60 x 10^6 gallons freeboard and negligible radiolytic gas production as shown in Figure 9, Section 4 of Chapter III).

4. Average residence time in rock is 40 years.

Using these assumptions, the mathematical models predicted the quantities of radioisotopes that would be released to the biosphere. Assuming 1.6 x 10^{-4} of the activity in solution is ingested through drinking water, the potential dose to man was estimated (Table V.2).

The ^{90}Sr is the most hazardous isotope for these conditions. The principal line of defense against releases greater than those estimated here is the assurance that 99.9% of the activity in the cavern at any time remains in the solid phase. For example, if only 99% of the ^{90}Sr were in the solid phase the total quantity released would be 10 times greater, and the potential dose to man for the postulated drinking water pathway would be 150,000 man-rem.

Triassic Formation

Assumptions:

1. All activity is in the liquid phase.

2. Time to reach hydrostatic equilibrium is 1000 years [Based on an initial water inleakage rate of about 0.1 gpm, 50 x 10^6 gallons of freeboard and an estimated 700 x 10^6 gallons of radiolytic gas produced (measured at 1 atmosphere pressure)].

3. Average residence time in rock is 10^5 years.

4. Credit taken for adsorption of cesium and plutonium on Triassic rock (K_d for Cs = 2, K_d for Pu = 53).

For this case, the principal hazard would be the release of about 0.7 Ci of ^{135}Cs to the biosphere. The estimated dose to man through the drinking water pathway is about 1 man-rem. This is a negligible addition to the anticipated dose to man of an estimated 130 man-rem due to the release of all ^{129}I, already assumed as a consequence of the use of the bedrock concept.

TABLE V.2

Potential Biomedical Consequences of Bedrock Storage Situations During Cavern-Filling Period

Situations	Biomedical Consequences	Probability
Normal and Abnormal Operating Conditions	~1000 man-rem	~1
Accidents		
1. Destruction of portion of shaft in Tuscaloosa aquifer during filling	Loss of Tuscaloosa aquifer at present plant site for several centuries if shaft in rock cannot be immediately sealed or all activity retrieved. *Minimum* potential biomedical consequence is 11,000 man-rem assuming the Tuscaloosa aquifer at the plant site is used for drinking water 100 years after the accident (negligible thermal convection in shaft, 99.9% of activity in solid phase at equilibrium). *Maximum* potential consequence at plant site after accident is about 5×10^8 man-rem (assuming 25% of all activity in waste flows into the Tuscaloosa aquifer from thermal convection in the open shaft and the aquifer is used for drinking water 100 years after accident).	$\sim 10^{-4}$ [a]
2. Sludge Spill	11 man-rem to single individual drinking water (1.2 liters) directly from Savannah River as activity passes by.	Less than 0.2 [b]
3. Supernate Spill	0.05 man-rem to single individual drinking water (1.2 liters) directly from Savannah River as activity passes by.	Less than 0.2 [b]

a. Assumes one earthquake of intensity VIII (Modified Mercalli scale) every 300 years, covering an area equivalent to that of the strongly affected area from the Charleston earthquake (18,000 sq. mi.) of 1886, but occurring randomly in the area designated 2 and 3 (180,000 sq. mi.) in vicinity of South Carolina in Figure I-13, Chapter I. Assumes three years to charge caverns. Also assumes engineered safeguards separating the base of the shaft from the cavern being filled add a safety factor of 10.

b. Based on an estimated 15 years operation of existing waste facilities without a spill of this magnitude. Assumes three year operation.

Earthquake Resulting in Fault Connecting Liquid Waste Phase With Tuscaloosa Aquifer

In general, the principal consequences of an earthquake occur at or near the surface of the earth. The bedrock usually moves as a single unit. The only way in which an earthquake could present a hazard to a sealed cavern would be the production of a fault that connected the liquid phase in the cavern with the Tuscaloosa aquifer. The probability of such an event is extremely low and is much less than the probability of an earthquake that would damage the shaft above the rock. The consequences are evaluated below for each rock system assuming first that an earthquake results in such a fracture and that the final "unhealed" effective width of the fracture is 10 μm.

