Radioactive Waste Management at the Savannah River Plant: A Technical Review (1981)

Pages
81

Size
8.5 x 10

ISBN
030903227X

Panel on Savannah River Wastes; Board on Radioactive Waste Management; Commission on Natural Resources; National Research Council

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81-0173

National Research Council, Washington, DC.*Department of Energy, Washington, DC. (019026000)

Final rept. 1 Jun 78-30 Jun 81.
G6775K2 Fld: 18G, 77G GRAI8214
1981 82p
Rept No: ISBN-0-309-03227-X
Contract: DE-AT01-76NE-93021
Library of Congress catalog card no. 81-85742.

Abstract: The report concludes that the Savannah River Plant's monitoring practices and management of low-level and transuranic wastes and wastes from large equipment and structural items (LESI wastes) have been sound and should be continued. Although the point is stressed that the report's recommendations should not be taken as an endorsement of on-site isolation or bulk transfer of slurried high-level wastes, the Panel concludes that all realized or proposed solidification processes for transport of high-level wastes are costly and complex and that the less costly and less complex concept of bulk disposal of waste in the bedrock at the Savannah River Plant, mixed with chemical additives and cement for solidification in place, should be reexamined. The Panel makes a number of detailed recommendations as guides to further research into SRP bedrock disposal.

Solidification, Cements, Bulk handling

Identifiers: *Savannah River Plant, *Radioactive waste management, Low-level radioactive wastes, Alpha-bearing wastes, Monitoring, Underground disposal, Vitrification, NTISNASNRC, NTISDE, NTISNASIOM, NTISNASNAE

PB82-182122 NTIS Prices: PC A05/MF A01

Also: NTIS DE85007459/XAB

Radioactive Waste Management at the Savannah River Plant: A TECHNICAL REVIEW

Panel on Savannah River Wastes
BOARD ON RADIOACTIVE WASTE MANAGEMENT
Commission on Natural Resources
National Research Council

NATIONAL ACADEMY PRESS
Washington, D.C. 1981

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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

This study was supported by the U.S. Department of Energy under Contract No. DE-AT01-76NE93021.

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Library of Congress Catalog Card Number 81-85742

International Standard Book Number 0-309-03227-X

Available from

NATIONAL ACADEMY PRESS
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

Printed in the United States of America

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CONTENTS

LIST OF FIGURES AND TABLES

PREFACE

At the request of the Department of Energy, the National Research Council (NRC) through its Committee on Radioactive Waste Management (now the Board on Radioactive Waste Management (BRWM)) undertook a review of previous reports and newly acquired data pertaining to the management of radioactive waste generated at the Savannah River Plant (SRP). Subsequently, the CRWM constituted the Panel on Savannah River Wastes to evaluate SRP waste management practices and plans, including (1) the effectiveness of current practices in managing low-level waste and the adequacy of programs to monitor existing disposal sites, (2) the effectiveness of current practices for the management of high-level waste, (3) plans for the long-term management of high-level radioactive waste, examining all reasonable alternatives, and (4) in connection with the above, an assessment of the environmental safety of current and planned practices in view of the existing environmental conditions at the site.

In considering feasible alternatives to current practices and plans, the Panel was to consider the cost, hazards, and technological status of alternatives as well as the effects on administration program schedules and goals. Where adequate data were available to support quantitative evaluations, such evaluations were to be provided.

The full Panel met 15 times, including a site visit and two public hearings. In addition, individual members made numerous trips to laboratories and to consult with researchers involved in work related to waste management at the SRP. The Panel received a large number of solicited and unsolicited documents from citizens, private organizations, and governmental organizations. A summary of the public meeting on October 17, 1978, was printed by the SRP and distributed as an informal document (NRC 1978c). Other material, including a lengthy but preliminary description of the results of the Panel's work (NRC 1980), is on file in the Archives of the National Academy of Sciences. It should also be noted that, in the course of its work, the Panel entered into two subcontracts for investigative reports on certain technical aspects of the disposal problems at the Savannah River Plant. Numerical Modeling of Some Geotechnical Considerations Associated with Underground Isolation of Nuclear Wastes at the Savannah River Plant, South Carolina was written by R.D. Hart, M.C. Christianson, and W.E. Holman of the University of Minnesota, and

Chapter 1

SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS

MONITORING PRACTICES

Conclusion: The radiation protection practices at the Savannah River Plant (SRP) for radioactive waste management have been adequate and effective. (p. 30)

Recommendation: All current monitoring procedures should be continued and improved, where appropriate, as new information and analytical capabilities become available. (p. 30)

Recommendation: Surveillance of tritium releases should be refined to include measurement of tritium hydroxide in water vapor as a standard procedure. (p. 31)

LOW-LEVEL WASTE

Conclusion: Current methods of managing low-level waste, including release of tritium gas, tritiated water vapor, and other process gases to the atmosphere, have not created radiation hazards to operating personnel or to the general public. (p. 27)

Recommendation: Current management practices of on-site shallow land burial of solid low-level waste and release of process effluents should be continued and certain procedural improvements should be implemented. (p. 28)

TRANSURANIC (TRU) WASTES

Conclusion: Past and current management practices for TRU waste have not resulted in radiation hazards to the public. (p. 28)

Recommendation: Current practices for handling and on-site storage of TRU waste should be continued and certain procedural improvements should be implemented (p. 29)

Recommendation: Surveillance of buried TRU waste should be continued to detect unexpected radionuclide movement that might necessitate exhumation. (p. 29)

LARGE EQUIPMENT AND STRUCTURAL ITEMS (LESI) AND OTHER SPECIAL WASTE

Conclusion: Past management of LESI waste, ion-exchange resins, spent solvents, chemical waste, and solid non-TRU waste at SRP has not resulted in a hazard to the public health. (p. 30)

Recommendation: LESI should be treated as TRU waste or decontaminated to the point that the extent of nonremovable TRU contamination can be determined. (p. 30)

Recommendation: Ion-exchange resins and spent solvent waste and should be incinerated under controlled conditions. (p. 30)

HIGH-LEVEL WASTE

Conclusion: Current tank storage is adequate as an interim storage method that will function safely for the years needed to select and implement a method of permanent isolation. (p. 51)

Conclusion: All management options involving realized or proposed solidification processes are costly and complex and are made more so by any transportation step, and will require additional development and demonstration before they become operational for SRP. (p. 51)

Conclusion: A thorough reexamination is warranted of the less costly, less complex, and probably no more hazardous concept of bulk disposal of the waste in SRP bedrock. (p. 51)

Recommendation: Current management practices of containing high-level radioactive waste in the double-walled carbon-steel tanks should be continued until a permanent method of isolation has been selected. (p. 52)

Recommendation: The technological and economic feasibility of permanent isolation of existing and future high-level radioactive waste in a bedrock repository under the site should be reexamined. As part of the reexamination, the following recommendations are made:

1. Additional field and laboratory investigations should be conducted to produce definitive information as to the three-dimensional characteristics of the Triassic rocks that underlie the site. Particularly important is information on (a) the fluid transmissivity of different parts of the rock unit, (b) the hydraulic gradients, (c) the ion-exchange capacities, (d) the chemical reactions between the waste and the potential host rock, and (e) the regional stress fields in the rocks.
2. If analysis of the information gained by carrying out recommendation 1 above supports further investigation, an exploratory shaft should be excavated on the SRP site to repository depth in the rock selected.
3. If analysis of the information gained by sinking the shaft mentioned in recommendation 2 above supports further exploration, horizontal borings should be made at repository depth to the limits of the proposed repository in order to collect the site-specific data

required to assess the suitability of the formation to receive SRP high-level waste.

4. Concurrently, unless the results of recommendations 1, 2, or 3 prove the concept invalid, the technology and economics of pumping slurries of high-level radioactive waste containing solidifying agents into a deep geologic repository for in situ solidification should be investigated and evaluated.
5. Also concurrently, research and development should be pursued on above-ground processing of high-level radioactive waste into solidified, low-leach forms suitable for bulk transfer to an on-site deep geologic repository as an alternative to the in situ solidification of slurried liquid waste. (p. 52)

Recommendation: Until the technological and economic feasibility of on-site isolation of high-level waste is evaluated, the following actions should be taken:

1. Research and development should be continued on above-ground solidification of SRP high-level radioactive waste into forms suitable for transport off site. A final choice of waste form should be postponed until the feasibility of on-site disposal is determined.
2. Plans should be developed--although construction should not start--for a full-scale processing and solidification plant based on currently existing waste management technology. (p. 53)

Recommendation: The major capital expenditures of a surface processing and solidification facility should be undertaken only if deep geologic isolation on site by bulk transfer and in situ solidification of slurry is proved to be less attractive. (p. 53)

General conclusion: These strong recommendations for further research into SRP bedrock disposal should not be taken as endorsement of on-site isolation or bulk transfer of slurried high-level waste, nor to mean that other alternatives are to be ignored. (p. 53)

General conclusion: In the absence of overriding technological or safety justification for a preemptive decision, an open-minded and responsible scientific approach to the problem of long-range management of high-level waste at the SRP requires that all reasonable options be kept open while the data necessary for informed judgment are assembled. (p. 53)

Chapter 2

INTRODUCTION

The Savannah River Plant (SRP) is located near Aiken, South Carolina. It includes three operating nuclear reactors, a fuel and target fabrication facility, two chemical separation plants, a facility to process and package tritium, and a heavy water production plant. The facility is part of the Nuclear Weapons Materials Production Program of the U.S. government. It was designed and built and has been operated continuously since the mid-1950s by E.I. du Pont de Nemours and Company for the Atomic Energy Commission (AEC) and its successors, the Energy Research and Development Administration (ERDA), and the Department of Energy (DOE).

As a result of SRP defense operations, large volumes of a variety of radioactive waste have accumulated; some waste has been disposed of by shallow land burial or intentional release to air or surface waters, but most of the waste has been stored in an interim manner awaiting disposal. Management practices and plans for disposal of the radioactive waste at SRP and other DOE sites have been reviewed by committees of the National Research Council (NRC) since the mid-1950s (NRC 1956, 1957, 1966, 1972, 1976, 1978a). Most previous studies of SRP focused on the high-level waste, because its permanent disposal presents the greatest difficulties. This report considers all SRP waste categories and in that respect differs from previous NRC reports on SRP waste. Those reports and other publications included in the bibliography provide the background and preliminary data base for this study. In the interests of conciseness and brevity, published information is usually not repeated. The interested reader is encouraged to consult the references.

The first part of this report is descriptive: it deals with the SRP's physical environment, the radioactive waste generated at the site and their current management, the associated monitoring procedures, and some of the hazards presented by the waste. The second part is a critique and evaluation of the practices and conditions described in the first part: it considers the major alternatives for long-range management and disposal of the waste, evaluates the effectiveness of current waste management practices and plans for future management and disposal, and presents the Panel's conclusions and recommendations for future action.

DESCRIPTION AND BACKGROUND OF THE SAVANNAH RIVER PLANT

Chapter 3

PHYSICAL ENVIRONMENT

The physical environment of SRP, including geology, hydrology, local climate and meteorology, seismicity, and ecology, has been described in detail in two recent Final Environmental Impact Statements concerning radioactive waste management operations at SRP (ERDA 1977c, DOE 1979a). Both documents contain abundant references to published literature regarding specific research and analyses undertaken to characterize the SRP site.

The plant is on a 775-km^2 tract, owned and controlled by the federal government, in southwestern South Carolina (Figure 1). It lies within the Atlantic Coastal Plain, and its southern boundary is formed by the Savannah River.

Climate in the SRP area is temperate, with mild winters and long, humid summers. Rainfall is heavy, on the average 1.2 m annually, and two types of severe storms, hurricanes and tornadoes, occur in the region (ERDA 1977c). The Savannah River Laboratory maintains its own meteorological station and has prepared computer programs and simulation models to predict movement of gaseous radionuclide releases (Cooper and Rusche 1968).

Prevention of contamination of the Savannah River and local ground waters with radionuclides is a major goal of production operations and radioactive waste management at SRP. In order to design facilities, plan emergency procedures, and assess the consequences of actual and potential radionuclide releases to waters in the public domain, it has been necessary to describe in detail the topography, geology, and hydrology of the SRP site.

The surface of the SRP site slopes gently seaward and is dissected by several surface streams and many small valleys in the northern half, giving way in the southern half to a series of scarps, terraces, and shallow depressions (bays) (Cooke 1936, Siple 1967, Flint 1970, Langley and Marter 1973, ERDA 1977c). The surface streams have been mapped, and their annual flow patterns and the sources of their waters have been determined (ERDA 1977c). An outline of the SRP site and the underlying bedrock is shown in Figure 2.

As shown in the geologic profile in Figure 3, the overburden has an average thickness of 300 m and consists of six distinct, layered, unconsolidated sedimentary formations interbedded with thin layers of

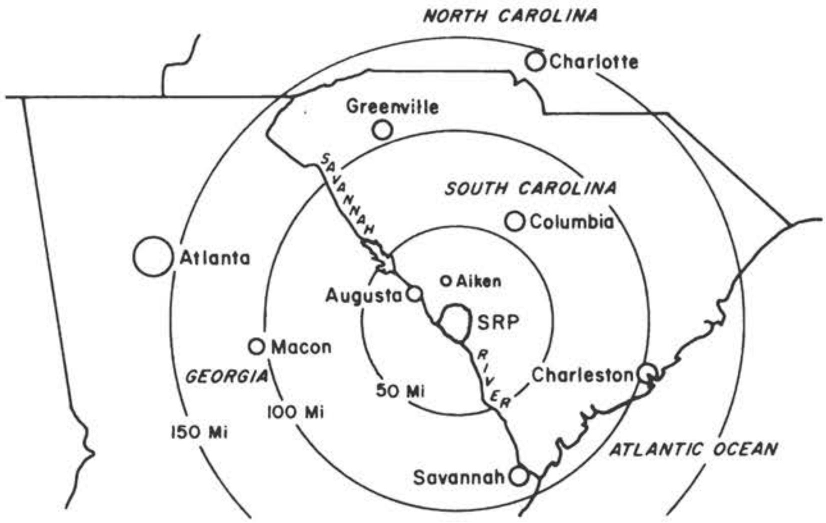

FIGURE 1 Location of SRP relative to surrounding population centers.

