ORNL-6317
(NVO/AEIC-306)

ornl

OAK RIDGE NATIONAL LABORATORY

MARTIN MARIETTA

Cleanup Procedures at the Nevada Test Site and at Other Radioactively Contaminated Sites Including Representative Costs of Cleanup and Treatment of Contaminated Areas

Sylvia S. Talmage
Betty D. Chilton

OPERATED BY
MARTIN MARIETTA ENERGY SYSTEMS, INC.
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
NTIS price codes—Printed Copy: A04 Microfiche A01

ORNL-6317
NVO/AEIC-306

Biology Division

CLEANUP PROCEDURES AT THE NEVADA TEST SITE AND AT OTHER RADIOACTIVELY CONTAMINATED SITES INCLUDING REPRESENTATIVE COSTS OF CLEANUP AND TREATMENT OF CONTAMINATED AREAS

Sylvia S. Talmage
Betty D. Chilton

Information Research and Analysis
Nevada Applied Ecology Information Center

Date Published—September 1987

Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
operated by
MARTIN MARIETTA ENERGY SYSTEMS, INC.
for the
U.S. DEPARTMENT OF ENERGY
under Contract No. DE-AC05-84OR21400

CONTENTS

LIST OF TABLES

ACKNOWLEDGEMENTS

This publication is made possible through funding from the Nevada Applied Ecology Group.

Special appreciation is given to Dr. Tsuneo Tamura for his contribution in reviewing this report, to Pat Quiggins for her assistance in editing, and to Dorla Arnwine for typing of the manuscript.

ABSTRACT

This review summarizes available information on cleanup procedures at the Nevada Test Site and at other radioactively contaminated sites. Radionuclide distribution and inventory, size of the contaminated areas, equipment, and cleanup procedures and results are included. Information about the cost of cleanup and treatment for contaminated land is presented. Selected measures that could be useful in estimating the costs of cleaning up radioactively contaminated areas are described.

1. INTRODUCTION

The Nevada Applied Ecology Information Center (NAEIC) at Oak Ridge National Laboratory (ORNL) has provided information support to the Nevada Applied Ecology Group (NAEG) since January 1972. In the early years, information collected for the first data file emphasized the movement of plutonium through the environment, particularly those studies pertaining to safety shot and nuclear weapon detonation sites on the Nevada Test Site (NTS). The data base was soon expanded to include environmental and laboratory studies of all the transuranics.

Since October 1977, NAEIC has concentrated its efforts on identifying and analyzing documents on the cleanup and treatment of radioactively contaminated land. In September 1982 a bibliography (Fore, Faust, and Brewster 1982) was published; it contains 472 references on the site specific methods of cleanup of radioactively contaminated sites. In support of the NAEG, particular attention was paid to cleanup procedures used at NTS.

This report summarizes available information contained in the bibliography on cleanup procedures at NTS. Radionuclide distribution and inventory, size of the contaminated areas, equipment and cleanup procedures, cleanup results, and costs, where available, are included. The largest amount of available information is for safety shot areas that are candidates for remedial action. These sites—in Areas 5, 11, and 13 at NTS and at the DOUBLE TRACK and CLEAN SLATE 1, 2, and 3 sites at the Tonopah Test Range—have been researched by the NAEG. At these sites, chemical explosives were detonated in close proximity to arrangements or assemblies of plutonium and/or uranium. According to Kordas and Anspaugh (1982), the total area of these 10 sites is 11.4 km^2. For comparative purposes, cleanup of radioactively contaminated soil following testing or accidents at other sites is described. Two applicable experimental studies are also discussed. Several chemical and physical methods of soil cleanup are being researched, and some of these methods are described. An inventory of equipment used for physical cleanup is included.

A survey of the literature on the cost of cleanup and treatment for contaminated land follows the sections describing cleanup procedures. Available data are scarce, so it is difficult to compare methods and/or costs or to conclude much of value from them. Most of the available data are for estimated rather than actual costs. Some of the information was published in the mid-1970s or earlier, and no allowance has been made for inflation since that time. This section consists of information about a few selected measures that, although not directly related to radioactive contamination in all cases, might prove useful in estimating the costs of cleaning up radioactively contaminated areas. Tables of data are included on (1) cost for each unit operation, (2) estimated costs of site stabilization, (3) estimated long-term care costs, (4) estimated cost of relocation of the radioactive material, (5) cost comparison of stabilization methods for fine-sized materials, and (6) cost estimates for fixatives used on radioactively contaminated surfaces. To avoid comparing unlike conditions, only data that can be applied to arid regions have been included. Additional references containing cost data (other than those cited in this report) are provided in Appendix A.

2. CLEANUP PROCEDURES AT THE NEVADA TEST SITE AND AT OTHER RADIOACTIVELY CONTAMINATED SITES

2.1 CLEANUP PROCEDURES AT THE NEVADA TEST SITE

The Reynolds Electrical and Engineering Co., Inc., (REECo) has been in charge of radiation safety at NTS for many years. A report from REECo files on land decontamination, specifically alpha decontamination, by Brown et al. (1964) is quoted by Wallace and Romney (1975): "Land area decontamination techniques at NTS vary with the contaminant and with future plans for use of the area. If immediate reuse is required, the contaminant is completely removed from the area and transported to a waste disposal site. If there are no plans for area use, intermediate procedures may be used to fix or seal the contaminant in place to inhibit resuspension or redistribution."