Unhealed 10 μm Fracture in Crystalline Rock

Assumptions:

1. 99.9% of all activity is in stable solid phase.

2. Time to reach hydrostatic equilibrium is 50 years.

The waste could flow through such a fracture at the maximum rate as soon as the system pressure increased to that of the surrounding rock. The time to reach this pressure would not be affected by the presence of the fracture because the rate of flow of water into the cavern through the fracture would not be large compared to the total rate of water inleakage. For the expected pressure difference between the crystalline rock and the Tuscaloosa aquifer of about 7 ft_{H_2O}, the maximum flow rate of waste up through the fracture would be about 1 gal/yr. The mathematical models predict negligible quantities of activity would enter the Tuscaloosa aquifer through this path for these conditions.

Unhealed 10 μm Fracture in Triassic Formation

Assumptions:

1. All activity is in the liquid phase.

2. Time to reach hydrostatic equilibrium is 1000 years.

For the expected pressure difference between the Triassic rock and the Tuscaloosa aquifer of an estimated 250 ft_{H_2O}, the maximum flow rate into the Tuscaloosa formation through the fracture is estimated to be about 50 gal/yr. The time to reach hydrostatic equilibrium in the Triassic system would not be affected by the small additional flow coming in through such a fracture. The waste would not begin to flow through the fracture at the maximum rate until the cavern reached the surrounding hydrostatic equilibrium pressure. Under these conditions, it is estimated that approximately 340 curies of ^{239}Pu and about 2,000 curies of ^{135}Cs would enter the Tuscaloosa aquifer. The potential dose to man for the drinking water pathway would be about 1400 man-rem for the ^{239}Pu and 1500 man-rem for the ^{135}Cs. Most of the ^{239}Pu would be expected to remain in the solid waste phase in a Triassic cavern and the soluble ^{135}Cs represents the true hazard for this accident.

Fracture Larger Than 10 μm

If the fracture were larger than 10 μm, the potential consequences would be greater. A fracture with an effective width of approximately one millimeter (mm) is estimated to represent an open flow path of negligible resistance. Under these conditions, the fracture behaves just as the open shaft. Water would fill up the cavern in less than one year (assuming that the gas escaped through another separate fracture) and activity would flow out of the cavern at a rate controlled by the rate at which water could flow into the cavern from the surrounding rock. The consequences of such an accident would depend upon the time that it occurred. The worst case would be soon after cavern sealing when most of the initial ^{90}Sr and ^{137}Cs activity was still in the waste. The potential consequences of this case would be the same as the first case estimated previously for the destruction of the shaft during cavern filling; bulk flow from the system would be due to the estimated 5,000 gallons per year from water inleakage through the rock.

Explosion in Cavern

Essentially all of the energy of nuclear decay will go into heating the rock surrounding the cavern. A very small fraction of this energy will go into radiolytic reactions in the liquid waste to produce a gas composition of approximately 80% O_2, 18% H_2, and 2% nitrogen and its oxides. If a piece of rock or metal were to fall and strike a surface in the gas phase, a spark might conceivably be produced that would ignite the mixture of hydrogen and oxygen, releasing some of the energy that had gone into producing the gases. The reaction of all of the hydrogen with oxygen to form water is estimated to result in the liberation of about 5×10^9 Btu in the gas phase. The main consequence of such an explosion would be cracks in the rock out to a distance of no more than two or three cavern radii. The total volume of the cavern would not be changed following the explosion. The pressure in the gas would reach about 4000 psi immediately after the explosion, and would decrease rapidly as the heat was transferred to the liquid phase by convection and conduction. The temperature increase of the liquid phase would be approximately 8°F. The final pressure in the gas phase would be about 30% lower than the pressure immediately before the explosion due to the removal of all of the hydrogen and some of the oxygen from the gas phase. Engineered barriers to waste migration at or near the cavern wall (such as grout, etc.) might be destroyed; however, the resistance of the large mass of rock in which the cavern was located would still be essentially the same. The high pressure immediately after the explosion might force some waste for a short distance, however, the direction of flow would soon reverse due to the reduced gas pressure and there would be a period of leakage into the cavern as hydrostatic equilibrium with a smaller gas phase was attained.