SOURCE: ERDA 1977c.

clay. The uppermost, Cenozoic, sequence is composed of about 60 m of marine sediments, the Hawthorn and Barnwell formations of Miocene age and, beneath them, the McBean and Congaree formations of Eocene age (Christl 1964). All except the Hawthorn formation yield water, which is used almost entirely for SRP operations. Water in these near-surface formations is recharged by percolating rainwater and at upland outcrops on the site: discharges occur where the formations are exposed, either into plant streams or into the Savannah River (Siple 1967, Bradley and Corey 1976, ERDA 1977c).

The Ellenton formation (marine origin, Upper Cretaceous age) and the Tuscaloosa formation (nonmarine origin, Lower Cretaceous age) lie between the near-surface formations and the bedrock (Christl 1964). The two formations, with a combined thickness of about 250 m, consist mainly of highly permeable sandbeds, which yield large amounts of ground water of consistently high quality (~30 mg/l of dissolved solids) (Siple 1967, Marine 1976). Much of the concern about past and present waste management practices at SRP and proposals to dispose of high-level waste in bedrock beneath the site has stemmed from the possible threat of contamination of aquifers by waste radionuclides.

The Tuscaloosa and Ellenton formations appear to be hydraulically separate from the overlying formations (Siple 1967, Bradley and Corey 1976). Water is recharged where their rocks crop out in the uplands about 30 km north and east of SRP; it follows an arcuate path beneath the site and discharges into the Savannah River near Augusta, Georgia. At present, some small communities upgradient from SRP draw water from those formations (where they are closer to the land surface), but by far the greatest amounts of ground water are taken for SRP operations. The Cretaceous sediments that extend into Georgia

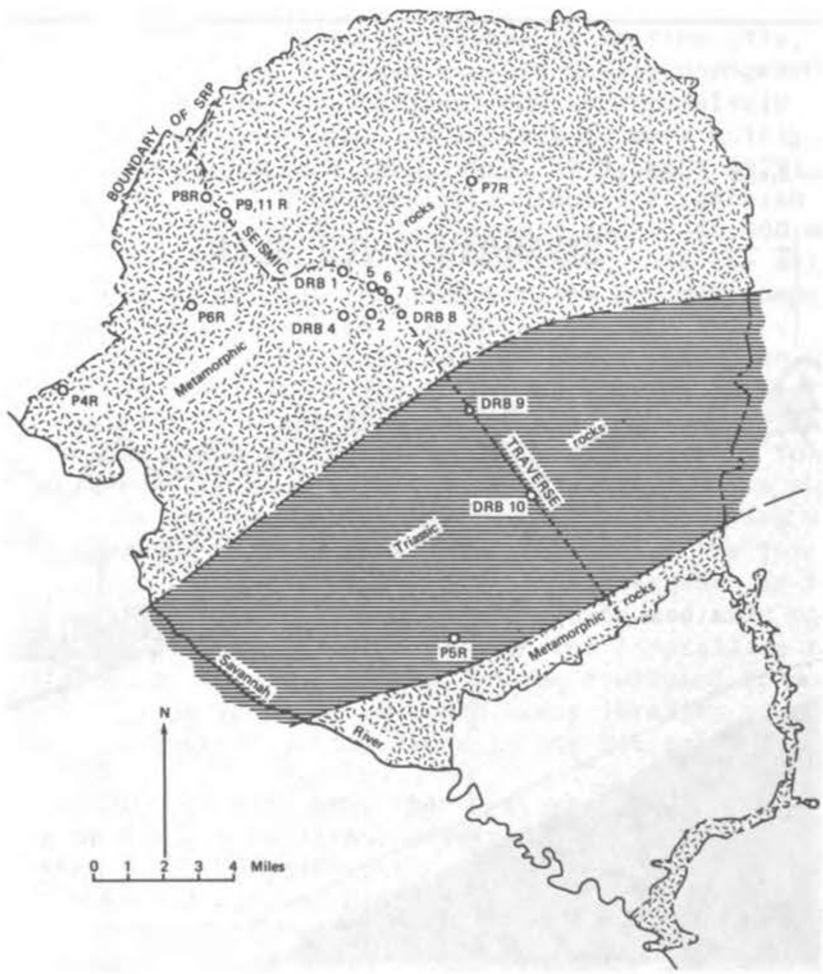

FIGURE 2 Distribution of bedrock types underlying SRP, showing location of deep rock boring sites (DRB1 through DRB10) and orientation of vertical geologic cross section (Figure 3).

SOURCE: NRC 1972.

are recharged in upland outcrops to the north and west, well away from the SRP site; thus the Tuscaloosa formation has been effectively divided by the cutting action of the Savannah River (Bradley and Corey 1976, ERDA 1977c).

There are two kinds of bedrock below the SRP site (Figure 2). The northern two thirds of the site is underlain by the metamorphic crystalline bedrock of Precambrian or Paleozoic age that is typical of the region (Christl 1964); beneath the southern one third of the SRP site is the consolidated sedimentary rock of a buried Triassic basin (NRC 1972, Marine and Siple 1974). The upper 25 m, on the average, of the bedrock is a zone of weathered bedrock materials rich in clay (Christl 1964, Marine 1976, USGS 1979). The hydrogeology of the bedrock formations has been investigated, but their relationships to the overlying aquifer are still not certain. The Triassic rock and

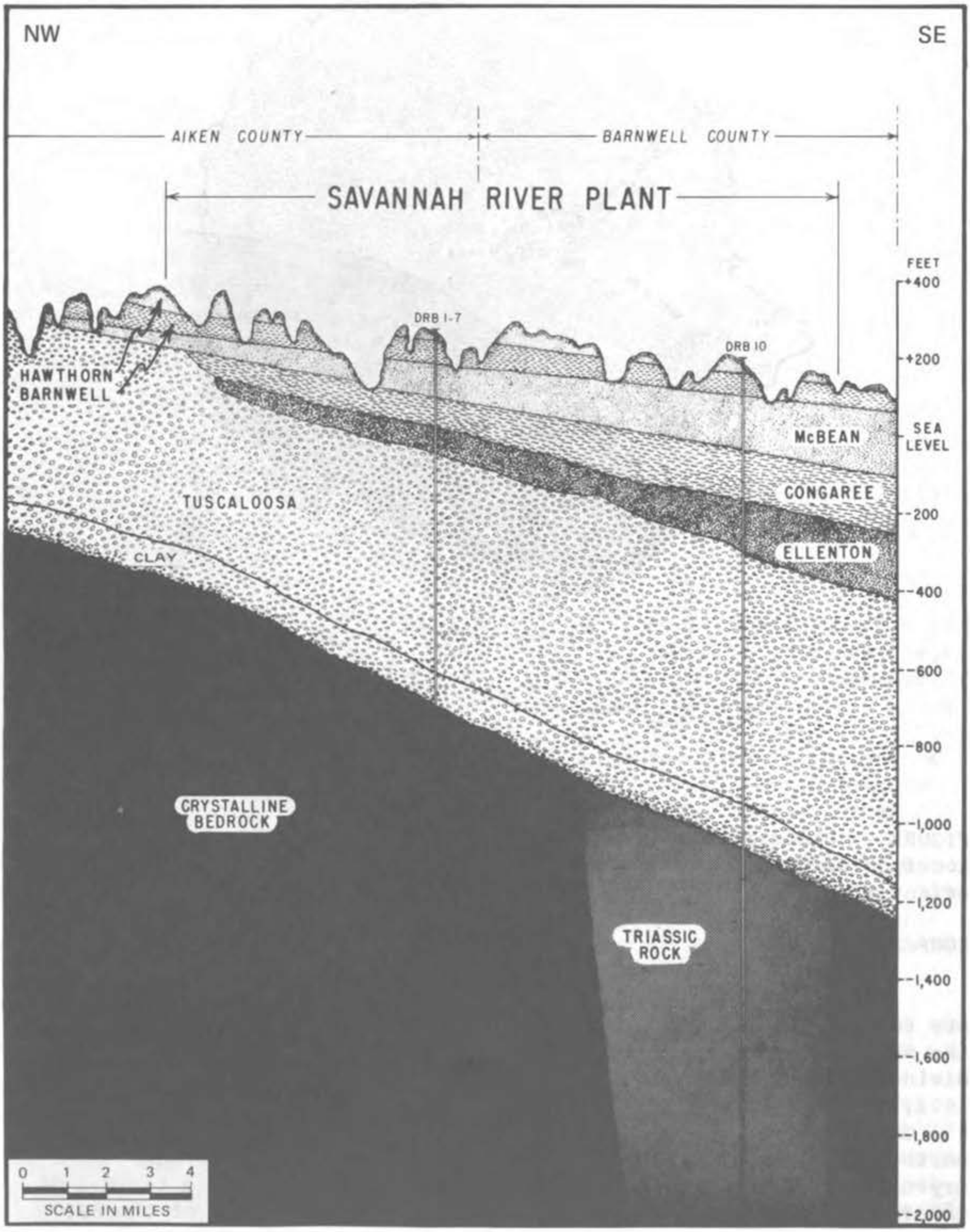

FIGURE 3 Vertical geologic cross section.

SOURCE: NRC 1972.

intact crystalline rock are sparingly permeable (Marine 1974, 1976; Marine and Siple 1974). The Triassic rock is nearly homogeneous and is minimally fractured. The crystalline rock is extensively fractured, and water in that formation appears to move mainly by way of those discontinuities (Marine 1966, 1967, 1979; USGS 1979; Webster et al. 1970). Waters in both bedrock formations are brackish to saline (crystalline rock, ~6000 mg/l; Triassic rock, ~18,000 mg/l) (Marine 1976). The salt concentrations are lower than the salt concentration in sea water, but the compositions are not compatible with the simple dilution of ancient sea water (Marine 1976). Estimates of the age of the crystalline rock water, based on He and ^{36}Cl contents, range upward from 500,000 years (Marine 1976), and the age of the water in the Triassic rock, based on its greater salinity and the low permeability of the rock, is presumed to be even greater. The hydraulic pressure in the crystalline rock is about 2 m of water greater, on the average, than that in the overlying aquifer. The pressure difference between the Triassic rock and the Tuscaloosa formation is about 64 m of water (average of measurements in two wells), and it appears to increase with both depth and salt content (Marine 1976). The pattern of water flow in the crystalline rock is considered to be about the same as that in the overlying formations with eventual discharge into the Savannah River (Bradley and Corey 1976), but the flow pattern of the water in the Triassic rock is not known (Marine 1976).

Regional seismicity is an important criterion in the design of facilities for producing, handling, storing, and disposing of radioactive materials. The SRP site is potentially subject to moderate ground shaking from earthquakes (Housner et al. 1968, ERDA 1977c); however, the only significant earthquake during the last three centuries occurred in 1886 and was centered near Charleston, South Carolina, 150 km to the southeast. Analyses and risk predictions indicate that a major earthquake near SRP is improbable (ERDA 1977c, DOE 1979a); however, surface facilities at SRP are designed to withstand an acceleration of 0.26 g, about 5 times the maximum acceleration estimated to have been experienced in the SRP area during the Charleston quake (DOE 1979a). The potential impact of seismic events on a waste repository, which has a bearing on decisions about disposal of the radioactive wastes at SRP, is discussed further in the second part of this report.

Chapter 4

RADIOACTIVE WASTE

The sources and characteristics of the radioactive waste and current radioactive waste management practices at SRP have been described (NRC 1972, 1976; Horton and Corey 1976; ERDA 1977a,b,c; DOE 1979a,b). The waste can be grouped in four categories: high-level; transuranic (TRU); low-level; and radioactive large equipment and structural items (LESI), including special waste. A summary of the amounts and types of radioactive waste stored at SRP is given in Tables 1, 2 and 3. A continuing discrepancy exists in the legal rules for classifying radioactive waste because concentration of low-level aqueous waste (e.g., by ion exchange) can lead to waste residues that clearly require the same management as high-level waste.

HIGH-LEVEL WASTE

High-level waste consists of liquids from the first-cycle solvent extraction system and concentrated waste from subsequent extraction cycles accumulated during reprocessing of irradiated reactor fuel for recovery of Pu and U, and concentrated waste from the production of a number of special radionuclides, in particular, heavy transplutonium elements. The liquid waste, initially acidic, is made alkaline, permitting sludge (insoluble metal oxides, hydroxides, and carbonates containing most of the activity) to settle out. The supernatant liquid is removed and reduced in volume by evaporation, producing a damp salt cake and highly alkaline residual liquor; the average composition of the high-level waste has been published (ERDA 1977c, DOE 1979a). Currently, 105,000 m^3 (27,744,000 gallons) of high-level waste is stored at SRP in buried double-walled carbon-steel tanks (Figure 4) in the form of alkaline liquids of various concentrations, semisolid sludge, or damp salt cake (see Table 1). The major radionuclides in the SRP high-level waste are shown in terms of recent curie inventory in Table 2.

The storage tanks are monitored for leakage both by automated means and by visual inspection. Despite the precautions, however, one tank (No. 16) was known to have leaked by seepage through a construction joint in the concrete outer shell. The leak occurred on September 8, 1960, went unchecked for 6 hours, and about 100 liters of liquid waste was estimated to have reached the soil. The leaked

TABLE 1 Volumes of High-Level Waste Stored at SRP by Phase as of March 20, 1981 (gallons)

	Total	Type III Tanks[a]	Type I, II, IV Tanks[b]
Supernatant liquid	17,869,000	10,114,000	7,755,000
Crystalline salt	7,070,000	3,028,000	4,042,000
Sludge	2,805,000	180,000	2,625,000
Total	27,744,000	13,322,000	14,422,000

[a]Type III tanks are full double-walled carbon steel as shown in Figure 4. Used since 1967 (ERDA 1977c).

