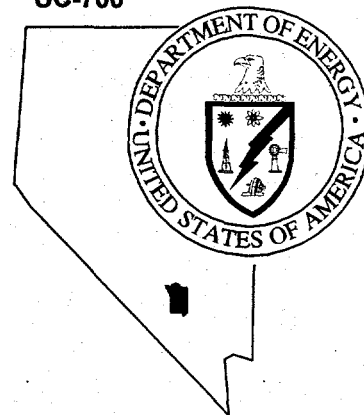


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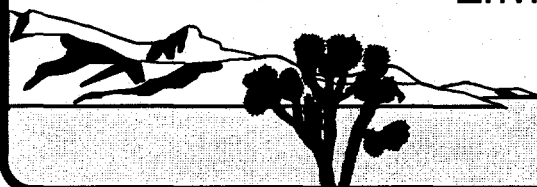
Focused Evaluation of
Selected Remedial Alternatives
for the Underground Test Area

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**FOCUSED EVALUATION OF
SELECTED REMEDIAL ALTERNATIVES
FOR THE UNDERGROUND TEST AREA**

DOE Nevada Operations Office
Las Vegas, Nevada

April 1997

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**FOCUSED EVALUATION OF
SELECTED REMEDIAL ALTERNATIVES
FOR THE UNDERGROUND TEST AREA**

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List of Acronyms and Abbreviations

ALARA	As low as reasonably achievable
ALMR	Advanced Liquid Metal Reactor(s) (for use as an actinide burner)
ARAR	Applicable or relevant and appropriate requirement(s)
CADD	Corrective Action Decision Document
CAI	Corrective action investigation
CAP	Corrective Action Plan
CAPZONE	Capture zone
CAS	Corrective Action Site(s)
CAU	Correction Action Unit(s)
CFR	<i>Code of Federal Regulations</i>
COC	Constituent(s) of concern
CERCLA	<i>Comprehensive Environmental Response, Compensation, and Liability Act of 1980</i>
DNAPL	Dense nonaqueous phase liquid(s)
DOB	Depth of Burial
DOE	U.S. Department of Energy
DOE/NV	U.S. Department of Energy, Nevada Operations Office
DRI	Desert Research Institute
EE/CA	Engineering Evaluation/Cost Analysis
EPA	U.S. Environmental Protection Agency
FS	Feasibility study
ft	Foot (feet)
ft/d	Foot (feet) per day
ft/yr	Foot (feet) per year
ft ³	Cubic foot (feet)
ft ² /d	Square foot (feet) per day
gpm	Gallon(s) per minute
HELP	Hydrologic Evaluation of Landfill Performance
HP	Horse power
h/yr	Hour(s) per year
in.	Inch(es)
INEL	Idaho National Energy Laboratory

List of Acronyms and Abbreviations (Continued)

K	Hydraulic conductivity
K _d	Partition coefficients
kg	Kilogram(s)
K _{intact}	Intact hydraulic conductivity outside of nuclear chimney
km	Kilometer(s)
kPa	Kilopascal(s)
kw	Kilowatt(s)
lb	Pound(s)
LLW	Low-Level Radioactive Waste
Lpm	Liter(s) per meter
m	Meter(s)
m ³	Cubic meter(s)
MCL	Maximum contaminant level(s)
MC_TRANS	Monte Carlo Simulation and Transport
m/d	Meter(s) per day
m ² /d	Square meter(s) per day
m ³ /d	Cubic meter(s) per day
mg	Milligram(s)
mg/L	Milligram(s) per liter
mi	Mile(s)
mL	Milliliter(s)
ML	Silty Clay
mL/g	Milliliter(s) per gram
mm	Millimeter(s)
mrem/h	Millirem(s) per hour
mrem/yr	Millirem(s) per year
m/yr	Meter(s) per year
NAGRA	Nationale Genossenschaft für die Lagerung Radioaktiver Abfälle
nCi/g	NanoCurie(s) per gram
NCP	National Contingency Plan
NDEP	Nevada Department of Environmental Protection
NRC	National Research Council

List of Acronyms and Abbreviations (Continued)

NTS	Nevada Test Site
ODAST	One-Dimensional Analytical Solute Transport
O&M	Operations and Maintenance
pCi/L	Picocurie(s) per liter
PE	Polyethylene
psi	Pound(s) per square inch
PT	Partitioning Transmutation
PVC	Polyvinyl Chloride Pipe
RCRA	Resource Conservation and Recovery Act
SCADA	Sensory Control and Data Acquisition
SM	Medium sand
SWIFTLOAD	Sandia Waste Isolation Fate and Transport Loading
TRU	Transuranic waste
UGTA	Underground Test Area
USCS	United States Conservation Service
VOIA	Value of Information Analysis
yd ³	Cubic yard(s)
α	Source depletion factor for ODAST/SWIFTLOAD
Θ	Volumetric moisture content, dimensionless
η	Porosity
λ	Solute decay factor, (time ⁻¹)

1.0 Introduction

The Nevada Test Site (NTS), located in Nye County in southern Nevada, was the location of 928 nuclear tests conducted between 1951 and 1992. Of the total tests, 824 were nuclear tests performed underground.

This report describes the approach taken to determine whether any specific, proven, cost-effective technologies currently exist to aid in the removal of the radioactive contaminants from the groundwater, in the stabilization of these contaminants, and in the removal of the source of the contaminants.

1.1 Purpose and Scope

At the conceptual level, this study examines the technical feasibility and cost issues of remedial alternatives for the NTS, focusing on the alternatives that are currently available and that have been proven to be sound, technical approaches. Specifically, this report examines the "no action" alternative to evaluate the worst-case scenario (no protection of human health and the environment). It evaluates the technical feasibility and costs of proven and available remedial alternatives and evaluates the natural attenuation of existing contamination as one possible remedial alternative.

1.2 Underground Test Area Strategy

Of the 921 historical nuclear detonations in shafts or tunnels at the NTS, 878 have been categorized into Corrective Action Sites (CASs) assigned to the Underground Test Area (UGTA) (IT, 1996). These CASs are located near each other and are grouped into six Corrective Action Units (CAUs). The CAUs are geographically distinct with different contaminant sources and with geologic and hydrogeologic characteristics related to their location. The CAUs presented in Figure 1-1 are listed in the following text:

- Frenchman Flat CAU consists of 10 CASs located in the northern part of NTS Area 5 and the southern part of Area 11. The events were conducted in vertical emplacement holes and mine shafts and were located in alluvium of great depth. The deeper geology is not well-known. Lateral transport in the alluvium is very slow due to the low lateral gradient.

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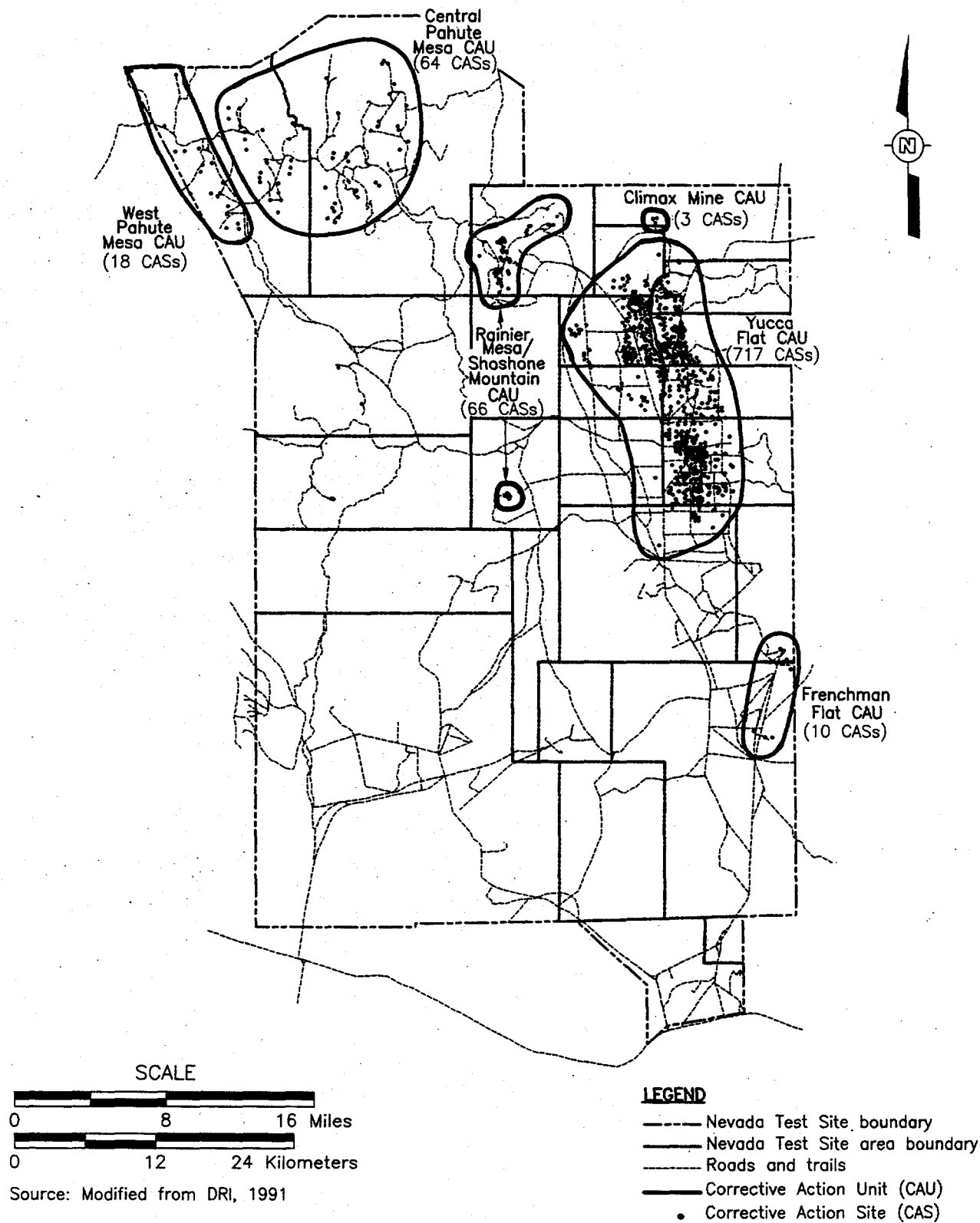


Figure 1-1
Underground Test Area Corrective Action Units

- Western Pahute Mesa CAU consists of 18 CASs along the western edge of NTS Area 20. The events were all conducted in vertical emplacement holes. This CAU is separated from Central Pahute Mesa by the Boxcar Fault and is distinguished by the relative abundance of tritium. Transport of contaminants on and from Western Pahute Mesa involves groundwater flow in welded and vitric tuffs in the rock matrix and in the fracture system.
- Yucca Flat CAU consists of 717 CASs located in NTS Areas 1, 2, 3, 4, 6, 7, 8, 9, and 10. These events were conducted in vertical emplacement holes. Contaminant transport in Yucca Flat may involve alluvium, welded and vitric tuffs, and carbonate rocks.
- Central Pahute Mesa CAU consists of 64 CASs in Areas 19 and 20 of Pahute Mesa. These events were all conducted in vertical emplacement holes. Transport of contaminants on and from Central Pahute Mesa involves the rock matrix, groundwater flow in fractures, welded and vitric tuffs, and lava flow aquifers. The influence of the large-scale block faulting is not well-known.
- Rainier Mesa/Shoshone Mountain CAU consists of 60 CASs on Rainier Mesa and 6 CASs on Shoshone Mountain which are located in NTS Areas 12 and 16. These events were conducted in tunnels.
- Climax Mine CAU consists of 3 CASs. These events were conducted in tunnels. The considerations for this CAU are similar to the Rainier Mesa/Shoshone Mountain CAU.

1.2.1 Corrective Action Strategy

The corrective action strategy for the UGTA is based on the complex corrective action investigation (CAI). The objective of the CAI process is to define boundaries around each UGTA CAU, thus establishing sites that contain water that may be unsafe for domestic and municipal use.

A regional flow model encompassing the NTS and the groundwater flow systems extending to downgradient discharge has been completed. Regional modeling cuts across several activities, supports the entire UGTA program (which provides the initial basis for assessing flowpaths from CAUs), determines potential receptors, evaluates isolation or interaction of CAUs, and creates a consistent hydrogeologic framework across all the CAUs. Regional transport modeling provides the initial basis for determining the magnitude of risk from this source to potential receptors and for scaling individual CAU work.

The second phase of the CAI process focuses on refining CAU boundaries through specific models that include CAU-specific data. The CAU-specific modeling will estimate the movement

of contaminants and will focus on the acquisition and evaluation of CAU-specific hydrogeologic data. It will define boundaries that encompass the extent of contamination. If CAU-specific modeling fails to achieve CAU objectives, this strategy will be re-evaluated. If it is not possible or feasible to achieve the CAU objectives, it may be necessary to consider alternative approaches.

Figure 1-2 maps the generalized decision process that will lead to the closure of CAUs. Three of four major decision points involve data review and consensus attainment before proceeding with the next phase of corrective action activities and decision points. The first decision is a U.S. Department of Energy (DOE) review of the CAU model and validation results. If DOE accepts the model, they will propose contaminant boundaries. The Nevada Department of Environmental Protection (NDEP) will then review the CAU model and proposed contaminant boundaries, as shown in the second decision box. If the NDEP accepts the proposed contaminant boundaries, DOE will prepare the Corrective Action Decision Document (CADD). If the CADD results are satisfactory, a decision will be made to evaluate the need for contaminant control or containment and implementation, as appropriate, or to initiate a five-year monitoring program. If the third decision indicates that contaminant control is not required, then DOE will develop a Corrective Action Plan (CAP) and/or monitor the contaminant boundary for five years. The fourth decision occurs after a review of the monitoring results. If DOE and NDEP are confident of the results, the closure process will begin. If the results of any of these decision points are not acceptable, contingency activities will be initiated and evaluated as appropriate to correct the deficiencies.

For saturated conditions, a flow model of each CAU will be constructed to provide local three-dimensional flow, to evaluate the range of flow conditions in the CAU that may be important in determining the maximum extent of transport, and to provide boundary conditions for modeling transport. Saturated conditions are planned to be modeled for Frenchman Flat, Yucca Flat, Western Pahute Mesa, and Central Pahute Mesa CAUs.

For CAUs where unsaturated groundwater conditions prevail (Rainier Mesa/Shoshone Mountain and Climax Mine CAUs), saturated zone flow and transport modeling results will be evaluated based on field data to determine if the saturated zone has been affected. If the saturated zone has been affected, the need for further examination of the unsaturated zone will be evaluated. The CAU models that use tritium as the source term will establish the contaminant boundary for each

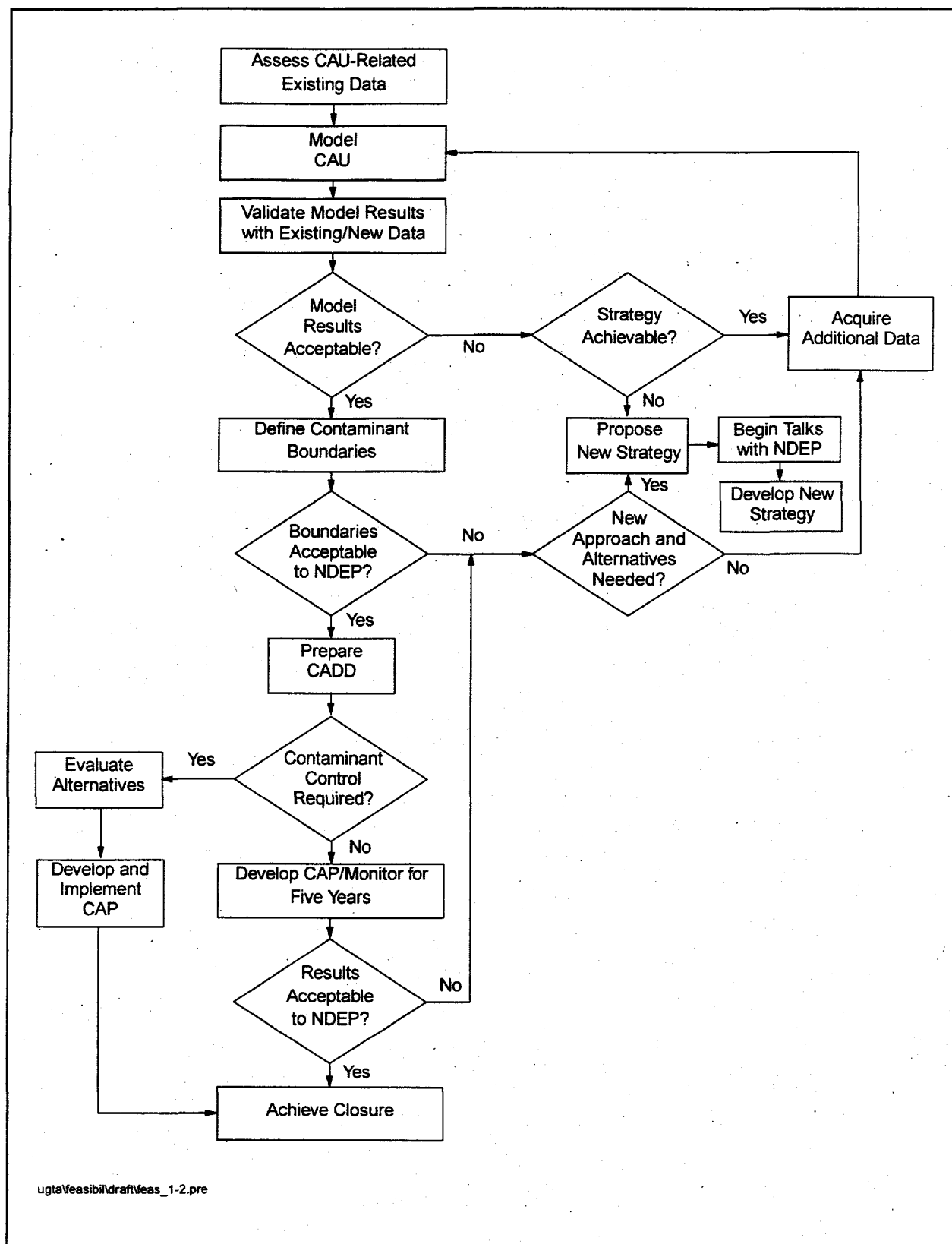


Figure 1-2
Process Flow Diagram for Underground Test Area Corrective Action Units

CAU, which includes both a perimeter boundary and a lower hydrostratigraphic unit boundary.

The perimeter boundary will define the aggregate maximum extent of contamination transport at or above the concentration of concern for the CAU. The lower hydrostratigraphic unit boundary will define the lowest aquifer unit affected by the contamination. Long-lived radionuclides, excluding tritium, will be included to evaluate the relative extent of migration for various radionuclides in the future. If predictions show that another radionuclide will migrate further than tritium at concentrations of concern, the contaminant boundary will include that prediction.

Figure 1-3 shows how confidence levels can express modeling uncertainty. Each contour reflects an increased level of confidence that no contaminants exceeding a given regulatory concentration will ever cross that boundary. As the confidence increases, the distance from the CAU increases. These confidence levels could lead to the development of different contaminant boundaries, depending on the degree of certainty decision makers need to select appropriate controls.

Measuring physical parameters in wells within the modeled region will monitor compliance with the CAU boundaries. Physical parameters that stay within the measurements used in the flow model will indicate that the conditions have not significantly changed. Sensitivity analysis of parameters related to the groundwater gradient will indicate how much physical parameters can vary before they exceed the acceptable confidence limit for the model.

The CADD will present the conclusions of the CAI and propose the CAU boundary. This document will include a complete report on the CAU model to document knowledge of the CAU flow system and contaminant transport predictions. This information will provide the basis for developing CAU-specific corrective actions.

The CAP for CAUs where contaminant control is not required will consist of a two-phase program. The first phase will be a verification program including a five-year, proof-of-concept period that further verifies the model's predictions. The second phase will start after acceptable results from Phase I verify that the contamination will be controlled within the agreed-to areal extent of contamination. The current assumption is that sufficient wells will exist as a result of data acquisition points (or wells) that are developed in the course of conducting the CAI. If additional monitoring wells are necessary, plans for their installation will be detailed in the CAP. The CAP will include maintenance plans for the monitoring system during the monitoring period.

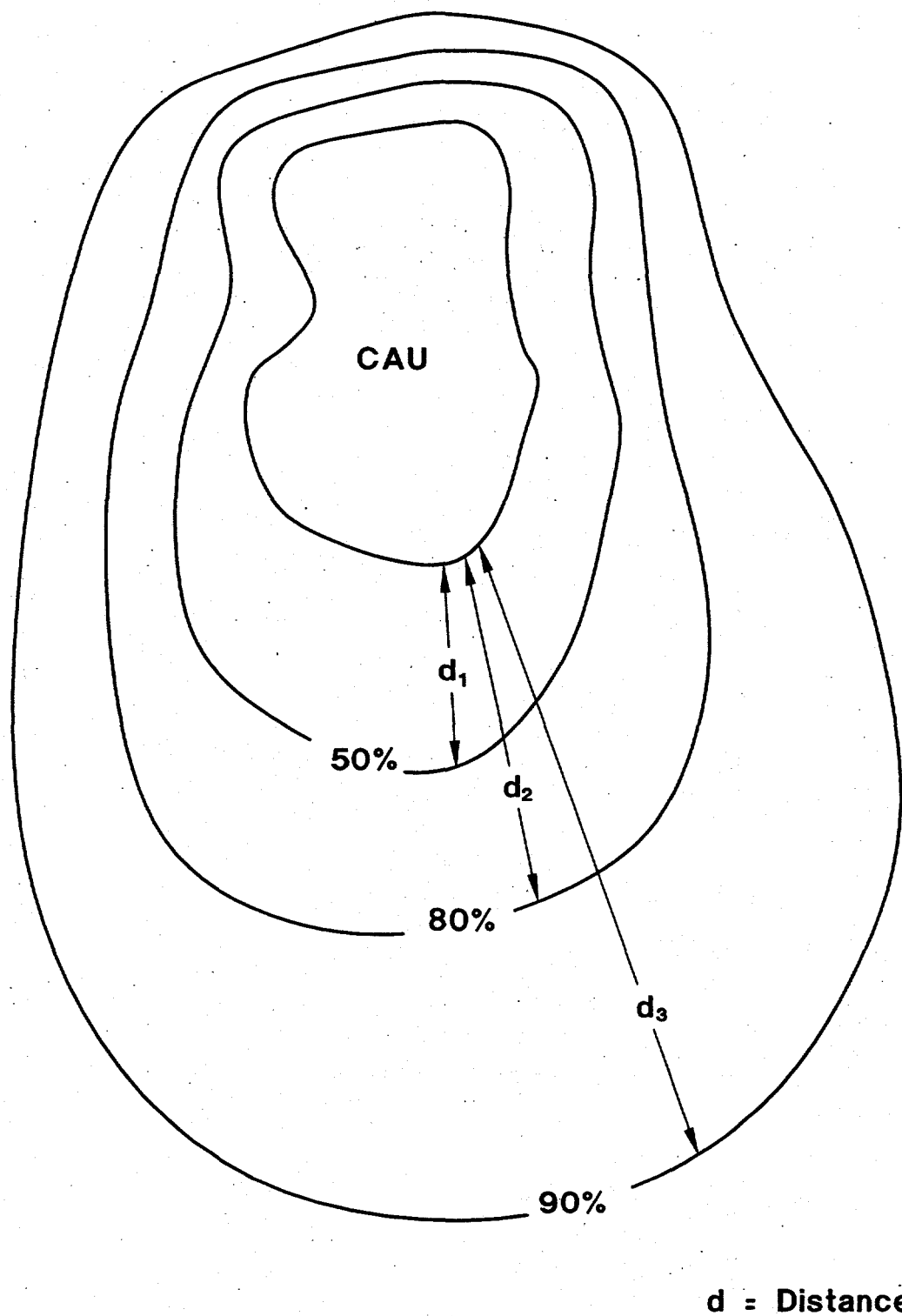


Figure 1-3
Example of Contaminant Boundary Confidence Levels

Once a CAU completes the interval of pre-closure monitoring, the results of that monitoring will be assessed. If the results fall within limits previously defined in the CAP, a Closure Report will propose that the CAU be designated as a "closed site." The Closure Report will also establish long-term monitoring requirements for the CAU, including contingency plans for actions to be taken if long-term monitoring results are not acceptable.

1.3 Technical Approach

The traditional feasibility study (FS) process looked at a "universe" of possible remedies and followed a formal series of steps to deal with uncertainties and unknowns. This process involved the following:

- Identifying potential treatment technologies and containment/disposal requirements
- Screening technologies
- Assembling technologies into alternatives
- Screening alternatives to reduce the number subject to detail analysis
- Refining alternatives
- Analyzing alternatives against each other as well as the nine criteria found in the "National Oil and Hazardous Substances Pollution Contingency Plan" (NCP) 40 *Code of Federal Regulations* (CFR) Section 300.430 (e)(3) and (7) (1993b)

The FS process has evolved to a more streamlined approach for site investigations and cleanup actions. The U.S. Environmental Protection Agency (EPA) (1993a and b) found that certain categories of sites share similar characteristics, such as the type of contaminants present, the disposal practices, or the way environmental media are affected. Consequently, the EPA has directed that reasonable remedies be used at all appropriate sites. Reasonable remedies are preferred technologies for remediating common categories of sites based on historical patterns of remedy selection and the EPA's scientific and engineering evaluation of performance data for technology implementation. Reasonable remedies streamline the FS and the analysis of alternatives in the Engineering Evaluation/Cost Analysis (EE/CA).

Typically, a focused FS or EE/CA that eliminates the technology identification and screening steps (the first four steps previously mentioned) would be prepared. This study would limit its consideration to the "no action" alternative and the reasonable remedy technologies. This is

possible because the EPA (1994) has analyzed potentially available technologies for most of the reasonable remedy site categories and has determined that certain technologies are routinely and appropriately screened out on the basis of effectiveness, implementability, and excessive cost (40 CFR 300.430(e)(3) and (7) [1993c]) or have not been selected under the nine criteria identified in NCP Section 300.430(e)(9) (CFR, 1993c).

To clarify, there will be no detailed evaluation and grouping of technologies into alternatives that will be screened later. However, some brief, qualitative statements will be made about the other alternatives that were not considered in detail (i.e., the more exotic remedial notions such as transmutation). The detailed analysis of the presumptive remedial alternatives will substitute for the development and screening of alternative phases of the FS and will allow the remaining alternatives to be limited to variations of the presumptive remedies. This focused evaluation will mainly perform a detailed engineering evaluation/cost analysis of the reasonable remedial alternatives. The costs will be estimated to correspond roughly to that performed for a rough conceptual design.

1.3.1 Detailed Analysis of Reasonable Remedial Alternatives

The reasonable remedial alternatives are typically ranked after a detailed analysis. This detailed analysis generally does the following:

- Refines the alternatives as necessary
- Analyzes alternatives against evaluation criteria
- Compares alternatives against each other

Typically, each alternative is assessed against the following evaluation criteria developed to address the *Comprehensive Environmental Response, Compensation, and Liability Act of 1980* (CERCLA) requirements as mandated by the 40 CFR 300.430(e)(9) (1993c):

- Overall protection of human health and the environment
- Compliance with applicable or relevant and appropriate requirement(s) (ARARs)
- Long-term effectiveness and permanence
- Reduction of toxicity, mobility, or volume
- Short-term effectiveness
- Implementability
- Cost
- State acceptance
- Community acceptance

In contrast, the detailed analyses discussed in this document for each of the reasonable remedial alternatives will focus mainly on the cost evaluation criterion and will only qualitatively consider the criteria for short-term effectiveness and implementability. The next few sections discuss the technical approach that identifies and describes the reasonable remedial alternatives, analyzes the alternatives against the evaluation criteria, and compares the alternatives against each other. In addition, these sections outline the specific deliverables or activities that will be involved.

1.3.1.1 Describe the Considerations for Determining Reasonable Remedial Alternatives

The EPA (1994) outlines the available treatment options for radioactive materials. Table 1-1 summarizes the alternatives considered by EPA (1994, Table 3-2). Unlike hazardous organic constituents, radionuclides cannot be destroyed, degraded, or readily detoxified; therefore, remediation technologies applicable to radionuclides involve separation, concentration/volume reduction, and/or immobilization. These are special considerations when remediating sites which are contaminated with radionuclides.

Evaluation of a Site's Potential for Radiological Exposure (Internal and External)

The degree of hazard is based on the radionuclides present and the type and energy of radiation emitted (i.e., alpha particles, beta particles, gamma radiation, and neutron radiation). The design should consider exposures and keep exposures as low as reasonably achievable (ALARA).

Ex Situ Techniques Require Eventual Disposal of Residual Radioactive Wastes

Radionuclides are not destroyed; therefore, these waste forms must meet disposal site waste acceptance criteria.

Radioactive Waste Types Require Different Disposal Methods

Remediation technologies addressed by EPA (1994) generally are applicable for low-level radioactive waste (LLW), transuranic waste (TRU), and/or uranium mill tailings. The technologies are not applicable to spent nuclear fuel and, for the most part, are not applicable to high-level radioactive waste thought to be present at the NTS. Spent fuel and commercial high-level waste must be stored in a monitored retrieval storage facility and/or an underground geologic repository, such as the one being investigated at Yucca Mountain (Nevada). However, none of these facilities has yet been licensed, built, or put into operation. We have assumed that all waste will be disposed of off site.

Table 1-1
Treatment Technologies Screening Matrix
 (Adapted from the EPA Screening Matrix Guide, 1994)

NOTE: Specific site and contaminant characteristics may limit the applicability and effectiveness of any of the technologies and treatments listed below. This matrix is optimistic in nature and should always be used in conjunction with the *referenced text sections*, (EPA, 1994) which contain additional information that can be useful in identifying potentially applicable technologies.

NOTE: Specific site and contaminant characteristics may limit the applicability and effectiveness of any of the technologies and treatments listed below. This matrix is optimistic in nature and should always be used in conjunction with the *referenced text sections, (EPA, 1994)* which contain additional information that can be useful in identifying potentially applicable technologies.

		Development Status		Residuals Produced	Treatment Train (exclude off-gas)	VOCs	Contaminants Treated				System Reliability/Maintainability	Cleanup Time	Overall Cost	O&M or Capital Intensive							
		Availability					SVOCs	Fuels	Inorganic	Explosives											
SOIL, SEDIMENT, AND SLUDGE																					
1. In Situ Biological Treatment																					
1. Biodegradation	Full	■	None	No	■	■	■	Δ	■	Δ	■	■	■	O&M							
2. Bioventing	Full	■	None	No	■	■	■	Δ	■	■	■	■	■	Neither							
3. White Rot Fungus	Pilot	Δ	None	No	Δ	Δ	Δ	Δ	■	Δ	■	■	■	O&M							
2. In Situ Physical/Chemical Treatment																					
4. Pneumatic Fracturing (enhancement)	Pilot	Δ	None	Yes	■	■	■	■	■	■	NA	■	■	Neither							
5. Soil Flushing	Pilot	■	Liquid	No	■	■	■	■	Δ	■	■	■	■	O&M							
6. Soil Vapor Extraction (In Situ)	Full	■	Liquid	No	■	■	■	■	Δ	■	■	■	■	O&M							
7. Solidification/Stabilization	Full	■	Solid	No	Δ	■	■	■	■	■	■	■	■	Cap							
3. In Situ Thermal Treatment																					
8. Thermally Enhanced SVE	Full	■	Liquid	No	■	■	■	Δ	Δ	■	■	■	■	Both							
9. Vittrification	Pilot	Δ	Liquid	No	■	■	■	■	Δ	Δ	■	■	■	Both							
4. Ex Situ Biological Treatment (assuming excavation)																					
10. Composting	Full	■	None	No	■	■	■	Δ	■	■	■	■	■	Neither							
11. Controlled Solid Phase Bio. Treatment	Full	■	None	No	■	■	■	Δ	■	■	■	■	■	Neither							
12. Landfarming	Full	■	None	No	■	■	■	■	Δ	■	■	■	■	Neither							
13. Slurry Phase Bio. Treatment	Full	■	None	No	■	■	■	Δ	■	■	■	■	■	Both							
5. Ex Situ Physical/Chemical Treatment (assuming excavation)																					
14. Chemical Reduction/Oxidation	Full	■	Solid	Yes	■	■	■	■	Δ	■	■	■	■	Neither							
15. Dehalogenation (BCD)	Full	Δ	Vapor	No	■	■	■	Δ	Δ	■	■	■	■	■							
16. Dehalogenation (Glycolate)	Full	■	Liquid	No	■	■	■	Δ	Δ	Δ	■	■	■	Both							
17. Soil Washing	Full	■	Solid, Liquid	Yes	■	■	■	■	■	■	■	■	■	Both							
18. Soil Vapor Extraction (Ex Situ)	Full	■	Liquid	No	■	■	■	■	Δ	Δ	■	■	■	Neither							
19. Solidification/Stabilization	Full	■	Solid	No	Δ	■	■	■	■	■	■	■	■	Cap							
20. Solvent Extraction (chemical extraction)	Full	■	Liquid	Yes	■	■	■	■	Δ	■	■	■	■	Both							
6. Ex Situ Thermal Treatment (assuming excavation)																					
21. High Temperature Thermal Desorption	Full	■	Liquid	Yes	■	■	■	■	Δ	Δ	■	■	■	Both							
22. Hot Gas Decontamination	Pilot	■	None	No	Δ	Δ	Δ	Δ	■	■	■	■	■	Both							
23. Incineration	Full	■	Solid, Liquid	No	■	■	■	■	■	■	■	■	■	Both							
24. Low Temperature Thermal Desorption	Full	■	Liquid	Yes	■	■	■	■	Δ	■	■	■	■	Both							
25. Open Burn/Open Detonation	Full	■	Solid	No	Δ	Δ	Δ	Δ	■	■	■	■	■	Both							
26. Pyrolysis	Full	Δ	Solid, Liquid	No	■	■	■	■	■	■	■	■	■	Both							
27. Vittrification	Full	■	Liquid	No	■	■	■	■	Δ	■	■	■	■	Both							
7. Other Treatment																					
28. Excavation, Retrieval, and Off-Site Disposal	NA	■	NA	No	■	■	■	■	■	■	■	■	■	Neither							
29. Natural Attenuation	NA	■	None	No	■	■	■	■	Δ	Δ	■	■	■	Neither							
GROUNDWATER, SURFACE WATER, AND LEACHATE																					
8. In Situ Biological Treatment																					
30. Co-metabolic Treatment	Pilot	Δ	None	No	■	■	■	■	Δ	■	■	■	■	O&M							
31. Nitrate Enhancement	Pilot	Δ	None	No	■	■	■	■	Δ	■	■	■	■	Neither							
32. Oxygen Enhancement with Air Sparging	Full	■	None	No	■	■	■	■	■	■	■	■	■	Neither							
33. Oxygen Enhancement with H ₂ O ₂	Full	■	None	No	■	■	■	■	Δ	■	■	■	■	O&M							
9. In Situ Physical/Chemical Treatment																					
34. Air Sparging	Full	■	Vapor	Yes	■	Δ	■	Δ	Δ	■	■	■	■	Neither							
35. Directional Wells (enhancement)	Full	Δ	NA	Yes	■	■	■	■	■	■	■	■	■	Neither							
36. Dual Phase Extraction	Full	■	Liquid, Vapor	Yes	■	Δ	■	Δ	Δ	■	■	■	■	O&M							
37. Free Product Recovery	Full	■	Liquid	No	Δ	■	■	■	Δ	Δ	■	■	■	Neither							
38. Hot Water or Steam Flushing/Stripping	Pilot	■	Liquid, Vapor	Yes	■	■	■	■	Δ	Δ	■	■	■	Cap							
39. Hydrofracturing (enhancement)	Pilot	■	None	Yes	■	■	■	■	■	■	■	■	■	Neither							
40. Passive Treatment Walls	Pilot	Δ	Solid	No	■	■	■	■	■	■	■	■	■	Cap							
41. Slurry Walls (contaminant only)	Full	■	NA	NA	■	■	■	■	■	■	■	■	■	Cap							
42. Vacuum Vapor Extraction	Pilot	Δ	Liquid, Vapor	No	■	■	■	■	■	Δ	■	■	■	Cap							
10. Ex Situ Biological Treatment (assuming pumping)																					
43. Bioreactors	Full	■	Solid	No	■	■	■	■	Δ	■	■	NA	■	Cap							
11. Ex Situ Physical/Chemical Treatment (assuming pumping)																					
44. Air Stripping	Full	■	Liquid, Vapor	No	■	■	■	■	Δ	Δ	■	NA	■	O&M							
45. Filtration	Full	■	Solid	Yes	Δ	Δ	Δ	■	■	■	■	■	■	Neither							
46. Ion Exchange	Full	■	Solid	Yes	Δ	Δ	Δ	■	■	■	■	■	■	Neither							
47. Liquid Phase Carbon Adsorption	Full	■	Solid	No	■	■	■	■	■	■	■	NA	Δ	O&M							
48. Precipitation	Full	■	Solid	Yes	Δ	Δ	Δ	■	■	■	■	■	■	Neither							
49. UV Oxidation	Full	■	None	No	■	■	■	■	Δ	■	Δ	NA	■	Both							
12. Other Treatment																					
50. Natural Attenuation	NA	■	None	No	■	■	■	■	Δ	Δ	■	■	■	Neither							
13. AIR EMISSIONS/OFF-GAS TREATMENT																					
51. Biofiltration	Full	■	None	NA	■	■	■	■	Δ	■	Δ	NA	■	Neither							
52. High Energy Corona	Pilot	Δ	None		■	■	■	■	■	■	Δ	NA	■	■							
53. Membrane Separation	Pilot	Δ	None		■	■	■	■	■	■	■	NA	■	■							
54. Oxidation	Full	■	None		■	■	■	■	■	■	■	NA	■	Neither							
55. Vapor Phase Carbon Adsorption	Full	■	Solid		■	■	■	■	■	■	■	NA	■	Neither							

Rating Codes (See EPA, 1994 Table 3-1)

■ Better

● Average

Δ Worse

I Inadequate Information

NA Not Applicable

Rating Codes (See EPA, 1994 Table 3-1)

■ Better
 ● Average
 Δ Worse
 I Inadequate Information
 NA Not Applicable

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Some Remediation Technologies Will Concentrate Radionuclides

By concentrating radionuclides, it is possible to change the classification of the waste, which affects the requirements for disposal. For example, concentrating radionuclides could turn LLW into TRU (if TRU radionuclides were concentrated to greater than 100 nanoCuries per gram [(nCi/g)]). Also, LLW classifications (e.g., Class A, B, or C for commercial LLW) could change because of the concentration of radionuclides. Waste classification requirements for disposal of residual waste (if applicable) should be considered when evaluating remediation technologies.

Disposal Capacity for Radioactive and Mixed Waste Is Limited

Commercial LLW disposal capacity will no longer be available for many out-of-state compact (regions without a licensed LLW disposal facility) generators because the disposal facility in Barnwell, South Carolina, closed (to out-of-compact generators) on June 30, 1994. Currently there is only one disposal facility (Envirocare of Utah, Inc.) licensed to accept mixed waste (i.e., low-activity mixed LLW and hazardous waste) for disposal. Mixed waste can be treated to address the hazardous characteristics of the soil, thereby allowing the waste to be addressed as solely radioactive waste.

Reasonable Remedial Alternatives

With these considerations, the reasonable remedial alternatives that will be described and analyzed in detail are the following:

- No Action. (Baseline risk assessment for current conditions is almost completed.)
- Institutional Controls (e.g., federal controls, cost of land acquisition, land withdrawal, and boundary control, fencing, personnel in perpetuity)
- Intrinsic Remediation (or natural attenuation). (Summarize the current UGTA strategy that is directed at modeling of CAUs to locate the 4-millirem per year (mrem/yr) organ dose contaminant boundary at the 95 percent confidence level.)
- Pump and *In Situ* Treatment
- Excavation and On-Site Disposal (with off-site disposal of fraction exceeding waste acceptance criteria for on-site disposal cell)

As has been previously mentioned, some brief, qualitative statements will be made about other alternatives that were not considered in detail, such as the more exotic remedial notions

(i.e., transmutation). Note that intrinsic remediation is not the same as "no action," even though it is often perceived as such. Intrinsic remediation (natural attenuation) is considered on a case-by-case basis (i.e., where removal of dense nonaqueous phase liquids [DNAPLs] has been determined to be technically impractical and where active remedial measures would be unable to improve the speed of remediation significantly).

Section 300.430(a)(iii)(B) (CFR, 1993c) of the NCP contains the expectation that engineering controls (such as consolidation, capping, and containment) will be used for waste that poses a relatively low long-term threat or when treatment is impractical. The preamble to the NCP identifies municipal landfills as the type of site where treatment of the waste may be impractical because of the size and heterogeneity of the contents. Waste in the NTS shot sites usually is present in large volumes and is a heterogeneous mixture of low- and high-level radioactive waste with some hazardous waste. Because treatment is impractical, the EPA would probably consider containment to be the appropriate response action or the "presumptive remedy" for source areas at the NTS.

The reasonable remedy for the NTS sites would relate primarily to the containment of the source radionuclides. In addition, measures to control leachate generated by remediation of debris from the nuclear chimneys may be required at each shot site (as well as measures to control affected groundwater at the perimeter of each shot site) and measures to control affected upgradient groundwater saturated of the source areas. Reasonable remedies may be implemented in the form of caps. However, the treatment of leachate would probably require *ex situ* disposal, both on site and off site, for those respective waste fractions that fall below or exceed the waste acceptance criteria for on-site disposal.

Treatment that eliminates or minimizes the need for long-term management could include excavation and treatment of all contaminated debris and soil, all soil above the 10^{-4} risk, or "hot" spots. Excluding cost, the critical concern in this remedial action would be the immediate health risks posed to the workers in the excavation, treatment, disposal, and transportation of the high-level radioactive waste.

1.3.1.2 Analyze the Alternatives Against the Evaluation Criteria

Each presumptive remedial alternative will be analyzed in detail against the cost evaluation criteria and, in general, against the criteria for short-term effectiveness and implementability. In

the detailed analysis of each individual alternative against the criterion of cost, each alternative will be analyzed roughly in terms of the following:

- Direct capital costs
- Indirect capital costs
- Annual Operating and Maintenance (O&M) costs

Assumptions about these costs will be derived from R.S. Means (1996) and other cost data that can be readily accessed.

1.3.1.3 Compare the Alternatives Against Each Other

Comparison of the alternatives identifies the advantages and disadvantages of each one relative to another to allow identification of key trade-offs that must be balanced by the decision maker. The discussion will focus on cost, short-term effectiveness, and implementability, as appropriate.

1.4 Report Structure

This report estimates the costs and analyzes the comments concerning the technical or regulatory feasibility of the following presumptive alternatives:

- No action baseline risk assessment
- Intrinsic remediation
- Institutional controls
- Pump and *in situ* treatment
- Excavation and on-site treatment and disposal
- Other alternatives not considered

Each chapter that discusses these alternatives will consider the technical approach and the technical feasibility and will estimate the conceptual costs.

2.0 No Action Alternative - Baseline Risk Assessment

The "no action" alternative is the baseline risk assessment. The baseline risk assessment evaluates the potential threat to human health and to the environment in the absence of any remedial action or degradation of the contaminant source.