The only other known mechanism that might store some small fraction of the nuclear decay energy and then suddenly release it is the "metamict" effect. This effect generally occurs when radiation is absorbed in well-ordered crystal lattices at low temperatures. A subsequent temperature increase can then initiate the sudden release of the energy. The probability of a sudden energy release by this mechanism is slight. In the bedrock system, there are no known materials that can store energy in this manner, and the cavern temperature is high during the initial period of radiation and then decreases. Even if such an effect did occur, the quantity of energy stored and released would not be expected to be as great as that in the postulated hydrogen explosion. The energy would be absorbed by the rock. The net result would be a temperature increase of a few degrees in the cavern and the consequences would be negligible.

Large scale external explosions at the ground surface above the cavern would have a negligible effect on the integrity of the cavern.

COMPARISON OF RISKS

The expected consequences of bedrock storage for normal and abnormal conditions and the potential consequences for postulated accidents are given in Table V.2 for the cavern filling period, and in Table V.3 for the period after sealing. Probability ranges were estimated for the accidents but they were based essentially on judgment and not on a complete statistical analysis of past data. The accidents, listed in order of their estimated risk (higher risk accidents listed first), take into account the estimated probability range as well as the potential consequences.

TABLE V.3

Potential Biomedical Consequences of Bedrock Storage Situations After Cavern is Sealed

Situation	Crystalline Cavern		Triassic Cavern	
	Consequences, man-rem	Probability	Consequences, man-rem	Probability
Normal and Abnormal Operating Conditions	$\sim$240	$\sim$1	$\sim$240	$\sim$1
Accidents				
1. Extremely large quantities of water removed from Tuscaloosa aquifer at present plant site	5,500,000 (Maximum)	*a*	760 (Maximum)	*a*
2. Unexpectedly high rate of migration	160,000	~ 0.1 [b]	$\sim$1	$<10^{-1}$ [c]
3. Earthquake occurring 100 years after sealing and resulting in $\sim$1 mm fracture connecting liquid waste phase to Tuscaloosa aquifer	2,700,000 (All activity in liquid)	*d*	2,700,000 (All activity in liquid)	$<<10^{-4}$ [d]
4. Explosion in cavern	<1	$\sim 10^{-3}$ [e]	<1	$\sim 10^{-3}$ [e]

a. Although the probability of removing all water from the Tuscaloosa aquifer is very low, the probability of drawing down the aquifer to some extent is relatively high.

b. Based on approximate fraction of rock that is highly fractured.

c. Assumed to be less probable than for crystalline due to greater homogeneity.

d. The probability of an earthquake resulting in such a fracture in the rock is assumed to be significantly less than the probability of an earthquake that could destroy the shaft in the Tuscaloosa aquifer (Footnote *a*, Table 1) and engineered safeguards separating the base of the shaft from the caverns containing the waste.

e. Assumes explosion set off by minor spalling of rocks in cavern during earthquake of Intensity VIII (Modified Mercalli scale).

Accidents postulated to occur during cavern filling would be more likely to result in economic costs associated with cleanup operations or loss of the economic potential of the Tuscaloosa aquifer rather than biomedical costs,because the occurrence of these accidents would very likely be recognized and remedial action taken. On the other hand, it is expected that the accidents postulated after cavern sealing would be much more likely to take place in such a manner that there would be no direct knowledge of their occurrence.

Analysis of the risks as presented in Tables 2 and 3 indicates that:

- For normal and abnormal operation, the greatest risk will be to the personnel removing waste from the tanks and decontaminating the tanks.
- The potential accident presenting the greatest risk during the cavern-filling period is an explosion or other catastrophe that destroys a portion of the shaft in the Tuscaloosa aquifer and the engineered safeguards separating the base of the shaft from the cavern being filled.
- The potential accident presenting the greatest risk after cavern sealing is the withdrawal of essentially all of the water from the Tuscaloosa aquifer. The potential consequences are much greater for a crystalline cavern (5,500,000 man-rem) than a Triassic cavern (760 man-rem) even if 99.9% of the activity were in a stable solid phase in the crystalline cavern.