[b]Type I, II, and IV tanks are single-walled carbon steel constructed between 1951 and 1961 (ERDA 1977c).

SOURCE: du Pont 1981, Table I.

TABLE 2 Radioactivity of Major Nuclides in SRP High-Level Waste (Ci)

Radionuclide	Total	Type III Tanks	Type I, II, IV Tanks
^{137}Cs (as of March 20, 1981)	1.3×10^8	9.0×10^7	3.7×10^7
^{90}Sr (as of March 20, 1981)	1.2×10^8	3.1×10^7	9.2×10^7
^{239}Pu (as of Nov. 30, 1980)	2.0×10^4	—	—
^{238}Pu (as of Nov. 30, 1980)	1.0×10^6	—	—

NOTE: One curie equals 3.7×10^{10} bq (becquerel).

SOURCE: du Pont 1981, Table II.

TABLE 3 Solid Waste Storage at SRP as of March 31, 1981

		Quantity of Radionuclides			Volume of Waste Packages (m^3)	
Waste Category	Species	Retrievable	Nonretrievable	Unit	Retrievable	Nonretrievable
U, Th	U, Th	3	480	kg	26	470,000
Low-level waste	Total	37,000	9,400,000	Ci	540	750,000
β, γ	Fission products	26,000	710,000	Ci	510	220,000
	Induced activity	900	4,500,000	Ci	15	480,000
	^{3}H	1,600	4,000,000	Ci	7	16,000
	Other[a]	8,500	180,000	Ci	11	390
α		0	5,000	Ci	0	30,000
TRU	Total	77	9[b]	kg	2,500	31,000[b]
	^{242}Pu	0.4	0	kg	8	11
	^{244}Cm	0.5	0.1	kg	390	5,800
	^{252}Cf	∿0	∿0	kg	220	56
	^{239}Pu	49	9	kg	940	11,000
	^{237}Np	8	0.2	kg	70	240
	^{238}Pu	19	0.2	kg	810	3,700
	$^{241,243}Am$	∿0	∿0	kg	21	∿0

[a]Other includes Zr, Po-Be sources, nonradioactive classified waste, and some control rods.

[b]Includes only the TRU waste buried before June 1974. Since June 1974, TRU waste has been stored retrievably.

SOURCE: du Pont 1981, Table III.

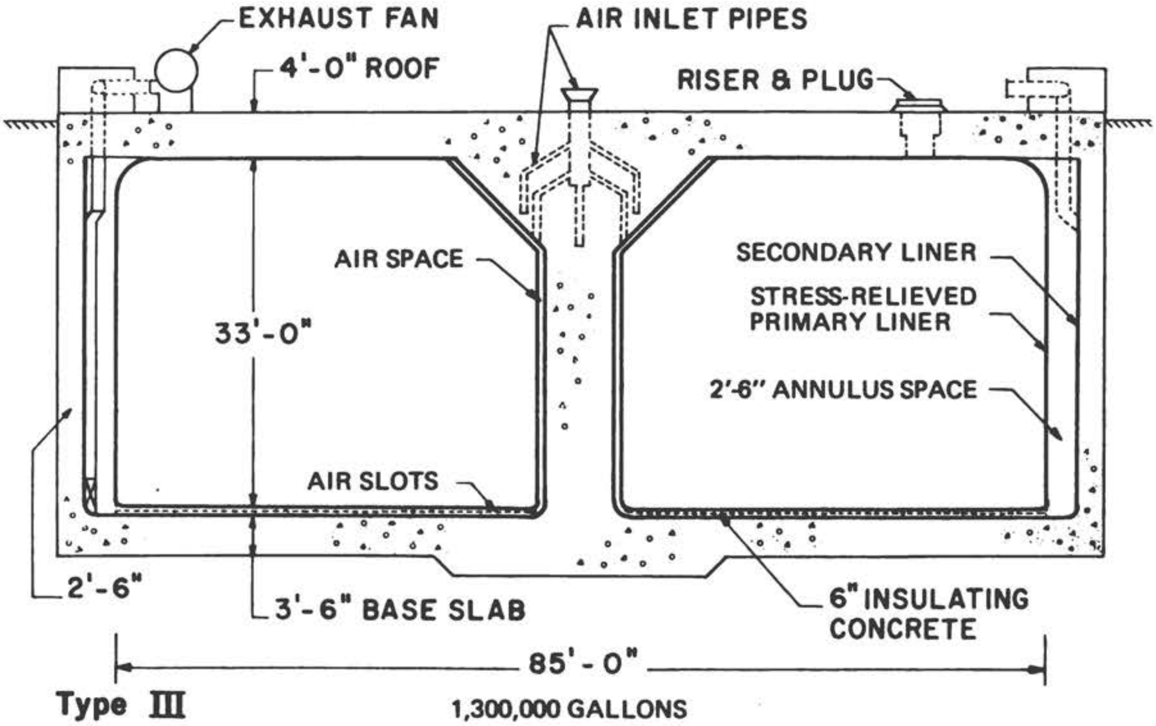

FIGURE 4 Type III tanks for cooled storage of high-level liquid radioactive waste at SRP.

SOURCE: ERDA 1977c, Figure II-23, simplified.

waste contained 2 Ci of radionuclides per liter: 87 percent $^{135,137}Cs$, 4 percent ^{106}Ru, 2 percent ^{90}Sr, and 7 percent of other nuclides with half-lives of 64 days or less. The tank was subsequently removed from service in March 1972. A study of the No. 16 tank leak (Poe et al. 1974) included detailed and quantitative analyses of possible leakage pathways to the adjacent soil, measurements of local ground-water flow rates, and sorptive characteristics of the subsoil beneath and around the tanks. The leak occurred within the water table, and waste reached the saturated zone of the soil immediately. However, the ground water moves so slowly in the area around the tanks that even a poorly sorbed nuclide like ^{129}I can move only about 1 m/year (3 mm/day). Nuclides such as ^{137}Cs and ^{90}Sr, which are delayed by sorption on soil particles, have moved much shorter distances. Radioactivity levels measured in cased wells, 4.5 m from the concrete tank foundation, show radionuclide concentrations of 5 to 15 pCi/l (1 pCi = 10^{-12} Ci), about 10 times normal background. Calculations based on the measured ground-water velocity indicate that the contaminated water will not reach a discharge area in less than 100,000 years.

The tanks are constructed underground with their tops at surface grade and are designed to withstand shaking from earthquakes up to 0.2 g horizontal acceleration. This design is conservative, given the seismic history of SRP, and makes the tanks virtually immune to man-made and natural disasters.

TRU WASTE

TRU waste has been defined in various ways at SRP since 1953. Currently, the term is applied to materials containing more than 10 NCi (1 NCi = 1 x 10^{-9} Ci) of long-lived alpha emitters per gram and low concentrations of beta-gamma emitters (DOE 1979b). Such waste is produced primarily in the SRP product-conversion areas and in the chemical separations plant, where U and Pu are separated from other radionuclides and matrix materials. The waste is in both liquid and solid forms, but the small volumes of liquid TRU waste have generally been combined with high-level waste in the tank farm (ERDA 1977c, DOE 1979b).

Past disposal practices for solid TRU waste have ranged from simple trench burial in a variety of containers, to retrievable or irretrievable burial, on the basis of maximum emission level at the surface of the container. At present, TRU waste is stored in retrievable containers on concrete pads (Figure 5). The containers are then covered with plastic and soil, which is seeded with a grass cover to retard erosion (Horton and Corey 1976). Such storage is considered an interim procedure, to be used until a method is decided on for disposal.

Buried TRU waste may be subject to unexpected leaching with slow migration of radionuclides into the shallow ground water. Continuous and extensive monitoring, however, has shown no trace of leaching thus far (ERDA 1977c, Wilhite 1978, DOE 1979b).

LOW-LEVEL WASTE

Solid waste containing less than 10 NCi/g of alpha-emitting, usually TRU radionuclides is considered low level. The dominant radionuclides are beta-gamma emitters, and the waste consists largely of small solid materials, resins, and equipment that can be handled without special shielding (Horton and Corey 1976, ERDA 1977c).

Low-level solid waste presents a problem, not so much because of the magnitude of its radionuclide content, but because of the volume of such material that is generated during routine handling of highly radioactive material. The SRP low-level waste is buried without intent to recover in trenches in a 195-acre area designated for that purpose, as shown in Figure 6 (Horton and Corey 1976, NRC 1976). Some potential for minor contamination of ground water exists, and the burial ground is equipped with a network of monitoring wells, which are sampled biweekly (Fenimore 1977, ERDA 1977c).

FIGURE 5 Storage pad and container for TRU alpha waste.

SOURCE: ERDA 1977c, Figure II-36.

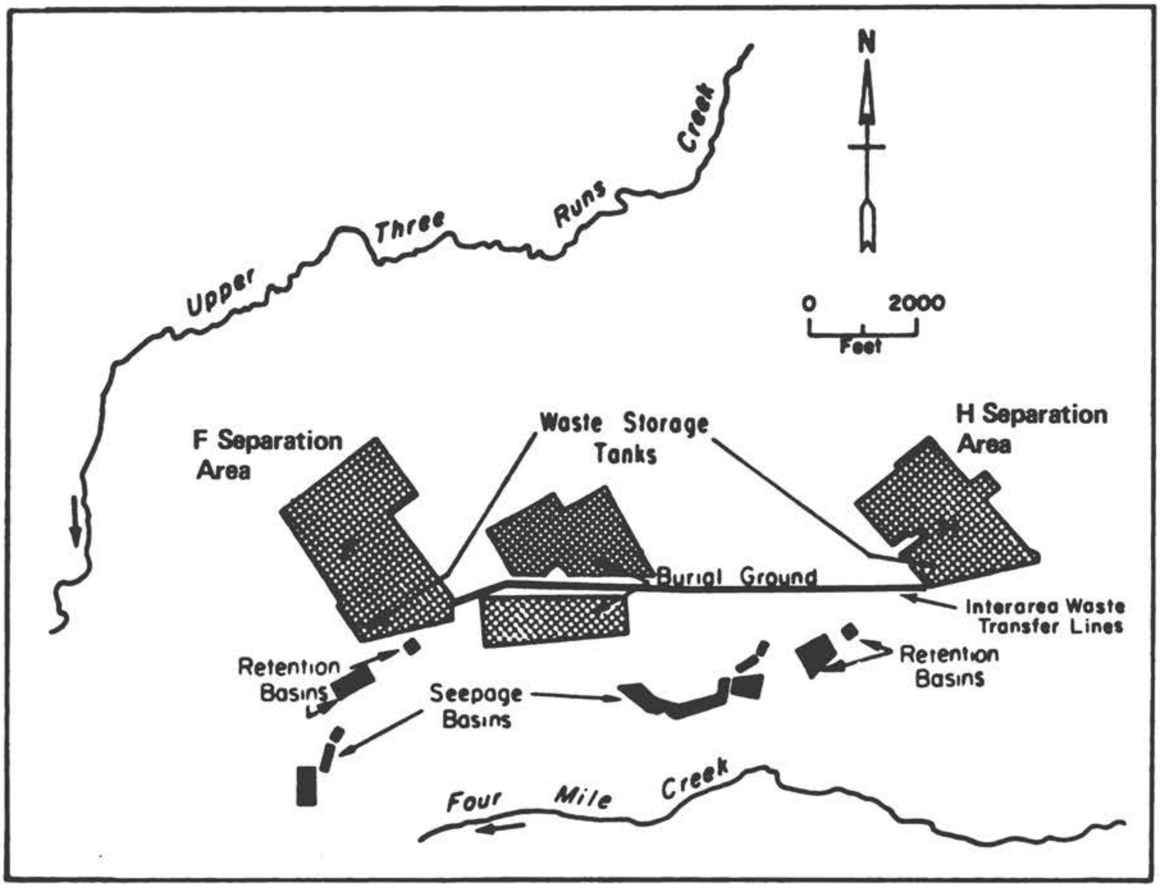

FIGURE 6 Relative locations of separation areas and associated waste-handling facilities.

SOURCE: ERDA 1977c, Figure II-13.

TABLE 4 Radioactive Effluents and Radioactive Waste Generated at SRP During 1975

Atmospheric Releases (Ci)

	Reactor Areas (P, K, and C)	Separation Areas (F and H)	Heavy Water Production Area	Laboratory Areas	Total
Tritium	159,000	325,000[a]	3,000	600	490,000
^{14}C	39	27	—	—	66
^{41}Ar	65,000	—	—	—	65,000
^{85}Kr	—	520,000	—	—	520,000

Aqueous Releases to Plant Streams (Ci)

	Reactor Areas (P, K, and C)	Separation Areas (F and H)	Heavy Water Production Area	Laboratory Areas	Total
Tritium	45,000	9,000	1,600	—	56,000

High-Level Liquid Waste (millions of gallons)

Fresh waste generated	3.0
Volume reduction by evaporator operations	2.0
Net volume increase	1.0

Radioactive Solid Waste (m^3)

Transuranium bearing	2,600
Other radioactive	18,200

[a]Includes 182,000 Ci accidentally released on December 31, 1975.

SOURCE: ERDA 1977c, Table I-1.

Two other types of low-level wastes at SRP also require disposal: gaseous process emissions and aqueous process effluents. The amounts and specific radionuclide composition of these wastes have been reported and are shown for a representative year in Table 4. The gaseous radioactive waste intentionally released to the atmosphere is primarily tritium or tritiated water vapor and noble gases, short-lived (^{41}Ar) or relatively short-lived (^{85}Kr). Aqueous waste containing acceptably low concentrations of radionuclides (as defined in ERDA (1977c) is piped to seepage and evaporation basins from which the water, but very little of the radionuclide content, makes its way to surface streams. Environmental monitoring networks trace the movement and disposition of the radionuclides in the atmosphere, in aquatic environments, and beneath seepage basins (Cooper and Rusche 1968, Fenimore 1968, Cooper 1974, ERDA 1977c).