2.1 Technical Approach

For groundwater, the baseline risk assessment uses current conditions to establish the risks to current and future receptors, regardless of their location. The baseline risk assessment uses the peak concentration within the plume to establish the risk when the aquifer is a drinking water aquifer. If the risks due to this peak concentration fall below 10^{-4} lifetime cancer risk and below ARARs and maximum contaminant levels (MCLs), then "no action" is allowed, and the site can be left without any remediation.

2.2 Technical Feasibility

The current baseline risk assessment (DOE, 1996) only looked at one constituent of the source term, tritium. The DOE (1996) estimated that, for a peak tritium concentration of approximately 1.2×10^8 picoCuries per liter (pCi/L), a maximally exposed member of the public would have a lifetime probability of 4.0×10^{-3} (approximately one in 250) of contracting a fatal cancer and a lifetime probability of 1.8×10^{-3} (approximately one in 600) of contracting any other detrimental effects. By comparison, the EPA allows a maximum tritium concentration in drinking water of 20,000 pCi/L. Consequently, the baseline risk assessment indicates that the "no action" alternative is not a viable alternative.

In addition, this baseline risk assessment must be viewed as incomplete, given that it only characterizes tritium. Daniels (1993) states that current characterization of the source terms is rather limited because relevant groundwater sampling data are available from only three shot cavities. Daniels (1993, Table 1) presents a representative mix of radionuclides with their maximum observed concentrations. Even those limited data indicate that the maximum probable cancer mortality risk exceeds the 1×10^{-4} level by one to two orders of magnitude.

2.3 Conceptual Costs

Given that the baseline risk assessment (DOE, 1996) clearly indicates that the "no action" alternative cannot be pursued, an extensive characterization program focused on proving the viability of the "no action" alternative would not be productive.

3.0 *Intrinsic Remediation Alternative - Natural Attenuation*

The intrinsic remediation alternative, often called natural attenuation, refers to the use of natural subsurface processes to reduce contaminant concentrations to acceptable levels. Natural subsurface processes include decay, dilution, volatilization, biodegradation, adsorption, and chemical reactions with subsurface materials. However, unlike organic contaminants, radionuclides cannot be destroyed or degraded; therefore, intrinsic remediation of radionuclides must rely principally on decay, adsorption, and chemical reactions to immobilized nuclides. In general, groundwater samples taken from groundwater monitoring networks have provided evidence of natural attenuation. Intrinsic remediation, while not considered a "technology," requires predicting the reduction of contaminant concentrations to below regulatory standards before exposure pathways are completed (Weidemeier et al., 1995).

The following sections of this report describe the UGTA strategy with respect to the intrinsic remediation, review the work currently planned, and discuss the costs involved to implement intrinsic remediation.

3.1 *Underground Test Area Technical Approach to Intrinsic Remediation*

To predict the potential extent, concentration, future of radionuclide migration over a lifetime, groundwater flow and transport models and are needed. These models quantify the migration and attenuation rates of constituents of concern (COC) in an aquifer by incorporating attenuation rates (chemical reaction terms, decay, sink, and source terms), constituent transport paths, and distribution. However, contaminant transport models require suitable site-specific field and laboratory data to estimate input model parameters and to achieve calibration. The accuracy of model predictions depends heavily on the quality and quantity of the input data. Because of the high cost of collecting geologic and hydrologic data at the NTS, data-collection activities must justly provide the most cost-effective information useful in reducing the level of uncertainty. The UGTA strategy (Section 1.2 of this report) describes the following general work elements that are essential for implementation:

- Perform a Value of Information Analysis (VOIA).
- Perform data collection activities, if justified by the VOIA.
- Perform data analysis activities.
 - Prepare geologic and hydrologic datasets for CAU-specific modeling.

- Perform flow and transport modeling to establish the contaminant boundary around the CAU.
- Design the well network for compliance monitoring.
- Perform initial 5-year monitoring; use results to demonstrate compliance.
- Close CAU and develop post-closure plan for 50-year monitoring.

The following paragraphs discuss the approach to intrinsic remediation in terms of this work scope, including the development of the CAU contaminant boundary by performing flow and transport modeling (which leads to CAU monitoring for eventual closure).

3.1.1 VOIA and Data Analysis Activities

The VOIA will identify the requirements for further data collection, if necessary, and data analysis to achieve the required level of certainty. The VOIA will evaluate the value of data collection and data analysis options to reduce uncertainty in predicting the location of the contaminant boundary. The VOIA will quantitatively define the improvements in confidence that would result from conducting various data collection and data analysis options. It will also estimate the cost of conducting these options. One of the assumptions of the VOIA is that CAU-specific flow and transport modeling will be conducted to establish the contaminant boundary.

Data analysis activities include the compilation of existing CAU-specific data to develop the conceptual model and involve the processes of intrinsic remediation to locate the contaminant boundary for the CAU. Objectives are the following:

- Define the CAU geologic model.
- Define the CAU hydrologic and transport processes and properties.
- Define the CAU source term (including other radionuclides excluding tritium).
- Define the CAU boundary conditions (from the regional modeling).
- Define the CAU geochemical processes.

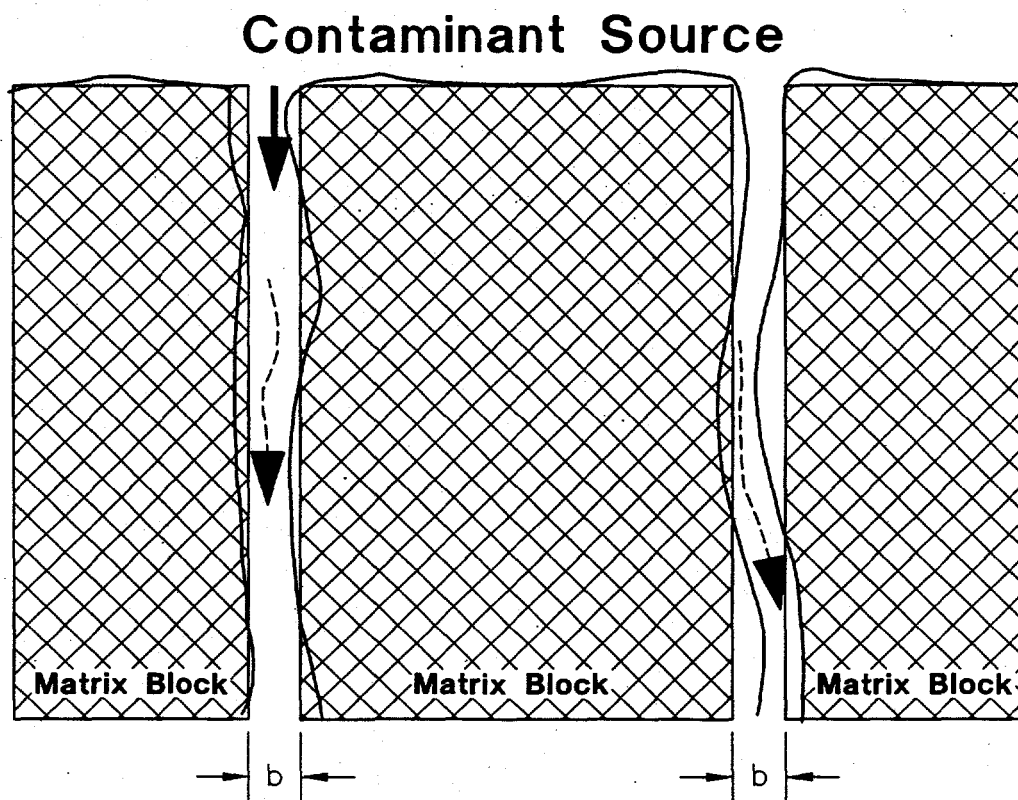
The NTS conceptual model assumes that the groundwater flow largely occurs within the fracture system (mobile domain) of the porous media. Diffusion (mass transfer) occurs between contaminated groundwater and the fracture surface and limits contaminant transport from the fracture to the porous matrix. Matrix diffusion, as presented here, is similar to the dual-porosity model used by van Genuchten and Wierenga (1976) in that it considered the immobile domain.

However, diffusion was the only transport process and was approximated by a first-order mass transfer equation. In contrast, the fracture-porous matrix model shown in Figure 3-1 better represents the hydrogeology at the NTS. Hydrogeologic features of the NTS include the low hydraulic conductivities of the sandstones and shales (porous matrix), the volcanics, and the high conductivities of the fractures and solution channels in the carbonate rock (Borg et al., 1976; Laczniak et al., 1994). The main assumptions of the NTS conceptual model for contaminant transport are as follows:

- Flow of fluid occurs in the fracture domain only.
- Mass transfer from the fracture (mobile domain) to the matrix domain (immobile domain) only occurs through diffusion, and the diffusion can be approximated by a first-order mass transfer equation.
- Transport processes in the fracture (mobile domain) include advection-dispersion; the matrix domain includes diffusion only.
- The system attains local adsorption equilibrium by means of linear isotherms.
- At any point along the longitudinal direction, complete mixing occurs across the mobile phase due to transverse diffusion, so average concentrations can be considered for this region.
- The volcanic confining unit is complex, and its stratigraphic positions can be difficult to predict. Zeolitized non-welded tuff, with additional ash-fall tuffs, ash-flow tuffs, breccia flows, rhyolite flows, and tuffaceous sandstone commonly compose the volcanic confining or aquitard tuff unit.
- The volcanic aquifer overlies the volcanic confining unit or aquitard. Bedded welded-tuff outside the calderas, lava flow basalts, and ash-flow tuffs within the calderas form this aquifer.

3.1.2 Development of the Corrective Action Unit Contaminant Boundary

As data analysis proceeds and the compilation of the required datasets for input into the flow and transport models is completed, the flow and transport models will be designed to simulate the effectiveness of intrinsic remediation in order to establish the 4-mrem/yr organ dose contaminant boundary at the 95th percent confidence level. (This definition of the contaminant boundary replaces the earlier 20,000-pCi/L compliance boundary based on the EPA's MCLs for tritium.) Here, design means the representation of the hydrogeologic system by a mathematical model implemented by a numerical code with appropriate data inputs. Existing CAU data will be



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Figure 3-1
Conceptual Diagram of Fracture and Matrix Systems

evaluated to estimate flow and transport parameters and the boundary conditions. Natural heterogeneities will be represented numerically by discretization of the flow domain. However, before one can assess the effectiveness of the flow system as it relates to intrinsic remediation, the uncertainty in model predictions must be established. Model prediction errors with flow and transport models can be traced to the following three basic sources in model design (NRC, 1990):

- Natural heterogeneity that cannot be completely described with a limited number of field samples
- Measurement errors
- Structural differences between the real-world system and the model used to represent it

A structurally perfect model that uses inputs estimated from perfect measurements of a homogeneous real world will produce perfect predictions. Departures from this ideal situation can be attributed to one or more of the above-mentioned error sources.

With these error sources in mind, the fundamental source and range of uncertainty will be identified and estimated during the design of the hydrogeologic system with the Monte Carlo Simulation and Transport (MC_TRANS) code (IT, 1996). Prediction accuracy will be investigated by analyzing the model's sensitivity to changes in an appropriate error source variable. A series of parameters and their sensitivities will be identified through a series of Monte Carlo simulations. The Monte Carlo simulations will repeat the entire modeling process of sampling, input estimation, and prediction—many times. This generalization of the traditional model sensitivity analysis includes field sampling and input estimation to define the distribution functions for each variable. These sensitivities and distributions will allow an assessment of model accuracy. For example, if the confidence intervals associated with two model predictions are greater than the difference between the predictions, the predicted difference cannot be considered meaningful (at least in a statistical sense). So, this is the minimum effort that must be performed to estimate model accuracy. Otherwise, there is no way to know whether suitable accuracy has been obtained or whether the predicted rates of intrinsic remediation are realistic.

3.1.3 Monitoring Network Design and Preparation of Monitoring Plan

The design of the monitoring network includes the technical requirements and the physical layout of the well system. The monitoring plan consists of developing a groundwater monitoring strategy and describes the implementation of this strategy to ensure compliance with the

necessary requirements. This strategy essentially verifies through appropriate monitoring activities that intrinsic remediation is occurring at rates sufficient to protect human health and the environment.

3.2 Technical Feasibility of Intrinsic Remediation at the Nevada Test Site

To assess the technical feasibility of intrinsic remediation, the following reports and on-going studies review and briefly summarize the technical basis for this alternative at the NTS:

- Daniels, J.I., Ed. 1993. *Pilot Study Risk Assessment for Selected Problems at the Nevada Test Site (NTS)*, UCRL-LR-113891. Prepared by Lawrence Livermore National Laboratory. Livermore, CA: University of California.
- GeoTrans, Inc. 1995. *A Fracture/Porous Media Model of Tritium Transport in the Underground Weapons Testing Areas, Nevada Test Site*. Prepared for the U.S. Department of Energy, Nevada Operations Office. Las Vegas, NV.
- IT Corporation. 1996. Draft, *Underground Test Area Project, Phase I Data Analysis Task: Transport Model Documentation Package*. Prepared for U.S. Department of Energy, Nevada Operations Office. Las Vegas, NV.
- Rehfeldt, K. 1996. "Solute Transport Model." Presentation to the U.S. Department of Energy, Nevada Operations Office, 31 January.

Daniels (1993) reports the evaluation of risk from tritium-contaminated groundwater to individuals at on- and off-site locations at the NTS over 70-year intervals (e.g., 1 to 70, 25 to 94, 70 to 139,..., 539 to 608 years). These estimates of risk used a travel-time transport approach based on groundwater velocity, advection, dispersion, and radioactive decay. However, these analyses assumed no sorption of nuclides onto geologic materials or diffusion of nuclides into dead-end pore space. These processes would have reduced the concentrations predicted at downgradient receptors. Importantly, this travel-time model considered parameter uncertainty and possible correlations among parameters.

Unfortunately, Daniels (1993) had data from only three shot cavities with which to develop the source term. He used the maximum observed concentrations of radionuclides measured from groundwater samples taken from the three sites to develop a representative source term.

The Daniels (1993) report looked at two scenarios for intake of contaminated groundwater: an individual living on the NTS (near the Area 20 boundary) and one living near the springs at

Oasis Valley. Results of the risk-screening analyses for these two scenarios indicated that tritium would constitute the dominant contributor to dose and risk for humans exposed to groundwater from the NTS. In addition, projected future concentrations for the representative mix of radionuclides did not appear to pose a serious concern for human exposure and risk, even though the source concentration exceeds the MCLs for tritium (see Table 1 in Daniels [1993]). However, Daniels (1993) speculates that, if the assumed concentrations present today are actually 10 to 100 times greater than the concentrations considered to be maximum, the predicted risks would also be 10 to 100 times higher. This increase in risk would then fall outside the range considered acceptable by the EPA. Consequently, Daniels (1993) recommends a more comprehensive characterization of the source terms at the NTS shot cavities and plans for maintaining institutional controls beyond 101 years. In contrast, IT (1996) shows that the calculated average initial concentration for tritium for all shot sites in Pahute Mesa is 8.31×10^8 pCi/L, which is an order of magnitude less than the 7.56×10^9 pCi/L concentration indicated in Daniels (1993, Table 1). So these data suggest that the actual source concentrations may be less than those considered by Daniels; therefore, the risk may actually be lower than the already acceptable risk estimated by Daniels (1993).

GeoTrans (1995) and Rehfeldt (1996) predicted similar results with transport analyses that include the effects of intrinsic remediation. They used a one-dimensional model to predict the transport of tritium from underground nuclear tests at Pahute Mesa and in southern Yucca Flat. These simulations considered the attenuation of tritium through two processes, decay and matrix diffusion, and neglected the minor sorption of tritium. In the absence of matrix diffusion, these simulations found that tritium moved rapidly with the concentration (primarily determined by the decay rate regardless of distance from the source). With matrix diffusion, these simulations predict that matrix diffusion significantly attenuates concentrations of tritium (especially at low velocities). Table 3-1 (Rehfeldt, 1996) gives the maximum distances in meters out to 20,000 pCi/L for tritium (for various shot areas) for cases with diffusion, without diffusion, and the literature values without diffusion.

The first two columns in Table 3-1 come from transport simulations based on the 95th percentile of the cumulative distribution function from 1,000 Monte Carlo simulations (IT, 1996). These simulations produced a large range of possible outcomes based on the distribution parameters for porosity, the dispersion coefficient, advective velocity, diffusion coefficient, and fracture spacing. Initial tritium activities were treated as constants and were not varied during the Monte Carlo runs.

Table 3-1
Maximum Distances Out to 20,000 pCi/L of Tritium
for Three Transport Simulations^a

Underground Test Area	Distance, meters (feet)		DRI ^b Literature Values without Diffusion
	With Diffusion ^a	Without Diffusion ^a	
Yucca Flat/Corduroy	12,700 (41,700)	16,600 (54,500)	50,500 (165,700)
Frenchman Flat	N/A	300 (1,000)	4,300 (14,100)
Pahute Mesa	6,700 (22,000)	16,100 (52,800)	24,500 (80,400)
Rainier Mesa/Shoshone	2,300 (7,600)	8,100 (26,600)	15,000 (49,200)

^aRehfeldt, 1996

^bDesert Research Institute

The simulations for Pahute Mesa predict that no measurable tritium will reach areas that are not presently controlled by the DOE or the U.S. Air Force such as Oasis Valley. An average hydraulic conductivity of 250 meters per year (m/yr) (820 feet per year [ft/yr]) would result in detectable concentration not occurring much further than 12 kilometers (km) (7.5 miles [mi]) from the shot cavities. The MCL (20,000 pCi/L) will not exceed beyond approximately 6 km (3.7 mi). In contrast, tritium transport along the Yucca Flat to Mercury flowpath occurs over a shorter distance because the two orders of magnitude lower gradient facilitates both decay and matrix diffusion. Simulations show that no detectable weapons testing-related tritium would occur 2.5 km (1.6 mi) from the source. With high hydraulic conductivities, the precipitation level of tritium concentration reached only 5 km (3.1 mi). Finally, monitoring wells at off-site locations have not detected tritium from underground tests in the groundwater. On-site wells have detected only low levels of tritium, except in wells drilled near the cavities.

3.3 Costs to Implement Intrinsic Remediation Strategy at the Nevada Test Site

The NTS has developed a comprehensive estimate of costs for a technical strategy that implements Intrinsic Remediation at the Nevada Test Site. Table 3-2 summarizes the costs of the main steps shown in Figure 1-2. The following text describes the steps in more detail.

3.3.1 Assess Corrective Action Unit-Related Existing Data

"Data Analysis" tasks of the current strategy will serve to review the available site data and to develop a preliminary conceptual model for intrinsic remediation.

Table 3-2
Costs to Implement Intrinsic Remediation Strategy
at the Nevada Test Site

UGTA Technical Decision Tree Steps (Figure 1-2)	Cost in \$
Assess CAU-Related Existing Data and Develop a Preliminary Conceptual Model	12,624,342
Model CAU and Verify Model Results with Existing/New Data	16,214,832
Use Modeling Results to Assess Whether Strategy for Intrinsic Remediation is Achievable	11,520,393
Assess Whether Intrinsic Remediation Passes Initial Technical and Regulatory Screening on Definition of Contaminant Boundaries	120,481,667
Prepare Draft Corrective Action Decision Document	17,245,414
Assess Need for Contaminant Control	13,983,176
Develop CAP/Monitor Plan for Five Years	5,277,204
Implement Closure Approach	24,114,594
Total Cost for Intrinsic Remediation Alternative with Five Years of Monitoring	221,461,622
Total Cost for Intrinsic Remediation Alternative with 50 Years of Monitoring	239,844,200

3.3.2 Model the Corrective Action Unit and Verify Model Results with Existing/New Data

Data analysis activities to support intrinsic remediation will include modeling of CAU and verifying model with existing or new data, as appropriate.

3.3.3 Assess Whether Strategy for Intrinsic Remediation Is Achievable

The current strategy uses as fundamental assumption that intrinsic remediation will effectively contain the movement of the nuclides so that the 4-mrem/yr organ dose contaminant boundary remains within a few kilometers of each CAU. Modeling results will help assess whether the

strategy for intrinsic remediation is achievable. Modeling tasks related to intrinsic remediation include the following:

- Refine conceptual model.
- Complete pre-modeling calculations.
- Simulate intrinsic remediation with flow and transport models that allow for nuclide decay and retardation.
- Conduct VOIA.

If the results are acceptable, DOE will propose contaminant boundaries.

3.3.4 Assess Whether Intrinsic Remediation Passes Initial Technical and Regulatory Screening

The current strategy assumes that intrinsic remediation alone will pass initial technical and regulatory screening and will be acceptable to the State of Nevada. The assumption is that the technical and regulatory reviews will agree that intrinsic remediation will effectively contain the movement of the nuclides so that the 4-mrem/yr organ dose contaminant boundary at the 95th percent confidence level remains within a few kilometers of each CAU.

However, if required, contingencies have been added for additional site characterization, assessment of the combined performance of intrinsic remediation, and possible response actions.

3.3.5 Prepare Draft Corrective Action Decision Document

If the proposed contaminant boundaries are acceptable to the NDEP, the Draft CADD will be developed. The CADD will evaluate the need for contaminant source control, containment and implementation (as appropriate), or a five-year monitoring program; it will then propose the most desirable option of the three.

3.3.6 Review CADD Results

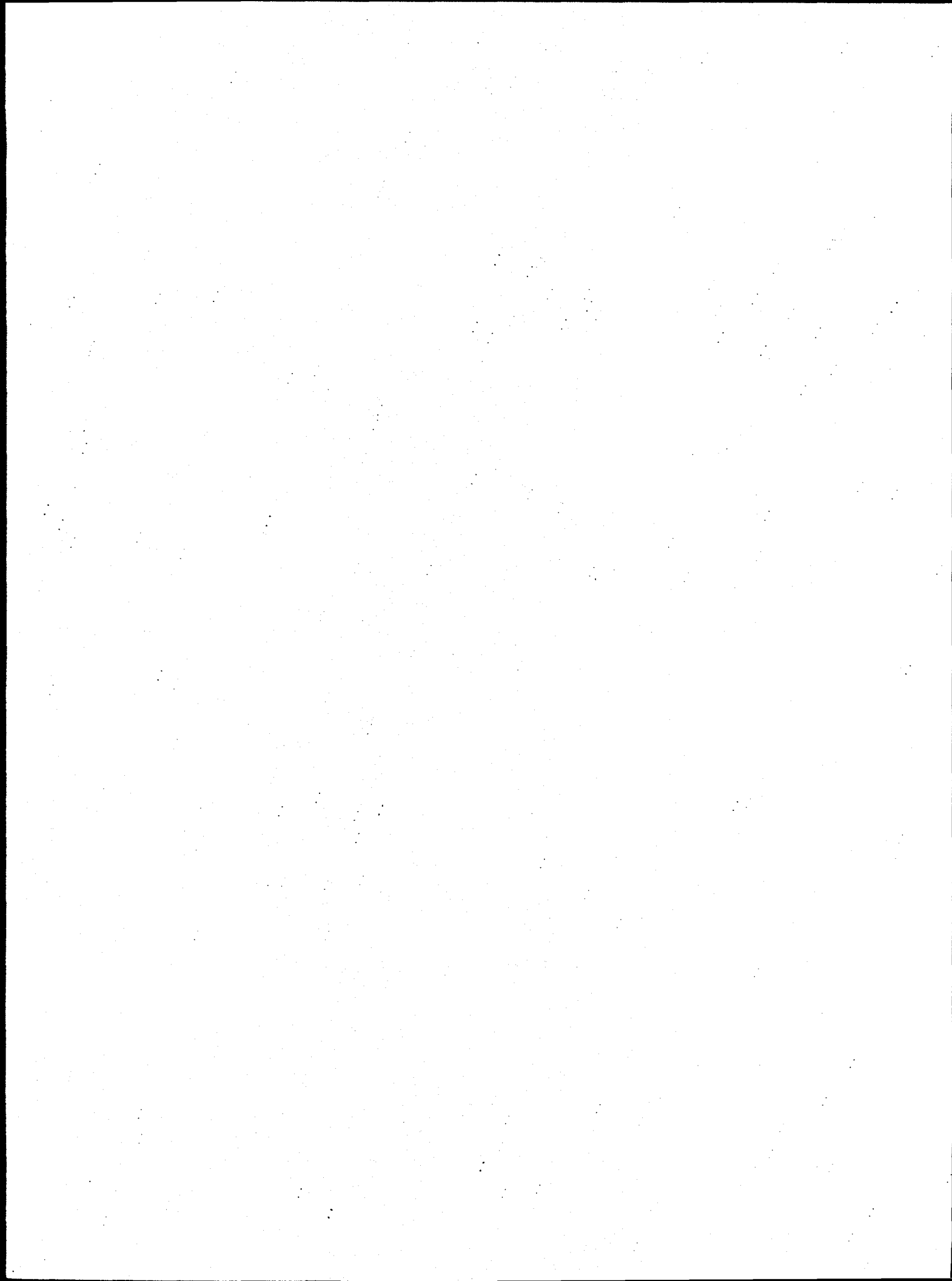
Following the CADD review, the appropriate option will be chosen.

3.3.7 Develop CAP/Monitoring Plan for Five Years

If contaminant control is not required, a CAP and/or five-year monitoring plan will be developed.

3.3.8 Implement Closure Approach

Implementation of the closure approach allows for the construction and monitoring of additional monitoring wells over 5 to 50 years, as appropriate. DOE and NDEP review the monitoring results. When the results are accepted, closure begins.



4.0 Institutional Controls

This treatment alternative briefly discusses the technical approach, the feasibility, and the costs of using institutional controls as a remedial alternative at the NTS.

4.1 Technical Approach

Institutional controls fall into two categories, passive and active (40 CFR 191.12 [1996a]).

Passive institutional control includes the following:

- Permanent markers at a disposal site
- Public records and archives
- Government ownership and regulations regarding land or resource use
- Other methods of preserving knowledge about the location, design, and contents of the disposal system

Active institutional control includes the following actions:

- Controlling access to a disposal site by any means other than passive institutional controls
- Performing maintenance operations or remedial actions at a site
- Controlling or cleaning up releases from a site
- Monitoring parameters related to disposal system performance

For the purposes of this focused evaluation, we have assumed that the costs associated with passive control are negligible.

4.2 Technical Feasibility

Institutional controls have been in place at the NTS for over 50 years, and these controls have taken the form of both active and passive. The public knows of the related risks and is aware that the U.S. Government strictly controls access to the NTS. Therefore, because of 50 years of "Institutional Memory," it seems reasonable to believe that such controls could continue indefinitely as they complement ongoing clean-up and monitoring efforts. The previous chapter on intrinsic remediation covered the issue of monitoring the "disposal system performance."

Later chapters in this report discuss remedial actions and control or cleanup of releases from the site. However, federal regulations (40 CFR 300.430(D) [1993c]) state that "institutional controls shall not substitute for active response measures as the sole remedy unless such active measures are determined not to be practicable, based on the balancing of trade-offs among the alternatives analysis that is conducted during the selection of the remedy." The remaining chapters in this report will examine the practicality and trade-offs involved in some of the more active remedial alternatives.

4.3 Conceptual Costs

Because passive institutional controls are negligible, this report focuses on the costs associated with active institutional controls, namely controlling access and performing maintenance operations at the site. The cost estimates for access control (security guards) and infrastructure maintenance (perimeter fence) are included.

4.3.1 Access Control

Security and administrative personnel are required to control access to the NTS. Access control will need approximately 75 people with an average cost of \$90,000 per person or \$6.75 million per year. Over a period of 50 years, this cost (assuming an annual escalation rate of 3 percent) is \$761.4 million.

4.3.2 Infrastructure Maintenance

Infrastructure maintenance is the effort required to install and maintain a perimeter fence of 262 km (163 mi) which is assumed to be the perimeter of the NTS. According to R.S. Means (1996), the installed cost for a 1.8-meter (m) (6-foot [ft]) chain link (9-gage, galvanized steel) fence with a 51-millimeter (mm) (2-inch [in.]) diameter posted 3 m (10 ft) high with 3 strands of barbed wire is \$41 per meter (\$12.60 per foot). This cost per meter (foot) includes labor and equipment. If 25 percent is added to enclose a remote site, then the cost per meter is \$52 (cost per foot is \$15.75). For 262 km (163 mi) of fence, the cost will be \$13,550,000, and the fence will need to be replaced every 15 years. Over a period of 50 years, this cost (assuming an escalation of 3 percent) is \$119.2 million.

5.0 Pump and In Situ Treatment

In the pump and *in situ* treatment alternative, two options that can help contain contaminated groundwater by establishing suitable zones of hydraulic capture are considered, and one option that is included evaluates the withdrawing, transporting, and reinjecting of clean groundwater. The first two options (as shown in Figures 5-1 and 5-2) look at the use of recovery wells to contain contaminated groundwater at each shot site and to treat it *in situ* by injection through the unsaturated zone of the nuclear chimney. Option 1 (Figure 5-1) uses recovery wells within each nuclear chimney to establish a zone of capture; Option 2 (Figure 5-2) uses recovery wells outside of the nuclear chimney to establish hydraulic control. These two options account for differences in the drilling costs and in the efficiency of the capture zones for recovery wells within and outside of each nuclear chimney. Options 1 and 2 reinject the contaminated groundwater into the unsaturated zone of the nuclear chimney to strip the nuclides by evaporation and filtration (Figure 5-3). However, Option 1 also considers reinjection not only by wells, but also by wick drains (Figure 5-4). Wick drains eliminate the soil cuttings generated during well installation and significantly reduce the related health and safety risks to remediation workers. Also, wick drains would avoid the required disposal of soil cuttings as radioactive waste.

The first two options (Figures 5-1 and 5-2) look at the use of recovery wells to pump and treat contaminated groundwater at each shot site by reinjecting groundwater into the nuclear chimney to strip out nuclides and increase the residence times near the shot cavity (EPA, 1994). This is an innovative application of the pump and *in situ* treatment alternative. Because the EPA no longer allows the use of Class V Injection Wells (those that inject waste into the subsurface), we also estimate the cost for removal of nuclides from the groundwater before reinjection. In other words, reinjection of contaminated groundwater into the aquifer is illegal. Furthermore, the use of soil columns as remedial systems is perceived as being against DOE Orders.

In contrast, the third option (Figure 5-5) looks at the cost of withdrawing clean groundwater from the hydraulically upgradient side of the NTS, transporting it to the hydraulically downgradient side of the NTS, and reinjecting it. This approach would avoid construction of wells in contaminated areas.

Section 5.1 discusses the overall technical approach used in the analysis of these three options. Section 5.2 assesses the technical feasibility and likelihood of any of these options achieving

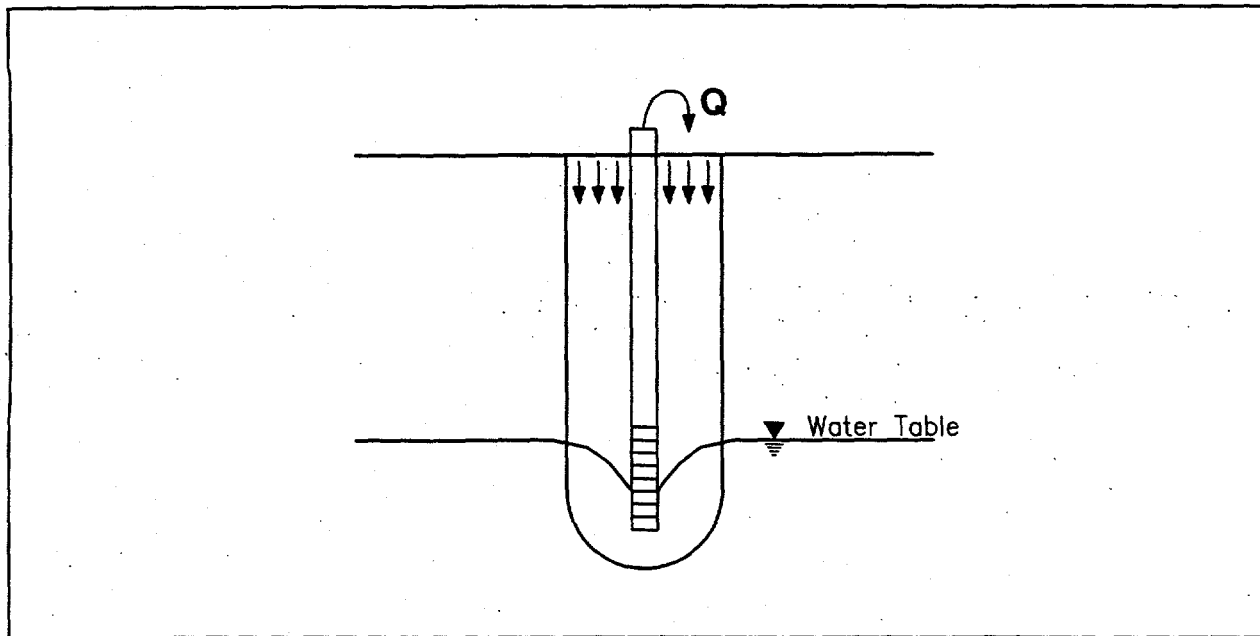


Figure 5-1
Option 1: Recovery Wells Inside the Nuclear Chimney

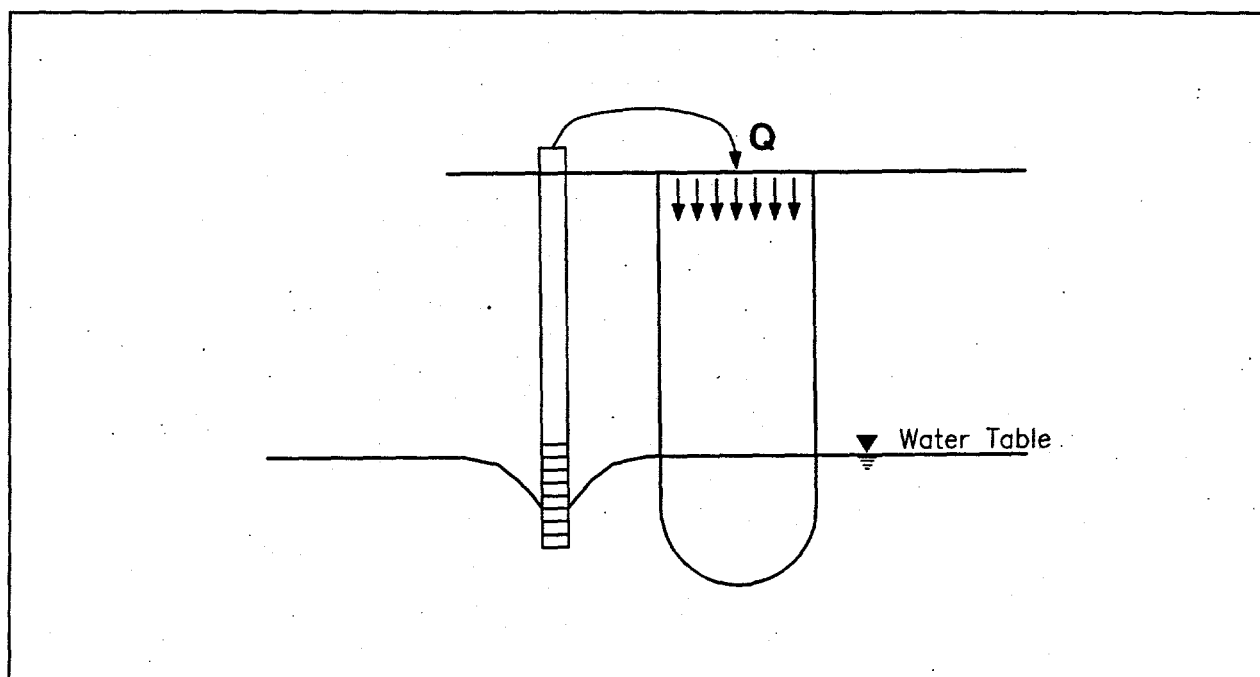


Figure 5-2
Option 2: Recovery Wells Outside the Nuclear Chimney

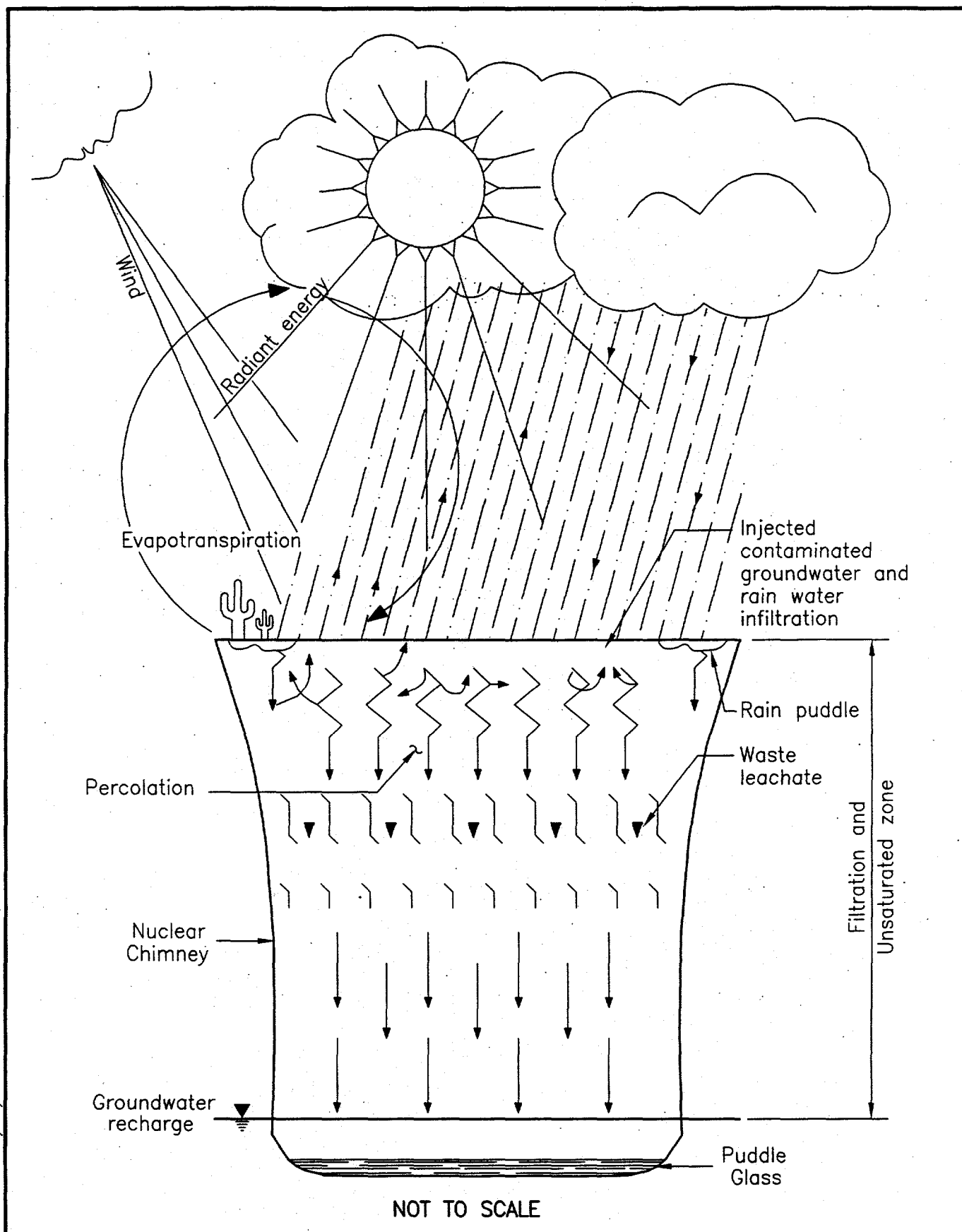
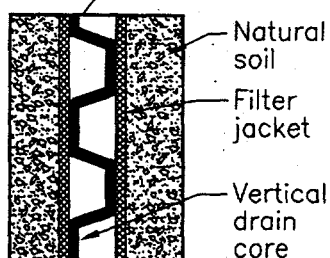
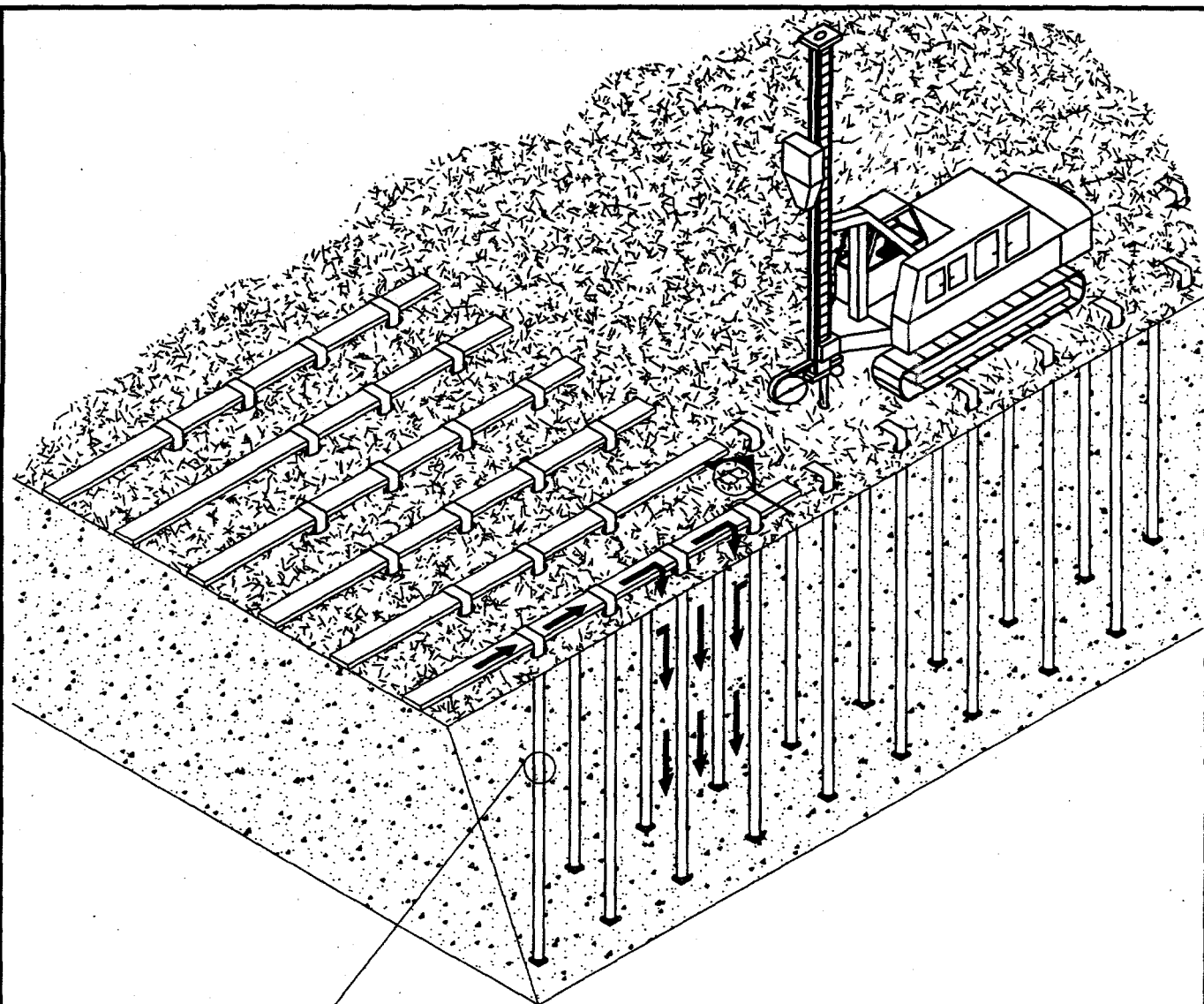
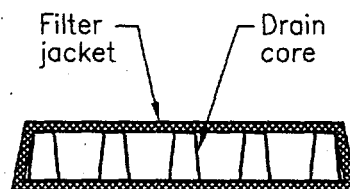