Based on the estimated consequences of significant withdrawal of water from the Tuscaloosa aquifer for a crystalline cavern and the relatively high estimated probability that such withdrawal could occur, the risk for a crystalline cavern is unacceptable unless it can be proven that such a situation could not occur.

RESIDUAL RISKS

Residual risks are defined for this analysis as those risks that remain even if the bedrock system performs as expected and if the potential accidents identified in the preceding part of this safety analysis do not occur.

From Anticipated Releases

Any bedrock cavern must be expected to ultimately release all of its stable constituents, such as nitrate, nitrite, and mercury, as well as radionuclides with half-lives measured on a geologic time scale, such as ^{129}I (1.6×10^7 yr half-life). These constituents will leave the rock very slowly and will be greatly diluted. However, the bedrock storage would not be undertaken unless there was a high degree of assurance that the consequences of releasing these constituents were acceptable, even though the quantities involved are not negligible. For example, there is a total of 80 tons of mercury in the waste and 62 curies of ^{129}I. If there is some unidentified pathway that would concentrate these materials in the food chain to a far greater extent than anticipated, the accompanying hazards of their release would be much greater. Likewise, if the consequences of the ingestion of these long-lived materials has been underestimated, the biomedical damage could be greater than anticipated.

From Unanticipated Releases

Accidental Entry by Man

The cavern will be constructed so that it should not be sensitive to normal activities outside of the region of rock in which it is located. However, the system will prematurely release the waste if rock borings are accidentally made into the cavern or near the cavern. Although the area could be controlled for some period of time, there is no guarantee that this control would extend indefinitely.

Unanticipated Natural Phenomena

The design of the caverns will consider all anticipated potential natural phenomena such as earthquakes, etc., and construction will be based on existing and anticipated conditions in the rock. If some totally unanticipated large scale natural phenomena were to occur, the cavern design would not necessarily take these conditions into account. Such phenomena are not anticipated; however, they illustrate that the bedrock storage concept is dependent upon man's ability to predict any large climatic or geologic changes during the required period of storage.

CHAPTER VI. PRINCIPAL CONCLUSIONS AND THE SIGNIFICANCE OF DEFICIENCIES IN KNOWLEDGE AND ASSUMPTIONS

The principal conclusions of this study are listed below. Any identified deficiencies in our knowledge that could change these conclusions are discussed following each principal conclusion. Significant assumptions that could change these conclusions are also discussed.

1. In order to avoid unacceptable uptake of radionuclides by man through drinking water, the waste should be excluded from the biosphere at least until most of the ^{239}Pu has decayed ($\sim$200,000 years). The release of all of the ^{135}Cs and ^{129}I may be acceptable if greatly diluted.

2. At least two separate and distinct bedrock formations exist beneath the Savannah River Plant site: crystalline and Triassic. The properties of these two systems differ significantly.

3. Triassic rock shows much more promise as a potential long-term waste storage location.

The principal assumption that leads to this conclusion is the set of preliminary design guidelines used for this analysis: all constituents should be less than 1% of MPC when leaving the rock and essentially no ^{90}Sr, ^{137}Cs, or ^{239}Pu should be allowed to enter the biosphere. Additional work is necessary to confirm the suitability of these interim guidelines. In addition, further research and development is needed to determine accurately the hydrology of the Triassic basin. Special attention must be given to evaluating the significance of the high piezometric head in the Triassic basin.

4. Using the same set of guidelines as applied to Triassic rock, the crystalline rock does not appear to be as promising a potential waste storage location. Significant alteration of the waste would probably be required for waste storage in a cavern located in the crystalline rock. This alteration would include removal of most of the activity from the waste supernate and incorporation of essentially all of the long-lived isotopes into a

stable solid waste phase. One of the principal drawbacks of the crystalline system is its apparent sensitivity to water withdrawal from the Tuscaloosa aquifer.

5. Any bedrock waste storage system will ultimately release all of the stable constituents (such as mercury) and all of the extremely long-lived radionuclides (such as ^{129}I). These constituents will be released only after a very long time and then very slowly and greatly diluted.