LESI WASTE

Some equipment and many structural items contaminated by radionuclides are too large to fit into prefabricated concrete containers. Such LESI waste is generated primarily at the separation plants. If the equipment is contaminated by TRU nuclides, it is stored using the same precautions used with other solid items containing TRU (DOE 1979b). LESI items not contaminated by TRU are sorted on the basis of emission level and buried without intent to retrieve in earthen trenches. The ground water in the proximity of buried LESI waste is monitored for any radionuclide contamination (Horton and Corey 1976, ERDA 1977c).

Chapter 5

MONITORING PRACTICES

Gaseous and liquid process waste is monitored before intentional release. In addition, a comprehensive surveillance program has been established at SRP, both on and off the site, to monitor all releases of radionuclides, whether intentional or accidental (ERDA 1977c).

AIRBORNE RELEASES

The principal radionuclides released are tritium and noble gases, which are intentionally vented as stack gas within current environmental guidelines for maximum permissible concentrations. As is shown in Figure 7, the amounts of tritium released have been reduced over the years (ERDA 1977c). Atmospheric releases from SRP operations disperse over off-site areas. Twenty-eight off-site stations have been established to monitor airborne radionuclides including tritium. That system, the Atmospheric Release Advisory Capacity (ARAC), provides an adequate method of detecting and predicting the fate of any accidentally large release of radioactive gases or particulates. Test exercises of emergency response to specific accident scenarios are periodically conducted using the system. Coordination of ARAC with the U.S. Air Force Global Weather Service and monitoring systems at other DOE sites and laboratories extends the usefulness of the system beyond the SRP area (ERDA 1977c, Dickerson et al. 1979).

AQUEOUS RELEASES

Accidental releases of significant amounts of nongaseous radionuclides would most likely be the result of leakage from buried storage tanks containing high-level waste. A variety of remotely controlled devices and automated systems are used continuously to detect such leaks, so that remedial action can be taken before the waste can reach the soil, and procedures have been developed to recover and contain the nuclides (ERDA 1977c, DOE 1980a).

The most likely pathway for significant off-site contamination from radioactive waste is through ground water. The measured rates of

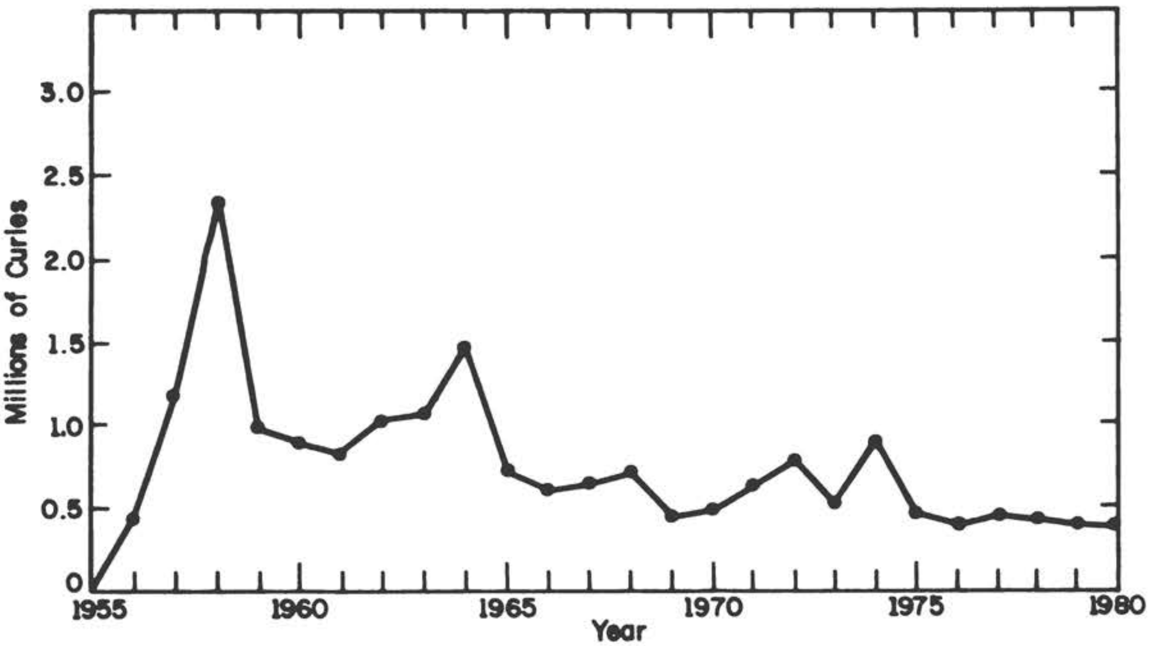

FIGURE 7 Annual releases of tritium to the atmosphere at SRP, including 0.479 million Ci of elemental tritium gas released on May 2, 1974, and 0.182 million Ci released on December 31, 1975, during abnormal operations. These two abnormal releases are treated separately for purposes of calculations of dose commitment.

SOURCE: ERDA 1977c, Figure III-1, for data through 1975 and du Pont 1976a, 1977, 1978, 1979, 1980 for data from 1976 on.

ground-water flow are low (Siple 1967, Fenimore 1968, Poe et al. 1974), and sorption of many of the radionuclides by the sediments retards the migration of the contaminants to such a degree that even this hazard is low, because most of the radionuclides would have decayed to insignificant levels before they reached the boundary of the plant site (Prout 1958, 1959; Fenimore and Horton 1968; Poe et al. 1974; Bradley and Corey 1976; Odum 1976). Surveillance to detect unexpected migration of buried radionuclides is, nevertheless, performed regularly by measuring the radioactivity in the water of the monitoring wells in the burial ground area. Streams, rivers, and other waters in the area are also monitored (ERDA 1977c, Alberts et al. 1979).

Because buried radionuclides can enter the biosphere through soil uptake by plants and ingestion of the plants by animals, biota in and surrounding the SRP site are monitored. Routine sampling is conducted of materials such as forage, fresh produce, milk, and domestic animals (ERDA 1977c).

REPORTING

All monitoring data are analyzed (Cooper 1974) and reported at least annually (for example, Reinig et al. 1973; Ashley and Zeigler 1976; du Pont 1976a). Radiation exposures, both occupational and to the general population, have been modeled, interpreted, and reported (ERDA 1977c; DOE 1979a,b, 1980c). The extensive investigations conducted thus far reveal no hazardous or adverse effects on the environment from SRP radioactive waste (NRC 1966, 1972, 1976; du Pont 1974, 1980; Poe et al. 1974).

Chapter 6

HAZARDS ASSOCIATED WITH SAVANNAH RIVER PLANT RADIOACTIVE WASTE MANAGEMENT

The major hazards associated with management of radioactive waste at SRP are those circumstances or events that could lead to significant radionuclide contamination of ground or surface water which, in time, could transport harmful amounts of radionuclides across the plant boundary and into the public domain. The largest accidental releases of nongaseous radionuclides at SRP to date have resulted from failures, e.g., leaking tanks, or spills of high-level waste during transfers to or within the tank farm. Leakage was stopped by moving the waste to sound tanks, and spills were contained on the SRP site and promptly cleaned up. The radiological consequences of those events to the off-site population were analyzed and found to be small (Poe et al. 1974, Odum 1976, ERDA 1977c). Emergency remedial action and monitoring procedures have been developed to cope with such events (ERDA 1977c).

Possible disastrous natural and man-caused events have also been analyzed to estimate their potential for releasing radionuclides from containment and dispersing them off site.

- Floods appear to pose little risk, because the facilities for handling and storing waste are on high ground in gently rolling topography (Horton and Corey 1976, ERDA 1977c).
- Hurricanes and tornadoes, as was noted earlier, occur in the SRP area. During the past 275 years, the region has been affected by a hurricane about every 7 years. However, the site is sufficiently far inland that open ocean wind velocities are diminished by the time they reach the plant. Risks posed by wind storms and tornadoes have been analyzed in conjunction with facility design and operating practices and found to be small. Because high-level waste is handled in massive reinforced concrete buildings and stored in underground steel and concrete tanks, the only significant potential hazard associated with winds would be the scattering of the usually small volume of low-level waste in transit to the burial ground at the time a tornado struck (Poe 1976a).
- As was mentioned previously, earthquakes have been considered a potential threat because SRP lies within an area of moderate seismic activity (ERDA 1977c). The risks of radionuclide dispersal from seismic activity have been

analyzed and are considered to be small for both current and proposed radioactive waste management practices (NRC 1972, Poe 1976b, ERDA 1977c, DOE 1979a).

Over long periods, soil erosion might uncover and move some of the shallowly buried waste (Horton and Wilhite 1978). However, any waste buried that shallowly is initially of a low radioactivity level, and most of the buried radionuclides have such short half-lives that no long-term hazard is involved.

Unlikely events such as airplane accidents with finite probability but near-zero damage and meteorite impacts with near-zero probability but finite damage have been postulated but found to constitute insignificant radiological hazards (Poe 1976c; ERDA 1977b,c). Sabotage is not considered a significant threat, because of the high level of security at SRP and the small potential for damage from the saboteur's point of view (du Pont 1976b).

CRITIQUE AND EVALUATION

Including Alternatives for Long-Term Management of Savannah River Plant Radioactive Waste, Conclusions, and Recommendations for Future Action

Chapter 7

MONITORING PRACTICES AND WASTE OTHER THAN HIGH LEVEL

Although neither past nor current management practices at SRP have released radioactive waste in amounts large enough to deliver significant radiation doses to the public, maintenance of the current level of safety requires continuing reappraisal, additional aims of which will be to achieve long-term solutions as well as to improve interim management practices. The public and the scientific community have been most concerned with the management and disposal of high-level waste, and much of the attention of the Panel was focused on those subjects. However, the current and planned practices for managing and monitoring the other categories of radioactive waste at SRP also needed to be evaluated. That evaluation has, in fact, pointed to procedural improvements that, in the judgment of the Panel, merit implementation in the near term.

The second part of this report is a critique and evaluation of the descriptive and background information about radioactive waste at SRP presented in the first part. The conclusions and recommendations given here, which relate specifically to the SRP monitoring program, current waste management procedures, and long-range alternatives, are based on the judgment of the Panel after study of the referenced documents and the material presented in briefings by SRP and DOE personnel.

LOW-LEVEL WASTE

Options for managing low-level waste in the future include the following: (1) continuation of present practices of shallow burial on site; (2) option 1 above coupled with monitoring for radionuclide movement and other improvements; (3) the construction of engineered surface structures or shipment to another site; and (4) the inclusion of low-level materials with high-level and TRU waste. The last two options are costly, and the Panel considers them unwarranted because the potential hazards of low-level waste are so small.

In the judgment of the Panel, current methods of managing low-level waste, including release of tritium gas, tritiated water vapor, and the other process gases to the atmosphere, have not created radiation hazards to the general public.

Recommendation: Current management practices of on-site shallow land burial of solid low-level waste and of release of process effluents should be continued. In addition, where not already accomplished, the following should be done:

1. Low-level burial grounds should be upgraded by contouring the land to promote surface runoff into concrète-lined ditches, thereby protecting the steeper slopes of burial sites against erosion.
2. The burial grounds should be monitored routinely to detect unexpected changes in the condition of the soil nearby and to detect unexpected leaching or movement of hazardous nuclides.
3. New low-level (non-TRU) solid waste should be incinerated or compacted, or both, as long as doing so is commensurate with economic and logistic considerations and regulations.
4. Low-level liquid waste should be processed only if discharge into evaporation and seepage basins would result in accumulation of substantial amounts of mobile radionuclides.

TRU WASTE

A broad assessment of alternatives for long-term management of TRU waste at SRP (DOE 1979b,c) revealed three fundamental options: (1) continue the present practice of placing TRU-contaminated materials in 55-gallon steel drums or prefabricated concrete vessels, (2) improve on the first option by reducing the volume of waste to be contained by incineration or compaction, or both, where appropriate, and (3) improve the first two options by adding immobilization as a final step.

Following treatment, the waste is currently stored awaiting the adoption of a final disposal plan. Interim storage on concrete pads can be continued, or more costly warehouses for storage can be constructed. Additionally, there is the alternative of moving the waste to another site.

With respect to the existing TRU waste, any discovered deficiencies can be remedied by upgrading the burial grounds or, if serious enough, by exhuming the waste and treating it in the manner chosen for TRU waste generated in the future. Such steps can be taken, if continued surveillance of the existing waste reveals unexpected radionuclide migration, which could, if ignored, lead to ground-water contamination.

In the judgment of the Panel, the past and current management practices for TRU waste have not resulted in radiation hazards to the public. The Panel believes, however, that the earlier methods of shallow land burial, now discontinued, should not be considered options for TRU waste in the future because of the high rainfall at SRP with its potential for nuclide leaching and subsequent ground-water contamination. The present method of storing TRU waste in retrievable barrels placed on concrete pads is an acceptable management alternative that can be continued as an interim measure. Continued storage in this retrievable manner will facilitate ultimate disposal once a method has been chosen.

Recommendation: Current practices for handling and on-site storage of TRU waste should be continued.

1. Current burial grounds for TRU waste should be upgraded by placing riprap or equivalent protection in areas of potential erosion, and the land surface should be recontoured where necessary to improve surface runoff.
2. Recoverable and new TRU waste should be prepared for further handling by storing them in containers in a compacted, nonflammable form for eventual isolation in a permanent repository.

Recommendation: Surveillance of previously buried TRU waste should be continued to detect any unexpected radionuclide movement that might necessitate exhumation. Exhumation of TRU waste should be reevaluated when an acceptable permanent disposal system has been identified. Exhuming buried waste is both difficult and potentially hazardous to operating personnel, and the waste should be exhumed only if hazards from previously buried waste is discovered or if the proposed disposal method has significant safety advantages over leaving the waste in place.