Figure 5-3
Conceptual Unsaturated Zone Model for Nuclear Chimney



(A) Detail Vertical Drain



(B) Section - Horizontal Drain

NOT TO SCALE

Figure 5-4
Typical Vertical/Strip Drain Installation for
Injection of Waste Leachate

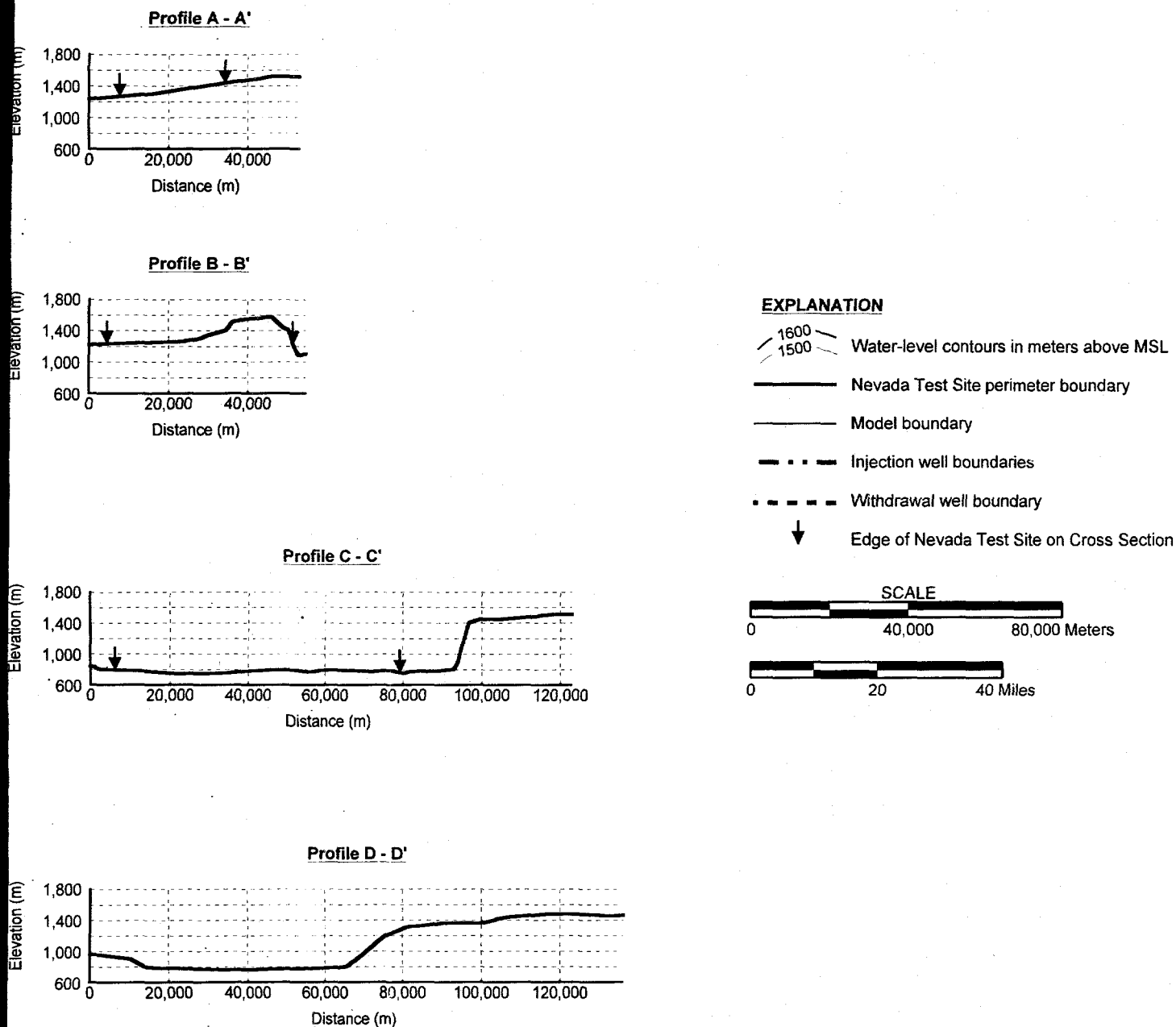
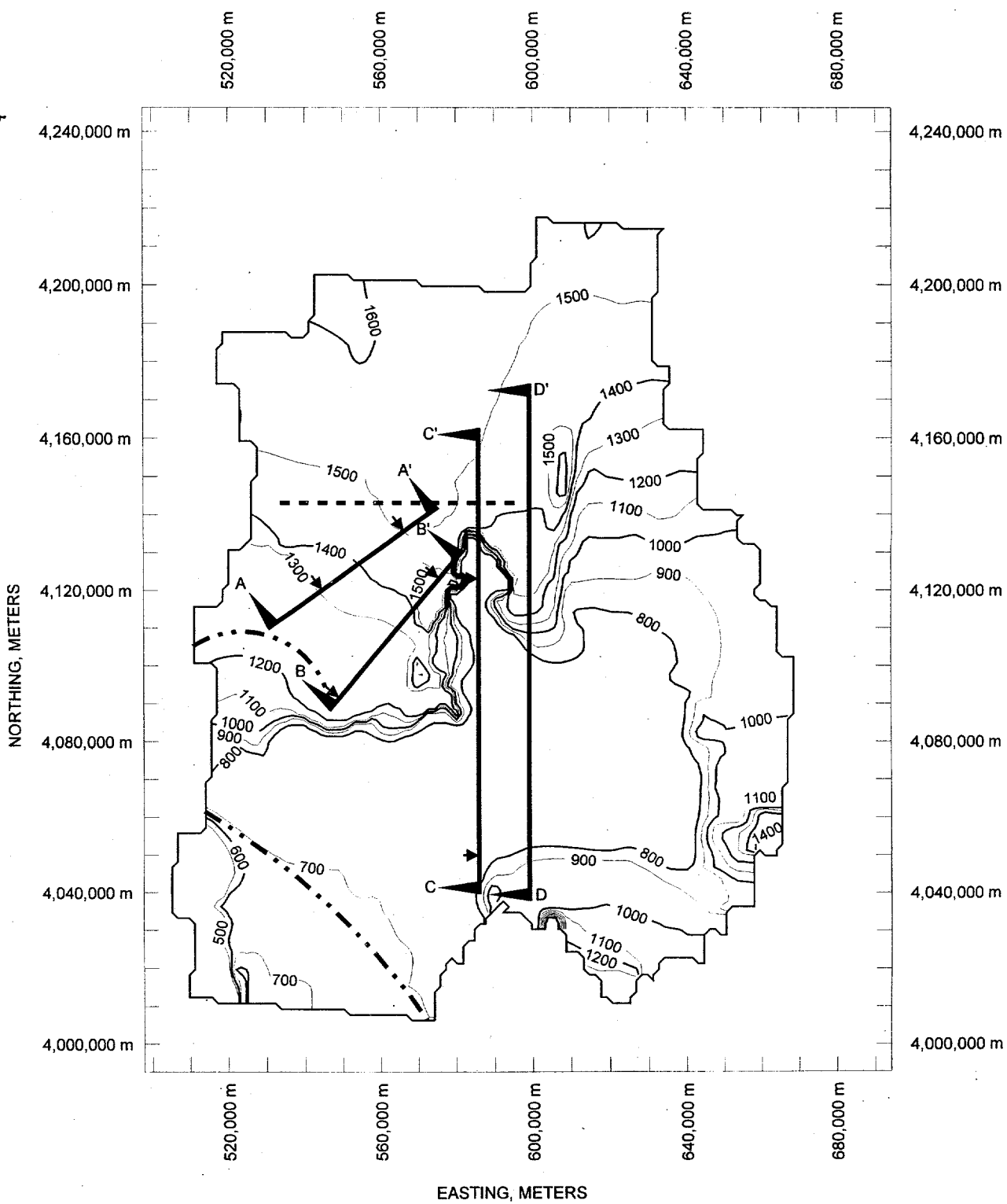


Figure 5-5
Option 3:
Withdrawal of Clean Groundwater from
North for Transport to South of NTS for
Reinjection as Artificial Recharge
(Elevation Contours
of the Simulated Water Table
for the Calibrated Model, IT [1996a])



their intended goals. This section also describes the site-specific details of the conceptual designs for all three options. Section 5.3 estimates the relative costs based on the conceptual designs; specifically, this section looks at the costs associated with the recovery and reinjection of contaminated groundwater versus the withdrawal and artificial recharge of clean groundwater. Section 5.4 reviews the health and safety issues associated with each of these options.

5.1 Technical Approach

The technical approach to evaluate the three pump and treat options involves primarily the following:

- Estimating the capture zone or zone of influence and drawdowns around each recovery or withdrawal well
- Preparing preliminary conceptual designs for each approach for injection or artificial recharge
- Estimating the low-end conceptual costs for each option
- Assessing, conceptually and qualitatively, some of the performance issues associated with each option

5.1.1 Estimation of the Capture Zone or Zone of Influence and Drawdowns

The estimation of capture zones or zones of influence and drawdowns around recovery and withdrawal wells in or near the NTS is not a trivial exercise, given the typically complex western hydrogeology. For example, regional geologic features dominate flow patterns in the various alluvial, volcanic, and carbonate aquifers. Also, recharge often occurs at higher elevations and is highly variable. And, with typically four inches of precipitation per year, rainfall contributes little, if any, water to the aquifer through direct infiltration. However, this study's main purpose is not to develop highly accurate estimates of capture zones; this study can accept crude estimates of these zones to evaluate the conceptual technical and economic issues associated with the three pump and treat options. Consequently, data from Jacobson et al. (1994, Tables 1 and 2) of DRI provide a suitable basis from which to estimate the capture zones throughout various areas of the test site.

Specifically, data from Jacobson et al. (1994) allow estimation of the number of wells required under each option, their depths, and their pumping requirements. With these estimates, conceptual designs and costs for each option can be prepared. For this document, the

steady-state, analytical equation described by Jacobson et al. (1994, Equation 2) was used to estimate the widths of the ultimate capture zones, $2y_L$:

$$2y_L = Q/TJ \quad (1)$$

where

Q = the pumping rate;

T = the transmissivity; and

J = hydraulic gradient.

Use of this equation ignores the change in the gradient when T is changed from the undisturbed value of intact rock, as is the case for rock within the nuclear chimney. Of the two cases for recovery wells within the nuclear chimneys, one case assumes that the hydraulic gradient within the chimney is the same as outside the chimney; the other assumes that the gradient within the chimney is essentially zero. In the first case, increasing the conductivity of the chimney rock by a factor of 10 will yield an ultimate capture zone width, $2y_L$, ten times smaller than in the intact rock because the gradient is the same. Typically, however, an increase in hydraulic conductivity in the nuclear chimney will lower the hydraulic gradient and tend to raise the capture zone width back to, or even possibly beyond, that for the intact rock. Therefore, the second case assumes a hydraulic gradient of zero and simply uses the same ultimate capture zone width to estimate the number of recovery wells required in a particular nuclear chimney.

The capture zone (CAPZONE) computer code (Bair, 1991) estimates the drawdowns. These drawdowns are used to calculate the required dynamic heads needed to size and select a suitable pump for the design discharge of each recovery well. Based on a site experience, design discharges of 757 liters per minute (Lpm) (200 gallons per minute [gpm]) are typical for recovery wells at the NTS. CAPZONE uses a semianalytical solution to calculate drawdowns and contours of hydraulic heads around recovery or recharge wells in homogeneous, isotropic, confined, or unconfined aquifers. Again, however, this study's main purpose is not to develop highly accurate estimates of drawdowns; it can accept crude estimates of steady-state drawdowns to design the conceptual systems and to evaluate the costs associated with the three pump and treat options. Closed-form equations were used for steady-state flow from pumping wells in confined and unconfined aquifers (Driscoll, 1986) to check the CAPZONE estimates of drawdown.

5.1.2 Conceptual Designs for Each Option

The conceptual designs for each recovery or withdrawal and treatment option develop conceptual layouts and installation approaches for various recovery and injection systems. In addition, preliminary designs of appropriate recovery pumps and piping systems were developed, as required, for each site and for identified site-specific costs and premiums for difficult conditions. Available baselines were used to verify cost estimates.

Conceptual layouts considered the efficacy of drilling recovery wells within or outside of each nuclear chimney. As mentioned in the introduction to this chapter, benefits of injecting contaminated groundwater into the top of the nuclear chimneys with wick drains as opposed to injection wells was also considered. The main advantages are in terms of health and safety and the reduction of generated contaminated soil.

As part of the preliminary design process, the drawdowns estimated above were used to design recovery pump systems. The estimated drawdowns were combined with estimates of the heads due to friction losses (from Moody Friction Factor Charts [Lindeburg, 1992]), the total vertical lift required, and the pressure head required before reinjection to obtain the total dynamic head required at each shot site. From there, the appropriate pump configuration could be selected with the necessary number of stages to guide cost estimates.

5.1.3 Estimating the Low End Conceptual Costs for Each Option

The costs for each option can be estimated within an accuracy of +100 percent. The costs are based on R.S. Means (1996) cost data, Richardson (1993) estimating standards, Pipeline Rules of Thumb Handbook (Gulf Publishing Company, 1982), and various project experience.

Allowances for increased difficulty have been made due to the following:

- Inside drilling as opposed to outside of a nuclear chimney, which typically increases costs by as much as 25 percent because of a need to case each hole as drilling proceeds
- Radiation premium for drilling inside of a nuclear chimney for health and safety reasons
- Need to load, transport, and dispose of drill cuttings when recovery and injection wells are constructed within a nuclear chimney

- Surface facilities at Pahute Mesa where the more uneven and hard-to-excavate rock, as opposed to alluvium at other CAUs, increases costs by 25 percent or more to build roads and sumps needed for drilling
- Increase depth of drilling at Pahute Mesa and Yucca Flat as opposed to Frenchman Flat. In addition, the usual costs associated with mobilization/demobilization, sump pumps, water storage, well materials and installation, power, construction of working base within each crater, and covering of some options with a clay cap have all been considered.

5.1.4 Conceptual and Qualitative Assessments of Some of the Performance Issues

Figure 5-3 illustrates how Options 1 and 2 reinject the contaminated groundwater into the unsaturated zone of the nuclear chimney to strip the nuclides by evaporation and filtration. Key performance issues are involved in how well this innovative use of pump and treatment technology actually works and what the likelihood of success may be. Various performance issues include the following questions:

- How fast and how much water will move through the nuclear chimneys as vertical infiltration?
- How well will the nuclear chimney strip out or retard the movement of nuclides as infiltration occurs?
- Will the injection of contaminated groundwater into a nuclear chimney actually leach out more nuclides (already present in the debris above the detonation point) than will be stripped out?

The section on technical feasibility (Section 5.3) will discuss some preliminary analyses which attempt to answer these points. The analyses focus on the first two points, but the third point has only a minor effect. The preliminary analyses have two parts: an infiltration analysis with the recovered contaminated groundwater and a one-dimensional, vertical flow and transport analysis which assumes that all the mobile mass produced by the nuclear detonation lies below the water table. In this way, the performance of the nuclear chimney in removing or retarding the spread of nuclides has been bracketed.

The EPA's Hydrologic Evaluation of Landfill Performance (HELP) (Schroeder et al., 1994) model has been used to estimate the rate of groundwater infiltration through the nuclear chimney. Fleenor and King (1995) have shown that HELP will overpredict, on the safe side, the infiltration rates in arid regions. The HELP model simulates (in a quasi two-dimensional sense) the

movement of water in landfills and other waste units. The model accepts weather, soil, and design data and uses solution techniques that account for the effects of surface storage, snowmelt, runoff, infiltration, evapotranspiration, vegetative growth, soil moisture storage, lateral subsurface drainage, leachate circulation, unsaturated vertical drainage, and leakage through soil, geomembrane, or composite liners. The model allows the comparison of design alternatives as judged by their water balances.

Percolation and vertical water routing use Darcy's law for saturated flow with modifications for unsaturated conditions:

$$q = K i = K \frac{dh}{dl} \quad (2)$$

where

q = rate of flow (discharge per unit time per unit area normal to the direction of flow), inches per day

K = hydraulic conductivity, inches per day

I = hydraulic head gradient, dimensionless

h = piezometric head (elevation plus pressure head), inches

l = length in the direction of flow, inches

This equation is also applicable to unsaturated conditions, provided that the hydraulic conductivity is considered a function of soil moisture and that the piezometric head includes suction head.

HELP also modeled the unsaturated zone for each of the nuclear test shot sites as a landfill without a geosynthetic liner; HELP also modeled various flowrates for both injection wells and wick drains to compute the infiltration rates. For example, for Yucca Flat injection wells; the unsaturated aquifer was divided into four layers. The top three layers had thicknesses of 15.2, 3, and 27.5 m (50, 10, and 90 ft), respectively, each with a United States Conservation Service (USCS) soil classification of a silty clay (ML). The last unsaturated layer down to the water table was modeled as a medium sand (USCS classification SM). Subsurface inflows were varied between 757 and 5,300 Lpm (200 and 1,400 gpm) and introduced the flow at 15.2 m

(50 ft) below surface. In each case, HELP ran iteratively over 20-year increments until the initial and final moisture contents were equal to calculate steady-state infiltration rates.

The One-Dimensional Analytical Solute Transport/Sandia Waste Isolation Fate and Transport Loading (ODAST/SWIFTLOAD) model, originally developed and verified by IT for DOE and updated by DOE (1994), was used on the Fernald Environmental Management Project. The ODAST/SWIFTLOAD predicts the vertical transport of contaminated groundwater through the nuclear chimney as a two-layer system to the water table. ODAST, which is a subroutine of SWIFTLOAD, evaluates the one-dimensional analytical solute transport equation as a function of seepage velocity, dispersion coefficient, source decay, retardation factor, depletion time, and source rate. SWIFTLOAD processes contaminant loading data for the SWIFT model (GeoTrans, 1994). It runs ODAST as a subroutine on a cell-by-cell basis using the same grid as the SWIFT model. SWIFTLOAD reads an external file that defines the layer thicknesses for each model cell and the hydraulic and transport properties for each block.

The ODAST computer code uses the analytical solution originally developed by Ogata and Banks (1961) and calculates the normalized concentrations of a given constituent in a uniform flow field from a source having a constant or varying concentration in the initial layer. Appendix A gives a brief discussion of the input parameters assumed for ODAST.

5.2 Technical Feasibility

This section assesses the technical feasibility and likelihood of success for the two pump and treatment alternatives: recovery and *in situ* treatment through reinjection of contaminated groundwater and the withdrawal and artificial recharge of clean groundwater.

5.2.1 Technical Feasibility of Recovery and In Situ Treatment Through Reinjection of Contaminated Groundwater (Options 1 and 2)

This alternative looks at the use of recovery and injection wells or wicks to remediate the nuclear test shots which occurred near or beneath the water table. The shot sites that would require remediation were determined by comparing the bottom elevations of each shot with the estimated water-table elevation. The first two options, as shown in Figures 5-1 and 5-2, look at the use of recovery wells to contain contaminated groundwater at each shot site and to treat it *in situ* by injection into the unsaturated zone of the nuclear chimney. Both of these options use the unsaturated zone of the nuclear chimney to strip the nuclides out of the groundwater by

evaporation and filtration (Figure 5-3). Then the use of wick drains instead of injection wells to inject water into the nuclear chimney (Figure 5-4) was considered.

Table 5-1 summarizes the number of shots that appear to have occurred below the water table and estimates the required well depths and minimum screen lengths needed to recover contaminated groundwater at each CAU. Option 1 uses recovery wells within each nuclear chimney to establish a zone of capture; Option 2 (Figure 5-2) uses recovery wells outside of the nuclear chimney to establish hydraulic control. Option 2 may result in easier installation of recovery wells because of the difficulty of drilling in the shot cavities, the need to dispose of cuttings as radioactive waste, and the increased concerns for worker health and safety. Tables 5-2 and 5-3 give the approximate number of wells required within and outside each nuclear chimney for Options 1 and 2, respectively. These tables help estimate the site-specific costs for recovery wells at each CAU (again for Options 1 and 2).

Table 5-1
Required Well Depths and Screen Lengths for Recovery Wells
at or Near the Nuclear Chimneys at the Nevada Test Site

Geographic Region	No. of Shots in the Water Table	Estimated Average Radius of Shots** meters (feet)	Required Well Depths (Avg. Depth of Shots, DOB or Working Point) meters (feet) I	Estimated Average Depth to Water** meters (feet) II	Minimum Screen Length*** meters (feet)
Pahute Mesa	71	70 (229)	2,490 (8,170)	2,070 (6,790)	430 (1,410)
Rainier Mesa	0	0	0	0	0
Buckboard Mesa	0	0	0	0	0
* Yucca Flat	122	203 (666)	1,850 (6,070)	1,670 (5,480)	190 (623)
U10K Corduroy	1	217 (712)	2,227 (7,300)	1,864 (6,110)	380 (1,250)
Frenchman Flat	6	118 (387)	1,340 (4,390)	826 (2,710)	525 (1,720)
Shoshone Mountain	0	0	0	0	0
Dome Mountain	0	0	0	0	0

* Denotes that, with the exception of U10K Corduroy which occurred in the carbonate aquifer, the remainder of the test shots in Yucca Flat occurred in the alluvial or volcanic aquifers.

** All radii and depths of shots are estimated average cavity sizes only.

*** $b = I - II + 10$ (meters)
 $= I - II + 32.808$ (feet)

Source: IT (1996)

Table 5-2
Number of Wells Required Within Each Nuclear Chimney:
Option 1 Nevada Test Site

Geographic Region	Hydraulic Conductivity of Nuclear Chimney ^a K = 10 K _{intact}		Required Screen Lengths Within Shots ^b		Transmissivity, T=Kb ^c		Gradient, J ^d	Maximum Width, 2y _L , at 200 gpm or Q = 1,090 m ³ /d ^e		Average Diameter of Shot Cavity ^f		Number of Wells Required per Shot $= \frac{f^2}{e^2}$
	m/d	ft/d	m	ft	m ² /d	ft ² /d	.009	m	ft	m	ft	
Pahute Mesa	15	49.21	131.1	430	1,967	21,160	.009	61.57	202	139.6	458	6
Yucca Flat	15	49.21	57.11	190	856.7	9,350	.009	139.6	458	123.7	406	1
U10K-Corduroy												
Q = 200 gpm ^g	2,200	7,218	115.8	380	254,760	2,742,750	.018	.238	0.78	131.9	433	308,167
Q = 500 gpm								.594	1.95			49,307
Q = 200 gpm ^h	148	486	115.8	380	17,138	184,512	.018	3.536	11.6	131.9	433	1,394
Q = 500 gpm								8.84	29			223
Frenchman Flat	15	49.21	160.0	525	2,400	25,836	.009	50.6	166	71.9	236	2

^{a,d} Based on 14 wells in alluvial aquifer (IT, 1996), K_{intact} for alluvial-unconfined aquifer = 10 x 1.5 m/d (10 x 4.9 ft/d). J = 0.009 based on pumping tests from Water Wells C and C-1, Jacobson et al. (1994)

^{b,c} The aquifer thicknesses and the corresponding transmissivities were calculated based on the alluvial-unconfined condition for Pahute Mesa, Yucca Flat and Frenchman Flat, with the exception of nuclear test shot U10K-Corduroy of Yucca Flat, for which the carbonate-unconfined condition was applied.

^e Maximum width of capture zone at 200 gpm (or 1,090 m³/d) = 2y_L = Q/TJ

^f Estimated average cavity size only (IT, 1996)

^g Based on Water Wells C and C-1, K_{intact} for carbonate-unconfined aquifer = 10 x 220 m/d (10 x 722 ft/d) and J = 0.018, Jacobson et al. (1994)

^h Based on Water Wells 4 and 4A, K_{intact} for carbonate-unconfined aquifer = 10 x 14.8 m/d (10 x 48.5 ft/d) and J = 0.018, Jacobson et al. (1994)

ft/d = feet per day

m/d = meter per day

ft²/d = square foot per day

m²/d = square meter per day

m³/d = cubic meter per day

Table 5-3
Number of Wells Required Outside Each Nuclear Chimney:
Option 2 Nevada Test Site

Geographic Region	Hydraulic Conductivity of Nuclear Chimney ^a $K = K_{\text{intact}}$		Required Screen Lengths Within Shots ^b		Transmissivity $T = Kb^c$		Gradient, J^d	Maximum Width at 200 gpm or $Q = 1,090 \text{ m}^3/\text{d}^e$		Estimated Average Diameter of Shot Cavity ^f		Number of Wells Required per Shot $= \frac{f^2}{e^2}$
	m/d	ft/d	m	ft	m ² /d	ft ² /d	ft	m	ft	m	ft	
Pahute Mesa	1.5	4.921	131.1	430	19.67	2,116	.009	615.7	2,022	139.6	458	1
Yucca Flat	1.5	4.921	57.11	190	85.67	935	.009	1,400	4,575	123.8	406	1
U10K-Corduroy											466	-
											480	-
											295	-
											460	-
$K = 220 \text{ m/d}$ $Q = 200 \text{ gpm}^g$ $Q = 500 \text{ gpm}$	220	721.8	11.58	380	25,476	274,275	.018	2.37 5.94	7.79 19.5	132.0	433 433	3,090 493
$K = 14.8 \text{ m/d}^h$ $Q = 200 \text{ gpm}$ $Q = 500 \text{ gpm}$	14.8	48.6	11.58	380	1,713.8 18,451	18,451	.018	35.36 88.39	116 290	132.0	433 433	14 3
Frenchman Flat	1.5	4.921	16.0	525	240	2,580	.009	505.4	1,658	71.9	236	1

^{a,d} Based on 14 wells in the alluvial aquifer Data Task Documentation Package (IT, 199a), K_{intact} for alluvial-unconfined aquifer = 1.5 m/d (4.9 ft/d). $J = 0.009$ based on pumping tests from Water Wells J-12, J-13, 5B, 5C, and UE-5C (Jacobson et al., 1994).

^{b,c} The aquifer thicknesses and the corresponding transmissivities were calculated based on the alluvial-unconfined condition for Pahute Mesa, Yucca Flat and Frenchman Flat, with the exception of nuclear test shot U10K-Corduroy of Yucca Flat, for which the carbonate-unconfined condition was applied.

^e Maximum width at 200 gpm (Diameter of Capture Zone) = $2y_L = Q/TJ$

^f Estimated average cavity size only (IT, 1996)

^g Based on Water Wells C and C-1, K_{intact} for carbonate-unconfined aquifer = 220 m/d (722 ft/d), Jacobson et al. (1994).

^h Based on Water Wells 4 and 4A, K_{intact} for carbonate-unconfined aquifer = 14.8 m/d (48.5 ft/d), Jacobson et al. (1994).

ft/d = feet per day

m/d = meter per day

ft²/d = square foot per day

m²/d = square meter per day

m³/d = cubic meter per day

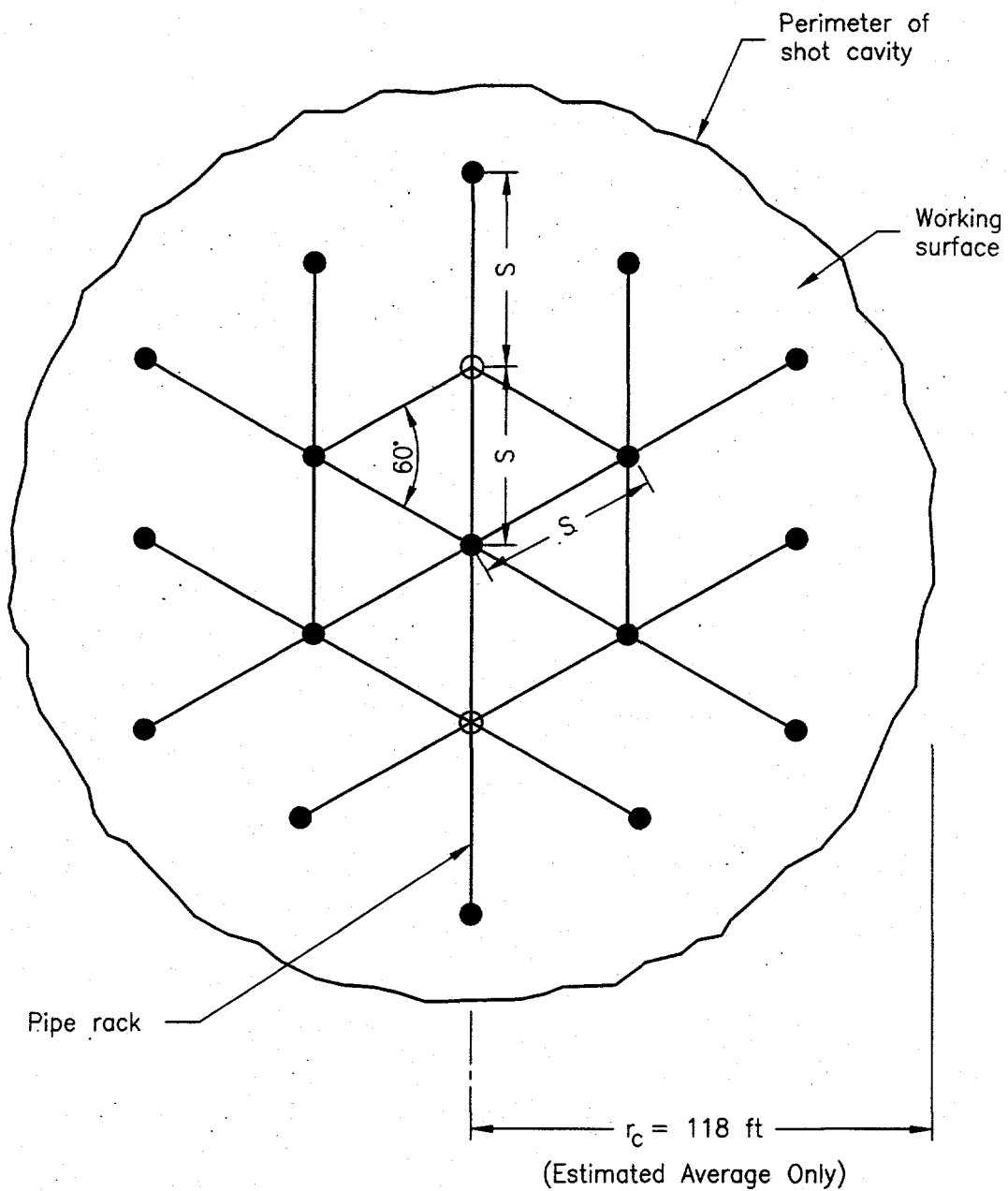
The capture zones were determined for each geographic region based on a pumping rate of 757 Lpm (200 gpm), and the hydraulic conductivities derive from existing water supply wells in the NTS (Jacobson et al., 1994). When using Equation 1 with $K_{\text{chimney}}=10K_{\text{intact}}$ (Jacobson et al., 1994), Table 5-2 shows the number of recovery wells required inside each nuclear chimney for each geographic region. For Option 1, Table 5-2 suggests the following:

- Two recovery wells for Frenchman Flat
- One recovery well for Yucca Flat
- Six recovery wells for Pahute Mesa

An exception to these numbers of recovery wells is the cavity for the Corduroy Test Shot in Yucca Flat. This is the only test shot which occurred in the unconfined carbonate aquifer. Based on the extremely high hydraulic conductivities/transmissivities (Jacobson et al., 1994), we calculated extremely small capture zones. So even though, theoretically, we would need about 300,000 wells (assuming a pumping rate of 757 Lpm [200 gpm]) to control the entire Corduroy Test Shot, it will not be practical to install this many wells. The number of recovery wells used would depend on the designed pumping rate and aquifer properties found at the Corduroy Test Shot. (The hydraulic conductivities/transmissivities are based on pump tests conducted in the unconfined carbonate aquifer and, therefore, represent only approximate values.) For the Corduroy shot site, Table 5-2 shows that the number of recovery wells could range from over 300,000 to as few as 200 or so for a range of pumping rates and hydraulic conductivities.

These are estimates only of the number of recovery wells that would theoretically be required. In the case of Corduroy, these numbers could range from 200 to over 300,000, depending on the assumed pumping rates and hydraulic conductivities. These large numbers of wells only illustrate how technically difficult it would be to pump out contaminated groundwater in these areas.

Figures 5-6 through 5-8 show what the appropriate layouts of recovery wells and injection wells may look like under Option 1 for each CAU, excluding U10K Corduroy of Yucca Flat. Because the U10K Corduroy shot occurred in carbonate as opposed to an alluvial aquifer, the combination of higher hydraulic conductivities and higher gradients results in much smaller capture zones and too many recovery wells with high flows to be feasible.



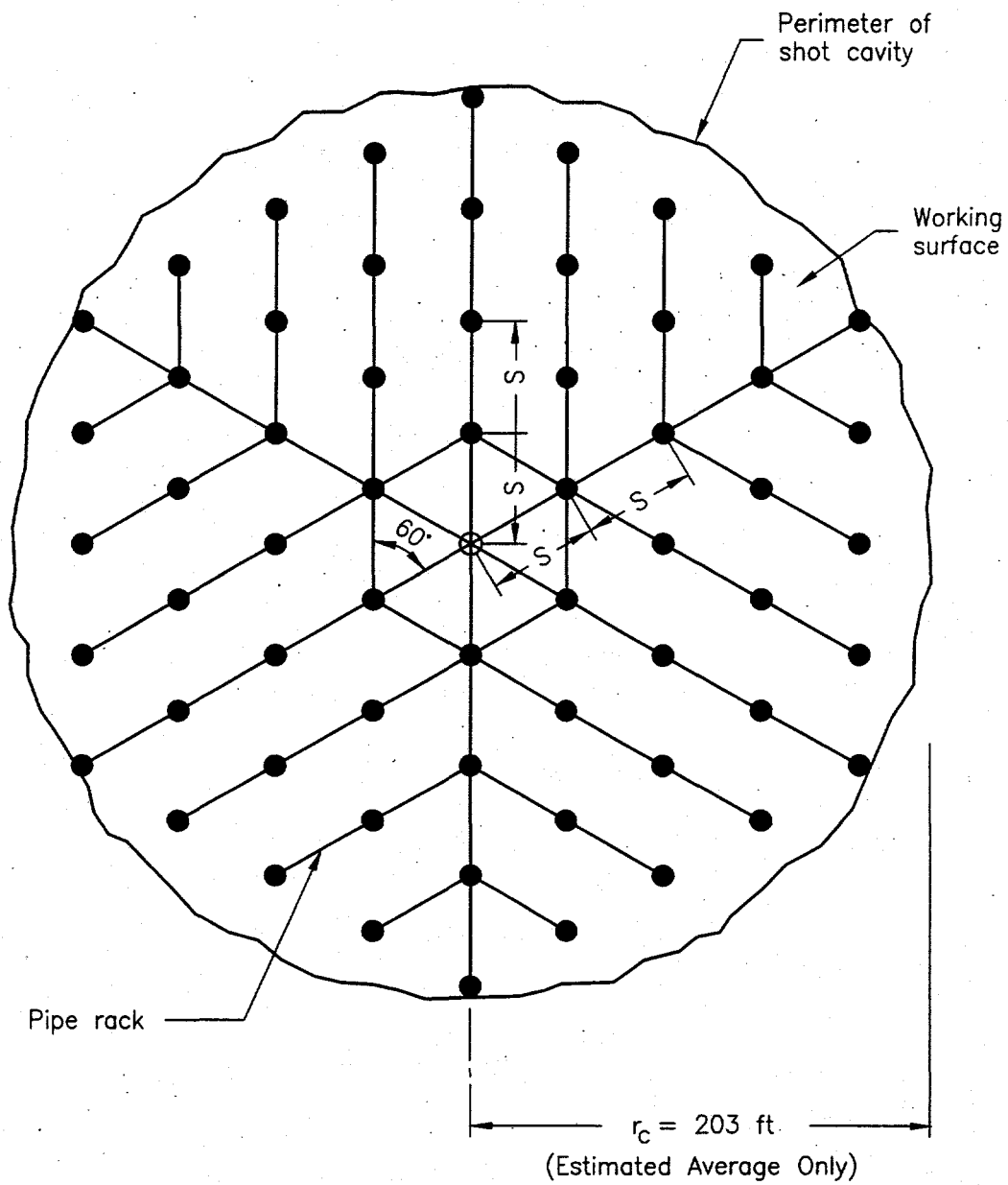
NOT TO SCALE

LEGEND

- Injection wells
- Recovery well
- S Well spacing = 50 ft

Figure 5-6a
Frenchman Flat Option 1
Injection Wells

5-17



LEGEND

- Injection wells
- Recovery well
- S Well spacing = 50 ft

Figure 5-7a
Yucca Flat Option 1
Injection Wells

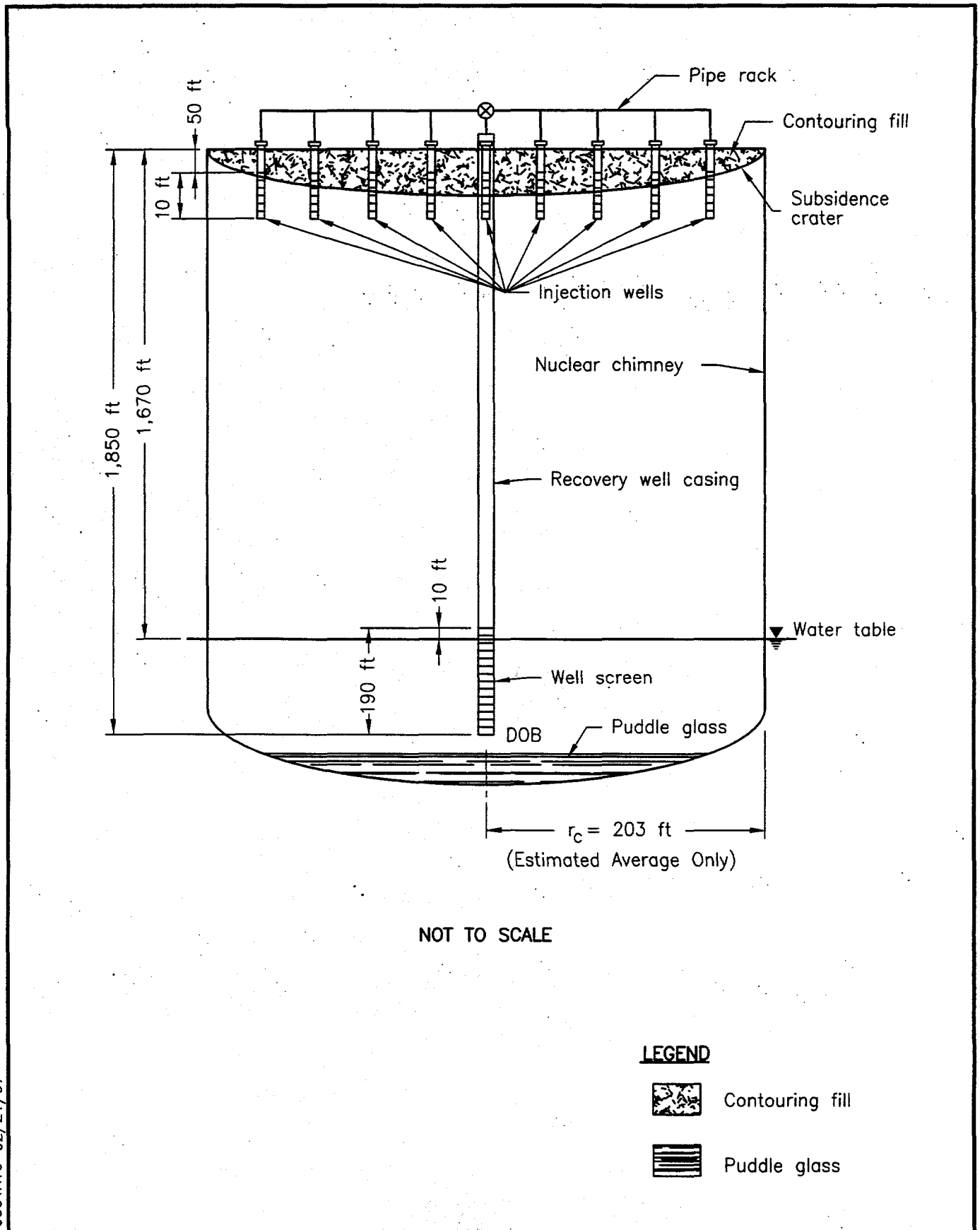


Figure 5-7b
Yucca Flat Option 1
Conceptual Triangular Injection Well Array Around Recovery Well