According to Wallace and Romney (1975), windrows that can be picked up for later disposal have been a very common means of decontamination at NTS. This method and other cleanup methods used at NTS are summarized in Table 1.

2.1.1 Area 3

Kordas and Anspaugh (1982) list 30 events in Area 3. Six of these were safety experiments.

Following shot COULOMB C (Operation Plumbbob), which took place on on December 9, 1957 (Miller 1958), the Civil Effects Test Operation Exercise CEX-57.1 was carried out. The objective of the exercise was to carry out and evaluate decontamination methods in a fallout area with low levels of radioactive contamination. The cleanup procedure began 1 d after the shot. Radiation levels were between 30 and 40 mrad/h. Data were obtained on reclamation of land areas scraped with a motorgrader, on fire hosing and scrubbing a concrete-slab roof, and on fire hosing a composition roof. Scraped soil was pushed away from the buildings and into windrows; the depth of cut was set to 1½ in. (3.8 cm). The decontamination effectiveness was reported in terms of the fraction (FR) of contamination remaining after cleanup. Radiation intensity in mrad/h at the ground surface around Building A decreased from an initial 30.5 to 6.1 mrad/h after scraping, giving a decontamination ratio, FR, of 6.06/30.5 or 0.2. Decontamination ratios for other surfaces are contained in Table 1.

Decontamination of other event sites in Area 3 was undertaken in 1960 (REECo Decontamination Report—Area 3, as cited in Brown et al. 1961). Reduction of surface contamination was accomplished by thin-layer windrowing of the top soil. Contamination was fixed by spraying a hot road-oil spray over the windrows.

Radioisotopes found in soil samples from Area 3 include ^{241}Am, ^{60}Co, ^{152}Eu, and ^{137}Cs (Fritzsche 1982). The Fritzsche report documents seven major contaminated areas, which are defined on aerial isopleth maps; two are waste dumps, one of which has since been removed. Locations of maximum measured exposure, identified isotopes, and associated event names are given. For example, the inventories of ^{60}Co, ^{152}Eu, and ^{137}Cs in the surface soil of a 3.1 km^2 area associated with events HARRY and HORNET are 0.3, 43.0, and 0.4 Ci (1.1×10^{10}, 1.6×10^{12}, and 1.5×10^{10} Bq). Americium-241, which is found throughout the contaminated areas, could not be inventoried from the aerial data because of the large gamma backgrounds of the other contaminants. From this aerial survey, total isotopic inventories for Area 3 are 0.8 Ci (3.0×10^{10} Bq) of ^{60}Co, 55.4 Ci (2.1×10^{12} Bq) of ^{152}Eu, and 3.2 Ci (1.2×10^{11} Bq) of ^{137}Cs in a 5.6-km^2 area.

Table 1. **Cleanup and treatment methods at the Nevada Test Site**

Area/event	Type/extent of contamination	Terrain/soil type	Decontamination method/equipment	Decontamination results/costs	References
Area 3					
Unspecified events	^{239}Pu	Flat; loose sandy loam	Oil-sealed windrows	Controlled access	Brown et al. 1961
COULOMB C	0.5-kt safety experiment	Smooth, level land	Scraping with motor-grader (8-ft blade) to depth of 1.5 in.; soil pushed into windrows	FR: 0.20–0.30[a]	Miller 1958
		Building roofs	Fire-hosing Fire-hosing + detergent	FR: 0.27–0.34 FR: 0.24	Miller 1958
Area 5					
SMALL BOY	Fused silica containing fission products	Not given	Grader and bulldozer to remove silica; water levels acceptable for truck to settle dust	Reduced contamination to limited operations (12-40 R/h down to 1 R/h)	Rarrick 1972
Area 9					
VESTA, JUNO	^{60}Co, ^{157}Eu, ^{137}Cs (VESTA); 24 and 1.7 ton surface safety experiments	Loose, sandy loam; clay-gravel aggregate	Thin-layer windrowing; fixation by hot road-oil spray	Controlled access	Brown 1961 Fritzsche 1982
Area 10					
SEDAN	^{241}Am, ^{60}Co, ^{137}Cs, ^{102m}Rh		Road decontamination by high pressure water spray. Road blader used to remove thin layer of contaminated surface soil from road shoulders; soil was water sprayed to prevent resuspension; wet topsoil windrowed and fixed with hot road oil. (Equipment: bladers, water tank trucks, road-oil trucks.)		Brown et al. 1964 Fritzsche 1982

Table 1 (continued)