LESI AND SPECIAL WASTE

Treatment and isolation of LESI waste are complicated by the frequent presence of long-lived TRU radionuclides among the other radioactive contaminants. Thus the extent of TRU contamination in this waste must be determined before final disposition can be considered. If intense short-lived beta and gamma radiation prevents a determination, the most viable options are to (1) decontaminate or hold the LESI waste in retrievable storage for beta-gamma decay to the point where TRU nuclide concentration can be assessed or (2) assume that the waste is TRU in nature and treat it as such.

For non-TRU LESI waste, the alternative treatment options are (1) no treatment, (2) decontamination by chemical or physical cleaning, and (3) volume reduction, i.e., dismantling. Non-TRU LESI waste can then be isolated in the same manner as are other non-TRU low-level waste.

For LESI waste that contains TRU contamination, the treatment options are to (1) dismantle and package to prepare the waste for the same kind of long-term isolation as other TRU waste or (2) decontaminate it to the extent possible, a process that may or may not generate non-TRU waste products, and isolate it in the same manner as other TRU waste.

Ion-exchange resins and spent solvents, although generally classified as low-level waste, can be special cases that must be dealt with separately. Resins can contain high concentrations of radionuclides, which should be isolated along with high-level and TRU waste. Ion-exchange waste is currently stored in containers on concrete pads. Treatment alternatives would be to dry them or incinerate them, or both. Similarly, spent solvents are now held in special tanks. Treatment alternatives for them include incineration to reduce volume and fire hazard, followed by isolation of the ash and sludge in the manner of TRU waste.

Past management of LESI waste, ion-exchange resins, spent solvents, chemical waste, and solid non-TRU waste at SRP has not resulted in a hazard to the public health (i.e., no population dose commitment significant with respect to normal background radiation). However, the method of burial of some TRU-contaminated waste in the past is no longer considered acceptable practice because of the long half-lives of the radionuclides, the high rainfall at SRP, and the potential for ground-water contamination. This situation will require continued surveillance until the near-immobility of the TRU wastes is assured.

Recommendation: LESI waste should be treated as TRU waste or decontaminated to the point that the extent of nonremovable TRU contamination can be determined. Large items from which loose material has been removed can be placed in open-air storage or cast into concrete blocks or monoliths depending on their level of radioactivity.

1. TRU LESI waste should be treated as other TRU waste by dismantling to the extent that is practical and stored in containers above ground for eventual isolation in a permanent repository.
2. Non-TRU LESI waste should be stored under controlled conditions until the beta and gamma radiation decays to a point that allows handling and dismantling or other methods of volume reduction and disposal in the manner of low-level waste in shallow land burial trenches.
3. Exhumation of non-TRU waste should be considered only if a clear and present danger to the public can be shown and such danger is greater than the risks of exhumation itself to operating personnel and the public.

Recommendation: Incinerate ion-exchange resins and spent solvent waste under controlled conditions and treat ashes containing significant amounts of long-lived nuclides as TRU waste.

MONITORING PRACTICES

In the judgment of the Panel, the radiation protection practices at SRP for radioactive waste management have been adequate and effective.

Recommendation: All current monitoring procedures should be continued and improved, where appropriate, as new information and analytical capabilities become available.

Recommendation: Surveillance of tritium releases should be refined. Because the form of tritium is of biological importance, efforts should be made to distinguish between tritium hydroxide (tritiated water) and elemental tritium gas as it is released. Further, measurements of tritium in atmospheric moisture will reflect variations in tritium released to the atmosphere better than concentrations in rainfall, because water vapor may be widely dispersed after release before being condensed as rain, and because so many extraneous variables operate on rainfall. Therefore tritiated water vapor collections by standard freezeout or desiccant columns should be made at least at the close-in locations to provide data on actual levels of airborne tritium hydroxide reaching the environment.

Chapter 8

HIGH-LEVEL WASTE

ALTERNATIVES

The suitability of various methods for long-term isolation (disposal) of the SRP high-level waste has been debated since the early 1960s, and as noted in the introduction, the NRC through its Committee on Radioactive Waste Management has been a major participant in the debate (NRC 1966, 1972). Comprehensive technical summaries and evaluations of alternatives for disposal of the SRP high-level waste have been prepared (ERDA 1977a,b). Subsequently, most of that material was incorporated into a Final Environmental Impact Statement on Long-Term Management of Defense High-Level Radioactive Wastes: Savannah River Plant (DOE 1979a). The reader is referred to those documents for concise statements of the history and status of alternatives for long-term management and disposal of SRP high-level waste.

The major alternatives for long-term management and/or disposal of existing and projected SRP high-level waste can be summarized as follows:

- Continue storage of the high-level waste in buried double-shelled tanks as sludge, salt cake, and alkaline supernate, replacing the tanks and transferring the entire contents to the new tanks as necessary (estimated to be about every 50 years).
- In a new processing building, separate the sludge and the radionuclides from the salts (allowing the decontaminated salts to be treated as low-level waste); convert the waste nuclides to a low-solubility solid form such as a glass or concrete product; package the solidified waste in containers; and (1) ship it off site to an engineered underground repository; or (2) store it in an engineered surface facility at SRP; or (3) dispose of it in an underground repository in the SRP bedrock.
- Reconstitute the waste to a slurry and dispose of it in a cavern excavated beneath the SRP site, either in raw form as originally proposed by du Pont (Christl 1964) or mixed with additives appropriate to solidify and immobilize the slurried waste in place (U.S. NRC 1979).

The primary considerations in deciding among the major alternatives are as follows:

- Technical readiness: Descriptions of the operational steps and the kinds of structures and processes required to execute each alternative are given in NRC (1975), Bradley and Corey (1976), ERDA (1976, 1977a,b,c), and DOE (1979a,c, 1980a,b) and will be described only briefly below.
- Capital and operating costs: The estimated costs of the three major schemes, prepared by the SRP and du Pont engineering staffs under the assumption of phase-out of production in 1987, are summarized in Tables 5 and 6.
- Safety: Three safety-related elements, which have been identified and analyzed for all of the disposal alternatives--occupational radiation exposure, industrial accidents, and radiation doses to off-site populations (population doses)--are summarized in Table 7 for normal operations and expected radionuclide releases.

TECHNOLOGICAL ASPECTS, PROCESSES, AND FACILITIES

Interim Storage of High-Level Waste in Tanks

A combination of factors has delayed action on disposal of the SRP high-level waste, and in the meantime some of the waste has been stored for as long as 25 years in underground double-walled steel-lined tanks. In the early years at SRP, the performance of the double-walled tanks was untested, and neither the near-surface soils nor the ground-water flows were well characterized. Consequently, there was concern that leakage from tanks might seriously contaminate the ground water and that rain runoff into surface streams might move radionuclides spilled during transfers. Underground tank storage is now a well-understood technical practice (DOE 1979c); over the years tank leakage has been minor, and tank design and surveillance techniques have been improved (Poe et al. 1974, Odum 1976, ERDA 1977c, DOE 1980a). A large body of data has been collected on the sorptive properties of the near-surface sediments and the flow rates and pathways of the shallow ground waters at SRP, and techniques have been devised to control movement of spilled radionuclides (Poe et al. 1974, Odum 1976, ERDA 1977c, DOE 1980a). Recent appraisals (ERDA 1977c, DOE 1980a) do not indicate any technical urgency for implementing disposal of the high-level waste, because the buried tanks serve adequately to confine them. Apparently, tank storage could be used safely and at relatively low operating cost (approximately $4 million per year) as long as surveillance, maintenance, and periodic replacement are continued.

Prolonged tank storage has actually provided a technical advantage for eventual disposal of the waste: its heat production after storage is much lower, because most of the short-lived radionuclides have decayed. One major plan for disposal of radioactive waste

TABLE 5 Costs Common to All Alternatives That Include Separation of Existing and Projected Radionuclides from Salts, Vitrification, and Packaging of Waste (millions of 1980 dollars)

	Capital	Operating	Total
Removal of waste from tanks	145	95	240
Decontamination of salts	1065	315	1380
Vitrification	820	325	1145
Return of salts to emptied tanks	45	25	70
Replacement tanks	75	—	75
Research and development	20	150	170
Total	2170	910	3080

SOURCE: DOE 1979a, pp. x-4 to x-8.

deliberately includes a 40-year delay before geologic emplacement, because old cool waste presents fewer engineering problems and requires less space in a repository than does fresh hot waste (Kärnbränslesäkerhet 1977).

Separation and Solidification Processes

Transfer from Tanks

All the alternatives for disposal of the SRP waste involve at least one transfer of the salt cake and sludge from the existing tanks. Reconstitution of the SRP waste from its present status in the waste tanks as alkaline liquor, salt cake (chiefly $NaNO_3$), and alkali-insoluble sludge (chiefly metal oxides) will produce a suspension of sludge particles in a strongly alkaline, concentrated $NaNO_3$ solution. The ability to remove the wastes and decontaminate the tanks has been demonstrated (Hill 1967, Goodlett 1968, ERDA 1977c).

Separations

All the disposal alternatives that have been considered by the Department of Energy involve surface conversion of the waste to a solid product (except for fused salt) and require separation of the radionuclides from the water and salts in the reconstituted waste slurry. If the volume of the high-level solid products is not substantially reduced by removal of water and salts, the costs for containers, transportation, and temporary storage space are greatly increased. The method proposed by the SRP staff and others involves

TABLE 6 Costs of Major Alternatives for Disposal of Existing and Projected SRP High-Level Radioactive Waste (millions of 1980 dollars)

	Capital	Operating	Total
Continued Storage in Buried Tanks			
Tanks and removal equipment (annuity cost)[a]	390	95	485
Surveillance	—	25	25
Total	390	120	510
Glass in Geologic Repository Off Site			
Removal from tanks, separation, vitrification[b]	2170	910	3080
Temporary storage	80	30	110
Transportation	20[b]	50	70
Geologic repository[c] and containers	290	50	340
Total	2560	1040	3600
Glass in Surface Storage at SRP			
Removal from tanks, separation, vitrification[b]	2170	910	3080
Storage facility and containers	590	80	670
Total	2760	990	3750
Glass in Geologic Repository at SRP			
Removal from tanks, separation, vitrification[b]	2170	910	3080
Bedrock cavern and containers	430	100	530
Total	2600	1010	3610
Raw Slurry to Bedrock Cavern at SRP			
Removal from tanks	145[c]	95	240[d]
Bedrock cavern	380	60	440[d]
Research and development	10	65	75
Total	535	220	755[d]

[a]See discussion on page 41.

[b]See Table 5.

[c]Repository cost share based on fraction of space occupied by SRP waste (calculated from heat production).

[d]In situ solidification will cost more for additives, about 25 percent larger cavern size, and additional research and development.

SOURCE: DOE 1979a, pp. x-4 to x-8.

TABLE 7 Unavoidable Radiation Exposures and Industrial Accidents for the Total Campaigns of Three Major Classes of SRP High-Level Waste Disposal Alternatives

	SRP Tank Replacement	Separated Waste in Glass Product: Off-site Repository	Separated Waste in Glass Product: On SRP Site Surface	Separated Waste in Glass Product: On SRP Site Repository	Raw Slurry in SRP Bedrock
Occupational exposure (man-rem)[a]	360	3750[b]	2640	2350	40
Industrial accidents--construction and operations[c]					
Major lost-time injuries	1600[d]	570	590	550	180
Fatalities	17[d]	7	6	6	2
Population exposure (man-rem)[a]	50[d] (2.4×10^4)[e]	750[f]	70 (200)[f]	200[f]	180[f]

[a]Data are from Table VI-1 (DOE 1979a) values rounded off to nearest 10.

[b]Includes 1350 man-rem for transportation at 50:50::truck:rail; derived from data in Tables V-24 (DOE 1979a) and VI-6 and VI-9 (ERDA 1977b). Range is 260 man-rem for all rail to 2450 man-rem for all truck.

[c]Data are from Tables V-5 and V-6 (DOE 1979a).

[d]If tanks are replaced every 50 years for 300 years.

[e]If tanks are abandoned after 100 years. Dose is from water ingestion only by a population of 7×10^4 people. Data are from Table V-25 (ERDA 1977c): values for industrial accidents and occupational exposures are one third of those shown.

[f]Population dose from eventual release of ^{129}I is estimated to be 130 man-rem (Bradley and Corey 1976) and the major unavoidable dose contribution for all disposal options. Normal background provides a dose to the same population of 2×10^5 man-rem each year.

separation of the sludge by a centrifugal process and removal of ^{137}Cs and ^{90}Sr from the stream by ion exchange on zeolite (Wiley and Wallace 1975, Wiley 1976). The separation steps reduce the $NaNO_3$ and Al^{+3} content and hence the volume of the high-level solid product. Ten of seventeen operations in the SRP proposed process are devoted to separations. The separation processes have been demonstrated in the laboratory, but further development and demonstration will be needed before they become operational at full scale.

Decontaminated Salts

The large volume of residual decontaminated salts adds to the complexity and cost of separating the radionuclides from the reconstituted waste. The salt cake consists of the nitrate, nitrite, hydroxide, aluminate, carbonate, and sulfate of sodium. The radionuclide content of the separated salts is expected to be low, but without a second decontamination step, it will have to be treated as low-level waste (DOE 1980b). At the present time, alternatives for management of the decontaminated salts start with a bulk process in which the salt solution from the separation process is fed back through existing evaporators from which it can either be stored as crystalline salt cake in the empty tanks or be solidified with cement in a saltcrete process for simple burial as low-level waste (Crandall 1980).

Solid Waste Form

The form in which the waste is emplaced in the repository will depend on the system alternatives. If the waste is to be shipped to another site for geological disposal, then a suitable solid waste form will be required. If the reconstituted waste slurry is piped into a deep geologic cavity under the plant without any separations, then the waste form is clearly different and may contain solidifying agents such as clay and cement. A third alternative is separation and surface solidification of the waste followed by emplacement in an on-site geological repository.