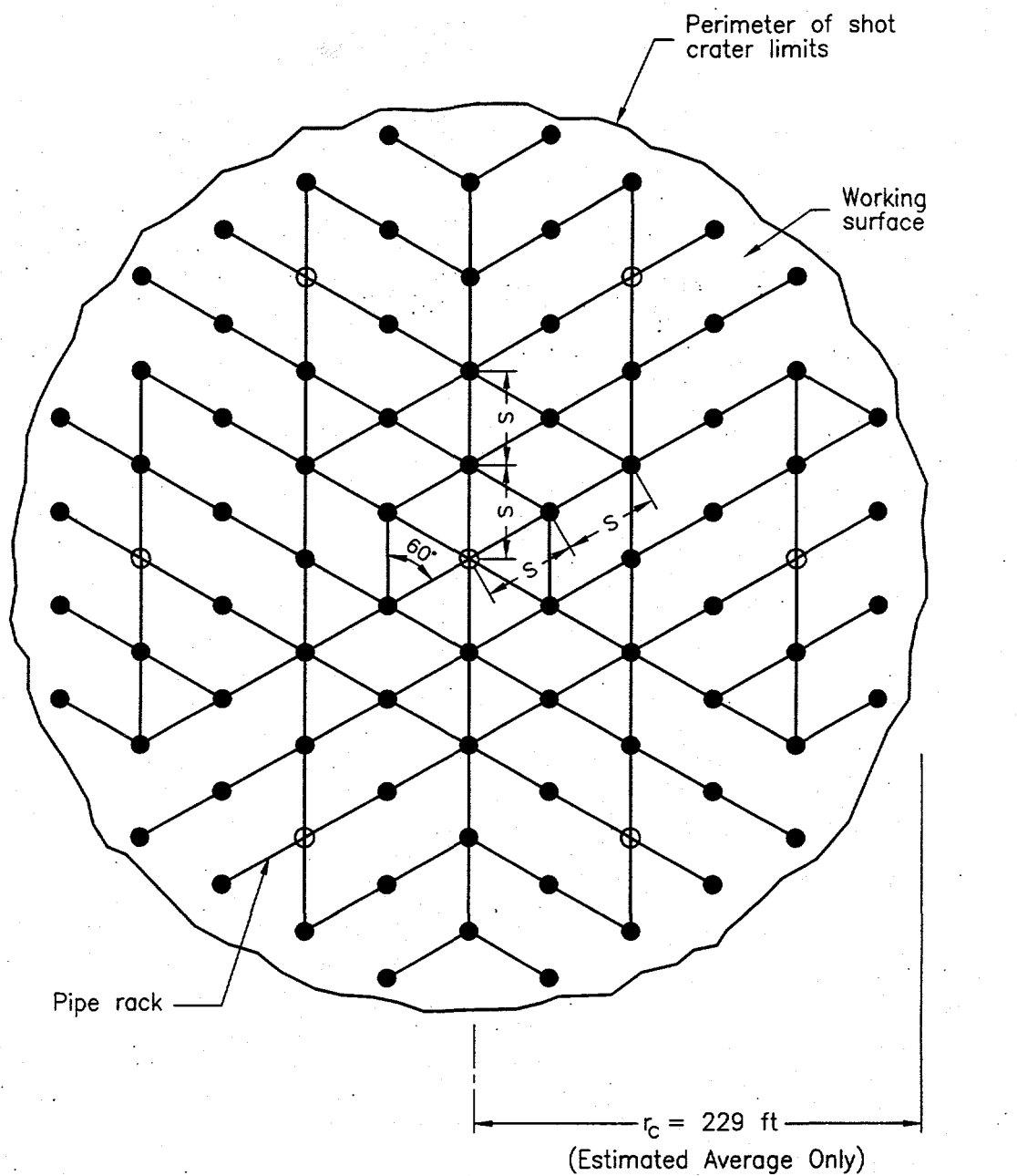
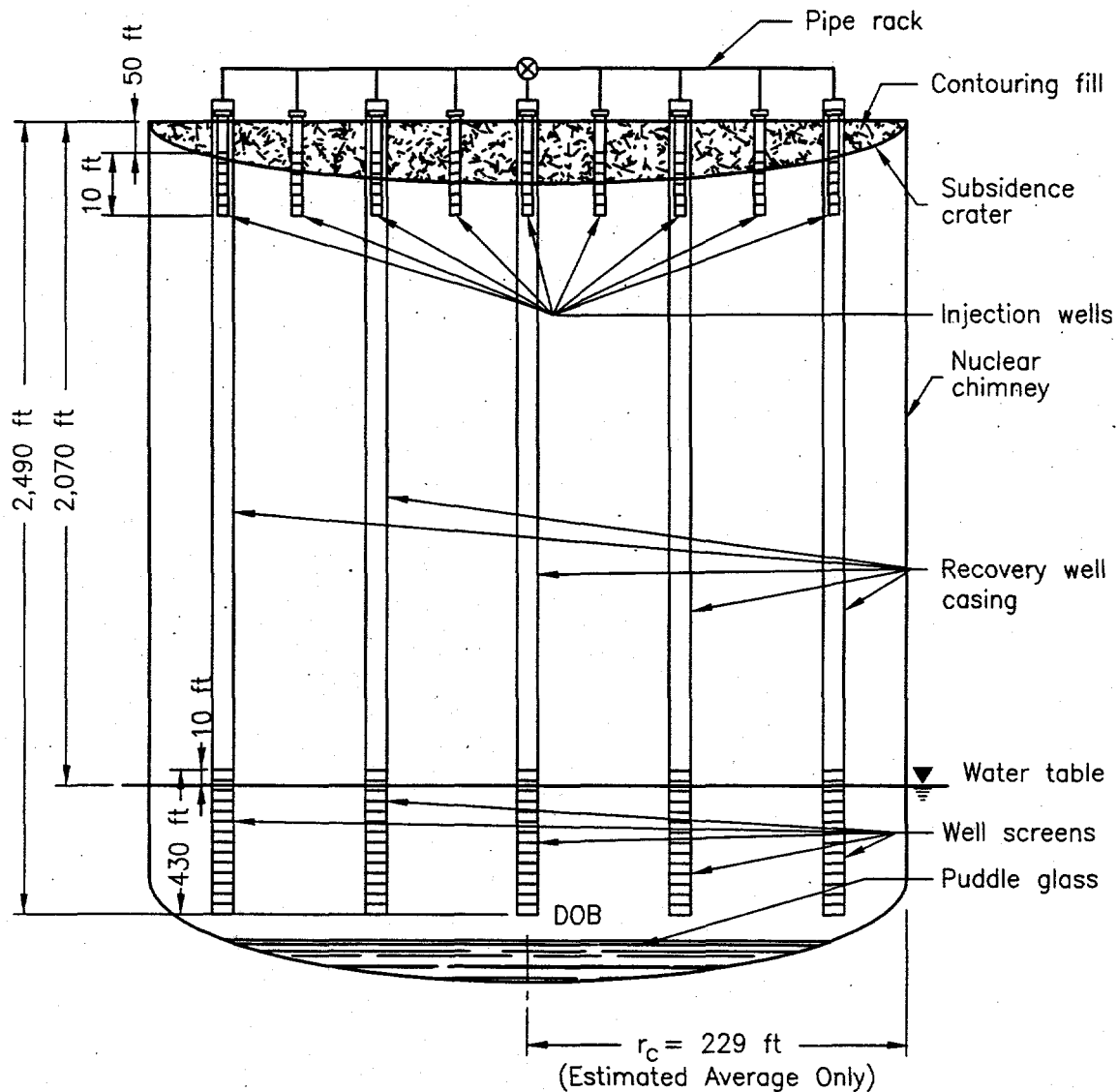


Figure 5-8a
Pahute Mesa Option 1
Injection Wells

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NOT TO SCALE

LEGEND



Contouring fill



Puddle glass

Figure 5-8b
Pahute Mesa Option 1
Conceptual Triangular Injection Well Array Around Recovery Well

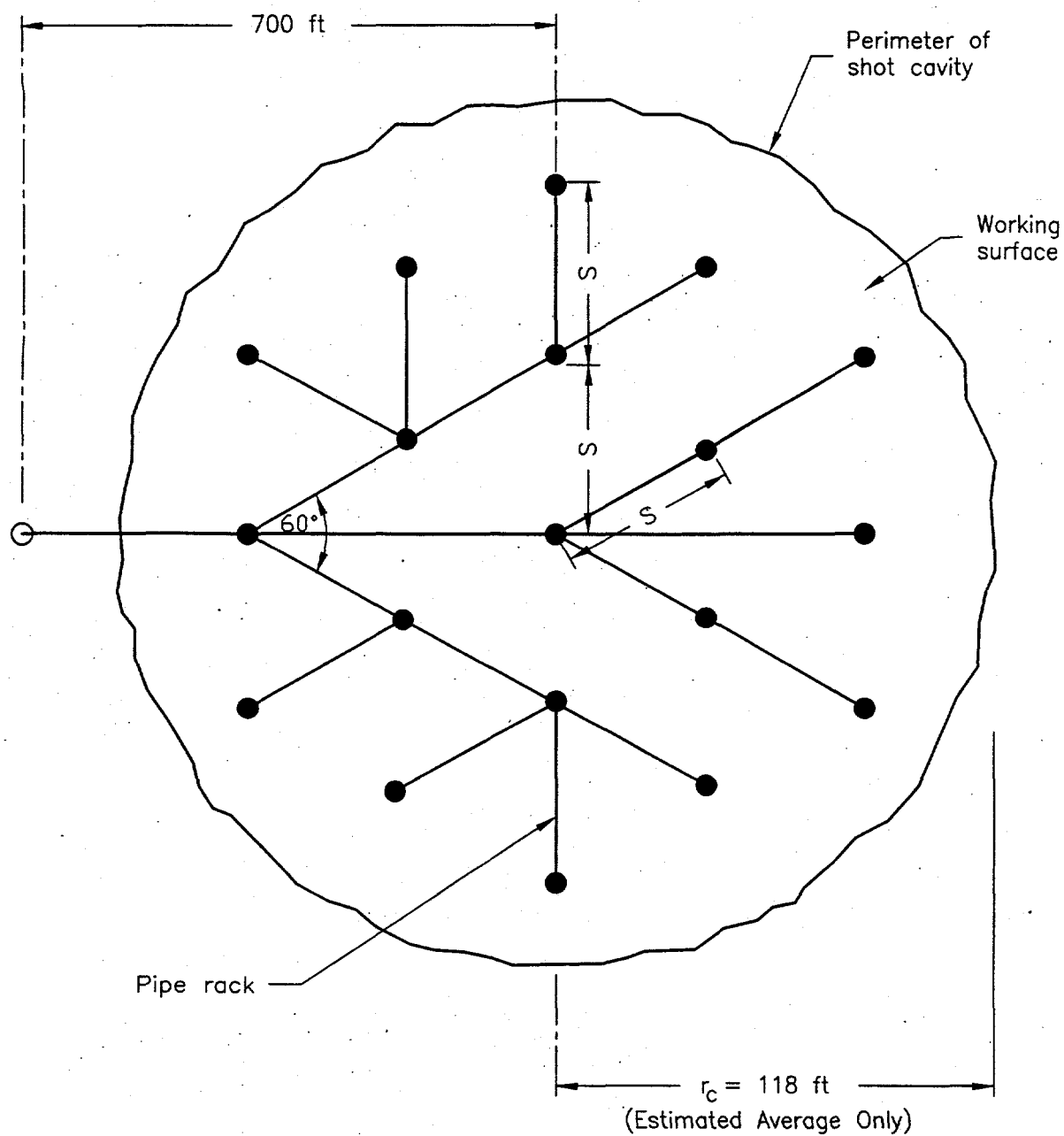
In contrast, Table 5-3 suggests that fewer recovery wells will be needed outside of the nuclear chimney when $K=K_{\text{intact}}$ under a gradient of .009. Figures 5-9 through 5-11 show how typical layouts may look under Option 2 for each CAU. Table 5-3 indicates that Frenchman Flat, Yucca Flat, and Pahute Mesa would require only one recovery well each, which is fewer recovery wells than for Option 1. In the case of Option 1, however, Equation 1 ignores the decrease in the hydraulic gradient that would occur. Figure 5-12 illustrates conceptually the decrease in the hydraulic gradient that would occur within the chimney with $K_{\text{chimney}}=10K_{\text{intact}}$.

Therefore, if the hydraulic gradient within the chimney decreases by a factor of about 10 times due to $K_{\text{chimney}}=10K_{\text{intact}}$, Equation 1 would then estimate a capture zone equal in size to that obtained for K_{intact} under Option 2. Figures 5-13 through 5-15 show how a decrease in the chimney hydraulic gradient to .0009 would change the layout of recovery wells in Option 1 for each CAU.

Finally, injection of the contaminated groundwater into the nuclear chimneys with wick drains (Figure 5-4) has been considered. Using vendor-supplied information, the number and total linear feet of wicks needed to replace the injection wells under Option 1 were estimated. Figures 5-16 through 5-18 show conceptually the main design elements of the wick drain injection system at each CAU. Typically, a static crowd or vibratory rig (Figure 5-4) drives a tubular steel mandrel of a small cross-sectional area (usually 2 by 5 inches) that contains the wick drain, with a small steel anchor plate attached to the wick at the bottom of the mandrel. Static crowd or vibratory rigs can install wick drains of various sizes up to 820 m (250 ft) into almost any soil or rubblized rock conditions as long as the rocks or shales are not intact. When the mandrel reaches the design depth, the rig extracts the mandrel. The anchor plate retains the drain in the soil. When the rig fully extracts the mandrel, site workers cut off the drain, install new anchor plates, and start the process again. Site workers then install larger prefabricated drains called "strip drains" to bring recovered groundwater to the individual wick drains.

As part of the assessment of technical feasibility, the total amount of dynamic heads to select a pump that could fit into a 178-mm (7-in.) diameter fiberglass casing was calculated. The estimated drawdowns, heads due to friction losses (from Moody Friction Factor Charts [Lindeburg, 1992]), total vertical lift required, and the pressure head required before reinjection were combined to obtain the total dynamic head required at each shot site. From there, an appropriate pump configuration with the necessary number of stages to fit into a 178-mm (7-in.) diameter fiberglass casing was developed to guide cost estimates. Table 5-4 summarizes the

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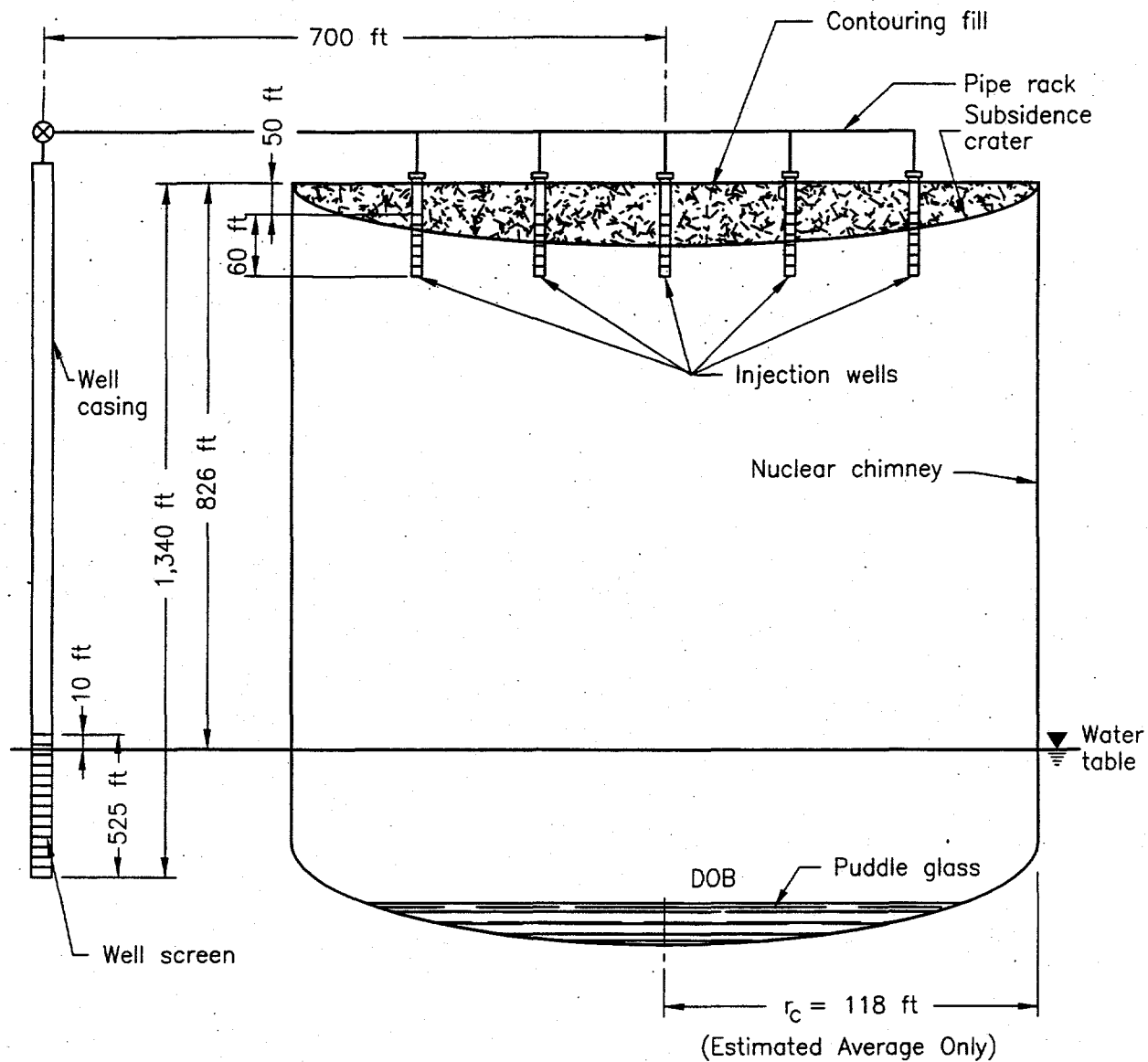


NOT TO SCALE

LEGEND

- Injection wells
- Recovery well
- S Well spacing = 50 feet

Figure 5-9a
Frenchman Flat Option 2
Injection Wells



NOT TO SCALE

LEGEND

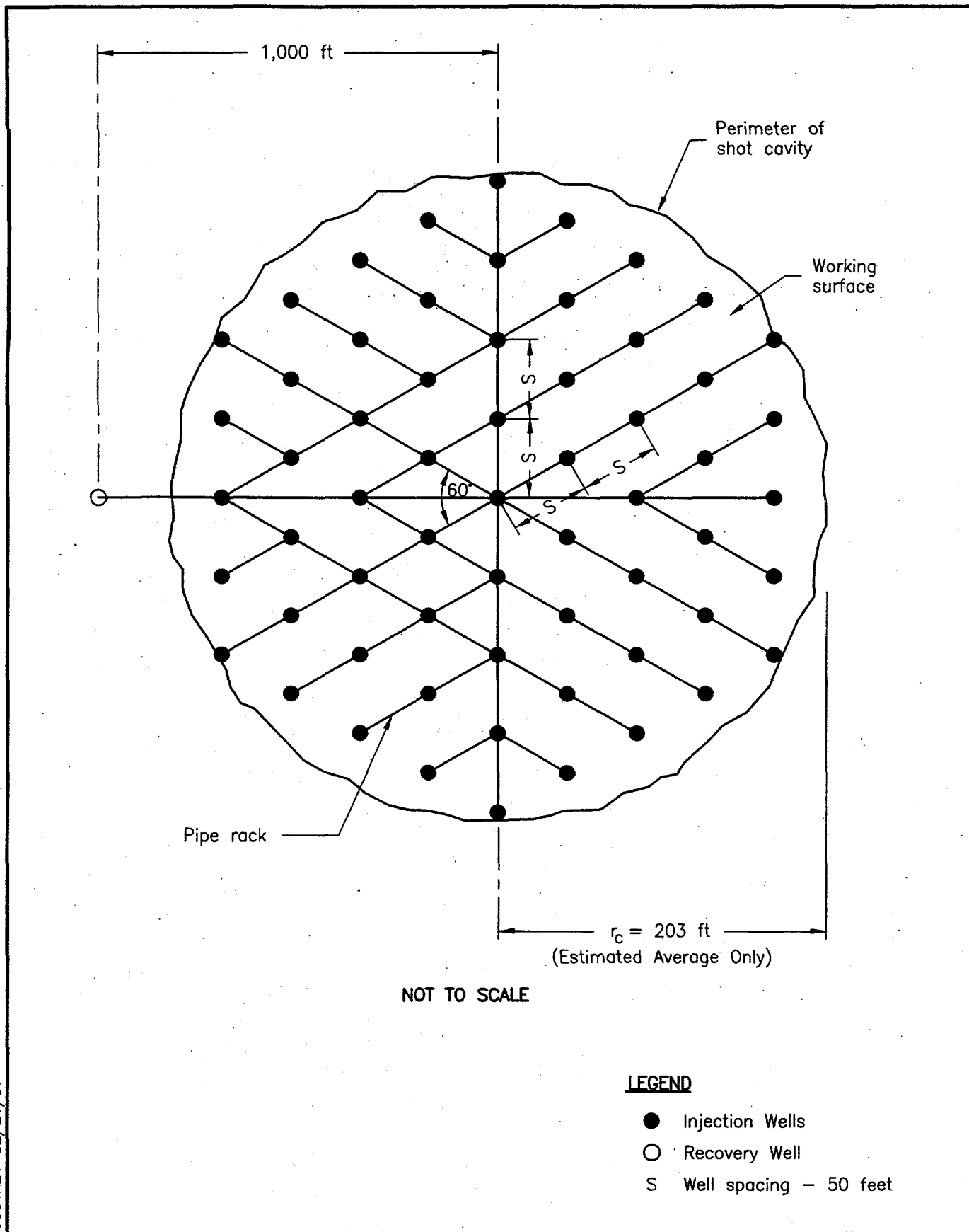


Contouring fill



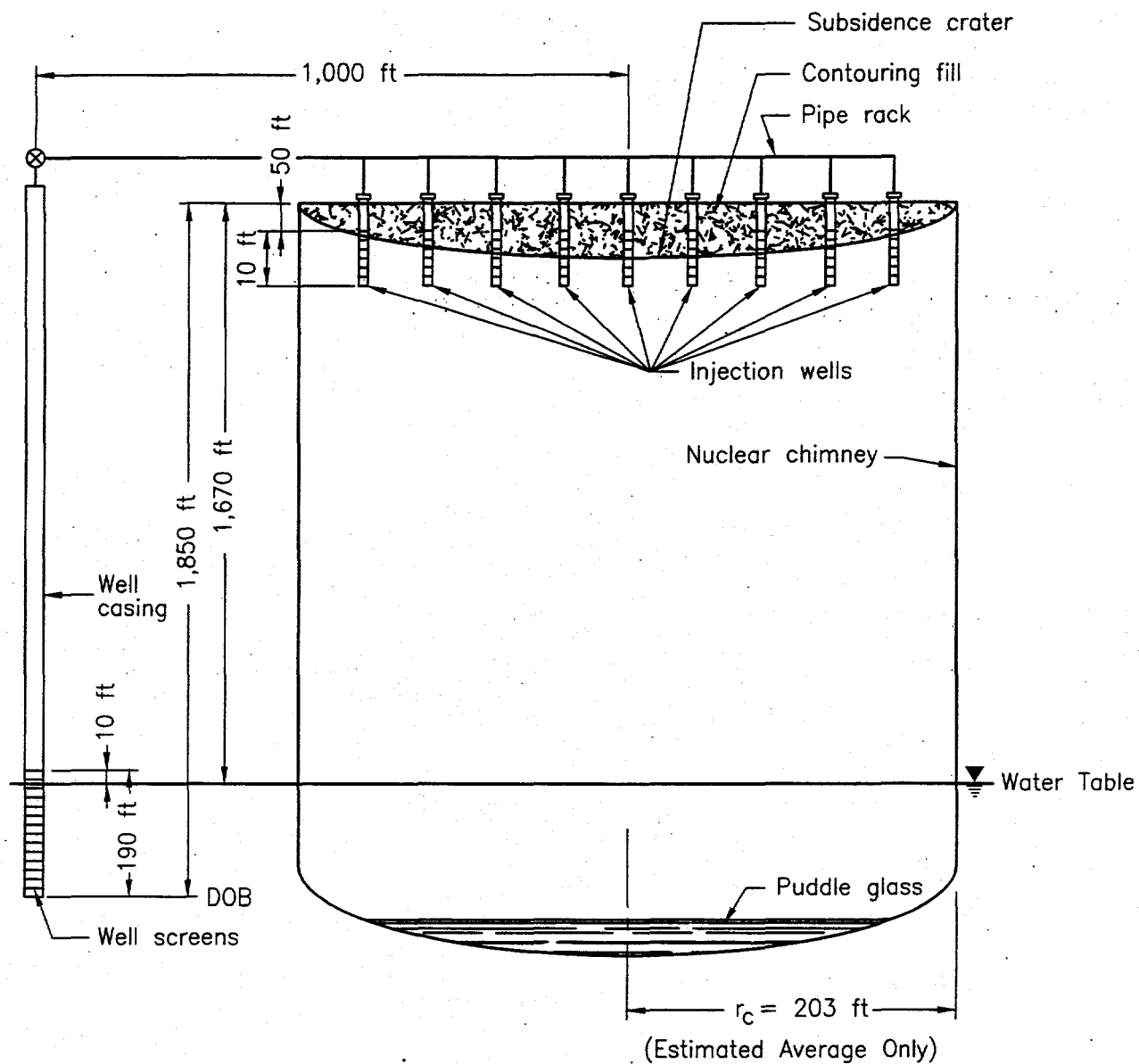
Puddle glass

Figure 5-9b
Frenchman Flat Option 2
Conceptual Triangular Injection Well Array
Around Recovery Well



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Figure 5-10a
Yucca Flat Option 2
Injection Wells



LEGEND

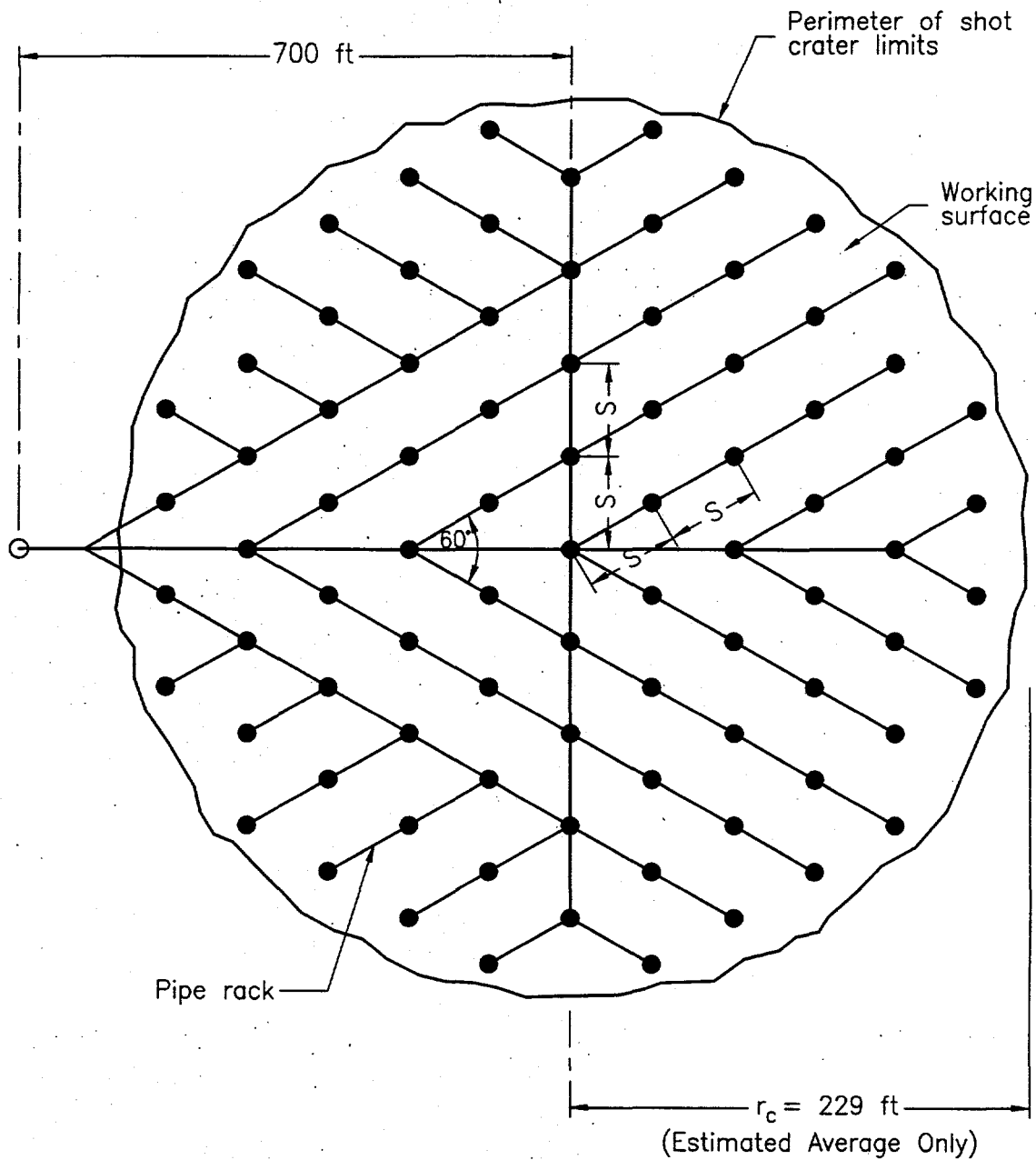


Contouring fill



Puddle glass

Figure 5-10b
Yucca Flat Option 2
Conceptual Triangular Injection Well Array
Around Recovery Well



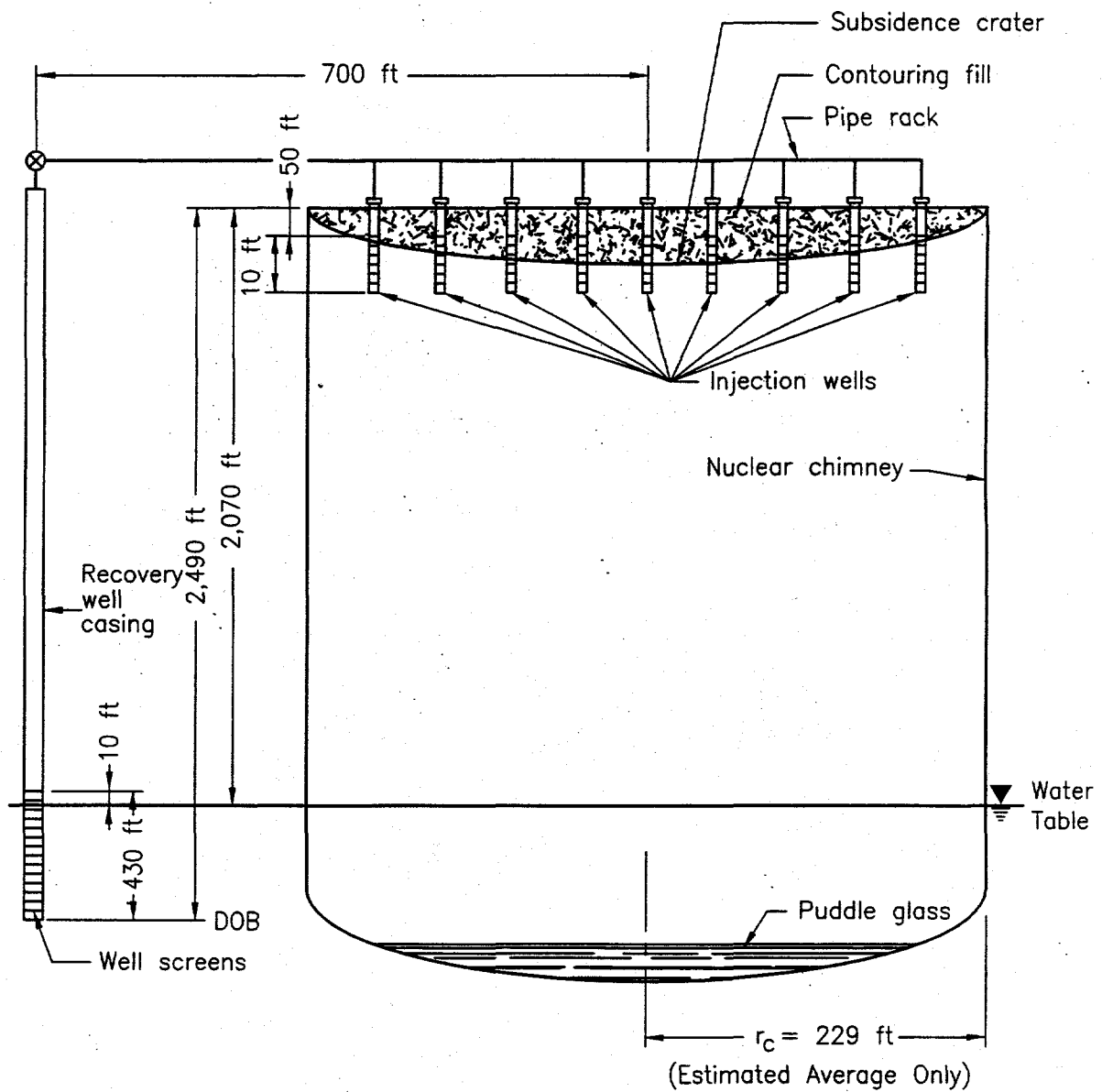
NOT TO SCALE

LEGEND

- Injection wells
- Recovery well
- S Well spacing = 50 feet

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Figure 5-11a
Pahute Mesa Option 2
Injection Wells



NOT TO SCALE

LEGEND

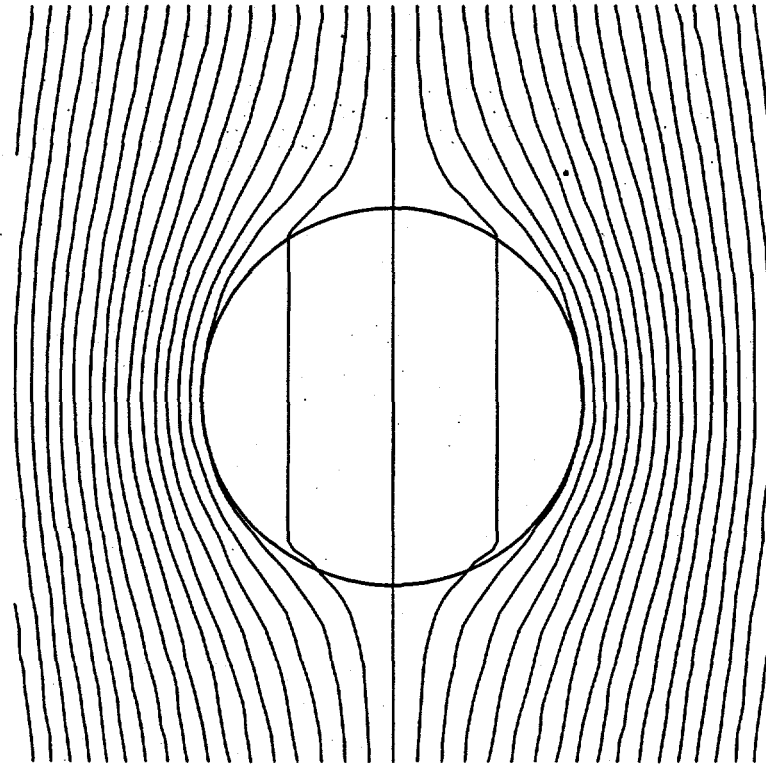


Contouring fill



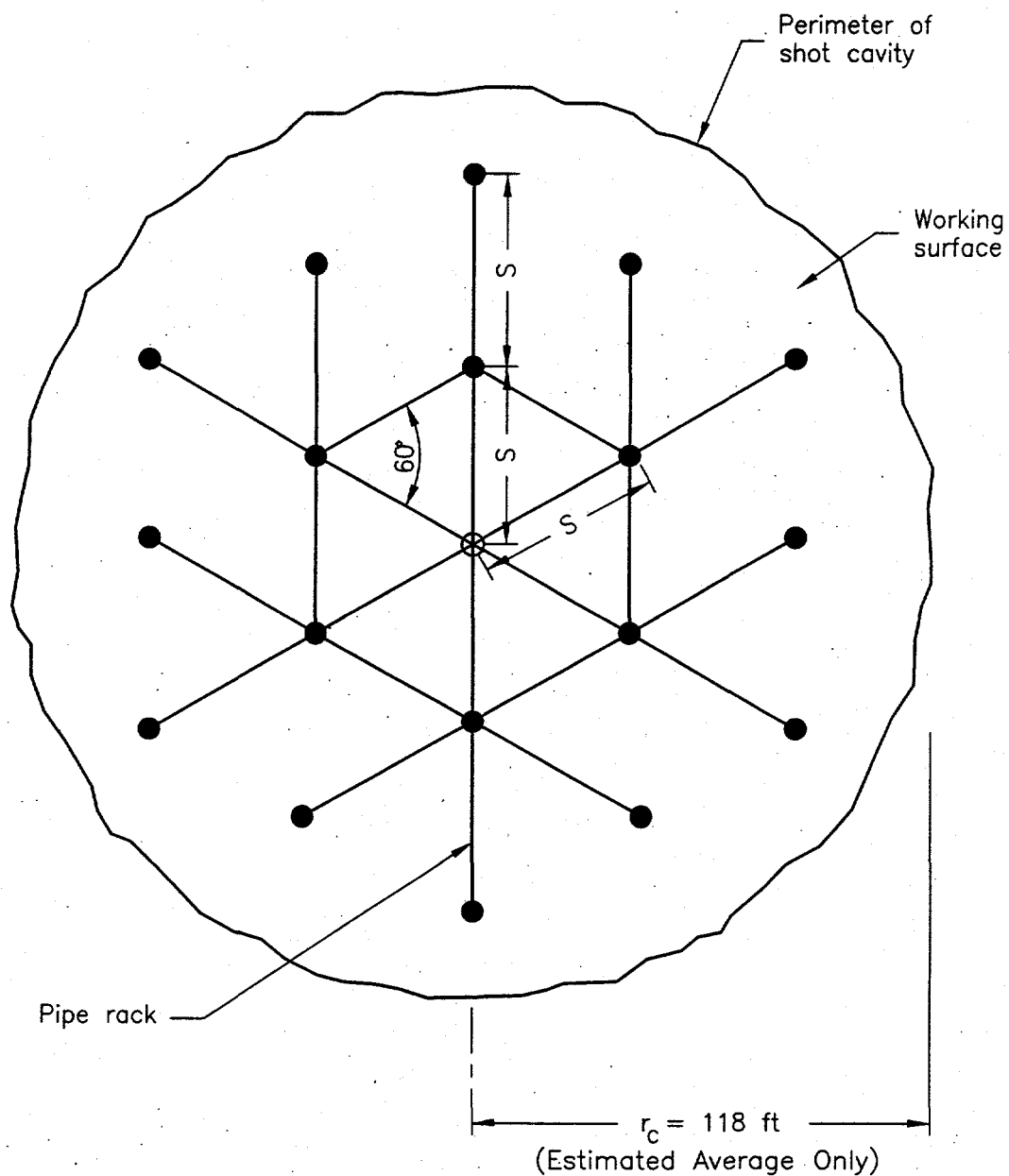
Puddle glass

Figure 5-11b
Pahute Mesa Option 2
Conceptual Triangular Injection Well Array
Around Recovery Well



(Adapted from Figure 6-8 of Strack, 1988)

Figure 5-12
Piezometric (Total Head) Contours for a Circular Heterogeneity
With $K_{\text{Chimney}} = 10K_{\text{Intact}}$



NOT TO SCALE

LEGEND

- Injection wells
- Recovery well
- S Well spacing = 50. feet

Figure 5-13a
Frenchman Flat Option 1
Injection Wells With Gradient = 0.0009

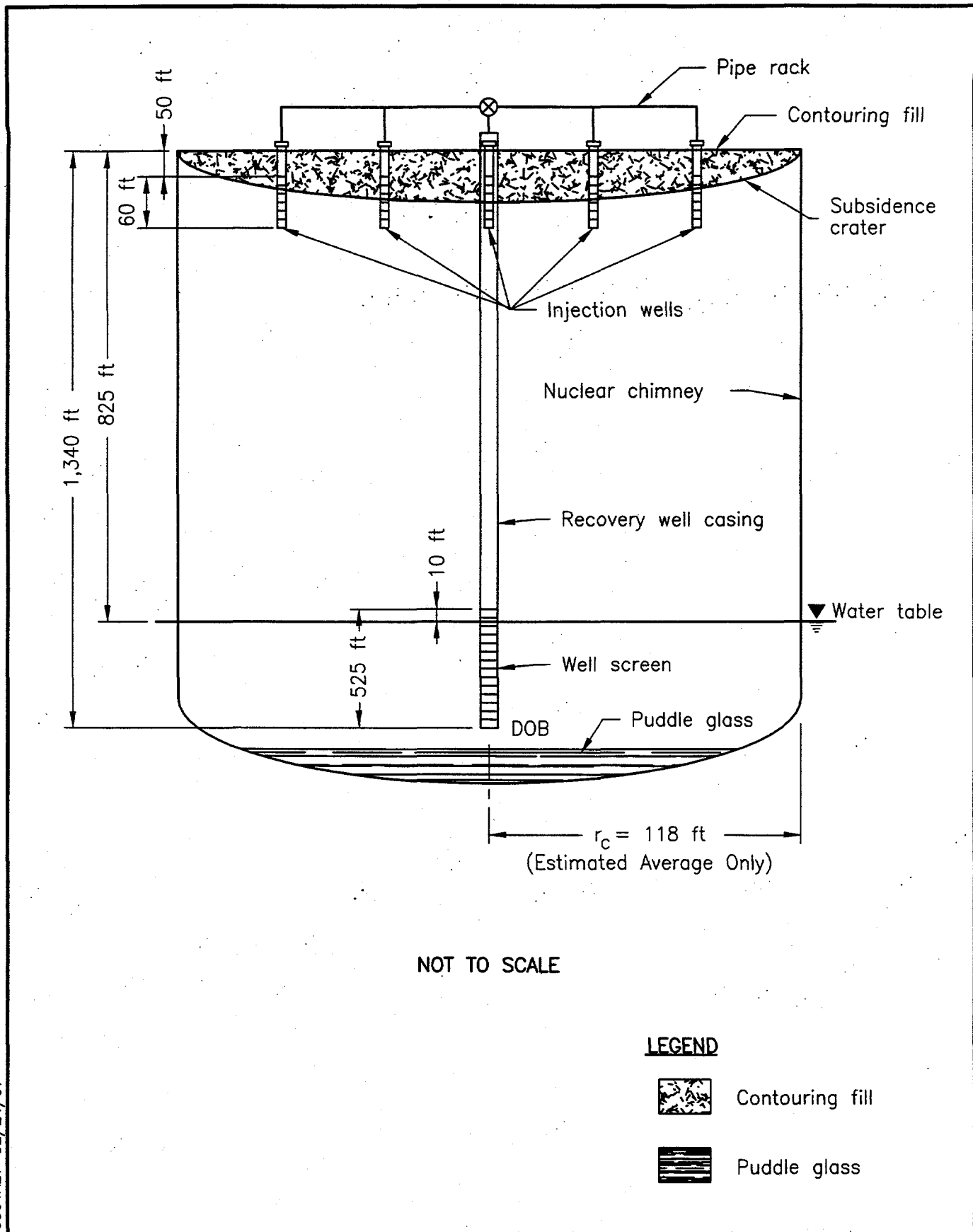
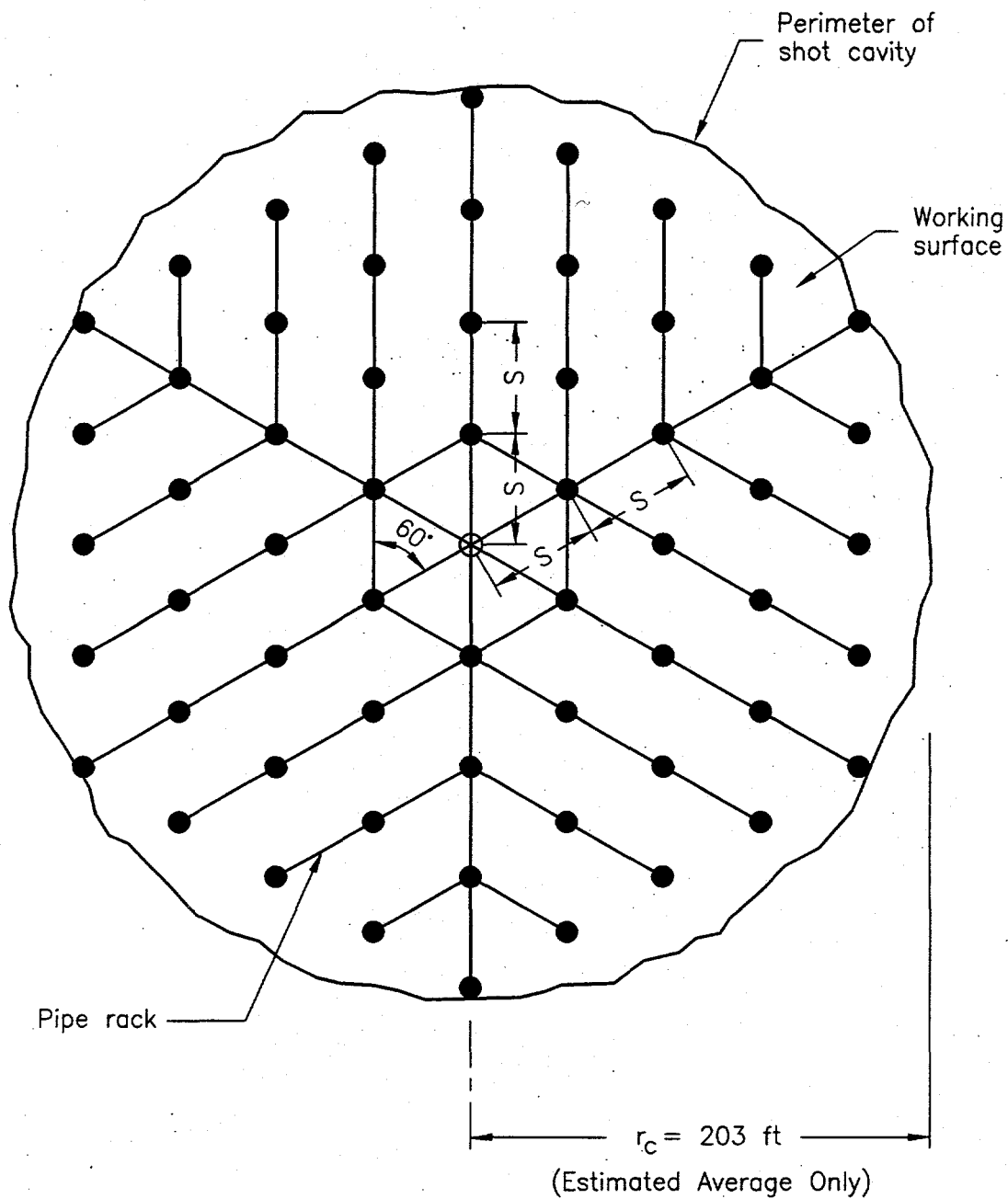