6. The potential accident having the greatest risk and the greatest consequences is the destruction of the shaft connecting the cavern to the ground surface in the vicinity of the Tuscaloosa aquifer by an earthquake or other means during filling of the caverns with waste. This accident could result in a loss of the use of the Tuscaloosa aquifer beneath the existing Savannah River Plant site for centuries. The contamination is not likely to spread beyond the existing plant site.

The principal assumption leading to this conclusion is that the waste would be in a mobile form in such a condition that before access to the cavern could be regained, a major portion of the waste would have entered the Tuscaloosa aquifer. If the waste were in a form, e.g. a thixotropic gel, such that it would not release any appreciable portion of the activity before it could be retrieved, these consequences would not occur. Although the design basis for this study is the waste in the tanks, it should be noted that bedrock storage could just as easily be applied to the waste after an interim engineered storage period. To the extent that the waste from an engineered storage facility was in a higher integrity form (such as solids in containers), the consequences of accidents during filling would be much smaller.

7. Risks after sealing of the shaft are lower than the risks during cavern filling with unaltered waste.

CHAPTER VII. RECOMMENDATIONS FOR FURTHER WORK

Recommendations for further work on the bedrock storage concept are listed below in their order of importance as determined in this study.

1. Criteria acceptable for long-term storage of Savannah River waste should be developed. These criteria should include consideration of all of the potential pathways for uptake by man for each hazardous constituent in order to define the critical pathway for each isotope. The extremely long-lived radionuclides such as ^{135}Cs and ^{129}I as well as stable constituents such as mercury must be included in considerations of the costs, benefits and risks of bedrock storage. Additional alternative concepts for storage of the waste should be defined and estimates of the potential costs, benefits, and risks of these alternative concepts should be brought up to the same level as that currently available for the bedrock storage concept for purposes of comparison and decision making. The evaluation of these alternatives should include all costs, benefits, and risks for the total time period during which the waste remains a hazard.

2. The serious potential consequences of the postulated accident involving destruction of both the shaft in the Tuscaloosa and the engineered safeguards, possibly including concrete bulkheads, separating the base of the shaft from the cavern being filled, requires the development of engineered approaches for reducing the probability and consequences of such an accident to acceptable levels. These approaches should include (a) consideration of shaft design to withstand accidents, (b) waste forms, and (c) waste retrievability.

3. Assuming that the outcome of the studies outlined in the two preceding recommendations indicate that bedrock remains a potential candidate for ultimate storage of Savannah River radioactive waste, the emphasis of the evaluation program should shift to a further investigation of the geology and hydrology of the Triassic basin. It is recommended that this program should include the following (listed in their order of importance as determined in this study):

(a) Evaluate the significance of the unusually high piezometric pressure in the Triassic basin compared to that expected for the Tuscaloosa aquifer overlying the Triassic basin. This evaluation should determine whether the large pressure difference creates large gradients throughout the Triassic basin in the vertical as well as the horizontal direction or whether the whole basin essentially has a uniform piezometric pressure. The piezometric pressure in the region of the Tuscaloosa aquifer overlying the Triassic basin would also be obtained in this program.

(b) Initiate long-term creep tests with selected samples of Triassic rock. Based on the results of these tests, evaluate the ability of the Triassic rock to maintain adequate volume for the extremely long time period required for bedrock storage.

(c) Perform tests to demonstrate that adequate shaft seals can be obtained. Any high piezometric head difference between the Triassic basin and the overlying Tuscaloosa aquifer would be applied to any crack in the shaft that connected the cavern to the Tuscaloosa aquifer.

(d) Sufficient additional deep rock borings should be made in the Triassic basin to confirm that the rock has a uniformly low permeability throughout a sufficiently large volume of the basin. The porosity and ion exchange characteristics of samples of rock from these borings should be measured and interaction of the rock with waste should be further evaluated.

4. An additional technical reassessment of the bedrock storage concept should be carried out taking into account all additional information derived from the preceding studies. If this assessment indicates that bedrock storage is the most suitable technique for ultimate storage of Savannah River wastes, an exploratory shaft and tunnels should be constructed at the location considered most suitable for the final bedrock cavern.