Waste Form for On-Surface Solidification. The status of research and development of waste forms for on-surface solidification of high-level radioactive waste has been reviewed (ERDA 1976; Cohen et al. 1977; DOE 1979c, 1980b; NRC 1979; Sandia Laboratories 1979). The solid forms that have been considered by the DOE for the SRP waste are fused salt, dry powder (dried sludge plus dried ^{137}Cs-zeolite), a concrete product, and borosilicate glass (Wallace et al. 1973, Kelley 1975, Stone et al. 1979). The choice of solid waste form will depend largely on the nature and location of the disposal site, e.g., surface or geologic repository on the SRP site or elsewhere, and the properties of the host rock in the case of a geologic repository. For purposes of discussion the SRP staff assumed that the host rock of a geologic repository off site would be salt or some other dry formation (ERDA 1977b, DOE 1980b). If the disposal is away from the SRP site, the solid waste form will have to meet as yet unspecified regulatory criteria for handling, transportation, and emplacement in a federal repository. An example of a proposed regulation is retrievability. Recent appraisals of the proposed solid waste forms indicate that neither dry powder (because of its dispersability) nor fused salts (because of solubility) may be able to meet regulatory criteria for waste form stability (Cohen et al. 1977; DOE 1979c, 1980b; du Pont 1979; U.S. NRC 1979).

The major research and development efforts to date in radioactive waste solidification have been directed toward glass, but considerable research has been carried out on the so-called advanced waste forms. Glass-making and forming processes are entering the pilot operation scale. Full-scale canisters of Savannah River Laboratory glasses have been cast. Further work is necessary to prevent devitrification and to optimize the process, but no insurmountable difficulties appear to be present. There is considerable activity on alternative waste forms in the fields of cement, artificial rock, supercalcine, and composite forms. Important characteristics of a waste form include heat conductivity and stability at higher temperatures, but the heat production of any high-level solidified waste depends on the concentration as well as the origin of the waste and is a systems variable that can be adjusted within limits (ERDA 1976; DOE 1979c, 1980b).

Each of these several forms has its own particular advantage and disadvantage. At the present time, it is premature to select one solid waste form as the prime candidate for isolation. That waste form must be considered in the light of the characteristics of the repository and its engineering design, as well as any multibarrier engineering that might be used.

Waste Forms for In-Situ Solidification. Actual disposal of intermediate-level waste has been accomplished by injection of liquid waste mixed with clay, cement, and other hardening agents directly into certain underground formations (De Laguna et al. 1968). These materials are of interest because of the proposal to investigate the pumping of unseparated reconstituted high-level waste in the form of a slurry containing hardening agents directly into mined on-site deep cavities. The cost has been estimated to be considerably lower than alternative disposal schemes, and the safety is claimed to be comparable because of the elimination of complex separation and on-surface solidification procedures. This option does, however, lack retrievability.

Transportation

Transportation of solidified waste off the SRP site does not appear to present any major technical or logistical problems (ERDA 1976, 1977b; DOE 1979c). Transportation by both truck and rail was considered. Spent reactor fuel (with much greater radiation and heat production) has been shipped successfully and safely by both methods, and designs approved by the Nuclear Regulatory Commission (U.S. NRC) for shielded shipping containers are available (10 CFR 71, 73 (1981); 49 CFR 171 (1980)). Weight limits were taken into account in estimating the number of shipments that would be required for various solid forms of the SRP waste, and costs of transportation were estimated from the number of trips required (ERDA 1977b, DOE 1979a).

Transportation of the SRP waste off the site adds to the complexity of the overall waste management system. It also adds an increment of potential radiation exposure to both occupational and population doses and moderate increments of monetary cost to disposal of SRP waste off site.

Surface Storage Facility

A preliminary design has been presented for a surface storage facility that would house packaged units of solidified SRP waste (ERDA 1977b). An extra concrete sleeve would serve as a radiation shield, and the units would be passively cooled. A similar design was considered by the NRC Panel on Interim Storage (NRC 1975) to be the most satisfactory form of surface storage for solid high-level waste. If solidified units of high-level waste are transported off the SRP site, a small surface storage facility will be needed to absorb differences in the timing of their production and transportation. A permanent surface storage facility would be an expansion of the temporary facility (DOE 1979a).

Such a facility appears not to present any serious technical problems, either in construction or maintenance, and in comparison with a geologic repository it could be constructed relatively quickly (DOE 1979c, 1980b). However, the cost of a surface storage facility large enough to accommodate the SRP waste inventory at any location is significantly greater for any solid form than the cost of geologic disposal at the same location.

The present Panel concurs with the conclusion of the Panel on Interim Storage (NRC 1975) that, "although acceptable for an interim period, retrievable surface storage is not a substitute for ultimate disposal of high-level radioactive wastes."

Geologic Repository

Two alternatives were considered for deep geologic disposal of the SRP wastes--a repository in SRP bedrock and a repository at an unspecified off-site location (DOE 1979a).

Off-Site Geologic Repository

Recent federal policy envisions establishment of regional federal repositories for commercially generated high-level waste, for which the capacities will be limited by the heat production of the waste inventory (DOE 1979c, 1980b; IRGNWM 1979). The 1979 Environmental Impact Statement for management of the SRP waste (DOE 1979a) made the reasonable assumptions that a federal repository would be available in a timely way to receive the SRP waste and that the costs of disposal would be allocated on the basis of the amount of repository space occupied (calculated from heat production).

As of the time that solidification of the SRP waste might begin (assumed in DOE (1979a) to be 1988), their total heat production will be about 1.7 MW, roughly 1 percent of the capacity of a conceptual federal repository. Total costs (as of 1980) for construction of such a repository ranged, depending on the host rock, from $2.4 to $4.0 billion (DOE 1980b), and so the estimated capital cost of emplacement of the SRP waste in an off-site federal repository for commercial high-level waste appears to be reasonable, based on repository heat loading.

As of now, no federal repository site has been finally selected, although data are being collected, and preliminary generic modeling studies are being conducted for several rock types (salt, shale, granite, basalt, tuff). It appears that it will be several years before the properties of a functioning off-site geologic repository and its distance from SRP are known with enough certainty to select an overall waste management system and make refined estimates of the potential radiologic hazards and the monetary costs involved. A premature decision on solid waste form and start-up of production, for example, could prove quite wasteful.

Geologic Repository in SRP Bedrock

The question of locating a disposal facility for the SRP wastes in bedrock beneath the site has been discussed for many years (Christl 1964; NRC 1966, 1972; Proctor 1968; Wolman et al. 1969; Bradley and Corey 1976); it is reconsidered in this report. It should be noted that the cost estimates for construction and utilization of caverns in SRP bedrock were based on preliminary designs prepared about 10 years ago for that specific facility and that the costs of that alternative have been adjusted for subsequent inflation. It should also be noted that no long-term hazard analyses were available for expected radionuclide releases from either the hypothetical geologic repositories discussed in ERDA (1977b) or a conceptual federal waste repository discussed in DOE (1979a). The long-term population dose that has been used for the case of a geologic repository off site (1.3×10^2 man-rem/year for the maximum year) is also postulated for normal performance of a Triassic cavern beneath the SRP site containing liquid waste. That value was based on the assumption that, although the major radionuclides would be retained for complete decay in each case, no rock formation could be expected to retain completely the very long-lived, geochemically mobile ^{129}I. That dose would be incurred over an extended period starting several tens of thousands of years hence.

MONETARY COSTS*

The monetary costs of the 29 waste management or disposal alternatives (ERDA 1977b) initially proposed for existing and projected SRP waste were reviewed. The costs of the three major prototype alternatives are shown in Tables 5 and 6.

The costs involved in removing waste from the existing tanks and for replacement tanks during a disposal campaign are common to all alternatives.

The costs of (1) research and development, (2) constructing, equipping and operating a shielded separation and solidification facility, and (3) packaging the solid waste and disposing of the decontaminated salts are common to all alternatives (except fused salts) that involve conversion of the waste to packaged solid units. In descending order, the cost of the solidification step plus containers is as follows: glass > concrete product > calcine > fused salts. However, the volume of fused salts produced would be very much larger than for any other solid form, and the cost advantages of not separating the radionuclides from the salts and disposing of them separately would be counterbalanced by the additional costs for temporary storage, transportation, and repository space (ERDA 1977b).

The cost of a temporary surface storage facility and additional radiation shielding and of transportation are common to those alternatives that involve shipment of the waste off the SRP site.

The costs attributable to a permanent surface storage facility or a geologic repository were discussed above and are tabulated in Table 6.

The Panel considers the cost estimates to be reasonable. However, because they involve facilities of a pioneering nature, the dollar values of the individual cost components, particularly of a geologic repository, may be in error by as much as ±50 percent. They appear to be internally consistent and therefore appropriate to use in judging the relative merits of the alternatives. Further, the present cost estimates agree in the aggregate with an estimate in 1972 that the cost of solidification (to dry powder), packaging, and transport of the SRP waste to an off-site geologic repository would be 5-10 times greater than the cost of disposal of a liquid waste slurry in an on-site geologic repository at the SRP (NRC 1972).

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* The Panel was informed that changes in the proposed solidification process were under consideration by DOE. If adopted, the changes would be expected to reduce costs of the baseline surface solidification process. Information on the proposed changes, however, was not available to the Panel early enough in the course of preparation of its report: DPST-81-507 was not transmitted to the Panel until June 19, 1981.

The figure for continued storage in tanks (see Table 6) is the approximate one-time cost of the annuity required to replace the tanks and transfer equipment every 50 years in perpetuity. It is the least expensive of the alternatives treated in Table 6.

The costs of the three major alternatives were also computed by using a 3 percent annual discount rate and the approximate dates that expenditures might be made. The absolute values of the costs of the alternatives were reduced, but the relative costs--tank storage < slurry in SRP bedrock < solidification alternatives--changed very little.

Certain relationships emerge from examination of the cost components of the various alternatives:

- The dominant costs of all alternatives (except continued tank storage and disposal of a liquid slurry in SRP bedrock) are those involved in separations and solidification.
- Geologic disposal at any location is significantly less costly than permanent emplacement in a surface storage facility.
- The cost of geologic disposal of packaged solid units of waste is not sensitive to the location of the repository. The disadvantage in cost of development of a repository at SRP versus an SRP share of a commercial off-site repository is offset by added costs of temporary storage at SRP, extra containers required for shipment off site, and transportation itself.
- Based on 1977 cost estimates (ERDA 1977b) for the subcases in which the waste is converted to packaged solidified units and placed in a deep geologic repository at any location, a glass product was expected to cost about 35 percent more than dry powder or fused salts and about 20 percent more than a concrete product.
- Disposal of decontaminated salts in any but bulk form is so costly that a second decontamination step might be considered, if bulk disposal were for some reason found not to be feasible.
- The economic costs of delay are small until major new facility construction is initiated.

SAFETY

Occupational Radiation Exposures

Radiation exposures of plant and transportation workers shown in Table 7 were estimated from SRP experience with comparable operations and from engineering estimates of the number of man-hours that would be required for each operation of each disposal alternative (DOE 1979a). Operatives will be exposed, mainly to whole-body gamma radiation during transfer, processing, and transportation of the waste, because gamma radiation, while reduced to low levels, is never completely absorbed by protective shielding. Thus the occupational exposures (all well below existing U.S. NRC limits as set forth in 10 CFR 20 (1981)) that would be incurred in executing the various disposal alternatives vary depending on the complexity of the system, i.e., the number of times waste units must be handled and the number of operatives needed to execute each procedure (10 CFR 20 (1981)).

Industrial Accidents

Industrial accidents are associated with the following aspects of the SRP disposal alternatives: construction, chemical technology, transportation, materials handling, and mining operations. Engineering estimates were prepared by the SRP staff for the numbers of man-hours required for various job categories, accident rates were obtained for each job category from industrial accident tables (National Safety Council 1976), and total numbers of lost-time injuries and fatalities were calculated and are shown in Table 7.

Radiation Exposure of the General Public

Population exposures, expressed as total radiation doses in man-rem, were estimated on a modular basis for normal operations and malfunctions (minor and major accidents) of the various procedures and facilities, and for a variety of plausible, but hypothetical, catastrophic events. The total population doses shown in Table 7 are those for normal operations and minor process incidents (for which there is SRP plant experience) of all components of each complete disposal alternative. Values for operation of surface facilities were calculated by the SRP staff (ERDA 1977b, DOE 1979a); those for a geologic repository were obtained from Bradley and Corey (1976) and DOE (1980b) as described above.

No numerical values of radiation dose to the general public were supplied for a surface storage facility even after abandonment (ERDA 1977b). However, for the very long term, a zero population dose seems inappropriate. The structure and its contents must be assumed to wear away eventually, causing a fraction of the very long-lived radionuclides to be entrained in surface waters and ultimately ingested by people. In the case of a surface disposal facility, it seems reasonable to apply at least as large a long-term population dose as was used for a deep geological repository.

Analytical Models

Pathways-to-man models are the accepted method of predicting radiation doses to the general public from radionuclides released to air or water by a nuclear facility. The amounts of individual radionuclides released to the environment are measured or predicted from the expected performance characteristics of the facility, e.g., efficiency of air filters (AEC 1973, 1974; Selby et al. 1973; U.S. NRC 1975; DOE 1979d). The amounts of released radionuclides that may be inhaled or ingested by human beings (intakes) are calculated from pathways-to-man models, and metabolic and dosimetry models are then used to convert the intakes to radiation doses in human tissues.