Figure 5-13b
Frenchman Flat Option 1
Conceptual Triangular Injection Well Array
Around Recovery Well With Gradient = 0.0009



NOT TO SCALE

LEGEND

- Injection wells
- Recovery well
- S Well spacing = 50 ft

Figure 5-14a
Yucca Flat Option 1
Injection Wells With Gradient = 0.0009

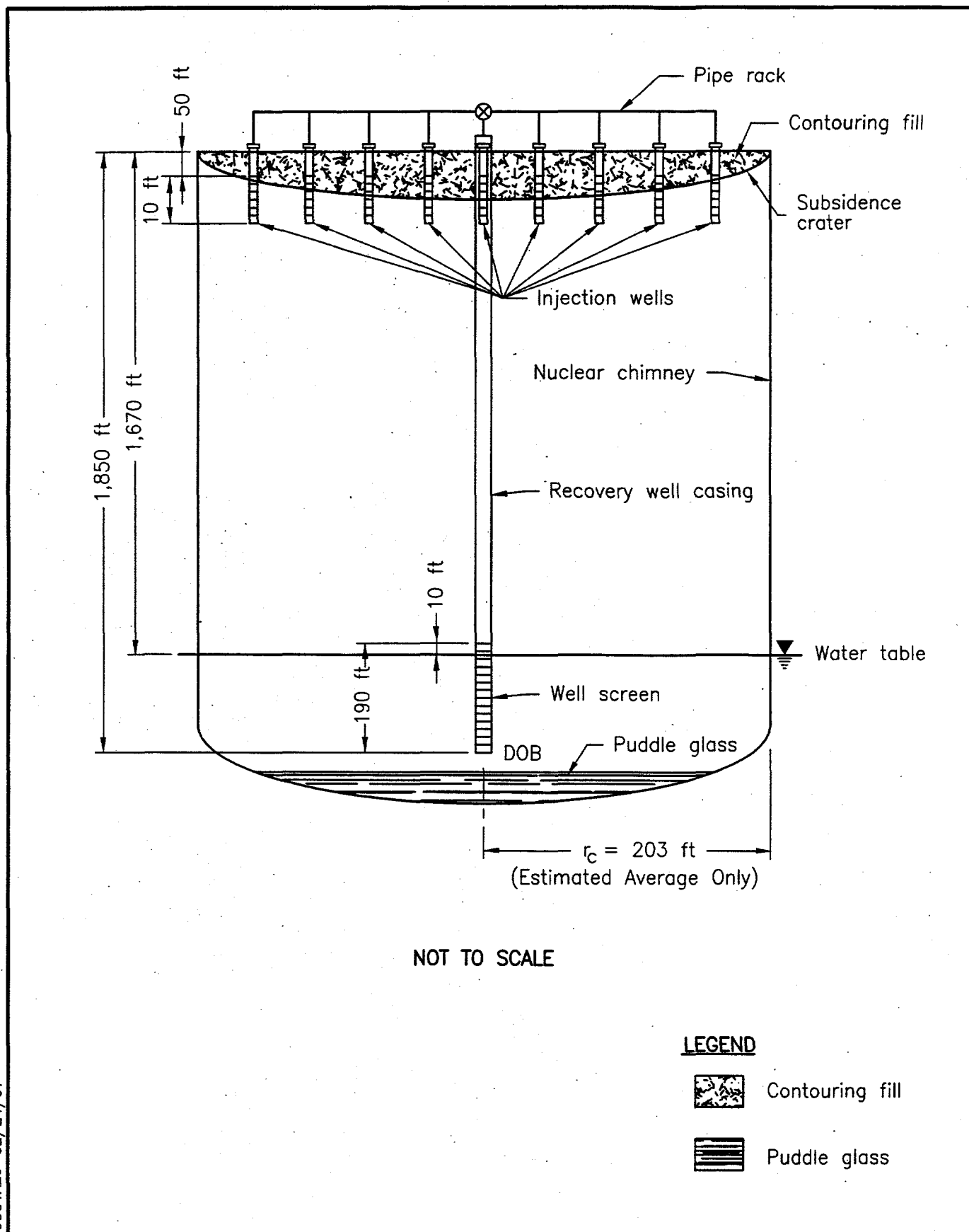
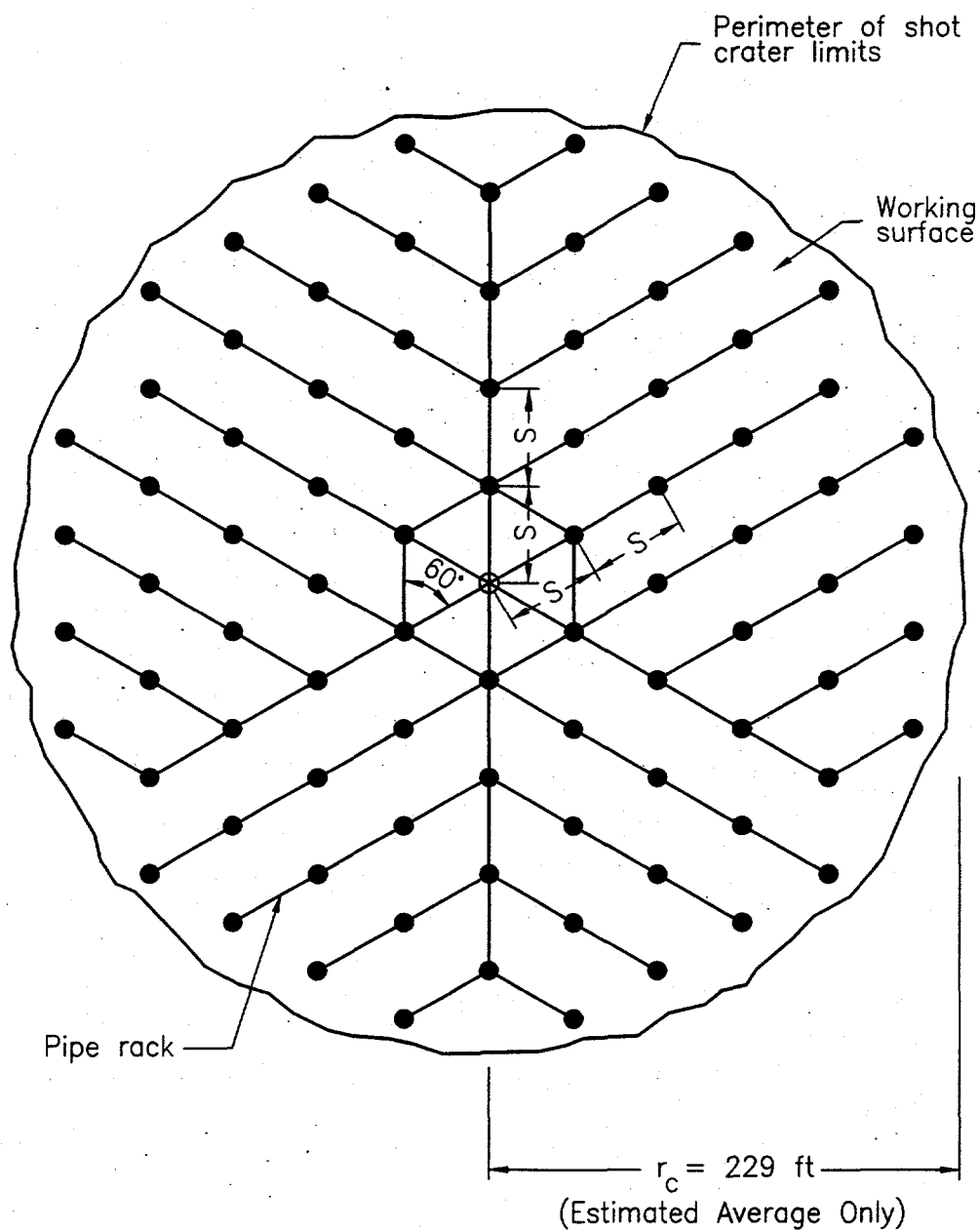


Figure 5-14b
Yucca Flat Option 1
Conceptual Triangular Injection Well Array
Around Recovery Well With Gradient = 0.0009

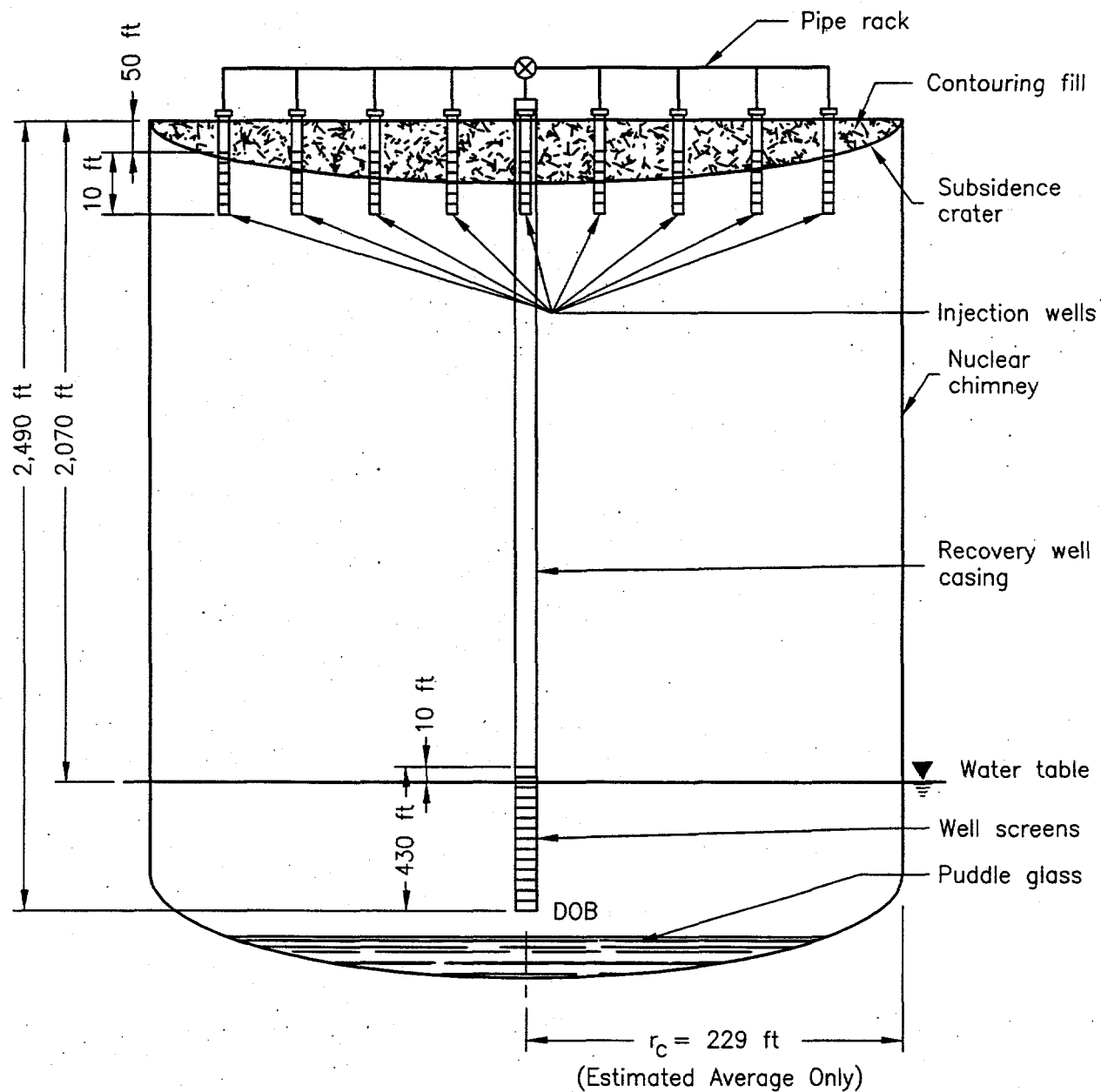


NOT TO SCALE

LEGEND

- Injection wells
- Recovery well
- s Well spacing = 50 ft

Figure 5-15a
Pahute Mesa Option 1
Injection Wells With Gradient = 0.0009



NOT TO SCALE

LEGEND

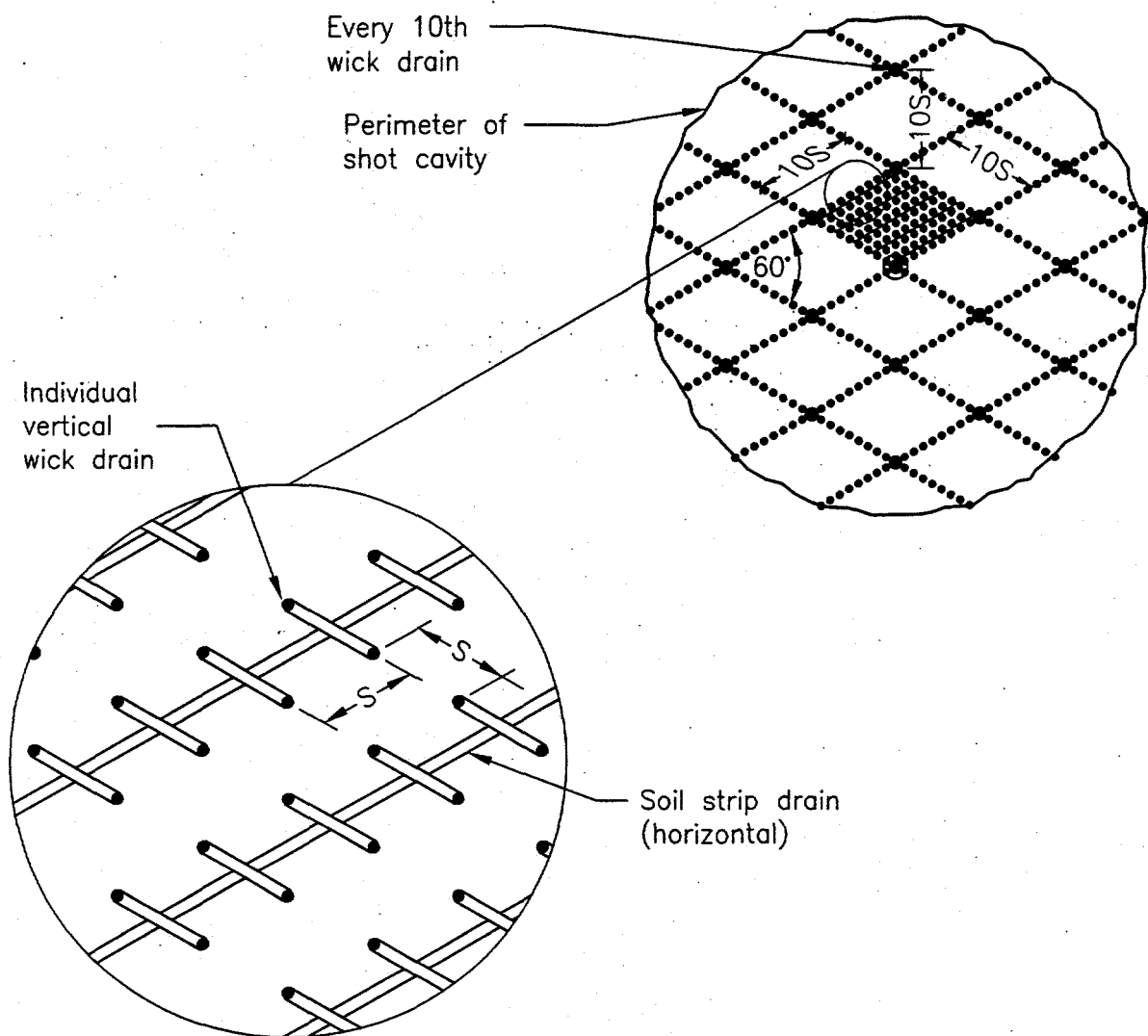


Contouring fill



Puddle glass

Figure 5-15b
Pahute Mesa Option 1
Conceptual Triangular Injection Well Array
Around Recovery Well With Gradient = 0.0009



NOT TO SCALE

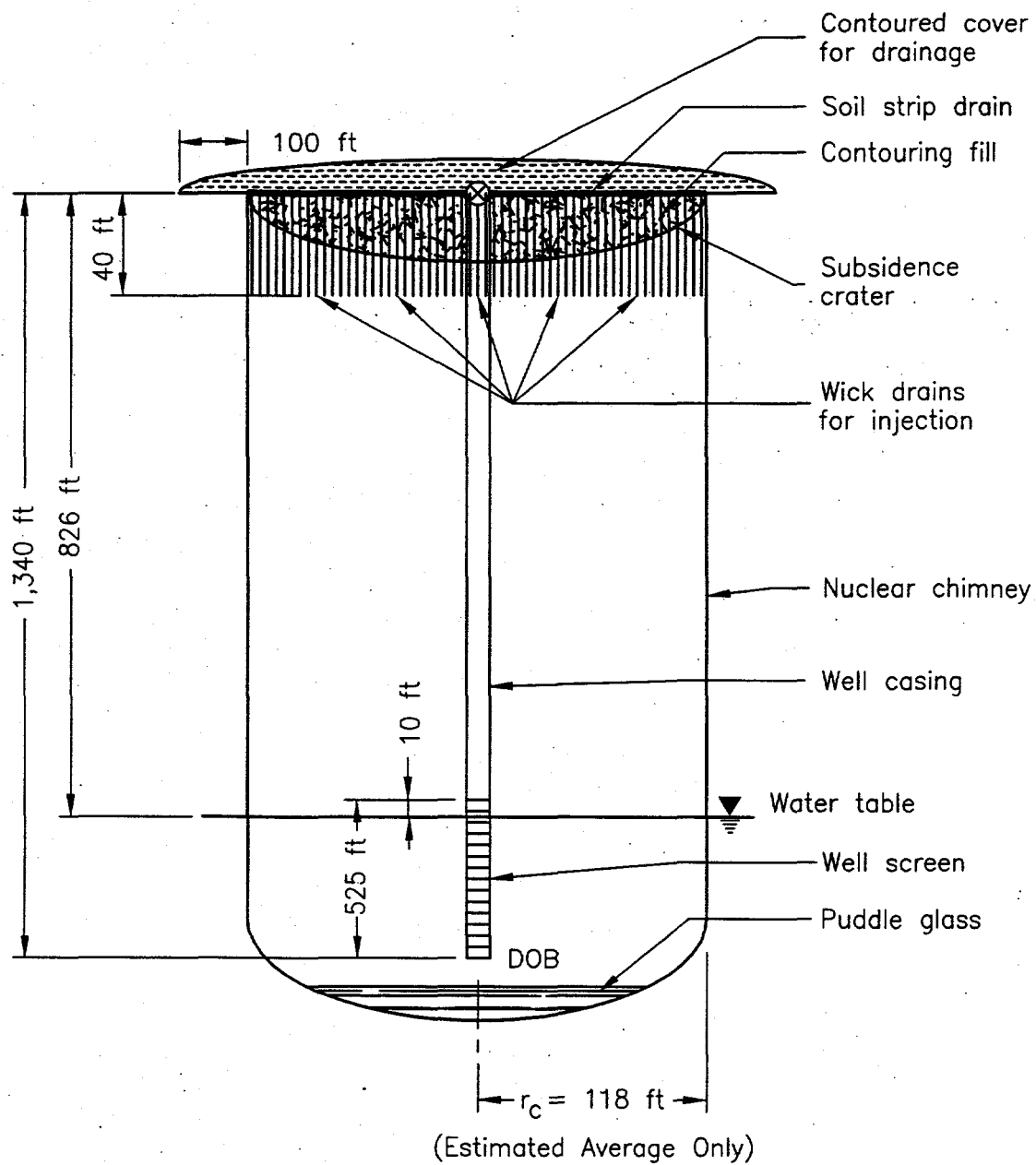
LEGEND

- Recovery well
- Every 10th vertical injection (Ameridrain 704)
- Soil strip drains through paired rows of vertical drains (Akwadrain, 6-inch width)

S = 10 feet

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Figure 5-16a
Frenchman Flat Option 1
Injection With Wick Drains Around Recovery Well

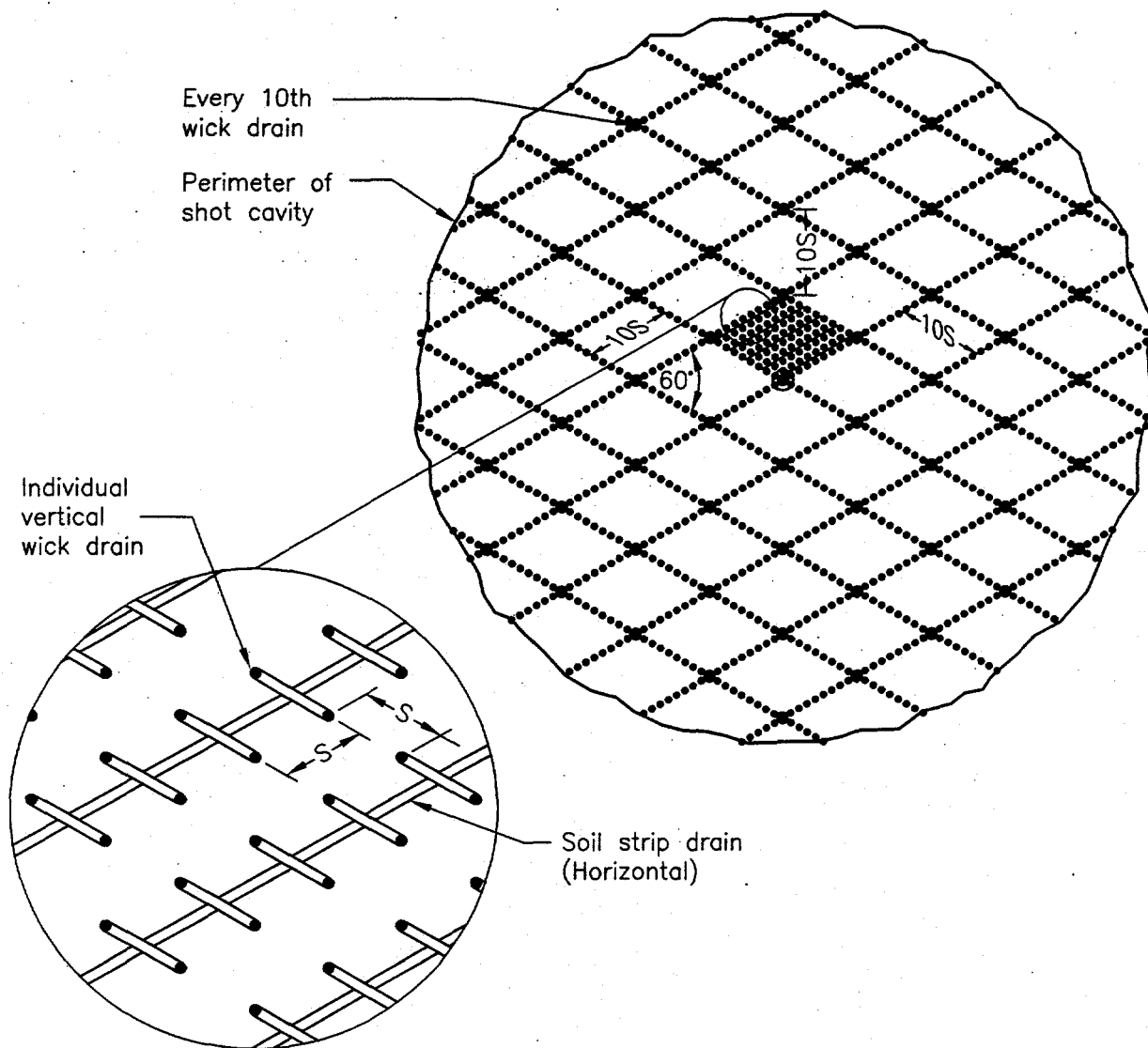


NOT TO SCALE

LEGEND

-  Contouring cover
-  Contouring fill
-  Puddle glass

Figure 5-16b
Frenchman Flat Option 1
Injection With Wick Drains Around Recovery Well

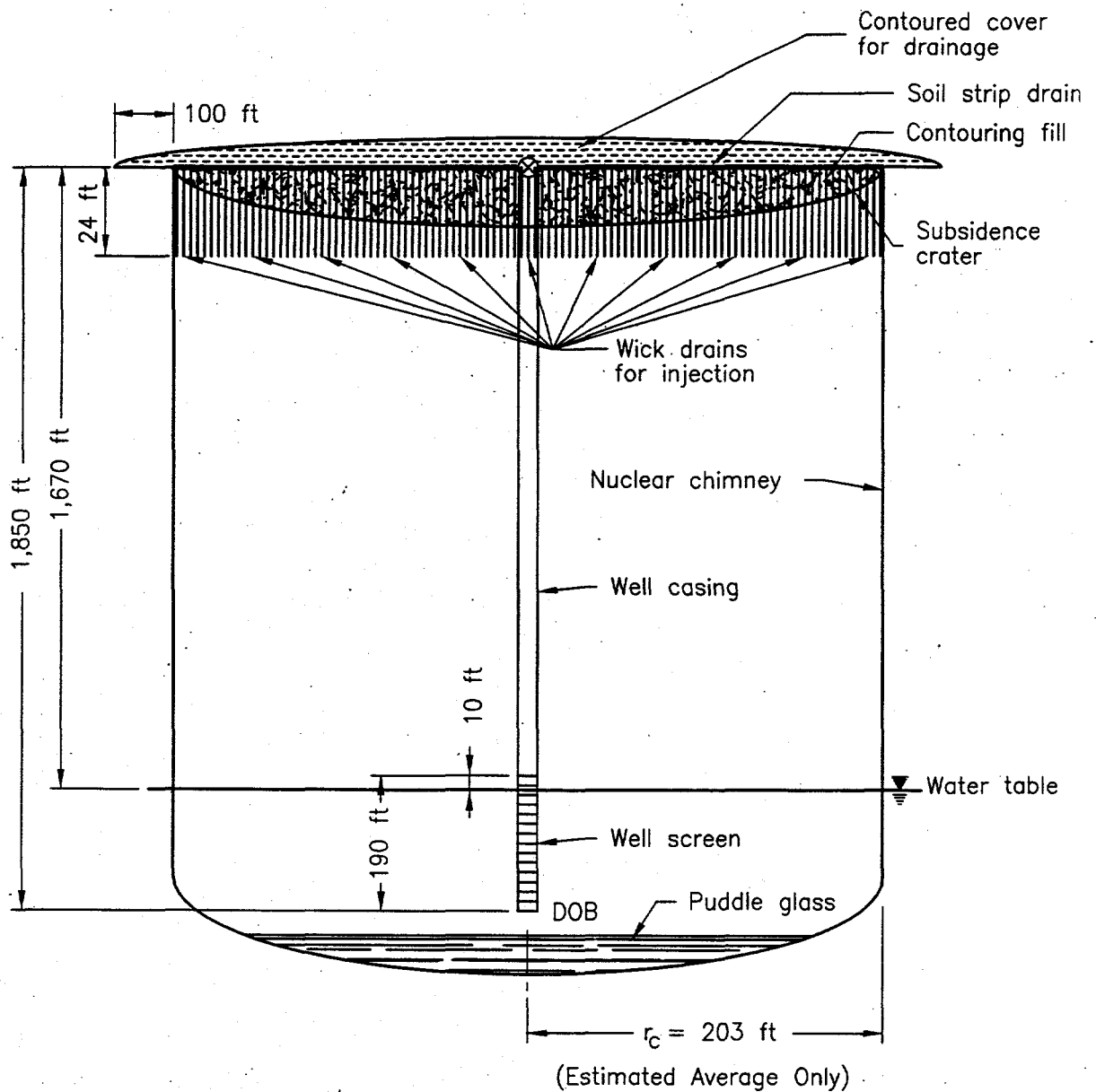


NOT TO SCALE

LEGEND

- Recovery well
 - Every 10th vertical injection (Ameridrain 704)
 - Soil strip drains through paired rows of vertical drains (Akwadrain, 6-inch width)
- S = 25 feet

Figure 5-17a
Yucca Flat Option 1
Injection With Wick Drains Around Recovery Well

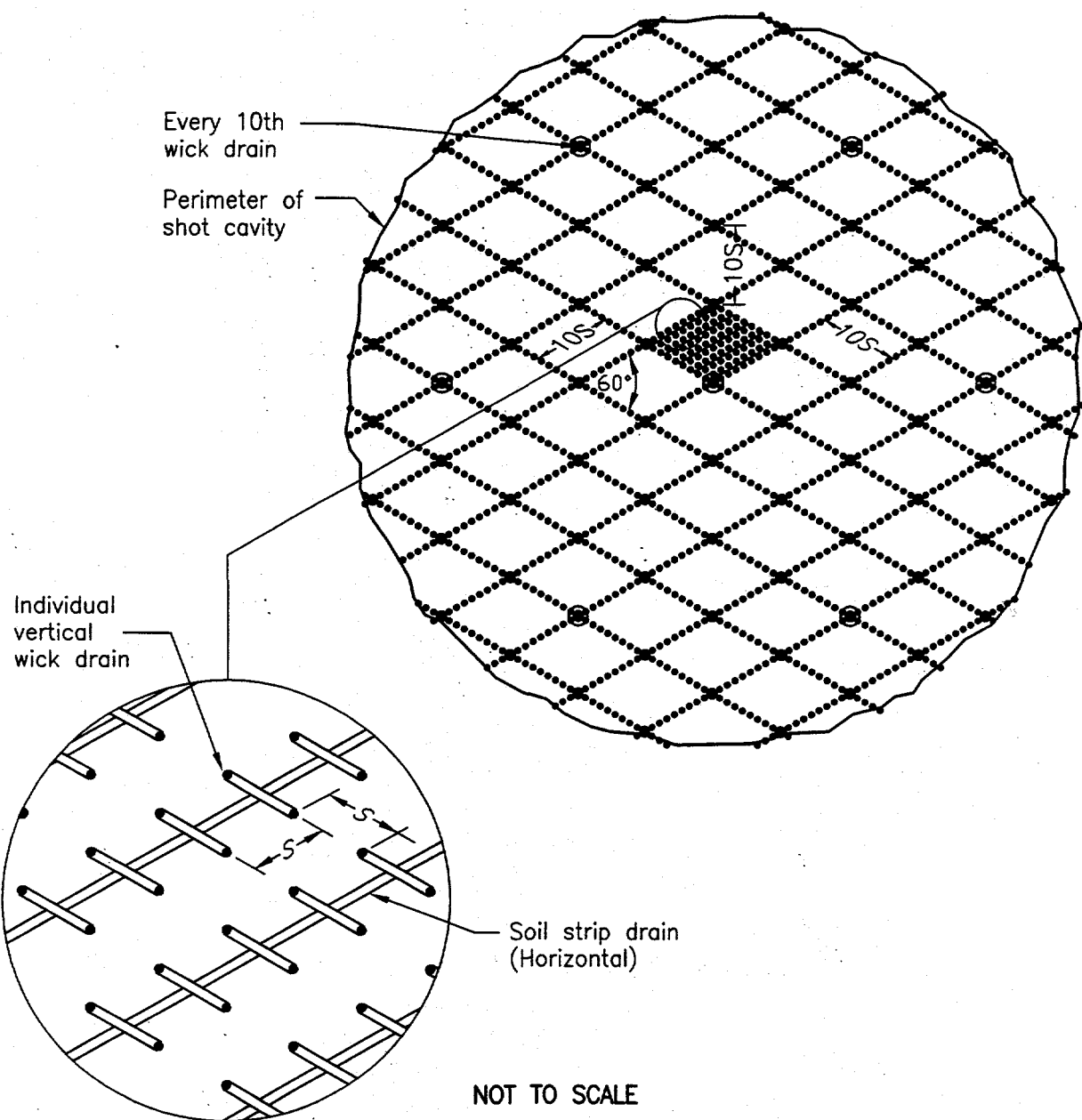


NOT TO SCALE

LEGEND

-  Contouring cover
-  Contouring fill
-  Puddle glass

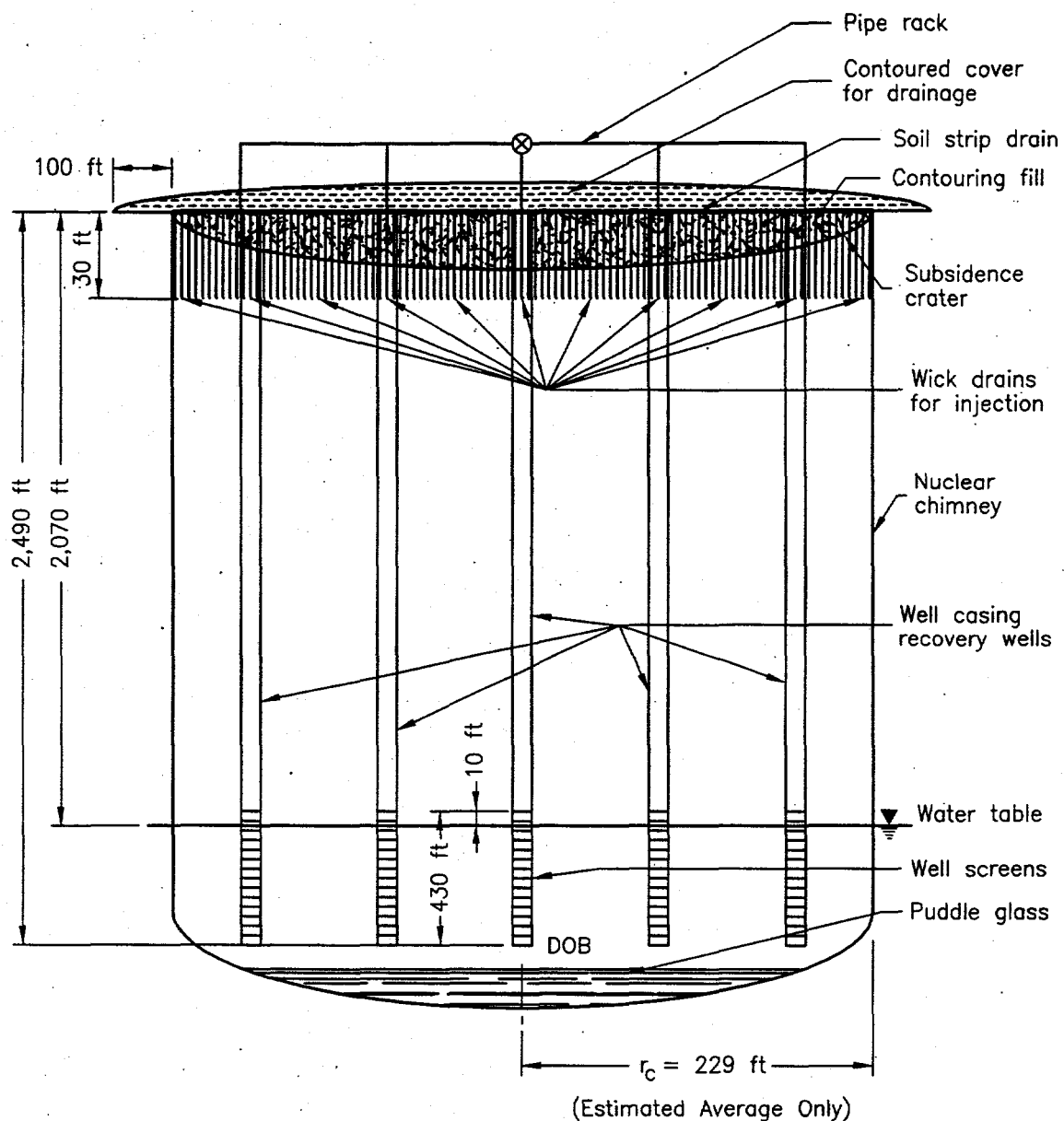
Figure 5-17b
Yucca Flat Option 1
Injection With Wick Drains Around Recovery Well



LEGEND

- Recovery well
- Every 10th vertical injection (Ameridrain 704)
- Soil strip drains through paired row of vertical drains (Akwadrain, 6-inch width)
- S = 10 feet

Figure 5-18a
Pahute Mesa Option 1
Injection With Wick Drains Around Recovery Wells



NOT TO SCALE

LEGEND

-  Contouring cover
-  Contouring fill
-  Puddle glass

Figure 5-18b
Pahute Mesa Option 1
Injection With Wick Drains Around Recovery Well

Table 5-4
Calculated Drawdowns for K_{intact} and $10K_{\text{intact}}$ for
Various Geographic Areas at the Nevada Test Site

Geographic Region	Drawdown by Driscoll Equation ^a meters (feet)		Drawdown by Capzone Analysis ^b meters (feet)	
	K_{intact}	$10K_{\text{intact}}$	K_{intact}	$10K_{\text{intact}}$
Pahute Mesa	1.52 (5)	0.11 (0.35)	7.83 (25.7)	0.86 (2.83)
Yucca Flat	0.98 (3.23)	0.17 (0.57)	19.7 (64.7)	1.90 (6.22)
<u>$K = 220 \text{ m/d}$</u>				
Q = 200 gpm	0.00 (0.01)	0.00 (0.0)	0.075 (0.247)	0.008 (0.027)
Q = 500 gpm	0.00 (0.02)	0.00 (0.001)	0.188 (0.617)	0.002 (0.068)
<u>$K = 14.8 \text{ m/d}$</u>				
Q = 200 gpm	0.09 (0.28)	0.004 (0.014)	1.02 (3.34)	0.11 (0.36)
Q = 500 gpm	0.26 (0.84)	0.015(0.049)	2.47 (8.12)	0.27 (0.90)
Frenchman Flat	0.91 (3)	0.06 (0.2)	6.43 (21.1)	0.71 (2.34)

^aDriscoll, 1986

^bBair, 1991

drawdowns calculated with K_{intact} and $10K_{\text{intact}}$ by means of steady-state flow equations found in Driscoll (1986) and analyses with CAPZONE (Bair, 1991).

The next few paragraphs will mainly discuss the flow and transport analyses that were conducted to answer the first two points. However, to address the third point, one must consider how long it would take for reinjected groundwater to flush out nuclides from the chimney if the entire mobile mass was placed above the water table rather than below it. This configuration of the source term will show that highly soluble, long-lived nuclides with a finite source term will be flushed out within about 200 years.

Our preliminary analyses have two parts: an infiltration analysis with the recovered, flow-contaminated groundwater with the HELP model and a one-dimensional, vertical fate and transport analysis with the ODAST/SWIFTLOAD model (described earlier). Table 5-5 gives the calculated infiltration rates for Option 1 at various geographic areas.

Differences among the modeled areas primarily involve the percolation distance through the unsaturated zone from the top of the nuclear chimney down to the water table and the surface area over which the recovered groundwater is distributed.

Table 5-5
Infiltration Rates Estimated with the EPA HELP^a Model for Injection of
Recovered Groundwater into Nuclear Chimneys in Various Geographic Areas

Geographic Region	Surface Area of Nuclear Chimney, square meters (acres)	Infiltration Rates (inches per year)			
		Injection Wells			Wick Drains
		Q = 200 gpm	Q = 400 gpm	Q = 1,400 gpm	Q = 200 gpm
Pahute Mesa	15,300 (3.78)	3,069	-	4,595	3,751
Yucca Flat	12,000 (2.97)	3,906	4,596	-	4,773
Frenchman Flat	4,050 (1.00)	4,598	4,596	-	7,165

^aSchroeder et al. (1994)
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The transport analyses with ODAST/SWIFTLOAD looked at the performance of the unsaturated zone in retarding and stripping out three nuclides: tritium, technetium-99, and iodine-129. These three nuclides represent some of the most mobile nuclides. However, they also have different half-lives, Curie inventories, initial concentrations, and transport parameters, as indicated by Table 5-6.

Table 5-6
Source-Term Data for ODAST/SWIFTLOAD Analysis of Contaminant
Loadings to the Water Table of the Nuclear Chimney in Yucca Flat (Appendix B)

Nuclide	Total Inventory of Fission and Nonfission Products, Curies	Initial Concentration, pCi/L	Mobile Mass,* mg	Initial Concentration, mg/L	Assumed Distribution Coefficient, K _d , mL/g	Decay Constant, λ, 1/d	Retardation Factors, R _d	
							Layer 1 η=.463** Θ=.232	Layer 2 η=.437 Θ=.105
Tritium	3.07 x 10 ⁷	3.28 x 10 ⁸	3.16 x 10 ⁶	3.42 x 10 ⁻⁵	0	1.5479 x 10 ⁻⁴	1	1
Technetium-99	3.06 x 10 ²	3.29 x 10 ³	1.8043 x 10 ⁷	1.94 x 10 ⁻⁴	.07	8.916 x 10 ⁻⁹	1.57	2.067
Iodine-129	0.889	9.559	3.904 x 10 ⁴	5.416 x 10 ⁻⁵	.07	1.186 x 10 ⁻¹⁰	1.57	2.067

* See Friedlander et al. (1964) for procedure to convert from pCi to mg.

** η=porosity, Θ=volumetric soil moisture content, derived in part from DOE (1994)

mg = milligram
 mg/L = milligram per liter
 mL/g = milliliter per gram

Figures 5-19 through 5-21 show the concentrations and cumulative infiltration loadings of these nuclides into the water table of a typical Yucca Flat Nuclear Chimney. Figure 5-19 illustrates that tritium has almost no additional contaminant loading after 100 years, even when the analysis uses a continuous source term. Tritium concentrations in the infiltrating groundwater also show an exponential decrease for either the finite or continuous source. So, in the case of tritium, analyses with either a finite or continuous source term yield nearly the same results because of the short half-life of tritium (12.26 years) and a retardation factor of 1 ($K_d = 0$).

In contrast, Figure 5-20 indicates a marked difference between the finite and continuous sources in their predicted concentrations and mass loadings to the water table. For the finite source, the long-lived and mobile nuclide, technetium-99, shows curves similar to tritium in that the concentrations decrease exponentially, and it takes about 200 to 300 years for increases in the cumulative loading to cease. The finite source case shows how long it would take for infiltrating groundwater to leach out technetium-99 if all the mobile mass resided initially in the unsaturated zone. However, a continuous source for technetium-99 produces a constant concentration for the infiltrating groundwater as it reaches the water table. The cumulative loading to the aquifer continuously increases, in part, because no significant decay occurs in technetium-99 as the groundwater recovery and injection system continues to operate. Also, the low retardation factors for technetium-99 result in little sorption to materials within the nuclear chimney.

In the continuous source case for iodine-129, Figure 5-21 also shows a constant concentration, with time, for the infiltrating groundwater as it reaches the water table and a continuous increase in the cumulative loading curve. However, in the finite source case, the relatively small initial mobile mass becomes depleted within 70 years because of the quantity of infiltrating water predicted by HELP; EPA's 70-year rule, therefore, applies (EPA, 1988). Figure 5-21 shows constant concentrations for the first 70 years, which go to zero after year 70. The 70-year rule likely predicts higher contaminant concentrations for all but the most soluble elements (e.g., cesium). For such highly soluble contaminants which would be depleted in less than 70 years, the EPA (1988) also assumes that 1/70 of the waste inventory would leach into the groundwater each year. All waste would leach into the environment within about one lifetime (70 years), and health effects would not be generally considered to be dose-dependent. Note that the 70-year rule assumes a constant mass flux, which means that the source decay factor α in ODAST becomes zero.

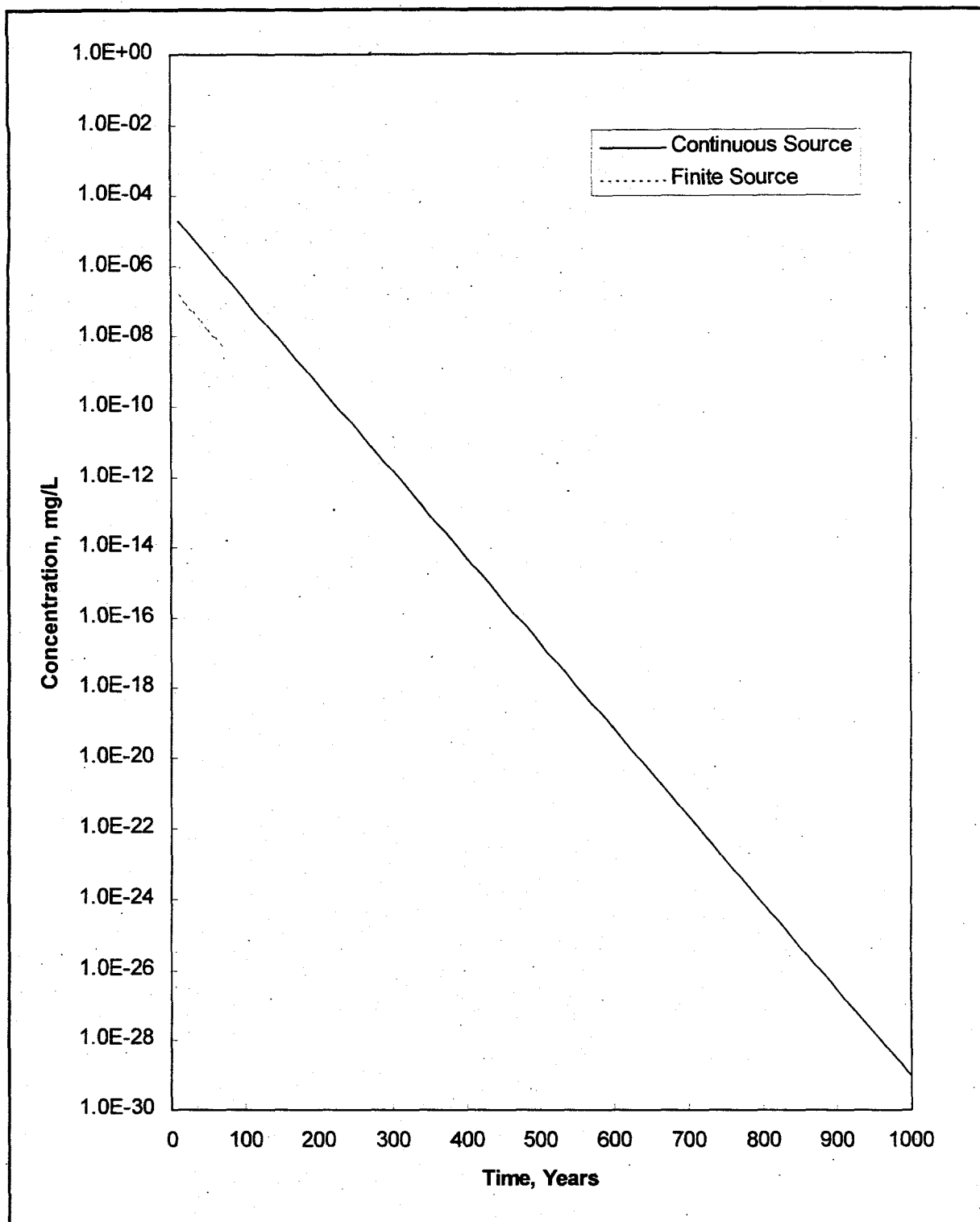


Figure 5-19a
Concentrations of Tritium with Time When Infiltration
Reaches Water Table of a Typical Yucca Flat Nuclear
Chimney for a Finite and a Continuous Source

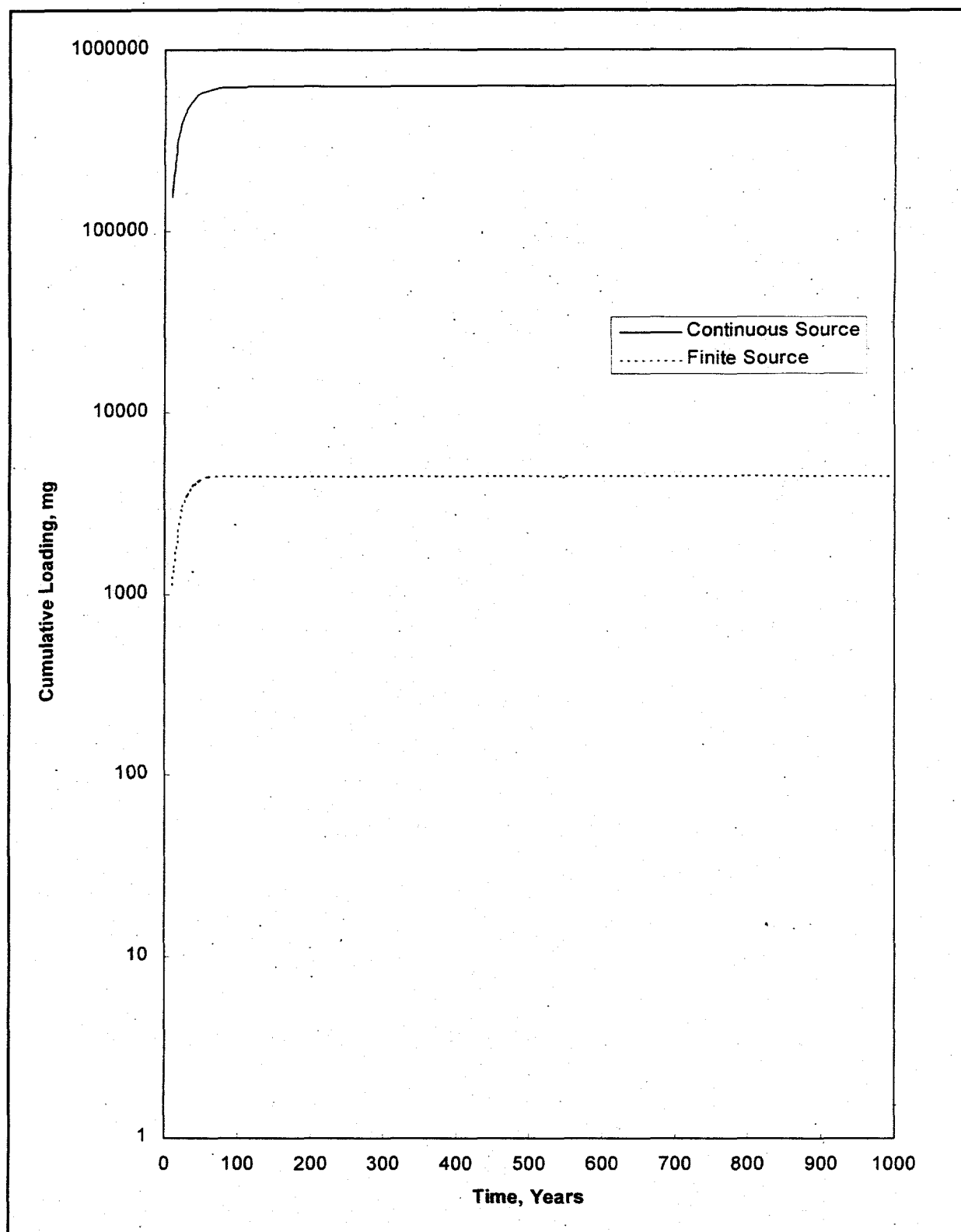


Figure 5-19b
Cumulative Infiltration Loading of Tritium Into Water Table of a Typical Yucca Flat Nuclear Chimney for a Finite and a Continuous Source

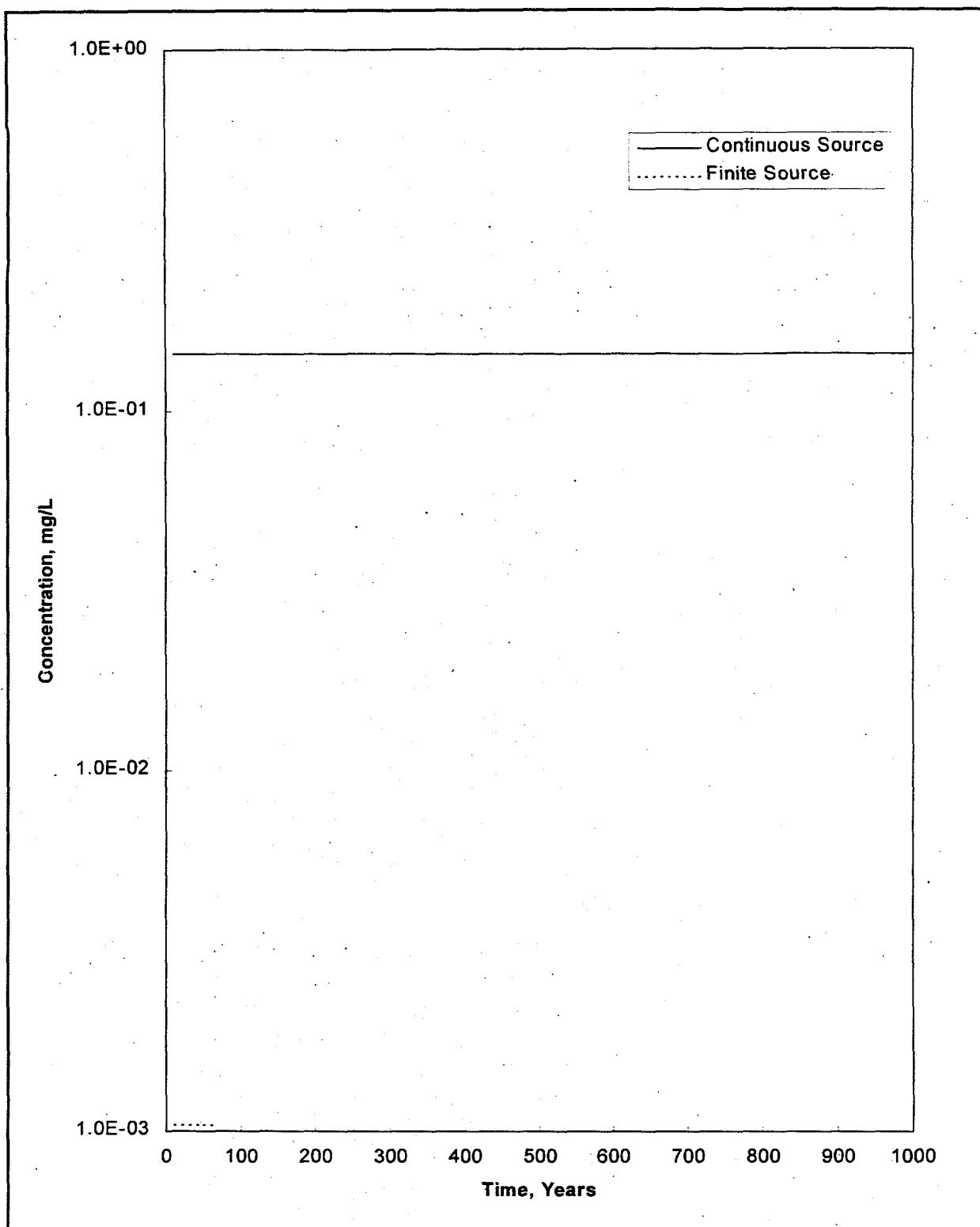


Figure 5-20a
Concentrations of Technetium-99 with Time When Infiltration Reaches Water Table of a Typical Yucca Flat Nuclear Chimney for a Finite and a Continuous Source

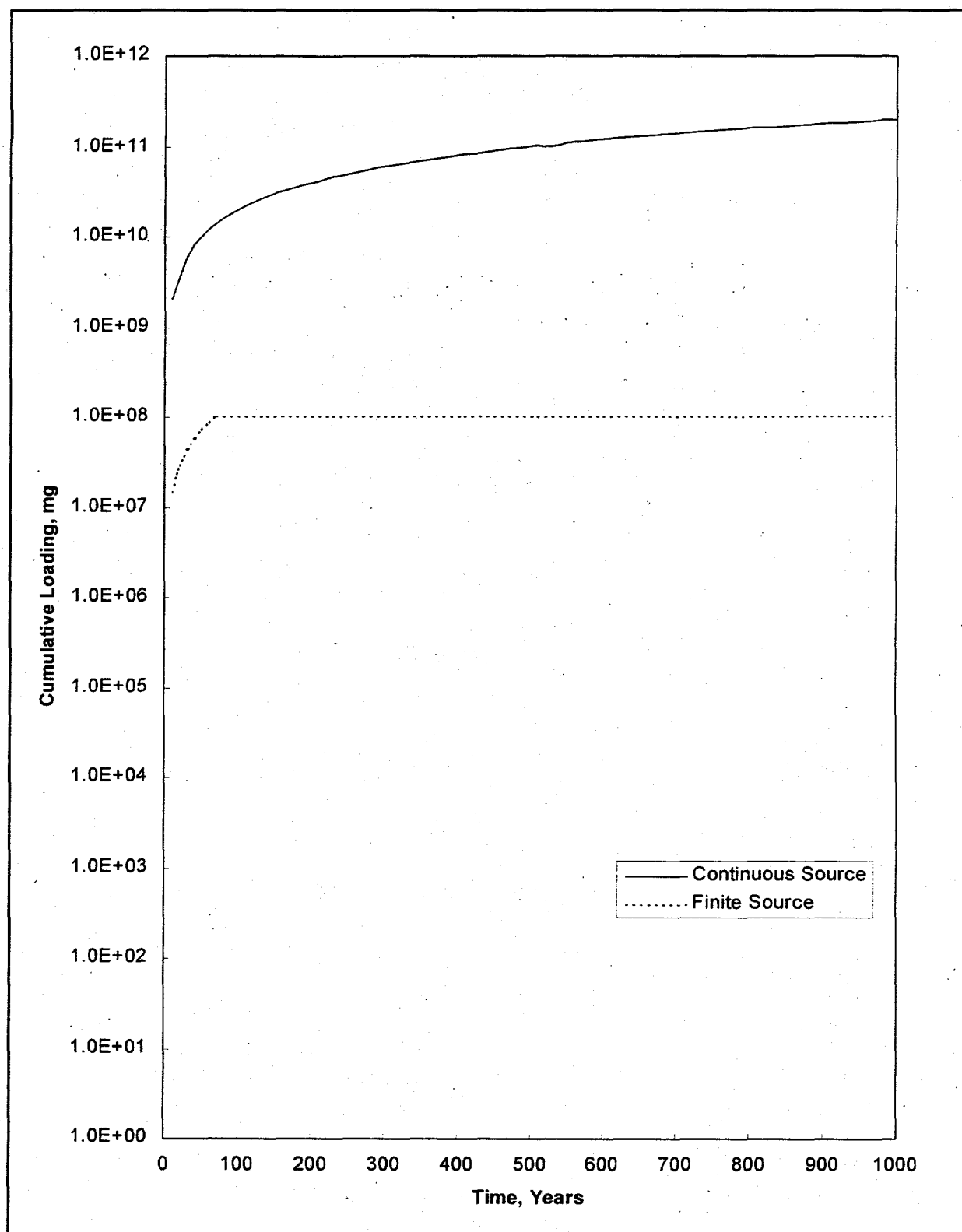


Figure 5-20b
Cumulative Infiltration Loading of Technetium-99 Into Water Table of a Typical Yucca Flat Nuclear Chimney for a Finite and a Continuous Source

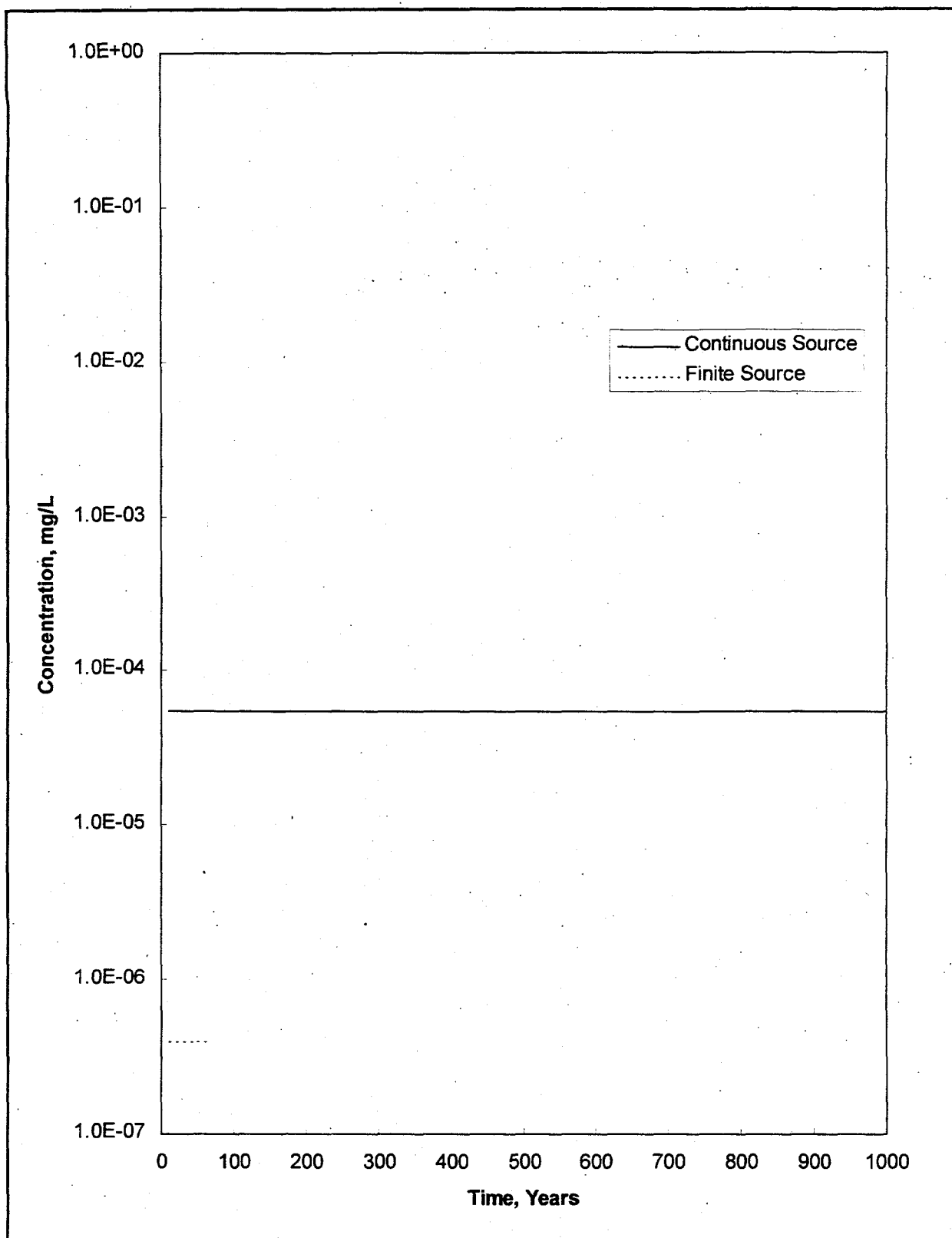


Figure 5-21a
Concentrations of Iodine-129 with Time When Infiltration Reaches Water Table of
a Typical Yucca Flat Nuclear Chimney for a Finite and a Continuous Source

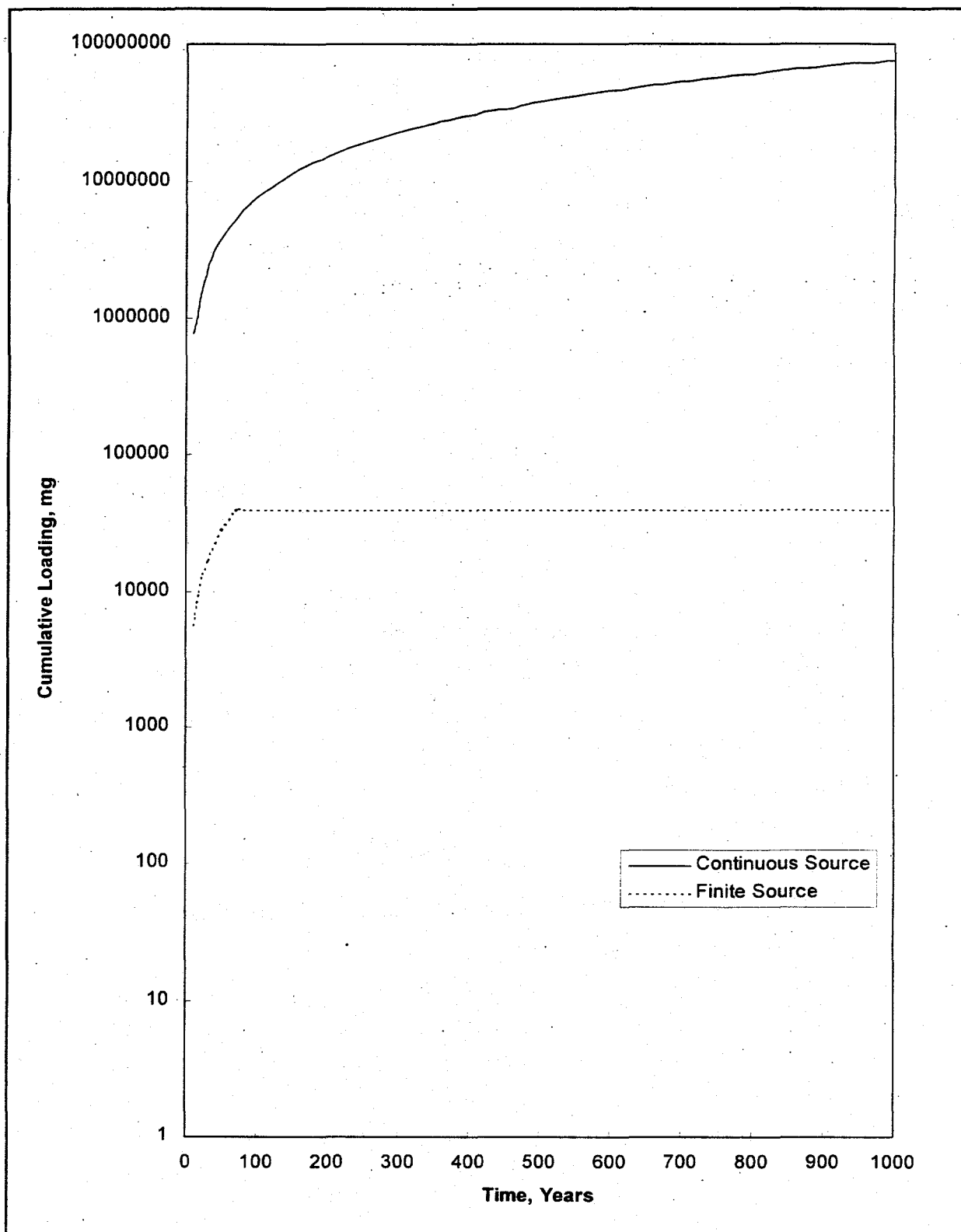


Figure 5-21b
Cumulative Infiltration Loading of Iodine-129 Into Water Table of a Typical Yucca Flat Nuclear Chimney for a Finite and a Continuous Source

The technical feasibility of the recovery and *in situ* treatment options can be summarized in terms of the performance issues presented earlier:

- The HELP analyses have suggested infiltration rates of 3,000 to about 7,000 inches per year. The assumed soil properties, total surface areas, and percolation distances were the primary variables which determined these infiltration rates.
- How well the nuclear chimney strips out nuclides depends mainly on the distribution coefficient and retardation factor of the individual nuclides in the particular geologic material. All three of the nuclides (tritium, technetium-99, and iodine-129) pass through the nuclear chimney without significant retardation. Only tritium, by virtue of its short half-life, showed an end to its contaminant loading of the water table by 210 years. For technetium-99 and iodine-129, the nuclear chimney fails to ease the contaminant loading of the water table, either through retardation or increased residence time. Therefore, very little *in situ* treatment will occur for long-lived, mobile nuclides (such as technetium-99 and iodine-129). However, the recovery wells could still create enough of a capture zone to contain most nuclides in an area around each shot site in spite of the recharge from the recycled groundwater. This kind of analysis was beyond the scope of this conceptual evaluation.
- The analyses with a finite source term show that the overall effect of leaching mobile nuclides from the nuclear chimneys will be minimal as compared to the cumulative loadings produced by the continuous operation of these pump and *in situ* treatment options.

It appears that these options are not realistically viable. The system would have to be perpetual to achieve complete environmental restoration.

5.2.2 Withdrawal of Groundwater From North Side of NTS and Transportation to the South Side for Reinjection as Artificial Recharge (Option 3)

This alternative looks at the withdrawal of "clean" groundwater from the hydraulically upgradient side of the NTS and transportation by pipeline to the hydraulically downgradient side for reinjection as artificial recharge. In contrast to Options 1 and 2, Option 3 moves clean groundwater from the upgradient areas of the site to replace the groundwater "lost" on the NTS to contamination from the underground test areas. As shown in Figure 5-5, Option 3 would avoid construction of wells in contaminated areas.

This section discusses the technical feasibility of the withdrawal, transportation, and artificial recharge of clean groundwater. It also describes the site-specific details of the conceptual designs for all three options (on which the last section on relative costs is based).

To be technically feasible, Option 3 will need to be implemented in a minimum of three phases:

- Preliminary feasibility study and conceptual design
- Field investigation and test program
- Design and construction of withdrawal, pipeline transport, and recharge facilities

The study described in this report includes the efforts required for the three phases cited above. Phase 1 frequently provides the key to success for withdrawal and artificial recharge. By planning the project in detail and evaluating all of the varied factors that comprise successful implementation, this phase provides a sound basis for the remainder of the program.

Success requires satisfactory performance for both technical and nontechnical issues. As Pyne (1995) points out, engineers and geologists have resolved many of the technical challenges that adversely affected recharge systems in the past. In contrast, regulatory, legal, political, environmental, and other issues have become the most significant factors for determining the success or failure of an artificial recharge program. The Phase 1 assessment can not only provide conceptual design of the withdrawal, transport, and recharge facilities, but it also evaluates the context of the program in the overall water management program.

This evaluation can gain a consensus of regulatory and public support for the overall program of moving groundwater from the north side of the NTS to the south side. The likelihood of success depends on how well Phase 1 is carried out, but it alone is not sufficient unless Phases 2 and 3 are adequately followed through as well. In particular, Phase 2 will reduce costs in the long run and avoid costly redesign and in-the-field adjustments of a new well withdrawal and recovery system. Typically, experience with injection wells used as artificial recharge systems shows that pilot tests pay for themselves very quickly through avoidance of problems and costly delays found in the full implementation of nontested designs. The following paragraphs will focus on the more immediate elements that will determine the likely success for implementation of Option 3 (i.e., the technical requirements that will later turn into conceptual estimates of cost).

Again using the data from Jacobson et al. (1994, Tables 1 and 2) of DRI and other information from Options 1 and 2, we have estimated that approximately 216 recovery wells are required on the north side, and approximately 374 injection wells are required on the south side of the Nevada Test Site (Figure 5-22). One assumption is that clogging of screens will cause most of the problems in the operation of the recharge wells. Therefore, in accordance with Driscoll (1986), the total linear feet of screen for the wells in the south side of the NTS has been doubled over those used for the north.



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The typical recovery well pumping rate is estimated to vary between 220 to 240 gpm, and the injection rate would be approximately 140 gpm. The injection wells will need high-quality water to reduce clogging problems, so the conceptual design includes pretreatment of the groundwater before recharge. The withdrawal, pipeline transport, and recharge of the groundwater will use a conceptual design that has elements similar to those shown in Figure 5-22.

5.3 Conceptual Costs

This section estimates costs to compare two methods of remediating the nuclear test shot cavities and one method to replace the contaminated groundwater located on the Nevada Test Site. These estimates assume that the contaminated rock and soil lie within cylindrical shot cavities of various sizes. In the Frenchman Flat area, the cavity sizes range from 70 m (230 ft) in diameter and 410 m (1,340 ft) deep; in the Pahute Mesa area, they range from 140 m (460 ft) in diameter and 730 m (2,400 ft) deep. The earlier sections examined several methods for recovering the existing subsurface water located in and around the shot cavities and reinjecting the water back through the shot chimneys with injection wells or wick drains (Options 1 and 2). Another option would recover subsurface water from wells north of the Test Site and pump it to the south side of the NTS for subsurface reinjection as artificial recharge. The next two sections discuss the estimate basis, assumptions, and the cost estimate.

5.3.1 Estimate Basis and Assumptions

To estimate costs for this remedial option, these were the assumptions:

1. The estimate is considered an order of magnitude with an accuracy of +50 or -50 percent. The costs are based on R.S. Means (1996) cost data, estimating standards (Richardson, 1993), Pipe Line Rules of Thumb Handbook (Gulf Publishing Company, 1982), and "in-house" costs from previous work.
2. The costs are based on the first quarter of 1996.
3. Wells drilled into the shot cavities are assumed to reduce the labor productivity by 25 percent since radiation hazards and drilling costs are assumed to increase by 100 percent because of the difficulties encountered while drilling into the fractured chimneys.
4. The recovery wells are assumed to produce an average of 757 Lpm (200 gpm) from each well. The recovery wells are assumed to require submersible pumps with motor capacities ranging from 75 to 150 kilowatts (kw) (100 to 200 horse power [HP]). Each well includes a 37,900-liter (10,000-gallon) water tank at the surface.

5. The recovery wells are assumed to be constructed of 178-mm (7-in.) carbon steel casing. The drilling costs were developed from similar well costs at the NTS. The cost for rotary drilling construction, labor, equipment, and materials was assumed to average between \$990 and \$1,310 per meter (\$300 and \$400 per foot).
6. The injection wells were assumed to be constructed of 64-mm (2½-in.) Poly Vinyl Chloride (PVC) and average \$115 per meter (\$35 per foot) for auger drilling installation, including materials.
7. The surface manifolding pipe for Options 1 and 2 was assumed to be constructed of PVC pipe, 102 to 64 mm (4 to 2½ in.) in diameter.
8. Low-level waste generated from drilling into the shot cavities was assumed to be disposed of at the NTS.
9. The wick drain system was assumed to be installed for \$9.80 per meter (\$3 per foot), including labor, materials, and equipment.
10. The wick drain system assumed that the cavities would be filled with local materials @ \$3.30 per cubic meter (m^3) (\$2.50 per cubic yard [yd^3]) and a 16.4-m (5-ft) thick clay cover installed over the top of the cavity for \$15.7 per m^3 (\$12 per yd^3).
11. Power was assumed to be provided from existing sources at a rate of \$0.05 per kilowatt hour. An additional 240 km (150 mi) of transmission line is required for electrical power for Option 3.
12. Option 3 consists of a system of recovery wells located north of the NTS and a pipeline system that pumps the water to a system of injection wells southwest of the NTS.
13. The annual volume of water to be recovered is 99,100,00 cubic meters per year (80,000 acre-feet per year), which equates to 189,200 liters per minute (50,000 gallons per minute). This number comes from Jacobson et al. (1994) and is the flow rate through the NTS.
14. The recovery wells are assumed to produce an average of 75 Lpm (200 gpm), and they will require 248 wells with a diameter of 127 mm (5 in.). There are 144 wells installed north of the NTS at a depth of 1,220 m (4,000 ft).
15. The wells require a 149-kw (200-HP) submersible pump to get the water to the surface.
16. At the surface, each recovery well would require a 3,780-liter (1,000-gallon) water tank and a 75-kw (100-HP) manifold pump to get the water into the piping system at 4,100 kilopascal (kPa) (600 pounds per square inch [psi]).

17. The manifolding pipe from each recovery well is assumed to have a 127-mm (5-in.) diameter and to average 61 m (200 ft) in length.
18. The main pipeline system consists of 306 km (190 mi) of pipe ranging in size from a 1,070-mm (42-in.) to 305-mm (12-in.) diameter, runs from north of the NTS to southwest of the NTS, and is designed for 4,100 kPa (600 psi).
19. The main header line size is a 1,070 mm (42-in.) steel pipe (19-mm [0.75-in.] wall thickness), 189,000 Lpm (50,000 gpm) at 4,100 kPa (600 psi) with a Fusion Bond Epoxy coating. The branch pipeline sizes are 610, 460, and 305 mm (24, 18, and 12 in.) in diameter and are API 5LX-60 grade steel pipe.
20. The pipeline is assumed to be buried and requires one pump station located at the north end of the line. The pump station consists of three, 12,000-HP electric pumps (one back-up pump) and a 35,800,000-liter (9,450,000-gallon) steel storage tank.
21. The injection system would consist of 374, 178-mm (7-in.) injection wells located at the south end of the NTS drilled to a depth of 1,220 m (4,000 ft).
22. The injection system also includes three, 8,940-kw (12,000-HP) pumps (one back-up pump) to maintain 189,000 Lpm (50,000 gpm) at 4,100 kPa (600 psi).
23. Costs do not include a sensory control and data acquisition (SCADA) system.
24. The cost of electricity is assumed to be \$.05 per kilowatt hour. This cost includes 240 km (150 mi) of new transmission line.
25. Costs include engineering and inspection of 20 percent of direct costs.
26. The estimate does not include any state or local taxes.
27. Costs include management and overhead at 15 percent of direct cost.
28. The estimate does not include any right-of-way costs.
29. Option 3 costs do not include any radiation treatment of water or soil.
30. A contingency factor of 50 percent is included.
31. Surface facilities are assumed to average \$100,000 per well (roads/berms/pits); Pahute Mesa is higher due to rocky terrain at \$150,000 per well.
32. Option 3 recovery wells assume field investigation and testing activities prior to well installation.

33. Option 3 includes a 3,785,000-liter (1,000,000-gallon) storage tank and filtration and chlorination facilities.
34. Life cycle costs are based on a 3 percent annual escalation in addition to an annual maintenance of 5 percent of the construction cost.

5.3.2 Cost Estimate

Generally, given these assumptions, Tables 5-7 through 5-11 estimate the low-end conceptual costs for Options 1, 2, and 3. These tables provide only the costs directly associated with the design and construction process and include no costs for extensive site characterization work or monitoring related to environmental issues. Also, Options 1 and 2 may require *ex situ* treatment of groundwater before reinjection if the DOE so orders and the EPA applies Class V injection well status to these options. Typical costs could reach as high as \$5.00 per 3,785 liters (1,000 gallons) treated and still not include disposal costs (EPA, 1994).

- Option 3: Withdrawal, Pipeline Transport, and Artificial Recharge - \$2.5 billion
- Option 2: Recovery and Reinjection with Wells - \$1.3 billion
Recovery with Wells and Reinjection with Wicks: - \$1.4 billion
- Option 1: Recovery and Reinjection with Wells - \$ 2.4 billion
Recovery with Wells and Reinjection with Wicks: - \$ 2.5 billion

When treatment of groundwater before reinjection is ignored, the most economical approach involves Option 2. The main difference between Options 1 and 2 is the cost of drilling recovery wells within or outside of a nuclear chimney. It remains to be seen whether wells installed outside the shot cavities can develop capture zones sufficient to contain and recover the nuclides. Furthermore, if Option 2 needs larger recovery rates or more wells to contain the nuclide plume, the cost to implement it may easily exceed that of Option 1.

However, given that Options 1 and 2 would essentially have to operate forever, the costs to treat the groundwater before reinjection would need about \$806,400 per day or \$294 million per year to treat the water alone (assuming \$5 per 3,785 liters [1,000 gallons] of contaminated groundwater [EPA, 1994]). Over a 50-year period, this would be \$14.7 billion without any excavation factor over time. Furthermore, we haven't considered disposal of the large filters (e.g., a 0.91-m [3-ft] diameter zeolite/resin filter). These filters may have to be disposed of in a high level waste repository. The costs associated with groundwater treatment alone would quickly overshadow all others.