Complete pathways-to-man models include (1) identification of the critical environmental pathways by which each radioelement is transferred to human beings through water and food chains, e.g., aquatic and irrigated foods and animal products, (2) direct inhalation of airborne particles or gases or of contaminated soil particles resuspended into air, and (3) contributions to the external radiation dose from gamma-ray-emitting radionuclides that have been deposited on surface soils where people live and work or that are present in surface water or shallow sediments where people work, boat, or swim. Data on the environmental movement of many radionuclides have been accumulated from laboratory studies and field measurements of radionuclides released by nuclear weapons tests above ground or from various nuclear facilities, and state-of-the-art transport models have been constructed for those radionuclides likely to be emplaced in a deep geologic respository. (For example, see references in Foster and Soldat 1966; Ng et al. 1968, 1976; ERDA 1975, 1977c; UNSCEAR 1977; British Nuclear Fuels 1978; ICRP 1978b.)

Metabolic and dosimetry models include (1)absorption of individual radioelements into the body from lung or intestine, (2) the amounts deposited and their time-dependent residence in tissues, and (3) calculation of the energy absorbed (radiation doses) in tissues (ICRP 1959, 1972, 1974, 1978a; Dolphin and Eve 1966; Morrow et al. 1966; Marshall et al. 1973).

Hydrogeologic Models

There is general agreement that the most likely mechanism by which radionuclides may be transferred from a deep geologic repository to the biosphere is transport in ground water to a point of discharge at the surface (APS 1978, IRGNWM 1978, NRC 1979). Hydrogeologic models, developed to analyze radionuclide migration through a geologic medium, utilize (1) the amounts and rates of supply of the radionuclides to ground water by dissolution or leaching of the waste form, (2) the distances and rates of ground-water flow to a water source accessible to people, and (3) the retardation of radionuclide movement by chemical interactions with the geologic medium, e.g., solubility, compound and complex formation, and sorption. Solution of a hydrogeologic migration model yields the time-dependent concentration of each radionuclide in water at a point of human access (Bradley and Corey 1976, Burkholder 1976, Cohen et al. 1977, A.D. Little, Inc. 1978, DOE 1979d).

Data for the two deep formations at the SRP site were used to estimate radiation doses resulting from radionuclides leaking out of bedrock caverns containing liquid waste, either laterally to the Savannah River or vertically into the Tuscaloosa aquifer. The study

(Bradley and Corey 1976) assumptions included an upward drive into the aquifer and low (conservative) values for sorption coefficients (K_d's). Any retarding effects of an intervening clay layer were ignored. The calculated radionuclide releases were combined with biological models to estimate the radiation doses in man resulting from ingestion of water containing the leaked nuclides. That modeling study indicated that prospects for a successful liquid waste repository were marginal in crystalline rock, but good in Triassic rock. Even in the most unfavorable case, direct upward migration 150 m to the aquifer, the Triassic rock appeared to be capable of retaining all but the most elusive long-lived anions, and their emergence into the biosphere would be delayed many tens of thousands of years (Bradley and Corey 1976). A recent three-dimensional analysis of the long-term performance of geologic repositories in the aftermath of catastrophic events, e.g., a major earthquake, suggests that, except as a backup in case of gross error in modeling geologic performance, the solubility of the solid waste form will be of little importance after the repository is sealed (Cohen et al. 1977).

Comparative Hazards of the SRP Disposal Alternatives

For the purpose of comparing the biological hazards of the disposal alternatives, the SRP staff used analytical modeling methods described above to calculate radiation doses to the general public from all expected releases of radionuclides from each component of the alternative waste management systems (Table 7). For each component, radionuclide releases were estimated, whenever possible based on SRP plant experience (ERDA 1977b).

Dose risks were calculated from a probability-consequence analysis of process accidents and a variety of unexpected catastrophic events, e.g., sabotage and natural disasters. For process accidents, both the radionuclide releases and the probability of occurrence of the events were based on SRP plant experience with similar facilities. There is a large body of general experience with transportation accidents, and both the rates of occurrence and the severity of various kinds of accidents are reasonably well known. However, both the probability of occurrence of events that are plausible but are not known to have occurred and the radionuclide releases that might result from such events are quite uncertain. In an effort to compensate for that uncertainty, highly conservative assumptions were made about both the radionuclide releases and the probabilities of occurrence of unexpected events; therefore their estimated dose risks tend to be inflated.

Dose risks from normal operations and from unexpected events were integrated over 10,000 years and summed to obtain a total dose risk for each disposal alternative. Some general observations can be made about the results of those procedures:

- Among all disposal alternatives, the largest total integrated dose risk to the public (expected releases plus catastrophic events) is a small fraction (~10^{-5}) of the dose from natural background radiation to the same population over the same interval.

- The same radiologic hazard to the public is expected from all separation and solidification procedures (with minor exceptions), regardless of the solid waste form produced, because the processing building is the primary source of potential contamination.
- Among the disposal alternatives not involving transportation, differences in population doses arise almost entirely from inclusion of the dose risks from unexpected events.
- For expected operating performance, total doses to the general public from disposal of liquid waste in the SRP bedrock are not greater, and in some cases they are smaller, than for alternatives involving solidification, packaging, and disposal of waste elsewhere.
- The preliminary safety analysis of disposal of liquid waste in SRP bedrock identified two unexpected events: large-scale sabotage and a catastrophic earthquake that were assumed to occur during filling of the caverns (Bradley and Corey 1976, ERDA 1977b). The dose risks estimated for those events overwhelm the total dose risk to the public for that alternative. Examination of the assumptions used to analyze those hypothetical events reveals that the calculated radiation doses would have been very much smaller if the waste had been assumed to be a solidifiable cement slurry rather than in a permanently liquid form.

FINDINGS OF PREVIOUS STUDIES OF DISPOSAL OF SRP WASTE

The general concept of disposal of a liquid waste slurry in a deep rock formation beneath the SRP site was first proposed in 1951 and was studied intensively from 1961 to 1972 (AEC 1972). From the outset, the major safety issue has been protection of the Tuscaloosa aquifer from contamination with radionuclides. Three panels of earth scientists and engineers reviewed the status of the bedrock proposal as the investigations progressed (NRC 1966, 1972; Wolman et al. 1969).

The NRC Committee on Geologic Aspects of Radioactive Waste Disposal, in a comprehensive report transmitted to the Atomic Energy Commission in 1966 and released to the press in 1970, produced a split assessment of disposal of liquid waste in the crystalline rock. (Triassic rock, discovered in one drill core in 1961, had not yet been investigated (Christl 1964).) The majority opinion was that "...the placement of high-level wastes 500 to 1000 feet below a very prolific and much-used aquifer is in its essence dangerous and certainly would lead to public controversy." Also, "...there is doubt that it will be possible to prove safety of the proposed bedrock-storage system for high-level liquid or soluble wastes." The basis for that opinion was the unpredictable nature of ground-water flow through fractured rock. A minority opinion of the Committee was that "...work on bedrock disposal at SRP should be continued"--especially with regard to the hydrology of fractured aquifers, tritium-tracer testing to gain evidence of direction and rates of movement, and sonic and seismographic mapping and analysis of the clay layer at the base of the sedimentary section (NRC 1966).

Some of the recommended work was undertaken (Marine 1966, 1967; Siple 1967; Proctor 1968), and in 1968, the data were reassessed by a panel of consultants to du Pont, who concluded that the concept of storing liquid waste in the SRP crystalline rock was promising, but could only be validated by construction of a shaft and exploratory tunnels (Wolman et al. 1969). That recommendation was not acted on, but laboratory study and surface exploration continued. New data were developed, and the hydrology of the fractured crystalline rock was reanalyzed (Webster et al. 1970). The Triassic basin had been mapped (Siple 1967), and preliminary investigations were made of its hydrology and the composition and properties of the sedimentary rock. (See chronology of geologic investigations in Bradley and Corey (1976).)

The Panel on Bedrock Storage (NRC 1972) reported on a detailed review of the concept of disposal of liquid waste in SRP bedrock. The scientific aspects, geology, hydrology, and geochemistry of both the crystalline and the Triassic rock, were studied along with the engineering problems of rock mechanics, underground construction, and production of radiolytic gas and heat by the waste. Their preliminary calculations indicated that ^{90}Sr and ^{137}Cs, the radionuclides of greatest abundance and greatest concern (because of their environmental mobility), would probably be retained in the crystalline rock on the SRP site for 1000 years and in the Triassic rock for much longer. No serious mining or chemical engineering problems were identified. Other methods of waste treatment were discussed or suggested for further study, including (1) production of a solid form for disposal either in vaults at SRP or off site and (2) addition to the liquid waste of zeolite to immobilize ^{137}Cs and/or cements or resins to solidify the liquid waste in situ, specifically to reduce formation of radiolytic gas and ensure an even heat distribution in the waste.

They concluded that "...there is a reasonable prospect of achieving [adequate] protection by storing the waste in vaults in rock underlying the Tuscaloosa Formation beneath the Savannah River Plant site." The Panel recommended additional field and laboratory investigations to permit a reasoned choice to be made between the two rock formations, including investigations on fluid transmissivity of different parts of the two rock units; hydraulic gradients within the Triassic; the ion exchange capacities of the two units; waste-rock chemical reactions; and the regional stress fields in the two units. The Panel concluded that "...no reasonable amount of exploration from the land surface can conclusively demonstrate the safety of waste storage in deep vaults. Essential for such a demonstration is in situ inspection and testing of the rocks in which vaults might be constructed." Accordingly, the Panel further recommended that "an exploratory shaft be sunk and exploratory tunnels be driven into the rock selected. Study of the recommended exploratory shaft and tunnels may indicate that the proposed deep vault storage at SRP is acceptable. In this case the Panel recommends that a competent and impartial review be made of this additional information before the decision is made to charge the vault with waste."

The report further stated (NRC 1972):

> The recently acquired data on the sedimentary rocks of Triassic age are encouraging and emphasize the need for complete exploration. The proposed shaft and tunnels would serve several purposes. First and most critical, such exploratory excavations would permit the examination...of the host rock throughout the extent of the proposed vaults. Extrapolation of rock conditions from the walls of a small tunnel to a full-sized vault is reasonably certain, in contrast to the less certain extrapolation of rock conditions from borings hundreds of feet apart. Also, it will be possible to make chemical and physical analyses of the rock throughout the entire dimension of the proposed vaults. Further, before the final decision is made to develop a full-scale storage facility, exploratory excavations will make possible observation of water movement in the host rock over a significant period. In addition, digging an exploratory shaft would identify the problems of engineering design and construction in penetrating the highly permeable water-bearing Tuscaloosa Formation that overlies the basement rocks. Because this is a primary regional aquifer, there must be assurance that a watertight shaft can be constructed through it and can be maintained. The decision as to whether the exploratory shaft should be located in the metamorphic rocks or in the Triassic sedimentary rocks will depend on results of geological, geophysical, and geochemical investigations yet to be completed. Preliminary data suggest that the Triassic rocks are not extensively fractured, but the presence and spacing of joints and faults would be disclosed by the lateral tunnels. The physical, chemical, and engineering properties of the Triassic rocks are not adequately known, and exploratory excavations would facilitate their thorough study. If data from the exploratory shaft and tunnels do not clearly confirm that use of excavated vaults is safe for long-term isolation of SRP wastes from the biosphere, the concept as herein defined would become invalid.

The Panel on Savannah River Wastes concurs completely in the 1972 recommendations of the Panel on Bedrock Disposal and regrets that the recommendations of the earlier Panel were not adequately implemented at that time.

In 1979, the NRC Panel on Waste Solidification (U.S. NRC 1979) examined the problem of disposal of the DOE waste, in particular at SRP and Hanford, in the broad context of recommending appropriate solid forms based on information about hazards, costs, and process readiness and simplicity (see the section on solid waste forms above). They discussed the grouting procedure developed at the Oak Ridge National Laboratory for disposal of intermediate-level radioactive waste, in which relatively concentrated salt solutions containing a variety of radionuclides are mixed with chemical additives and cement and pumped into hydraulically fractured shale for solidification in place (De Laguna et al. 1968). Although the procedure was developed for intermediate-level waste with a different salt composition, the Panel "did not find evidence that indicated further research could not lead to high-level waste applications." They recommended reexamination of the feasibility of grouting high-level waste (suitably modified as "supergrout") directly into appropriate geologic formations.

The Panel on Savannah River Wastes concurs in that recommendation and regrets that a procedure for grouting defense waste has not yet been developed.

CURRENT STATUS OF THE CONCEPT OF DISPOSAL OF SRP WASTE IN BEDROCK

Plans for executing the recommendations of the 1972 NRC report were discontinued when the U.S. Environmental Protection Agency (EPA) objected in 1972 that deep geologic disposal of high-level liquid waste beneath the SRP was environmentally unsound and DOE had not studied any other alternatives (as cited in DOE (1979a), page B-69). In its review of the Draft EIS for Long-Term Management of SRP Defense High-Level Wastes (DOE 1979a), EPA raised the issue that the Triassic faults bounding the Dumbarton basin beneath the SRP and the mylonites (fractured metamorphic rock at its contact with the Triassic formation) hold potential for movement that could affect the integrity of a repository located within those formations.

It is concluded here, however, that the objections raised by EPA were not justified, because the hydrogeological studies on which such decisions should logically be based have not yet been conducted. However, the existence of the Tuscaloosa aquifer beneath SRP and the nearby Savannah River must be considered in any plans for on-site future waste management; an ill-based decision to use SRP bedrock for waste disposal might risk contaminating the aquifer and the river. The Panel on Savannah River Wastes believes that bedrock disposal remains a viable concept that has not been shown to carry real risk of dispersing radionuclides into the environment. The important fact is that the research needed for a decision has not been conducted. The Panel on Bedrock Storage (NRC 1972) outlined a research program calling for step-by-step site-specific verification of geologic detail that, if carried out, would have provided the basis for a sound decision.

In support of reevaluating the option of disposal of SRP waste in caverns in the Triassic rock, it is appropriate to review the available, but limited data. The formation is massive (Daniels 1974) and extends to at least a depth of more than 1500 meters (Marine 1974, Marine and Siple 1974). The samples of sediments recovered by coring have uniformly low permeability (Marine 1974) and exhibit radionuclide sorption similar to that of surface soils (4 meq/100 g of ground rock) even in fairly concentrated salt solutions (Bradley and Corey 1976). The rate of ground-water flow appears to be very slow on the basis of the low permeability of the formation and the high salt concentration of the rock water (Marine 1976). Rock mechanical properties are adequate for safe underground construction (Parsons-Brinkerhoff-Quade-Douglas, Inc. 1972a,b,c; Bradley and Corey 1976): the small degree of rock creep (5-10 percent) is not a serious disadvantage for mining. Furthermore, the physical and chemical properties of the Triassic rocks are such that cracks tend to heal.

The layer of clay that overlies the SRP bedrock formations has long been considered to be a major barrier against upward migration of radionuclides into the Tuscaloosa aquifer, and proof of its continuity has been considered essential. The high clay content of the layer where it overlies Triassic rock suggests that it was formed by in situ weathering (Plaster and Sherwood 1971, Pavich 1974, Marine 1976, USGS 1979) and is likely therefore to be effectively continuous. The best available evidence indicates that the large upward-directed piezometric pressure difference between the Triassic rock and the Tuscaloosa formation is osmotic in origin (Marine 1976). The clay may therefore act as a semipermeable membrane (Isherwood 1981) permitting water to move down into the Triassic rock, but effectively preventing or greatly delaying the movement of ions (which would include radionuclides) from the deep ground water into the aquifer above. The great and abruptly occurring difference in the chemical compositions of the waters in the two formations (low salt concentration in the Tuscaloosa formation above the clay layer and high salt concentration in the Triassic rock below) supports both hypotheses--that the clay layer is effectively continuous and that it is an efficient barrier to the upward migration of ions.

Finally, in considering potential seismic effects, it can be argued that the main faults bounding large masses of the crystalline rocks and the Triassic sediments would provide potential planes of movement and attenuation of the seismic wave, thus providing protection to a repository located centrally within those sediments.

It has been estimated (Pratt et al. 1978) that earthquakes in the SRP region with an acceleration of 0.15 g at ground level occur less than once in ~500 years. Properly designed underground structures can withstand shaking up to 0.5 g or more with little damage provided they are not constructed across a fault along which movement takes place.

Faults bounding and within the Triassic basin are overlain by undisturbed Cretaceous sediments (>60 million years old). Triassic rock was encountered at the same depth in two drill holes on either side of a fault (initially revealed by seismic survey) indicating no relative movement since deposition of the Tuscaloosa sediments began (Parsons-Brinkerhoff-Quade-Douglas, Inc. 1973, Bradley and Corey 1976). A directionally drilled hole encountered slick fractured rock in the suspected fault zone, but water leakage into the well did not increase.

From surface observations of the most recently active fault in the region, the 20-km-long Belair fault located about 35 km to the west of SRP (Prowell 1978), the rocks that have been affected appear not to have moved for at least 13 million years (Case 1977, USGS 1977, Prowell and O'Connor 1978). Additional evidence about seismic stability could be obtained from measurements of local rock stresses, but such measurements cannot be made from the surface and would require the sinking of an exploratory shaft (Cook 1975, Jaeger and Cook 1976).

The greatest susceptibility to seismic damage of a repository in SRP bedrock for liquid or cemented waste would occur during the interval that the shaft is open for filling (Bradley and Corey 1976, DOE 1979a).

In summary, study of the Triassic rocks to date has shown no characteristics that would make them unsuitable as a medium for waste isolation. Additional data will be needed, however, before their suitability can be reliably assessed. In particular, the assessment will require the driving of exploratory shafts and tunnels and the completion of appropriate tests, as was previously recommended (NRC 1972).

CONCLUSIONS AND RECOMMENDATIONS

Examination of the technological processes, monetary costs, and preliminary analysis of hazards for the various alternatives proposed for disposal of the SRP waste leads the Panel to the following conclusions:

Conclusion: The current management practice by which high-level radioactive waste is contained in double-walled carbon-steel tanks is adequate as an interim storage method that will function safely for whatever time is needed to select and implement a method of permanent isolation.

Conclusion: Although DOE and U.S. NRC currently favor a solidification process for all high-level waste that will produce transportable, packaged units of waste in a stable, low-solubility form, all realized or proposed solidification processes are costly and complex, and all will require some development and demonstration before they become operational for the SRP waste. Introduction of a transportation step increases the complexity and cost of the total waste management system.

Conclusion: Evidence available for the Triassic sedimentary rock below the SRP site strongly suggests that it will meet the major geologic requirements for a waste repository (NRC 1978b). Recent analyses indicate that the hazards from expected releases of radionuclides during and after disposal of liquid waste in caverns in the Triassic rock are no greater, either to the operators in the short term or to the public at large in the long term, than those of other disposal alternatives investigated. Therefore a thorough reexamination is warranted of the less costly, less complex, and, in the view of the Panel, probably no more hazardous concept of bulk disposal of the waste mixed with chemical additives and cement for solidification in situ in SRP bedrock.

The Panel's recommendations concerning the disposal of high-level waste at SRP can be summarized as follows:

Recommendation: Current management practices of containing high-level radioactive waste in the double-walled carbon-steel tanks should be continued until a permanent method of isolation has been selected.

Recommendation: On the basis of the merits of the Triassic rocks at the SRP for the permanent isolation of high-level SRP defense waste, and in concurrence with previous recommendations of the Committee on Radioactive Waste Management, the technological and economic feasibility of permanent isolation of existing and future high-level radioactive waste in a bedrock repository under the site should be re-examined, with particular attention to the cost of the procedure, which is anticipated to be lower.

As part of the reexamination, the following recommendations are made:

1. Additional field and laboratory investigations should be conducted to produce definitive information as to the three-dimensional characteristics of the Triassic rocks that underlie the site. Particularly important is information on (a) the fluid transmissivity of different parts of the rock unit, (b) the hydraulic gradients, (c) the ion-exchange capacities, (d) the chemical reactions between the waste and the potential host rock, and (e) the regional stress fields in the rocks.
2. If analysis of the information gained by carrying out recommendation 1 above supports further investigation, an exploratory shaft should be excavated on the SRP site to repository depth in the rock selected.
3. If analysis of the information gained by sinking the shaft mentioned in recommendation 2 above supports further exploration, horizontal borings should be made at repository depth to the limits of the proposed repository in order to collect the site-specific data required to assess the suitability of the formation to receive SRP high-level waste.
4. Concurrently, unless the results of recommendations 1, 2, or 3 prove the concept invalid, the technology and economics of pumping slurries of high-level radioactive waste containing solidifying agents into a deep geologic repository for in situ solidification should be investigated and evaluated.
5. Also concurrently, research and development should be pursued on above-ground processing of high-level radioactive waste into solidified, low-leach forms suitable for bulk transfer to an on-site deep geologic repository as an alternative to the in situ solidification of slurried liquid waste.

Recommendation: Until the technological and economic feasibility of on-site isolation of high-level waste is evaluated, the following actions should be taken:

1. Research and development should be continued on above-ground solidification of SRP high-level radioactive waste into forms suitable for transport off site. A final choice of waste form should be postponed until the feasibility of on-site disposal is determined.
2. Plans should be developed--although construction should not start--for a full-scale processing and solidification plant based on currently existing waste management technology.

Recommendation: The major capital expenditures of a surface processing and solidification facility should be undertaken only if deep geologic isolation on site by bulk transfer and in situ solidification of slurry is proved to be less attractive.

General conclusions: These strong recommendations for further research into SRP bedrock disposal should not be taken as endorsement of on-site isolation or bulk transfer of slurried high-level waste, nor to mean that other alternatives are to be ignored. At this point, to ignore alternatives would be as grave an error in scientific judgment as summarily to reject the SRP bedrock disposal concept. Much valuable work has been done in the pursuit of alternatives that remain viable at this time. In the absence of overriding technological or safety justification for preemptive decisions, an open-minded and responsible scientific approach to the problem of long-range management of high-level waste at the Savannah River Plant requires that all reasonable options be kept open while the data necessary for informed judgment are assembled.

GLOSSARY

actinide - radioactive element with atomic number of 89 through 93; the name is taken from actinium, the first member of the series.

AEC - Atomic Energy Commission (discontinued with formation of ERDA and U.S. NRC on January 19, 1975).

alpha radiation - an emission of particles (helium nuclei) from a material undergoing nuclear transformation; the particles have a nuclear mass number of four and a charge of plus two.

aquifer - a subsurface formation containing sufficient saturated permeable material to yield significant quantities of water.

becquerel (Bq) - a unit of radioactivity defined as giving one disintegration per second (3.7×10^{10} becquerels = 1 curie).

beta radiation - essentially weightless (in comparison with alpha particles) charged particles (electrons and positrons) emitted from the nuclei of atoms undergoing nuclear transformation.

calcination - the process in which the water portion of slurried waste is driven off by evaporation at high temperature in a spray chamber leaving a residue of dry solid unmelted particles, also referred to as the calcine.

carbon-14 - heavy radioactive isotope of carbon of mass number 14 used especially in tracer studies and in dating archeological and geological materials.

cretaceous sediments - sediments having characteristics of or abounding in chalk dating to the last period of the Mesozoic era.

curie (Ci) - a unit of radioactivity defined as the amount of a radioactive material that has an activity of 3.7×10^{10} disintegrations per second; nanocurie (nCi) = 10^{-9} curie.

ecosystem - complex of a community and its environment functioning as an ecological unit in nature.

fault (movement) - a fracture in the earth's crust accompanied by a displacement of one side of the fracture with respect to the other and in a direction parallel to the fracture.

fission - the splitting of a heavy nucleus into two roughly equal parts (which are nuclei of lighter elements), accompanied by the release of a relatively large amount of energy and frequently one or more neutrons.

fission products - nuclei formed by the fission of heavy elements; many are radioactive.

gamma radiation - an emission of high-energy photons by a nucleus in transition between two energy levels.

geomorphology - science that deals with the land and submarine relief features of the earth's surface or the comparable relief features of a celestial body and seeks a generic interpretation of them.

gneiss - a foliated metamorphic rock corresponding in composition to granite or some other feldspathic plutonic rock.

ground water - water in the part of the ground that is wholly saturated that supplies wells and springs.

half-life - the time required for the activity of a radionuclide to decay to half its value; used as a measure of the persistence of radioactive materials; each radionuclide has a characteristic constant half-life.

heavy water (D_2O) - water in which normal hydrogen atoms have been replaced with deuterium atoms. D_2O has a low neutron absorption cross section and hence it is used as a moderator in some nuclear reactors; in SRP reactors, it is used as the moderator and primary coolant.

high-level waste - material that is contaminated by greater than 100 μCi/ml of fixed fission products or more than 2 μCi/ml of ^{137}Cs, ^{90}Sr, or long-lived alpha emitters.

hydraulic conductivity - the parameter relating the volumetric flux to the driving force in flow through a porous medium (particularly water through soil); a function of both the porous medium and the properties of the fluid.

igneous plutonic rocks - rocks formed by solidification of a molten magma deep within the earth and crystalline throughout.

ion exchange - process for selectively removing a constituent from a waste stream by reversibly transferring ions between an insoluble solid and the waste stream; the exchange medium (usually a column of resin or soil) can then be washed to collect the waste or taken directly to disposal.

irradiation - exposure to radiation resulting from proximity to a radioactive source; in the case of fuel materials, usually results from being placed in an operating nuclear reactor.

isotopes - nuclides with the same atomic number (i.e., the same chemical element) but with different atomic masses; although chemical properties are the same, radioactive and nuclear properties may be quite different for each isotope of an element.

large equipment and structural item (LESI) waste - machinery and portions of structures that have been contaminated by radionuclides and that become waste items too large to fit into prefabricated concrete containers.

low-level radioactive waste - material that is contaminated by less than 5×10^{-5} µCi/ml of mixed fission products.

metamorphic rocks - rocks formed from preexisting solid rocks by mineralogical, structural, and chemical changes, in response to extreme changes in temperature, pressure, and shearing stress.

nuclides - any atomic nucleus specified by its atomic weight, atomic numbers, and energy state.

quartzite - a compact granular rock composed of quartz and derived from sandstone by metamorphism.

radionuclide - any unstable nuclide of an element that decays or disintegrates spontaneously emitting radiation.

retention basin - an excavation that receives aqueous streams for temporary storage; after sampling, this water may be processed further or transferred to a seepage basin or an on-site stream.

riparian zone - located on the bank of a natural watercourse (as a river) or sometimes of a lake or a tidewater.

salt cake - the solid residue resulting from a concentration of high-level liquid waste.

schist - a metamorphic crystalline rock having a closely foliated structure and admitting of division along approximately parallel planes.

seepage basin - an excavation in the ground to receive aqueous streams containing chemical and radioactive waste; the water evaporates or seeps from the basin through the soil column to the ground water.

separations - chemical processes used to separate nuclear products from by-products and from each other.

siltstone - a rock composed chiefly of indurated silt.

sludge - the precipitated solids (primarily oxides and hydroxides) that settle to the bottom of the storage tanks containing liquid high-level waste.

slurry - a suspension of solid particles (sludge) in liquid.

solidification - conversion of radioactive waste to a dry, stable solid.

supernate - that portion of high-activity liquid waste that contains fission products (primarily ^{137}Cs) in solution. Other portions are the insoluble sludge and crystallized salt.

tank farm - an installation of interconnected underground tanks for the storage of radioactive high-level liquid waste.

tertiary sediments - sediments dating back to the first period of the Cenozoic era.

tracer - an element or compound that has been made radioactive so that the radiation emitted can be followed and its location pinpointed in biological and industrial processes.

triassic - system of rocks corresponding to the earliest period of the Mesozoic era.

tritium - a radioactive isotope of hydrogen with two neutrons and one proton in the nucleus.

transuranic (TRU) waste - waste material obtained from elements with an atomic number above 92 that contains more than a specified concentration of uranium activity per gram.

vitrification - the incorporation of radionuclides (nuclear waste) into glassy or noncrystalline material.

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