Table 5-7
Summary of UGTA Focused Evaluation of Selected Remedial Alternatives
Option 1: Injection Wells

Life Cycle Costs Based on 3% Escalation of Electrical Power at \$0.05 per KWH Maintenance at 5% Construction

ITEM	DESCRIPTION	FRENCHMAN	YUGCA	PAHUTE	TOTAL
1	RECOVERY WELLS	\$ 1,094,950	\$ 1,494,750	\$ 13,262,250	\$ 15,851,950
2	SURFACE PIPING	\$ 26,400	\$ 66,000	\$ 88,000	\$ 180,400
3	INJECTION WELLS	\$ 87,280	\$ 163,400	\$ 210,920	\$ 461,600
4	WASTE DISPOSAL	\$ 73,584	\$ 127,260	\$ 450,240	\$ 651,084
5	FILL CRATER	\$ 101,250	\$ 299,675	\$ 381,375	\$ 782,300
6	SURFACE FACILITIES	\$ 100,000	\$ 100,000	\$ 150,000	\$ 350,000
7	CONSTRUCTION EACH CAVITY	\$ 1,483,464	\$ 2,251,085	\$ 14,542,785	\$ 18,277,334
8	DAILY POWER CONSUMPTION	\$ 100	\$ 180	\$ 1,400	\$ 1,680
9	NUMBER OF CAVITIES	6	122	71	199
10	TOTAL CONSTRUCTION ALL CAVITIES	\$ 8,900,784	\$ 274,632,370	\$ 1,032,537,735	\$ 1,316,070,889
11	ENGINEERING, DESIGN & INSPECTION (20%)	\$ 1,780,157	\$ 54,926,474	\$ 206,507,547	\$ 263,214,178
12	MANAGEMENT & INTEGRATION (15%)	\$ 1,335,118	\$ 41,194,856	\$ 154,880,660	\$ 197,410,633
13	CONTINGENCY (50%)	\$ 4,450,392	\$ 137,316,185	\$ 516,268,868	\$ 658,035,445
14	TOTAL COST	\$ 16,466,450	\$ 508,069,885	\$ 1,910,194,810	\$ 2,434,731,145
15	TOTAL ANNUAL POWER CONSUMPTION	\$ 219,000	\$ 8,015,400	\$ 36,281,000	\$ 44,515,400
16	ANNUAL MAINTENANCE COST	\$ 445,039	\$ 13,731,619	\$ 51,626,887	\$ 65,803,544
17	LIFE CYCLE COSTS 50 YEARS	\$ (91,367,992)	\$ (2,961,065,444)	\$ (11,825,929,045)	\$ (14,878,362,481)
18	LIFE CYCLE COSTS 100 YEARS	\$ (419,729,311)	\$ (13,714,767,442)	\$ (55,295,576,040)	\$ (69,430,072,793)

Table 5-8
Summary of UGTA Feasibility Study
Option 2: Injection Wells

Life Cycle Costs Based on 3% Escalation of Electrical Power at \$0.05 per KWH Maintenance at 5% Construction

ITEM	DESCRIPTION	FRENCHMAN	YUCCA	PAHUTE	TOTAL
1	RECOVERY WELLS	\$ 558,950	\$ 754,750	\$ 6,542,250	\$ 7,855,950
2	SURFACE PIPING	\$ 47,400	\$ 96,000	\$ 109,000	\$ 252,400
3	INJECTION WELLS	\$ 87,280	\$ 163,400	\$ 210,920	\$ 461,600
4	WASTE DISPOSAL	\$ 47,124	\$ 90,720	\$ 118,020	\$ 255,864
5	FILL CRATER	\$ 101,250	\$ 299,675	\$ 381,375	\$ 782,300
6	SURFACE FACILITIES	\$ 100,000	\$ 100,000	\$ 150,000	\$ 350,000
7	CONSTRUCTION EACH CAVITY	\$ 942,004	\$ 1,504,545	\$ 7,511,565	\$ 9,958,114
8	DAILY POWER CONSUMPTION	\$ 100	\$ 180	\$ 1,400	\$ 1,680
9	NUMBER OF CAVITIES	6	122	71	199
10	TOTAL CONSTRUCTION ALL CAVITIES	\$ 5,652,024	\$ 183,554,490	\$ 533,321,115	\$ 722,527,629
11	ENGINEERING, DESIGN & INSPECTION (20%)	\$ 1,130,405	\$ 36,710,898	\$ 106,664,223	\$ 144,505,526
12	MANAGEMENT & INTEGRATION (15%)	\$ 847,804	\$ 27,533,174	\$ 79,998,167	\$ 108,379,144
13	CONTINGENCY (50%)	\$ 2,826,012	\$ 91,777,245	\$ 266,660,558	\$ 361,263,815
14	TOTAL COST	\$ 10,456,244	\$ 339,575,807	\$ 986,644,063	\$ 1,336,676,114
15	TOTAL ANNUAL POWER CONSUMPTION	\$ 219,000	\$ 8,015,400	\$ 36,281,000	\$ 44,515,400
16	ANNUAL MAINTENANCE COST	\$ 282,601	\$ 9,177,725	\$ 26,666,056	\$ 36,126,381
17	LIFE CYCLE COSTS 50 YEARS	\$ (67,035,288)	\$ (2,278,906,389)	\$ (8,086,874,756)	\$ (10,432,816,434)
18	LIFE CYCLE COSTS 100 YEARS	\$ (315,072,500)	\$ (10,780,749,402)	\$ (39,213,618,829)	\$ (50,309,440,731)

Table 5-9
Summary of UGTA Focused Evaluation of Selected Remedial Alternatives
Option 1: Wick Drains

Life Cycle Costs Based on 3% Escalation of Electrical Power at \$0.05 per KWH Maintenance at 5% Construction

ITEM	DESCRIPTION	FRENCHMAN	YUCCA	PAHUTE	TOTAL
1	RECOVERY WELLS	\$ 1,094,950	\$ 1,494,750	\$ 13,262,250	\$ 15,851,950
2	SURFACE PIPING	\$ 26,400	\$ 66,000	\$ 88,000	\$ 180,400
3	INJECTION WELLS	\$ 157,200	\$ 305,640	\$ 523,620	\$ 986,460
4	WASTE DISPOSAL	\$ 26,460	\$ 36,540	\$ 332,220	\$ 395,220
5	FILL CRATER	\$ 101,250	\$ 299,675	\$ 381,375	\$ 782,300
6	SURFACE FACILITIES	\$ 100,000	\$ 100,000	\$ 150,000	\$ 350,000
7	CONSTRUCTION EACH CAVITY	\$ 1,506,260	\$ 2,302,605	\$ 14,737,465	\$ 18,546,330
8	DAILY POWER CONSUMPTION	\$ 100	\$ 180	\$ 1,400	\$ 1,680
9	NUMBER OF CAVITIES	6	122	71	199
10	TOTAL CONSTRUCTION ALL CAVITIES	\$ 9,037,560	\$ 280,917,810	\$ 1,046,360,015	\$ 1,336,315,385
11	ENGINEERING DESIGN & INSPECTION (20%)	\$ 1,807,512	\$ 56,183,562	\$ 209,272,003	\$ 267,263,077
12	MANAGEMENT & INTEGRATION (15%)	\$ 1,355,634	\$ 42,137,672	\$ 156,954,002	\$ 200,447,308
13	CONTINGENCY (50%)	\$ 4,518,780	\$ 140,458,905	\$ 523,180,008	\$ 668,157,693
14	TOTAL COST	\$ 16,719,486	\$ 519,697,949	\$ 1,935,766,028	\$ 2,472,183,462
15	TOTAL ANNUAL POWER CONSUMPTION	\$ 219,000	\$ 8,015,400	\$ 36,281,000	\$ 44,515,400
16	ANNUAL MAINTENANCE COST	\$ 451,878	\$ 14,045,891	\$ 52,318,001	\$ 66,815,769
17	LIFE CYCLE COSTS 50 YEARS	\$ (92,392,423)	\$ (3,008,142,405)	\$ (11,929,455,757)	\$ (15,029,990,585)
18	LIFE CYCLE COSTS 100 YEARS	\$ (424,135,466)	\$ (13,917,249,037)	\$ (55,740,852,312)	\$ (70,082,236,814)

Table 5-10
Summary of UGTA Feasibility Study
Option 2: Wick Drains

Life Cycle Costs Based on 3% Escalation of Electrical Power at \$0.05 per KWH Maintenance at 5% Construction

ITEM	DESCRIPTION	FRENCHMAN	YUCCA	PAHUTE	TOTAL
1	RECOVERY WELLS	\$ 558,950	\$ 754,750	\$ 6,542,250	\$ 7,855,950
2	SURFACE PIPING	\$ 47,400	\$ 96,000	\$ 109,000	\$ 252,400
3	INJECTION WELLS	\$ 157,200	\$ 305,640	\$ 523,620	\$ 986,460
4	WASTE DISPOSAL	\$ -	\$ -	\$ -	\$ -
5	FILL CRATER	\$ 101,250	\$ 299,675	\$ 381,375	\$ 782,300
6	SURFACE FACILITIES	\$ 100,000	\$ 100,000	\$ 150,000	\$ 350,000
7	CONSTRUCTION EACH CAVITY	\$ 964,800	\$ 1,556,065	\$ 7,706,245	\$ 10,227,110
8	DAILY POWER CONSUMPTION	\$ 100	\$ 180	\$ 1,400	\$ 1,680
9	NUMBER OF CAVITIES	6	122	71	199
10	TOTAL CONSTRUCTION ALL CAVITIES	\$ 5,788,800	\$ 189,839,930	\$ 647,143,395	\$ 742,772,125
11	ENGINEERING, DESIGN & INSPECTION (20%)	\$ 1,157,760	\$ 37,967,986	\$ 109,428,679	\$ 148,554,425
12	MANAGEMENT & INTEGRATION (15%)	\$ 868,320	\$ 28,475,990	\$ 82,071,509	\$ 111,415,819
13	CONTINGENCY (50%)	\$ 2,894,400	\$ 94,919,965	\$ 273,571,698	\$ 371,386,063
14	TOTAL COST	\$ 10,709,280	\$ 351,203,871	\$ 1,012,215,281	\$ 1,374,128,431
15	TOTAL ANNUAL POWER CONSUMPTION	\$ 219,000	\$ 8,015,400	\$ 36,281,000	\$ 44,515,400
16	ANNUAL MAINTENANCE COST	\$ 289,440	\$ 9,491,997	\$ 27,357,170	\$ 37,138,606
17	LIFE CYCLE COSTS 50 YEARS	\$ (68,059,719)	\$ (2,325,983,350)	\$ (8,190,401,469)	\$ (10,584,444,538)
18	LIFE CYCLE COSTS 100 YEARS	\$ (319,478,655)	\$ (10,983,230,996)	\$ (39,658,895,101)	\$ (50,961,604,752)

Table 5-11
Summary of UGTA Feasibility Study
Option 3: Pipeline Withdrawal—Recharge

Life Cycle Costs Based on 3% Escalation of Electrical Power at \$0.05 per KWH
Maintenance at 5% Construction

ITEM	DESCRIPTION	TOTAL COST
1	248--WITHDRAWAL WELLS--4,000 FT DEEP	\$ 467,776,800
2	SURFACE PIPING & FACILITIES	\$ 43,581,040
3	374--INJECTION WELLS--4,000 FT DEEP	\$ 647,360,000
4	SURFACE PIPING & FACILITIES	\$ 40,852,020
5	INJECTION WELLS PUMPING STATIONS	\$ 9,036,000
6	PIPELINE PUMPING STATION	\$ 8,231,000
7	MAIN PIPELINES--190 MILES (42-INCH--12-INCH)	\$ 114,485,344
8	POWER TRANSMISSION LINES--156 MILES	\$ 13,572,000
9	TOTAL CONSTRUCTION	\$ 1,344,894,204
10	ENGINEERING, DESIGN & INSPECTION (20%)	\$ 268,978,841
11	MANAGEMENT & INTEGRATION (15%)	\$ 201,734,131
12	CONTINGENCY (50%)	\$ 672,447,102
13	TOTAL COST	\$ 2,488,054,277
14	DAILY POWER CONSUMPTION	\$ 122,400
15	TOTAL ANNUAL POWER CONSUMPTION	\$ 44,676,000
16	ANNUAL MAINTENANCE COST	\$ 67,244,710
17	LIFE CYCLE COSTS 50 YEARS	\$ (15,112,359,773)
18	LIFE CYCLE COSTS 100 YEARS	\$ (70,456,128,616)

5.4 Some Health and Safety Considerations

Without going into a detailed analysis of health and safety evaluation, Option 3 appears to offer the least risk to remediation workers from a radiological and accident rate standpoint. First, because these workers would not be constructing wells within areas contaminated by nuclides, there would be less chance for cancers induced by radiation. Furthermore, given that a fewer number of wells would have to be constructed over a much larger area, there would be less chance for fatalities due to accidents with construction equipment.

In contrast, Options 1 and 2 would have greatly increased risks in both areas. With or without treatment of the groundwater, workers will be exposed to radiation fields from groundwater flowing through the pipes and other system components. As a worst-case scenario, we can look at the dose rate in the vicinity of filter systems that may be used to treat the water.

For example, assume a 0.91-m (3-ft) diameter zeolite/resin filter is filtering water from non-Pahute Mesa while operating with fresh water; no build-up of radioactive material occurs on the zeolites/resins, because the water is just flowing through the filter system. Therefore, the radiation field is in the range of 15 to 20 millirems per hour (mrem/h). You should not have people around it continually, but it could easily be shielded so that people could be in the vicinity to change filters, maintain and repair pumps, etc. The dose rate increases in time as the radioactive material builds up due to the filtration/ion exchange/absorption process. The dose goes up rapidly.

It is not unusual for a water filtration system to "capture" particulates with an efficiency of greater than 100. That is to say, the activity of the radioactive material in the filter is greater than 100 times the average activity in the water flowing through it. For example, if the filter had a volume of 100 liters (26.4 gallons) and the concentration of radioactive material is 40 pCi/L, the concentration of radioactive material on the filter will be $4E+5$ pCi, 40 by 100 by 100. A filter with an efficiency of 10 will have a radiation field of about 150 mrem/h, while a filter with an efficiency of 100 will have a radiation field of about 1,500 mrem/h. High efficiency filters will be needed due to the large volumes of water to be treated. Even with an efficiency of 1,000, rad fields without shielding would be about 15,000 mrem/h. To clean up the water from an average shot would require over 183 m (600 linear ft) of filter, each with a 0.91-m (3-ft) diameter. That would be an incredible radiation field because the dose rate would be 15,000 mrem/h along its length.

For Pahute Mesa water, the radiation fields are about 1.33 times higher.

It would take about 0.91 m (3 ft) of concrete or nearly 0.30 m (1 ft) of steel to get the radiation field down to a level that is safe for someone to be near.

Consequently, if Options 1 or 2 cannot be conducted without *ex situ* treatment of the groundwater, the radiation fields associated with the filters will render these options as infeasible from a health and safety standpoint. In that case, Option 3 would be the only viable alternative.

6.0 Excavation, Physical Separation/Chemical Extraction, and On-Site Disposal

In this remediation alternative, the contaminated soil and rock will be excavated from the nuclear test chimneys (Figure 6-1) and treated, and the residual wastes will be placed back into the excavation. The nuclides will be removed from the excavated debris by techniques such as ion exchange, reverse osmosis, precipitation or evaporation, or settling basins. The options analyzed here assume that the waste generated will be returned to the excavation through construction of an on-site disposal cell. The subsections in the following text briefly outline the technical approaches to excavate the contaminated chimney debris; they assess the technical feasibility of these treatment and disposal options, evaluate the conceptual costs for this alternative, and look at some health and safety considerations.

6.1 Technical Approaches to Excavation of Nuclear Test Chimneys

The following two approaches to excavating the shot sites were considered:

- Braced-shaft excavation
- Open-pit mine

The braced-shaft excavation would result in less material being excavated, but it would require lateral rock support because the shaft was excavated through the nuclear chimney. In contrast, the open-pit mine would require excavation of much more rock in addition to that immediately associated with the nuclear chimney, but it would not require the sophisticated construction operation required for the braced-shaft excavation. However, handling of contaminated water once excavation is below the water table is a concern for both approaches. Handling of contaminated groundwater pumped out of holes during the construction of both options would not be very logical from a radiological health and safety standpoint. Section 5.4 addressed this issue briefly and showed it to be a rather insurmountable technical challenge. Section 6.4 of this chapter examines the radiological exposure issue when there is no water. The next two subsections describe the technical concepts involved in both of these approaches.

6.1.1 Braced-Shaft Excavation

Figure 6-2 gives the general elements of a typical, braced-shaft excavation (a 30.5-m [100-ft] cylinder extending to a depth of 762 m [2,500 ft] through the nuclear chimney and cavity shown in Figure 6-1).

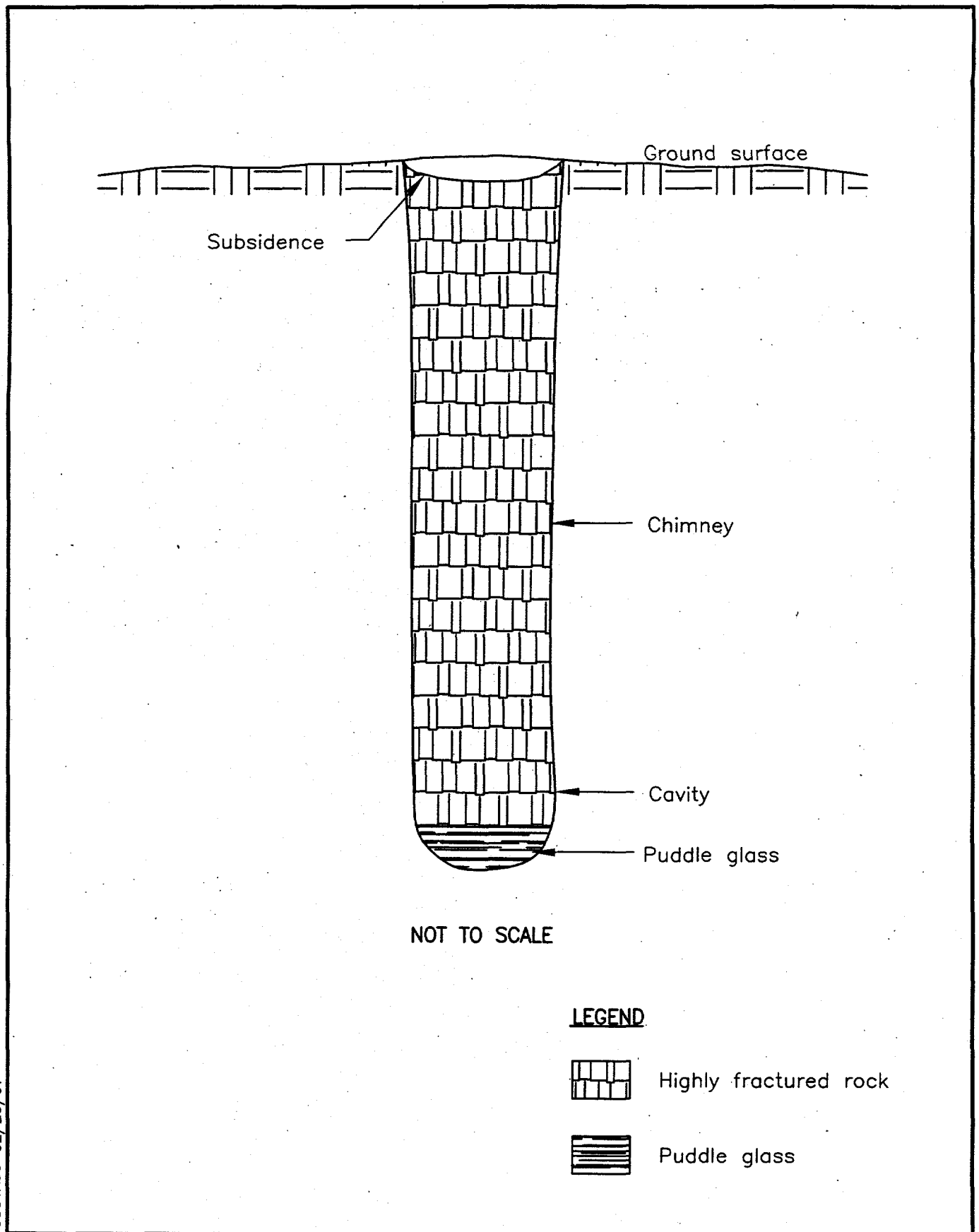
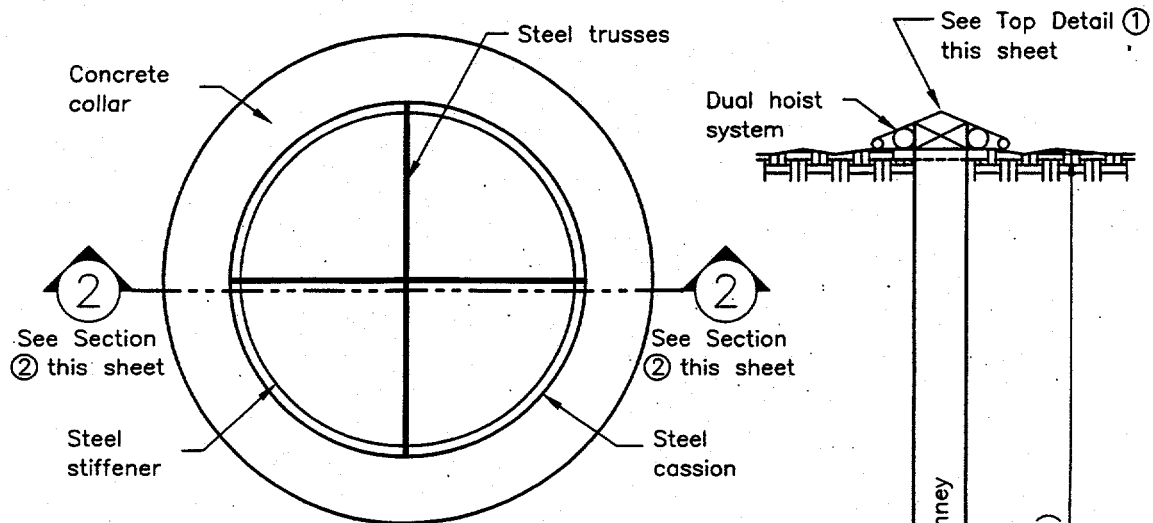
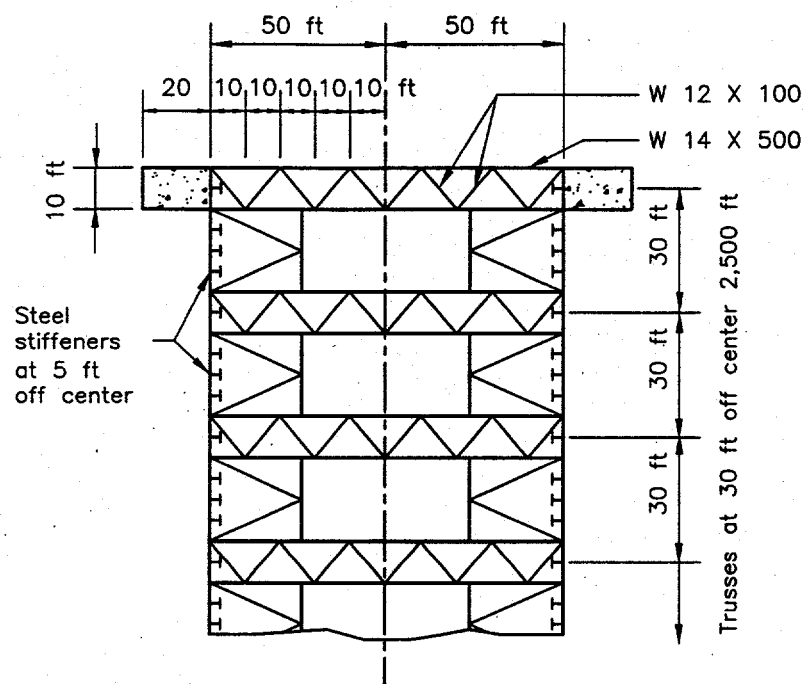


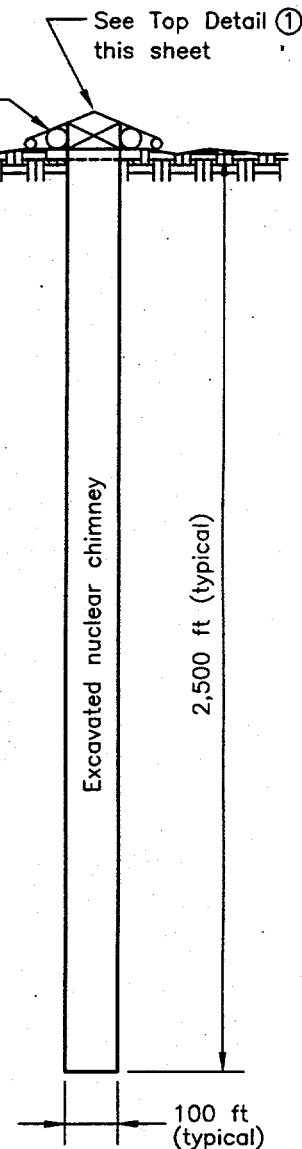
Figure 6-1
Nuclear Chimney and Cavity Following Detonation
of a Nuclear Device Underground



① TOP DETAIL BRACED SHAFT EXCAVATION
NOT TO SCALE



② SECTION THRU MINE SHAFT
NOT TO SCALE



NOT TO SCALE

Figure 6-2
Structural Details of Braced-Shaft Excavation

The actual depth and radius of the nuclear chimney and cavity vary among the tests. Table 6-1 gives the average shot depths and radii for tests according to their geographic location. The braced-shaft excavation consists of a concrete ring supported by a steel caisson. Steel trusses across the shaft opening will support the steel caisson and concrete ring at 9.1-m (30-ft) vertical intervals. Because the shaft will be advanced in 1.5-m (5-ft) sections, steel stiffeners will be placed at 1.5-m (5-ft) off-centers and plate welds along the seams of the 1.5-m (5-ft) steel caissons. Excavation of the shaft would proceed in 1.5-m (5-ft) increments to avoid the need for a massive winch once the shaft has reached a depth in excess of 762 m (2,500 ft). This arrangement will support lateral loads of 14,600 to 29,300 kilograms per square meter (3,000 to 6,000 pounds per square foot), assuming that the site has 15.2 m (50 ft) of alluvium overlying 747 m (2,450 ft) of tuff basalt. The caisson would be fabricated into quarter sections, 1.5 m (5 ft) in depth with a weight of 20 tons (44,000 pounds [lbs]). This fabrication would take place aboveground near the shaft. The assumption is that the truss sections will be prefabricated off

Table 6-1
Average Depth and Radius of Each Geographic Area at the Nevada Test Site
 (IT, 1996, Appendix B)

NTS Area	Geographic Area	Estimated Average Depth to Working Point meters (feet)	Estimated Average Radius meters (feet)
1	Yucca Flat	287 (942)	38 (126)
2	Yucca Flat	341 (1,120)	48 (157)
3	Yucca Flat	268 (878)	41 (135)
4	Yucca Flat	479 (1,570)	52 (172)
5	Frenchman Flat	237 (776)	33 (109)
6	Yucca Flat	277 (907)	39 (128)
7	Yucca Flat	512 (1,680)	57 (187)
8	Yucca Flat	338 (1,110)	41 (135)
9	Yucca Flat	229 (750)	43 (141)
10	Yucca Flat	277 (908)	45 (148)
11	Frenchman Flat	261 (857)	39 (129)
12	Rainier Mesa	329 (1,080)	35 (115)
15	Yucca Flat	287 (941)	41 (133)
16	Shoshone Mountain	298 (978)	38 (124)
19	Pahute Mesa	716 (2,350)	66 (216)
20	Pahute Mesa	698 (2,290)	67 (220)

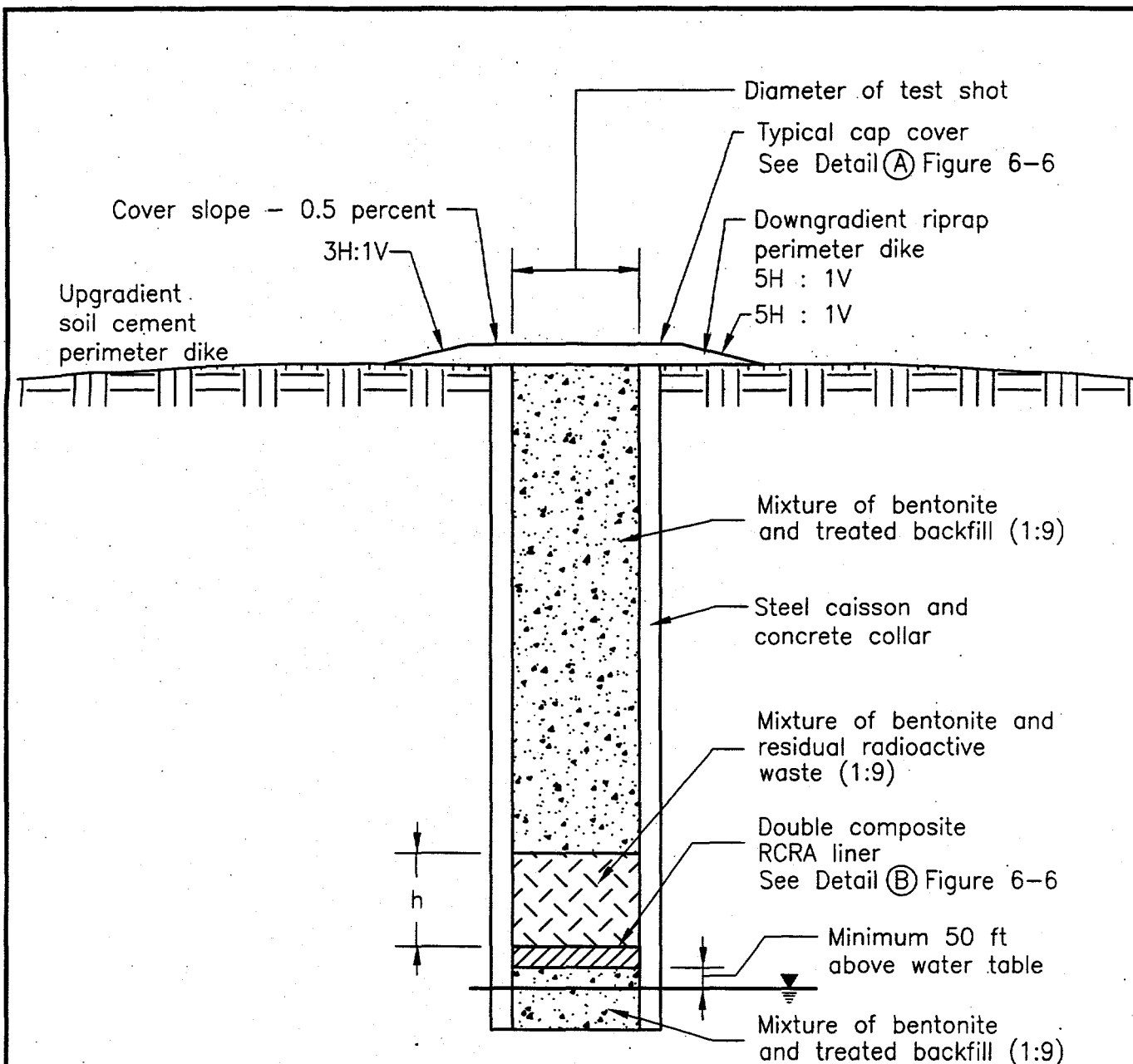
site. Each 15.2-m (50-ft) truss section would weigh 30 tons (66,000 lbs). The trusses will use a 9.1-m (30-ft) spacing and will brace the caisson at 90-degree points. The concrete collar will consist of 6,230 m³ (8,150 yd³) of reinforced concrete. The hoist system will use two hoists, each with 7.6-m³ (10-yd³) buckets, and will have 50 tons (110,000 lbs) of capacity. The sequence of construction would proceed as follows:

- Drill and blast ½-diameter area to a depth of 1.5 m (5 ft) and excavate.
- Place a 1.5-m (5-ft) caisson in the excavated area .25 ring at a time, each ring weighing 20 tons (46,000 lbs) and weld.
- Drill, blast, and excavate a 1.5-m (5-ft) section on ½-diameter area.
- Place a 1.5-m (5-ft) caisson in the excavated area .25 ring at a time and weld.
- Drill, blast, and excavate a 1.5-m (5-ft) section.
- Place truss system (four, 15.2-m (50-ft) sections at 31 tons [68,200 lbs] each).
- Place 1.5-m (5-ft) caissons and weld.
- Drill, blast, and excavate a 1.5-m (5-ft) section and return to top bullet.

The average excavation rate is assumed to be 0.7 m (2.5 ft) per day, and it takes about 1,000 days to excavate a 762-m (2,500-ft) deep, 30.5-m (100-ft) diameter braced-shaft excavation. Nuclides in the excavated debris will be removed by some combination of physical and chemical extraction/treatment (e.g., ion exchange, reverse osmosis, precipitation, or evaporation). The excavated shaft would then serve as an engineered barrier that would help contain the residual radioactive waste left over from the debris washing. Bentonite will be mixed with the residual radioactive waste to inhibit the release of radionuclides and will be placed in the excavated shaft (which will be used as an on-site disposal cell as shown in Figure 6-3). Figure 6-4 shows the cap cover and liner details of over-the-shaft excavation after being converted to an on-site disposal cell.

6.1.2 Open-Pit Mine

Another option discussed briefly is the open-pit mine. In this option, the contaminated material from each geographic area would be excavated by open-pit mining. Nuclides in the excavated debris would be removed by some combination of physical and chemical extraction/treatment and returned to an engineered barrier constructed within the open-pit mine of the excavated

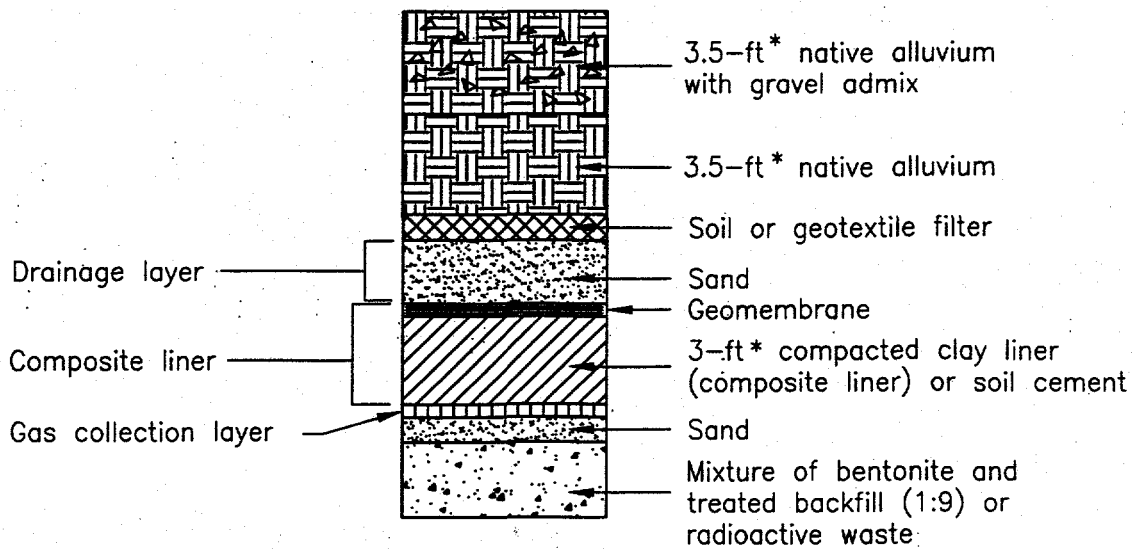


NOT TO SCALE

Note: Nuclear test shot converted to disposal-cell. "h" will depend on amount of residual radioactive waste with concentration levels above that accepted for treated backfill.
RCRA = Resource Conservation and Recovery Act

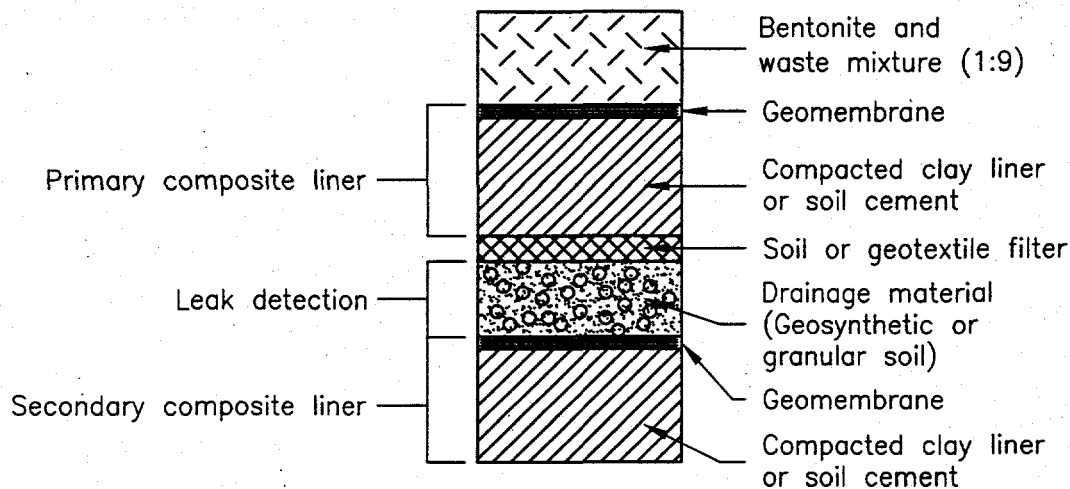
h = height of bentonite and residual radioactive waste mixture

Figure 6-3
On-Site Disposal Cell
(Excavation and On-Site Disposal)



(A) TYPICAL CAP COVER DETAILS
NOT TO SCALE

* Typical thickness to be refined



(B) DOUBLE COMPOSITE LINER DETAILS
NOT TO SCALE

Note: Nuclear test shot converted to disposal-cell

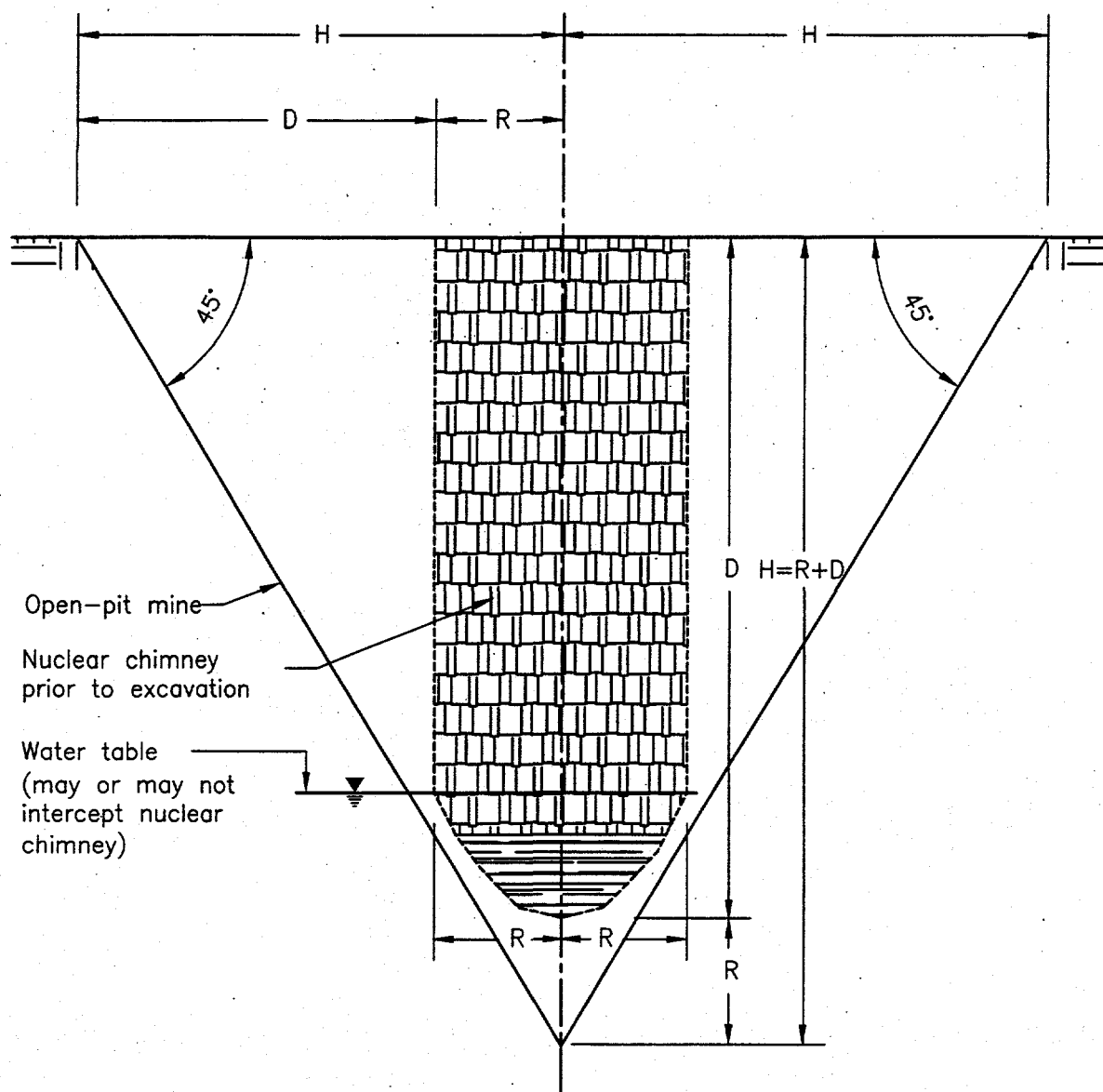
Figure 6-4
Cap Cover and Liner Details of On-Site Disposal Cells

nuclear chimney. In this option, the assumption is that the residual radioactive waste would be solidified and encapsulated with polyethylene (PE). Figure 6-5 shows conceptually the relationship of the open-pit mine to the nuclear chimney. We have assumed that slopes of 45 degrees will remain stable. Figure 6-6 shows the conceptual elements of an open-pit mine, on-site disposal cell. The mine would extend to a depth of H, where H is the sum of the average depth and radius over the entire CAU area with 45-degree slopes extending radially outward from the base of the CAU. In contrast to the braced-shaft excavation, the open-pit mine approach will require the removal of far more soil and rock. Figure 6-7 shows, conceptually in the case of Yucca Flat, where several shot sites overlap how the final on-site disposal cell may be configured.

6.2 Technical Feasibility of Treatment and Disposal Approach

The nuclides in the excavated debris will be removed by some combination of physical and chemical extraction/treatment (e.g., ion exchange, reverse osmosis, precipitation, or evaporation). Materials handling would involve screening, segregation, and leaching with hot nitric acid. Experience at the DOE demonstration at Idaho National Engineering Laboratory (INEL) (EPA, 1994) has shown that this process still has difficulty removing cesium-137 and costs over \$1,310 per m³ (\$1,000 per yd³). Residuals management would involve storage or staging areas before and after treatment with the possible need for a solidification facility. The residual radioactive wastes will be returned to the excavation and placed in an engineered barrier (as shown by the conceptual design in Figure 6-3). Note there is no assumed distinction between low-level and high-level radioactive wastes and no attempt to address the proper way to dispose of these wastes. For our evaluation, we have assumed that all residual radioactive wastes would use the existing excavations as a waste disposal area.

Before placement of residual radioactive waste, there would be a double composite liner (as shown in Figure 6-4) installed on the bottom of each excavation. In the case of the braced-shaft excavation, the waste itself would be mixed with 10 percent bentonite (by weight) and placed above the double composite liner. The use of bentonite is innovative because of its use by the high-level radioactive waste programs of Sweden and other European countries for underground nuclear waste repositories (NAGRA, 1994). In the case of the open-pit mine excavation, the residual radioactive waste would be solidified and encapsulated with polyethylene because of the high expense of bentonite. Waste solidification and encapsulation with various materials must minimize the release of toxic contaminants to the environment, comply with all applicable



NOT TO SCALE

LEGEND



Highly fractured rock



Puddle glass

R = Radius of Nuclear Chimney
Maximum Radius = 400 feet

D = Depth of Nuclear Chimney
Maximum Depth = 4,800 feet

H = Height of Open-Pit Mine

Figure 6-5
Open-Pit Mine

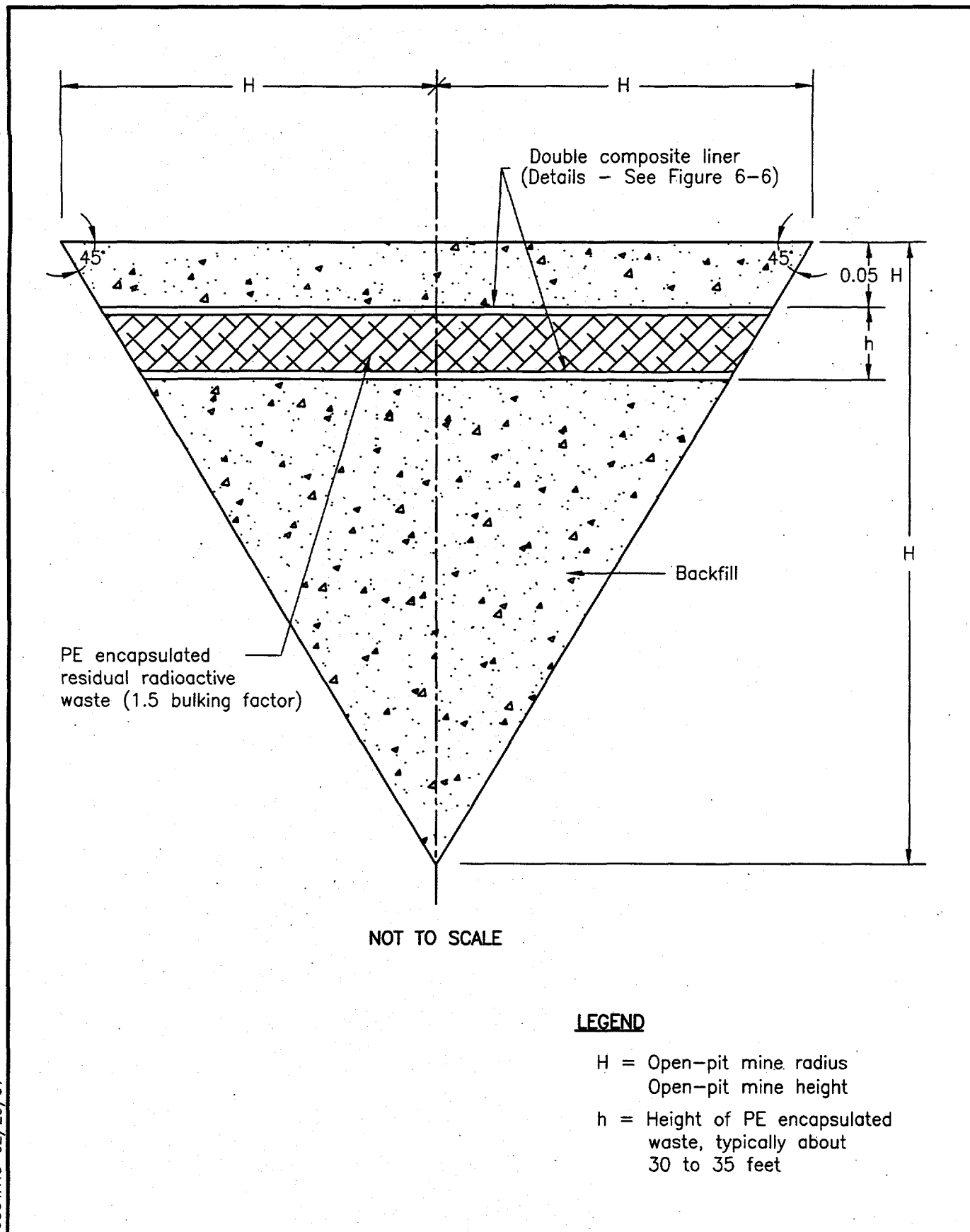
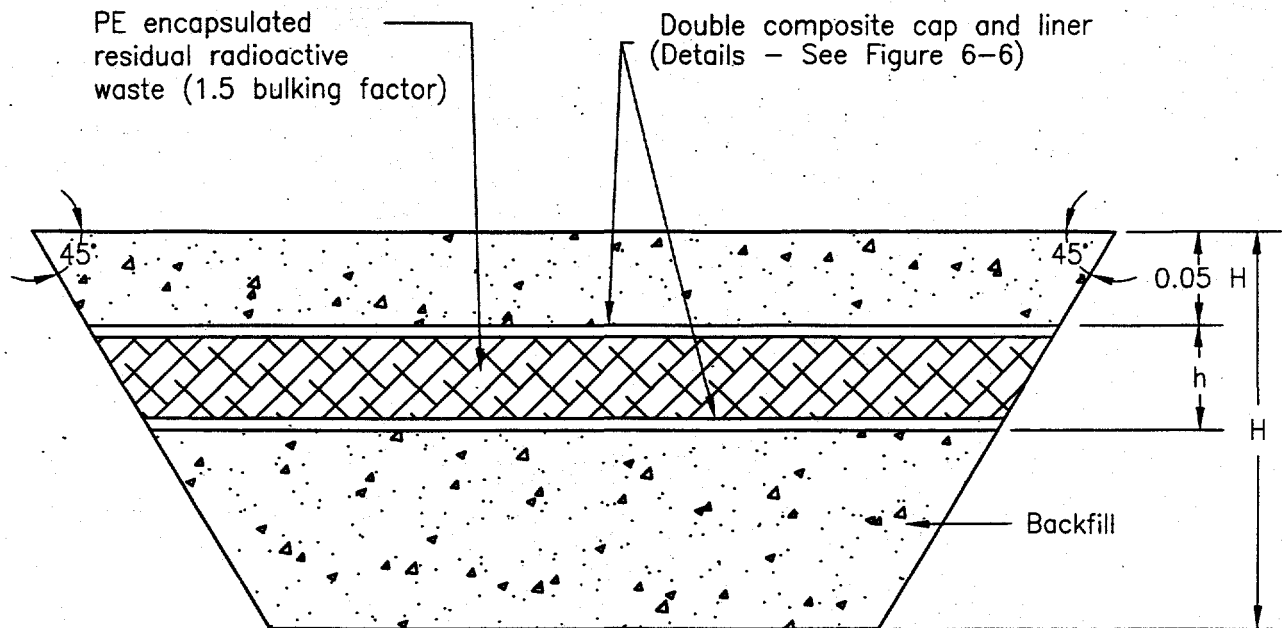


Figure 6-6
Open-Pit Mine On-Site Disposal Cell



NOT TO SCALE

LEGEND

- H = Open-pit mine depth, typically about 1,230 feet (for Yucca Flat)
- h = Height of PE encapsulated residual waste, typically about 60 feet (for Yucca Flat)

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Figure 6-7
Open-Pit Mine On-Site Disposal Cell

regulatory criteria, and maintain these characteristics under long-term storage or disposal conditions.

The PE encapsulation has an advantage over conventional hydraulic cement solidification which is currently used to solidify the majority of the problem wastes generated by DOE and the commercial sector (EPA, 1993c). In contrast to hydraulic cement, PE encapsulation materials are inert and cannot react with waste of any kind. In addition, more waste can be mixed (loaded) with PE than with portland cement forms. This difference in loading can translate into substantial cost savings. A bulking factor of 1.5 was used for PE encapsulation of the treated radioactive waste in the open-pit mine disposal (EPA, 1993c). Other designs may consider the use of concrete or various resins to contain the radionuclides. When all the residual radioactive waste had been returned to the excavation, a final cap cover may be placed followed by clean soil or debris.

6.3 Conceptual Costs

The estimated costs for the braced-shaft excavation and open-pit mine options are based on the total volume of material to be excavated, the costs of removing radionuclides from the debris, and the bentonite and PE encapsulation costs for on-site disposal of residual radioactive waste. Table 6-1 lists the average shot depth and radius for each NTS area shown in Figure 1-1. For the geographic areas shown in Figure 1-1, Tables 6-2 and 6-3 indicate the volumes of material to be excavated by the braced-shaft excavation and open-pit mine options, respectively. Tables 6-4 and 6-5 give lower-end conceptual costs for the braced-shaft excavation and open-pit mine alternatives, respectively. Additional costs for design and construction of each disposal cell, remobilization of equipment to new shot sites, and a contingency of at least 100 percent have not been included in the estimates for both of these options.

The estimated costs are based on the following additional assumptions:

- A. The estimate is considered an order of magnitude with an accuracy of +100 percent.
- B. The costs are based on R.S. Means' (1996) cost data, Richardson's (1993) estimating standards, *Pipe Line Rules of Thumb Handbook* (Gulf Publishing, 1982), and "in-house" costs from previous work. The costs are based on the first quarter of 1996.
- C. Presence of radioactive waste is considered to reduce labor productivity by 100 percent. Work will occur 3 days per week, 24 hours per day, in 8-hour shifts.

Table 6-2
Volume of Material to be Excavated Based on Geographic Region,
Braced-Shaft Excavation

Geographic Region	No. of Shots	Estimated Average Depth to Working Point meters (feet)	Estimated Average Radius meters (feet)	Volume ^a m ³ (ft ³)	Volume m ³ (yd ³)
Pahute Mesa	85	707 (2,320)	66 (218)	832,490,000 (29,400,000,000)	833,300,000 (1,090,000,000)
Rainier Mesa	59	330 (1,080)	35 (115)	75,920,000 (2,650,000,000)	74,920,000 (98,000,000)
Yucca Flat	748	330 (1,080)	45 (146)	153,190,000 (54,100,000,000)	1,529,000,000 (2,000,000,000)
Frenchman Flat	10	250 (816)	36 (119)	10,279,000 (363,000,000)	10,240,000 (13,400,000)
Shoshone Mountain	6	298 (978)	38 (124)	8,013,000 (283,000,000)	8,027,000 (10,500,000)
Total Volume of Material to be excavated	--	--	--	--	2,455,487,000 (3,210,000,000)

^aTo be excavated
-- Intentionally left blank

m³ = cubic meter
yd³ = cubic yard
ft³ = cubic foot

Table 6-3
Volume of Material to be Excavated Based on Geographic Region,
Open-Pit Mine, Nevada Test Site

Geographic Region	Number of Shots	Estimated Average Depth (D) meter (feet)	Estimated Average Radius (R) meter (feet)	R+D= Avg. (D+R) meter (feet)	Shot Volume ^a m ³ (ft ³)	Cumulative Shot Volume in Region m ³ (yd ³)
Pahute Mesa	85	707 (2,320)	66 (218)	774 (2,540)	487,000,000 (17,200,000,000)	41,360,000,000 (54,100,000,000)
Rainier Mesa	63	303 (1,080)	35 (115)	366 (1,200)	51,250,000 (1,810,000,000)	3,226,000,000 (4,220,000,000)
Yucca Flat	746	330 (1,080)	46 (146)	375 (1,230)	55,200,000 (1,950,000,000)	41,130,000,000 (53,800,000,000)
Frenchman Flat	10	249 (816)	36 (119)	285 (935)	24,240,000 (856,000,000)	242,350,000 (317,000,000)
Shoshone Mountain	6	298 (978)	38 (124)	335 (1,100)	39,360,000 (1,390,000,000)	237,000,000 (310,000,000)
Total Volume (yd ³)	--	--	--	--	--	86,200,000,000 (113,000,000,000)

^aMaterials to be excavated
-- Intentionally left blank

m³ = cubic meter
yd³ = cubic yard
ft³ = cubic foot

Table 6-4
Summary of Costs for Braced-Shaft Excavation, Physical Separation/Chemical Extraction, Braced-Shaft Construction, and On-Site Disposal

Item	Unit Costs	Total Quantity	Total Costs
Braced Shaft Excavation			
1. Concrete Ring	\$16,600,000	843	\$11,000,000,000
2. Hoist System	\$60,000,000	100*	\$6,000,000,000
3. Steel Caisson	\$204,000,000	843	\$172,000,000,000
4. Steel Trusses	\$120,000,000	100*	\$2,000,000,000
Excavation Costs	\$99/m ³ (\$76/yd ³)	2,455,687,000 m ³ 3,210,000,000 yd ³	\$244,000,000,000
Bentonite (Assume 10% of excavated volume)	\$118/m ³ (\$90/yd ³)	245,548,700 m ³ 321,000,000 yd ³	\$29,000,000,000
Total Costs Without Treatment	-	-	\$467,000,000,000
Physical Separation/ Chemical Extraction	\$1,310/m ³ (\$1,000/yd ³) EPA (1994, Table 3-8, Page 3-42)	2,455,487,000 m ³ (3,210,000,000 yd ³) (See Table 6-2)	\$3,210,000,000,000
Total Costs With Treatment	-	-	\$3,680,000,000,000

* Assumes reuse of 100 sets of equipment to complete the job within 30 years.

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m³ = cubic meter

yd³ = cubic yard

Table 6-5
Summary of Costs for Excavation, Physical Separation/Chemical Extraction, Open Mine, and On-Site Disposal

Item	Unit Costs	Total Quantity	Total Costs
Open-Pit Mine	\$34/m ³ (\$26/yd ³)	86,200,000,000 m ³ (113,000,000,000 yd ³)	\$2,940,000,000,000
Drilling, Blasting		(See Table 6-3)	
Loading, Hauling			
Physical Separation/ Chemical Extraction	\$1,310/m ³ (\$1,000/yd ³)	2,455,487,000 m ³ (3,220,000,000 yd ³) (See Table 6-2)	\$3,220,000,000,000
Bentonite Costs (Assume 10% of excavated volume)	\$118/m ³ (\$90/yd ³)	245,548,700 m ³ (322,000,000 yd ³)	\$29,000,000,000
Total Costs With Bentonite	-	-	\$6,190,000,000,000
Polyethylene	\$1.9/kg (\$0.86/lb)	2,455,487,000 m ³ 3,220,000,000 yd ³	\$1,130,000,000,000
Encapsulation Costs of Residual Radioactive Waste	EPA (1993c)		
Total Costs With Polyethylene Encapsulation	-	-	\$7,290,000,000,000

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m³ = cubic meter

yd³ = cubic yard

kg = kilogram

lb = pound

- D. The volume of material to be excavated depends on the radius of each nuclear chimney and the depth of the shot. For a 30-m (100-ft) diameter and 762-m (2,500-ft) deep shot chimney, the volume of material to be excavated would be 556,000 m³ (727,220 yd³) of rock. Drilling and blasting will be needed to remove the rock, and a steel caisson will be necessary to maintain the shaft.
- E. The average rate for drilling and blasting is assumed to be 1,110 m³ (1,450 yd³) per 24 hours.
- F. It is assumed that a 38-mm (1½-in.) plate, reinforced with stiffener rings at intervals of 5 m (5 ft) and steel trusses at intervals of 9.1 m (30 ft), will be required. This arrangement will support lateral loads of 14,600 to 29,300 kilograms per square meter (3,000 to 6,000 pounds per square foot). It is assumed that the site consists of 15.2 m (50 ft) of alluvium overlying 747 m (2,450 ft) of tuff basalt.
- G. The caisson would be fabricated in quarter sections, 1.5 m (5 ft) in depth; each section would weigh 20 tons (66,000 lbs). The fabrication would take place aboveground near the shaft.
- H. The excavation would proceed in 1.5-m (5-ft) increments: drill and blast one half of the shaft area to 1.5 m (5 ft) and load and excavate this half of the shaft area while the drill and blast crew prepares the other half of the shaft area. The excavation would advance at an average rate of 0.76 m (2.5 ft) per day.
- I. The truss sections are assumed to be fabricated off site. Each 15.2-m (50-ft) truss section would weigh 30 tons (66,000 lbs). The trusses are installed every 9.1 m (30 ft), and the caisson is braced at 90-degree points.
- J. The hoist is assumed to consist of two hoists, each with 7.6 m³ (10-yd³) buckets. The hoisting capacity would be 50 tons (110,000 lbs). Average excavation rate is assumed to be 1,680 m³ (2,200 yd³) per 24 hours. The cost of excavation for the braced shaft is assumed to be \$99/m³ (\$76/yd³) (calculated based on crew and equipment assumption). The assumed cost for excavation of the open-pit mine (including drilling, blasting, and hauling of 3.2 km [2 mi]) is \$34/m³ (\$26/yd³).
- K. The caisson collar would require 6,230 m³ (8,150 yd³) of reinforced concrete for a 30.4-m (100-ft) diameter shaft.
- L. The excavated debris (or "muck") is assumed to be stored near the shaft.
- M. Costs of removing contaminated debris from below the water table are assumed to be the same as those in the unsaturated zone.
- N. Assumed costs of treatment of soil and water is \$1,310/m³ (\$1,000/yd³) (EPA, 1994).

- O. The cost of electricity is not included.
- P. Engineering and construction management costs are not included.
- Q. The estimate does not include any state or local taxes.
- R. Estimate does not include DOE management or oversight costs.
- S. A contingency of at least 100 percent should be added for subsurface unknowns.

Given these assumptions, Tables 6-4 and 6-5 tend to underestimate the potential costs in remediating these shot sites by excavation, treatment, and disposal. The braced-shaft excavation and disposal cell approach would cost at least \$3.7 trillion dollars (or about \$0.5 trillion if the excavated radioactive debris was not treated with physical and chemical extraction). To get a feel for these costs, \$0.5 trillion dollars is about what it cost the federal government for the bailout of the Savings and Loan financial disaster of the 1980s (Wills, 1989). In contrast, the open-pit mine approach would cost at least \$6.19 trillion dollars (or about \$3.2 trillion if the excavated radioactive debris was not treated with physical and chemical extraction). As a comparison, the cost of the open-pit mine option would likely exceed the current national debt of \$5 trillion dollars (Gage, 1996).

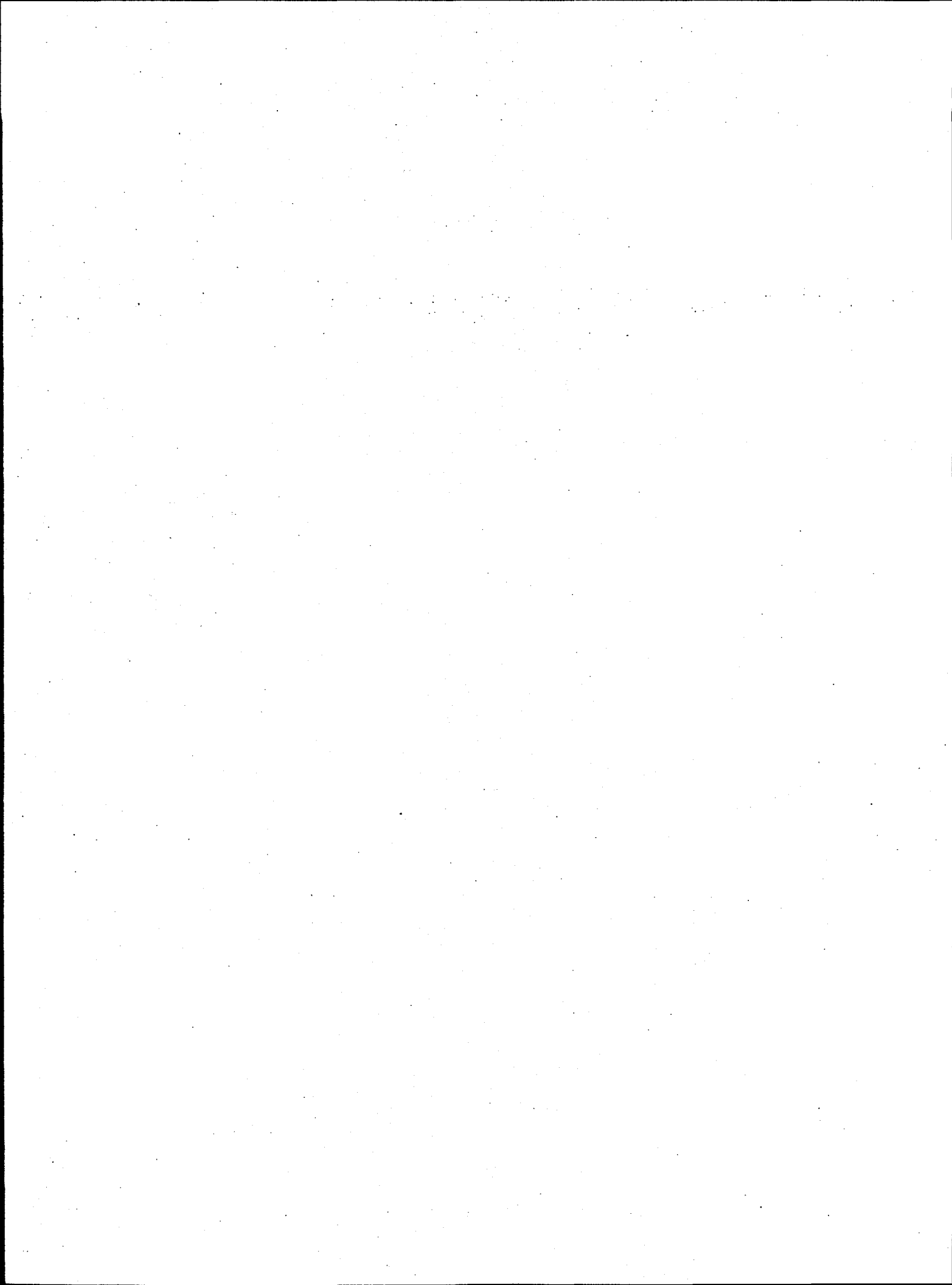
6.4 Some Health and Safety Considerations

Section 5.0 discussed how significant radiation fields would be generated from contaminated groundwater flowing from treatment filters. In the case of the braced-shaft and open-pit mine excavation, workers would also be exposed to radiation fields even if no water was present. For example, the radiation field experienced by a worker during braced-shaft excavation work would severely limit the stay time (total time in area of radiation field) unless significant amounts of shielding are used to reduce the dose rate. Halfway down the shaft, the unshielded dose rate would be on the order of 100 mrem/h. That would restrict the time a worker could be in the vicinity to about 4.5 hours per year (h/yr). As you approach the cavity, the dose rate is in the order of 300 mrem/h about 100 ft above the bottom of the shaft. That would limit your stay time to about 1.5 h/yr without shielding.

If the material near the bottom of the chimney is brought up to the surface to be treated and then placed back into the shaft, the dose rate in the vicinity of the "spoils" is estimated to be on the order of 200 mrem/h. All material from the shaft would have to be shielded during all operations in order to reduce the dose rate.

The calculated dose rates are not killer dose rates until the exposure time gets on the order of a year. But the DOE limits are reached in just an hour or two. Therefore, the designs, cost, and planning will have to be drastically modified to provide some serious shielding, about 0.30 m (1 ft) of steel or 0.90 m (3 ft) of concrete between the workers and the radioactive material in the last 30.4 m (100 ft) or so of the shafts. Similar difficulties with radiation could be expected in the open-pit mine excavation option as well.

In addition to the possible radiation exposures, there would be significant concern of health and safety from an industrial accident standpoint. The report entitled *Cost/Risk/Benefit Analysis of Cleanup Requirements of Plutonium-Contaminated Soils On and Near the NTS* (IT, 1995) found that only a small reduction in population risk could be obtained from a costly remediation. In addition to being extremely costly, large earth-moving efforts produce a risk of injuries and fatalities to workers. IT (1995) concluded that for the case of surface soils "from a cost benefit perspective that achieving even a moderate concentration or dose-based reduction to the NTS would imply a willingness to spend vast economic resources to gain very little reductions in population risk."



7.0 Other Alternatives

Of the alternatives that have not been considered (EPA, 1994), none has held the imagination of scientists and ordinary people over the years more than the conversion of radioactive waste by "Partitioning Transmutation" (PT) into something more benign. The term "transmutation" was referred to in the Middle Ages when alchemists claimed to have transmuted lead into gold. Today, nuclear "transmutation" refers to the conversion of one element or nuclide into another (either naturally by radioactive decay or artificially by nuclear reaction). In the following sections, there is a description of the general technical approach involved with PT, an assessment of its technical feasibility, and a brief qualitative statement of the type of costs that may be involved.

7.1 Technical Approach

PT refers to a process in which elemental or isotopic separation of waste (which occurs during reprocessing) is followed by transmutation of long-lived radionuclides in the neutron flux of a reactor or accelerator into stable or short-lived nuclides. "Reprocessing" refers to the chemical treatment of spent fuel from a nuclear reactor to recover isotopes. Further separation of residual isotopes is called "partitioning."

The history of PT can be divided into pre-1982 studies and post-1982 documentation. Before 1982, most studies focused on transmutation with fission reactor systems; only a few papers dealt with the possible uses of fusion reactors and accelerator driven systems (Skalberg and Liljenzin, 1992). Recently, partitioning actinides in light-water reactor spent fuel and transmuting them in actinide-burning Advanced Liquid Metal Reactors (ALMRs) has been put forth as a way to reduce public risks from geologic disposal of nuclear waste. Spent fuel can be reprocessed, and the waste can be partitioned or separated into elemental fractions which can then be transmuted into stable or short-lived isotopes by bombardment with neutrons. Actinide burning is the concept of using the transuranics in a light-water reactor spent fuel in a liquid-metal fast reactor to generate electricity as well as perform transmutation (Skalberg and Liljenzin, 1992).

7.2 Technical Feasibility

A study by the University of California, Lawrence Berkeley Laboratory, evaluated the benefits of PT for waste disposal (Ramspott et al., 1992). Actinide burning can reduce the actinide

inventory by up to 99.9 percent. PT would reduce the uncertainty of the performance predictions of release rates by lowering the upper bounds of release possibilities.

All other things being equal, less inventory means less risk. However, the risk reduction benefits that PT might offer depend on the release scenario involved; in many cases, they may not be as great as the 99.9 percent reduction in actinide inventory might suggest. Where solubility limits the release, PT will not substantially reduce the risk because the low solubility of the actinides prevents them from being a problem in the first place. Where solubility fails to limit releases, PT could reduce risk by several orders of magnitude in the 100- to 100,000-year time frame.

However, Ramspott et al. (1992) and Lee and Choi (1991) found that for key radionuclides that are likely to reach the accessible environment, the release rates from reprocessed waste packages were approximately the same as the release rates from light-water reactor spent fuel. If the released radionuclides behave similarly during transport, then it would appear that the releases from reprocessed waste packages were similar to light-water reactor spent fuel. Consequently, Ramspott et al. (1992) concluded that actinide burning appeared to offer no benefit for waste disposal in terms of radionuclide releases from a geologic repository. This conclusion corroborated similar studies in other countries (Lee and Choi, 1991).

In the 1970s, Ramspott et al. (1992) stated that the worldwide scientific community in the United States and other countries concluded that the partitioning and transmutation of radionuclides (including tritium) was among the least-favored options for the safe and final disposal of high-level radioactive wastes. Ramspott et al. (1992) also described a 1982 report by the International Atomic Energy Commission that summarized the key reason for that ranking: "Since the long-term hazards are already low, there is little incentive to reduce them further by partitioning transmutation."

Furthermore, the technical feasibility of using ALMRs to reduce the actinides remaining for disposal involve long burning times in a reactor, on the order of a 1,000 years (NRC, 1992). The NRC (1992) reports that it would take more than 100 years (a reduction factor of 10) to burn 90 percent of the actinides. To reduce the inventory of actinides to a factor of 100 (i.e., a 99 percent reduction) would take a reactor burning time of more than 1,000 years.

7.3 Conceptual Costs

The incremental costs of introducing partitioning and transmutation appear unduly high in relation to the prospective benefits (Ramspott et al., 1992). Skalberg and Liljenzin (1992) concluded that, while partitioning and transmutation were technically feasible, there were "no cost or safety incentives for the partitioning and transmutation of the actinides for waste management purposes." The fundamental reasons for the rejection of partitioning and transmutation as a viable waste management option in the early 1980s were poor economics and failure to significantly reduce risk from waste disposal.

Introduction of partitioning and transmutation as a waste management option will not eliminate the need for radioactive waste disposal. But reducing the long-term potential risks can make it easier to choose a site location and method of disposal. However, new problems will arise regarding siting and safety of the necessary reprocessing and transmutation facilities. It should also be remembered that long-lived radiotoxic nuclides, in practice, cannot be quantitatively destroyed by transmutation. There will always be some fraction of these nuclides present in the high-active waste remaining after partitioning and remaining in secondary waste streams.

Ramspott et al. (1992) states (for the case of commercial nuclear energy systems) the following:

- Economically, PT would greatly increase the net cost of the overall nuclear energy system. Reprocessing is currently noncompetitive with the once-through fuel cycle.
- The French and the British sell commercial reprocessing for about \$1,000 per kilogram (\$455 per pound) of heavy metal. At that price, U.S. uranium prices would have to increase 15 times before the costs of the once-through and reprocessing cycles are the same. A recent report indicates that the United Kingdom is rethinking its commitment to reprocessing.
- To put these costs in perspective, at \$1,000 per kilogram (\$455 per pound) reprocessing price, the heavy metal projected for life-time operation of all U.S. reactors would cost more than \$84 billion to reprocess. That is more than double the \$33 billion that geologic disposal is currently projected to cost. Even if reprocessing were to cost \$42 billion, a repository would still be required, and its cost is not likely to be much less than \$33 billion.

Furthermore, the NRC (1992) concludes that such cost is uncertain and is likely to be high because of several factors:

- The low concentration of actinides in light-water reactor fuel
- The relatively early state of development of the reference pyro-chemical process for light-water reactor fuel
- The uncertainty of capital costs for all of the facilities involved
- The wide variability in the methods and costs of financing an industrial-scale reprocessing facility in the U.S.

The large uncertainty about costs in information presented to the NRC has yet to be resolved.

Ramspott et al. (1992) concludes that there is no incentive (i.e., for utilities) to adopt any form of PT now or in the future because of its high costs. PT can only be considered as a government-financed option.

8.0 Comparison of Alternatives

This section compares the alternatives and identifies the advantages and disadvantages of each alternative to outline the key tradeoffs that will influence the ultimate decision. The discussion focuses on the overall technical feasibility and conceptual costs of each alternative.

8.1 Technical Feasibility

All the alternatives, both passive and active, are possible either from a practical or theoretical perspective according to the EPA Screening Matrix Guide (EPA, 1994). However, the guide emphasizes that the matrix is optimistic. These alternatives represent reasonable uses of the presumptive remedies outlined by EPA (1994). The EPA has directed that presumptive remedies are to be used at all appropriate sites. The presumptive alternative for the NTS site under the CERCLA viewpoint relates primarily to the containment of the source radionuclides by passive measures. The essentially passive alternatives (such as intrinsic remediation and institutional controls), while costly, hold the most promise for achieving their goals of using the site to contain the contaminated groundwater.

In addition, the more active alternatives to pump and treat contaminated groundwater within the nuclear chimneys (replace water sources or excavate, remediate, and dispose of contaminated soils and rock) represent other presumptive remedies. The pump and *in situ* treatment alternative to control the movement of nuclides away from the nuclear chimneys holds promise for only the nuclides with short half-lives or those with high retardation coefficients. Forced infiltration through the nuclear chimney of both technetium-99 and iodine-129 failed to decrease their concentrations over the course of 1,000 years. Only tritium, because of its short half-life, shows significant attenuation, and even tritium requires about 220 years of pump and treatment within the nuclear chimney.

These preliminary transport analyses show that the nuclear chimney had little effect on some of the mobile nuclides of concern. Certainly further engineering adjustments can be made, but it remains unclear what additional active remedial measures would significantly improve the speed of remediation by the nuclear chimney—and at what cost. However, the pump and *in situ* treatment alternative may still provide some benefit in terms of assisting intrinsic remediation through containment, either through recovery of contaminated groundwater or withdrawal, transport, and artificial recharge to establish another form of hydraulic control. However,

without the expense and health and safety hazards involved with the treatment of contaminated groundwater prior to reinjection, these options would essentially have to operate forever.

In terms of the excavation, physical separation/chemical extraction, on-site disposal, and the treatment of leachate generated, this alternative has limits on its feasibility. Treatment of groundwater contaminated with radionuclides would probably require *ex situ* disposal both on site and off site. Off-site disposal would be required for those respective waste fractions that fall below or exceed the waste acceptance criteria for on-site disposal. Treatment that eliminates or minimizes, to the extent feasible, the need for long-term management could include excavation and treatment of all contaminated debris and soil, all soil above the 10^{-4} risk, or "hot" spots. Excluding cost, the critical concern for remedial actions at the NTS would be the immediate health risks posed to the workers in the excavation, treatment, disposal, and transportation of the high and low-level radioactive waste.

8.2 Comparison of Conceptual Costs

Table 8-1 compares the conceptual costs of the various alternatives. Performance of any of the alternatives represents a capital investment by the American taxpayer on a level approaching or exceeding that of the financial cleanup of the Savings and Loan disaster of the 1980s. To look at it another way, several of the alternatives would cost more than the Apollo Moon Program, which cost \$25 billion at the program's end (or about \$100 billion in 1996).

If we consider the active alternatives, the numbers start to increase rapidly. The pump and *in situ* treatment options involving contaminated groundwater (Options 1 and 2) range in cost from about \$1.4 to \$2.4 billion dollars. These options, however, do not replace the groundwater lost as a potential resource, and these costs do not include any pretreatment of groundwater before reinjection. In contrast, a preferred way may be Option 3 which costs less than half as much as the first two, but has the added benefit of investing in an infrastructure that can supply drinking water over the long term and avoids the health and safety hazards of the first two. Still, the costs for Option 3 probably represent the low side because it does not include any environmental studies to show that contaminated groundwater from the NTS does not and will not reach the withdrawal wells.

Table 8-1
Comparison of Conceptual Costs of Various Alternatives

Alternative	Option Category/Comments	Technical Feasible?	Conceptual Cost, \$ (Millions)
No Action/Baseline Risk Assessment	NTS fails to satisfy EPA requirements for no action	No	NA
Intrinsic Remediation	Current UGTA Strategy	Yes	269
Institutional Controls	Already in place and could be continued	Yes	881
Pump and <i>In Situ</i> Treatment - Establishes hydraulic control around shot cavities and attempts to strip or decay nuclides with increased residence time within nuclear chimney		Yes, but disposal costs are large.	
Option 1: Recovery Well Inside Nuclear Chimney	With Injection Wells-Creates waste that needs disposal, including operation and disposal of zeolite/resin filters	Yes, but does not replace waste contaminated by shots within the water table.	2,435
	With Wick Drains-Minimizes waste created by drilling, but still must dispose of zeolite/resin filters	Yes, but does not replace water contaminated by shots within the water table.	2,472
Option 2: Recovery Well Outside Nuclear Chimney	With Injection Wells-Creates waste that needs disposal, but still must dispose of zeolite/resin filters	Yes, but does not replace water contaminated by shots within the water table.	1,337
	With Wick Drains-Minimizes waste created, but still must dispose of zeolite/resin filters	Yes, but does not replace water contaminated by shots within the water table.	1,374
Option 3: Withdrawal, Pipeline Transport, and Artificial Recharge	Avoids drilling in areas with contamination and invests in long-term supply of water	Yes, but does not include costs from environmentally related studies that may be required by local and state governments.	2,488
Excavation, Physical Separation/Chemical Extraction, and On-Site Disposal	Especially on physical separation/chemical extraction side, very easy to badly miscalculate the technical challenges involved. Host of issues have not been examined.	Yes, but high cancer/radiation and industrial accident risks to workers and involves exorbitant costs.	
Braced-Shaft Excavation	Analysis ignores additional technical challenges/costs with water table shots.	Yes, but high cancer/radiation and industrial accident risks to workers and involves exorbitant costs.	3,170,000
Open-Pit Mine	Analysis ignores additional technical challenges/costs with water table shots.	Yes, but high cancer/radiation and industrial accident risks to workers and involves exorbitant costs.	7,290,000

NA = Not applicable

The last active alternative (excavation, physical separation/chemical extraction, and on-site disposal) may theoretically be possible, but it is likely to be politically and fiscally impossible. Such intensely active alternatives still represent an investment greater than what put a man on the moon. The exorbitant costs and immediate health and safety issues associated with the braced-shaft or open-pit mine options render them as unfeasible. The national debt of about \$5 trillion would ultimately pale in comparison to the trillions of dollars involved in these two options, especially when experience has shown that, with much less ambitious kinds of remediation projects, it is very easy to miscalculate the difficulty of the technical challenges and ultimate costs involved (*Las Vegas Review Journal*, 1996).

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Appendix A

Input Parameters for ODAST

A.1.0 Input Parameters for ODAST

Input parameters for ODAST were assumed given the lack of site-specific data for each of the CAUs. These include:

- Seepage velocity and the dispersion coefficient that depend on the characteristics of the waste area and the unsaturated zone materials. HELP calculates the percolation rate, and seepage velocity is calculated as an empirical function of the percolation rate, saturated hydraulic conductivity, and effective porosity (EPA, 1988). An empirical function of seepage velocity developed by Biggar and Nielsen (1976) calculates the dispersion coefficient.
- The retardation factor accounts for transport delays due to reversible reactions between the chemical constituent and the solid matrix of the unsaturated zone. Thus, the retardation factor depends on both the solute and medium characteristics and is calculated as a function of the constituent's partitioning coefficient, the bulk density, and the moisture content of the unsaturated zone (Walton, 1988; Mills et al., 1985)
- The source decay factor also depends on the constituent. We have considered three inorganics (tritium, technetium-99, and iodine-129) because of their different half-lives, different mobile masses, and different retardation characteristics. The source decay factor in ODAST/SWIFTLOAD accounts for radioactive decay.
- The source depletion time and factor control the mass flux history of the constituent at the top of the modeled layer. Based on the upstream boundary condition, source mass flux decays exponentially. To calculate depletion time and factor for the waste loading at the top of Layer 1, one must integrate the time-dependent expression for mass flow from the source from zero to the source depletion time. This integral is equated to the depleted mass of the constituent to provide a single equation in two unknowns. A second equation is obtained by arbitrarily specifying a mass depletion factor. This is the level (very close to, but less than one) at which the source is declared depleted; technically, the source becomes depleted only as time approaches infinity.

Appendix B

Source-Term Data

June 23, 1995

Janet,

The contact for further questions concerning these data is Tim Benjamin, (505) 665-3182. Any requests for more elaborate information will probably require funding to Tim's organization, CST-11.

The data enclosed include events that were detonated below or within 100 meters of the water table at NTS.

For an explanation of the methods used to estimate these data, please refer to LA-CP-94-0222, *Total Radionuclide Inventory Associated with Underground Nuclear Tests Conducted at the Nevada Test Site, 1955 1992 (U)*, September 26, 1994 (SRD).

Sincerely,

Mike Paukratz

Mike Paukratz

Los Alamos
NATIONAL LABORATORY
memorandum

*Chemical Science and Technology
Responsible Chemistry for America*

CST-11, Nuclear and Radiochemistry
Los Alamos, New Mexico 87545

To/MS: M. Pankratz, FSS-16
From/MS: T.M. Benjamin, CST-11 *RB* (505) 665-3182
Phone/FAX: 5-3182/5-4955/benjamin@lanl.gov
Symbol: CST-11: V-95-11
Date: June 23, 1995

Selected NTS Underground Inventory Data

- Enclosed is a complete inventory of the radionuclides compiled for the NTS underground inventory (LA-CP-94-0222) sorted as specified with respect to water table and location.
- This compilation is a good faith effort to use the available data. None of the principal authors of the source database is currently available for assistance in answering the present request. Any errors are totally unintentional and will be corrected if any are detected. I am the point of contact.
- Discussion of data collection criteria, estimation methods, and uncertainties are given in the LA-CP-94-0222 document.
- The fission product table is for Los Alamos events only and represents only a fraction of the total inventory. Scaling by the Total/Los Alamos fission yields will likely produce an adequate estimate for modeling purposes.

VB5 Request

Fission Yield Sum Estimates

(Fission Yield information from LLNL was estimated)

Fission Yield Not on Pahute Mesa (kt)	9292
Fission Yield on Pahute Mesa (kt)	18130

Fission Products

Information from LANL shots only

	(1/2 life in years)	CURIES ON 1/1/94		ATOMS ON 1/1/94	
		Not on Pahute Mesa	Pahute Mesa	Not on Pahute Mesa	Pahute Mesa
Fission Yield from LANL shots (kt)		4836	3703		
Kr-85	10.73	3.58E+04	3.04E+04	6.46813E+23	5.4956E+23
Sr-90	29.1	4.65E+05	3.75E+05	2.27651E+25	1.8361E+25
Zr-93	1.50E+06	1.62E+01	1.26E+01	4.10171E+25	3.1904E+25
Fis Prod Nb-94	2.00E+04	4.30E-03	2.94E-03	1.44911E+20	9.9039E+19
Tc-99	2.13E+05	1.16E+02	8.82E+01	4.15279E+25	3.1645E+25
Pd-107	6.50E+06	5.28E-01	3.41E-01	5.78175E+24	3.7339E+24
Cd-113	14.1	3.21E+02	2.81E+02	7.61196E+21	6.686E+21
Sn-121	55	1.26E+03	1.05E+03	1.16625E+23	9.7103E+22
Sn-126	1.00E+05	1.50E+01	1.23E+01	2.52829E+24	2.0702E+24
I-129	1.57E+07	3.39E-01	2.64E-01	8.97463E+24	6.9912E+24
Cs-135	2.30E+06	1.21E+01	9.14E+00	4.68506E+25	3.5418E+25
Cs-137	30.17	5.67E+05	4.39E+05	2.88154E+25	2.2301E+25
Sm-146	1.03E+08	8.41E-09	3.76E-09	1.45816E+18	6.5209E+17
Sm-151	90	1.92E+04	1.41E+04	2.90285E+24	2.1335E+24
Fiss Prod Eu-152	13.48	4.18E-02	3.88E-02	9.50002E+17	8.8096E+17
Fiss Prod Ho-166	1.20E+03	6.35E-03	3.83E-03	1.28334E+19	7.7376E+18

Unfissioned fissile materials, neutron-activated radionuclides, and tritium results
Information on LLNL and LANL shots

SHOTS NOT ON PAHUTE MESA

1/2 LIFE IN YEARS

CURIES ON 1/1/94 ATOMS ON 1/1/94

1.23E+01	H-3	3.07E+07	6.3579E+26
5.73E+03	C-14	8.00E+02	8.3019E+24
7.30E+05	Al-26	4.17E-02	5.1321E+22
3.01E+05	Cl-36	2.27E+02	1.1516E+26
2.69E+02	Ar-39	9.61E+02	4.3533E+23
1.28E+09	K-40	2.47E+02	5.3246E+29
1.03E+05	Ca-41	1.70E+03	2.9403E+26
7.60E+04	Ni-59	4.23E+01	5.4083E+24
1.00E+02	Ni-63	5.14E+03	8.6558E+23
1.07E+01	Kr-85g	5.40E+04	9.7292E+23
2.91E+01	Sr-90	7.26E+05	3.5588E+25
1.50E+06	Zr-93	2.63E+01	6.6493E+25
1.61E+01	Nb-93m	6.35E+03	1.7227E+23
2.00E+04	Nb-94g	1.95E+02	6.5598E+24
2.13E+05	Tc-99	1.90E+02	6.8224E+25
6.50E+06	Pd-107g	9.70E-01	1.0619E+25
1.41E+01	Cd-113m	4.83E+02	1.1479E+22
5.50E+01	Sn-121m	1.95E+03	1.8044E+23
1.00E+05	Sn-126	2.35E+01	3.9646E+24
1.57E+07	I-129	5.50E-01	1.4548E+25
2.30E+06	Cs-135g	2.00E+01	7.7541E+25
3.02E+01	Cs-137	9.15E+05	4.6478E+25
9.00E+01	Sm-151	3.23E+04	4.8979E+24
3.60E+01	Eu-150	8.86E+01	5.3696E+21
1.35E+01	Eu-152	6.40E+04	1.4525E+24
8.59E+00	Eu-154	4.84E+04	6.9979E+23
1.20E+03	Ho-166m	5.06E+01	1.0218E+23
1.40E+10	Th-232 (device)	4.01E-04	9.4655E+24
1.40E+10	Th-232 (soil)	1.77E+01	4.1645E+29
7.00E+01	U-232	3.65E+02	4.2979E+22
1.59E+05	U-233	1.50E+02	4.0312E+25
2.46E+05	U-234 (device)	1.41E+02	5.8231E+25
2.46E+05	U-234 (soil)	8.85E+00	3.6668E+24
7.04E+08	U-235 (device)	2.79E+00	3.3076E+27

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Final Worksheet Sums

7.04E+08	U-235 (soil)	4.15E-01	4.915E+26
2.34E+07	U-236	3.42E+00	1.3482E+26
4.47E+09	U-238 (device)	7.00E+00	5.2706E+28
4.47E+09	U-238 (soil)	8.83E+00	6.6456E+28
2.14E+06	Np-237	1.10E+01	3.9525E+25
8.77E+01	Pu-238	1.18E+04	1.7465E+24
2.41E+04	Pu-239	2.88E+04	1.1703E+27
6.56E+03	Pu-240	7.42E+03	8.2004E+25
1.44E+01	Pu-241	1.03E+05	2.5077E+24
3.75E+05	Pu-242	4.52E+00	2.8542E+24
4.33E+02	Am-241	6.83E+03	4.9765E+24
7.37E+03	Am-243	3.42E+00	4.2393E+22
1.81E+01	Cm-244	2.35E+03	7.1478E+22

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1.23E+01	H-3	6.99E+07	1.4483E+27
5.73E+03	C-14	5.55E+02	5.3521E+24
7.30E+05	Al-26	8.94E-03	1.0991E+22
3.01E+05	Cl-36	2.14E+02	1.0835E+26
2.69E+02	Ar-39	1.85E+03	8.3728E+23
1.28E+09	K-40	4.69E+02	1.0118E+30
1.03E+05	Ca-41	1.64E+03	2.8443E+26
7.60E+04	Ni-59	3.99E+01	5.1083E+24
1.00E+02	Ni-63	4.21E+03	7.0883E+23
1.07E+01	Kr-85g	9.54E+04	1.7185E+24
2.91E+01	Sr-90	1.19E+06	5.8303E+25
1.50E+06	Zr-93	4.17E+01	1.0542E+26
1.61E+01	Nb-93m	7.59E+03	2.0573E+23
2.00E+04	Nb-94g	1.73E+02	5.842E+24
2.13E+05	Tc-99	3.07E+02	1.0995E+26
6.50E+06	Pd-107g	1.57E+00	1.7207E+25
1.41E+01	Cd-113m	1.16E+03	2.7479E+22
5.50E+01	Sn-121m	4.31E+03	3.9945E+23
1.00E+05	Sn-126	4.92E+01	8.284E+24
1.57E+07	I-129	9.45E-01	2.4979E+25
2.30E+06	Cs-135g	3.17E+01	1.2269E+26
3.02E+01	Cs-137	1.51E+06	7.6051E+25
9.00E+01	Sm-151	5.71E+04	8.6613E+24
3.60E+01	Eu-150	1.11E+03	6.756E+22
1.35E+01	Eu-152	3.29E+04	7.4658E+23
8.59E+00	Eu-154	1.55E+04	2.2405E+23
1.20E+03	Ho-166m	4.48E+01	9.0533E+22
1.40E+10	Th-232 (device)	5.84E-02	1.3765E+27
1.40E+10	Th-232 (Soil)	3.38E+01	7.9755E+29

Final Worksheet Sums

7.00E+01	U-232	2.55E+02	3.0047E+22
1.59E+05	U-233	1.71E+02	4.5929E+25
2.46E+05	U-234 (device)	1.23E+02	5.1072E+25
2.46E+05	U-234 (soil)	1.67E+01	6.9137E+24
7.04E+08	U-235 (device)	1.66E+00	1.971E+27
7.04E+08	U-235 (soil)	7.94E-01	9.414E+26
2.34E+07	U-236	4.73E+00	1.8666E+26
4.47E+09	U-238 (device)	2.19E+00	1.6459E+28
4.47E+09	U-238 (soil)	1.67E+01	1.255E+29
2.14E+06	Np-237	3.65E+01	1.314E+26
8.77E+01	Pu-238	7.16E+03	1.0576E+24
2.41E+04	Pu-239	1.93E+04	7.852E+26
6.56E+03	Pu-240	6.20E+03	6.8491E+25
1.44E+01	Pu-241	9.00E+04	2.1816E+24
3.75E+05	Pu-242	3.36E+00	2.1232E+24
4.33E+02	Am-241	4.67E+03	3.3998E+24
7.37E+03	Am-243	1.79E-01	2.226E+21
1.81E+01	Cm-244	2.97E+03	9.0416E+22

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