Area/event	Type/extent of contamination	Terrain/soil type	Decontamination method/equipment	Decontamination results/costs	References
Area 11					
Site C (two 12 x 100 m plots)	^{239,240}Pu, ^{241}Am,	Flat; gravelly loam	Devegetation, watering to control dust; harrowing followed by vacuuming (12.3-m^3 capacity VAC-ALL truck); soil removed to average depth of 6.4 cm; 162 m^3 total soil removed from 2453 m^2 area.	^{241}Am reduced to ≤10 pCi/g (≤0.3 Bq/g) of ^{241}Au in surface soil; controlled acces site	Essington et al. 1976 Gilbert 1977 Dunaway and Sorom 1982 Orcutt 1982 Clark 1983
Area 13					
Eleven 50 x 100 ft test plots	46 Ci ^{239,240}Pu in 4,017,000 m^2 62.1–90.5 Ci ^{230,240}Pu, 9.6 Ci ^{234}Am	Flat; gravelly, sandy loam	Plowing	97.9[b]	Gilbert 1977, Dick and Baker 1967, Pinson et al. 1957, Baker et al. 1958, Brown et al. 1961
			Oiling and scraping	95.6	
			0.3-in. water leaching and scraping	92.7	
			0.3-in. water $FeCl_3$ leaching	91.6	
			Disking	89.2	
			1.0-in. water leaching	87.4	
			Scraping	86.0	
			Oiling (RC-0 road oil)	69.4	
			0.3-in. water leaching	55.0	
			0.3-in. water-Alconox leaching	18.7	
			Controlled access site		
Hard surfaces	^{239}Pu	Concrete; highway asphalt; wood pads	Sandblasting	98.83	Fritzsche 1979
			Water-detergent scrubbing	98.84	
			Water-detergent hosing	98.61	
			Water hosing	96.12	
			Water scrubbing	94.59	
			Steam cleaning	87.80	
			Vacuum	66.40	

Table 1 (continued)

Area/event	Type/extent of contamination	Terrain/soil type	Decontamination method/equipment	Decontamination results/costs	References
Area 20					
(Pahute Mesa)	^{103}Ru (38 Ci) ^{106}[Ru-Rh] (6 Ci)	Large, flat area; fine grain, compact dirt; small inaccessible areas; rocky surfaces; flat area, fine-grain dirt, contaminated	Front-end loaders; shovels and bags; flushing with water; vacuuming (VAC-ALL)	Decontamination to 1 mrem/h contact. Where not practically achieved, contamination covered with sufficient amount clean dirt.	Straume et al. 1977, 1978 Bicker 1981
			Deep contamination	Achieved radioactive fraction remaining (FRs) of 10^{-1} to 10^{-3}; 900 work-days; 1,975 m^3 dirt removed.	
Area 25					
Nuclear Rocket Development Station	Reactor fission and activation products; 10^7 Ci of gamma-emitting radiation; 20,234 m^2	Not given; some rocks	Remotely controlled small model vacuum cleaner; small, remotely controlled mobile manipulator. Soil removed, piled, sprayed with oil	\$100,000	Sanders 1966 Church 1981
			Soil removal; debris removed from building	As low as practicable. Cost: \$1.28 million (FY 1978–82)	
Tonopah Test Range DOUBLE TRACT CLEAN SLATE 1 CLEAN SLATE 2 CLEAN SLATE 3	^{238,239,240}Pu, ^{241}Am 3.6 Ci ^{239,240}Pu; 179,000 m^2 4.2 Ci ^{239,240}Pu; 177,000 m^2 17 Ci ^{239,240}Pu; 470,500 m^2 37 Ci ^{239,240}Pu; 1,732,000 m^2	Flat, gravelly sandy loam	Debris in vicinity of each ground zero was collected and buried. Scraping of 12,130–20,234 m^2 around each ground zero followed by burial in a trench; other material was scraped, windrowed, and fenced	Controlled access	Burnett et al. 1964, Wallace and Romney 1975, Gilbert 1977

[a]Fraction of radioactivity remaining.
[b]Decontamination efficiency (%).

2.1.2 Area 5

The SMALL BOY event was a low-yield nuclear detonation that took place on July 14, 1962. The device was located slightly above ground and within 150 and 250 ft (45.2 and 76.2 m) of bunkers in which experiments had been set up (Rarrick 1972). Because the bunkers were within fireball radius, the entire area was covered with fused silica containing fission products. Recovery operations were started one month after the event. Radiation levels at the rear bunker were ~12 R/h and at the forward bunker were up to 40 R/h. The immediate area around the bunkers was scraped with a grader and bulldozer, and a water truck was used to settle the dust. Following removal of slag from the bunkers, radiation levels were reduced to ~1 R/h.

Information on cleanup activities at the GMX area, which is being considered for cleanup, was not located. The GMX area is within Area 5 and was exposed to a safety shot. Gilbert (1977) estimates an inventory of 1.5 Ci of $^{239,240}Pu$ (5.6×10^{10} Bq) in the top 5 cm of soil in a 125.3-km^2 area. The soil in this area is gravelly, sandy loam.

2.1.3 Area 9

Kordas and Anspaugh (1982) list 22 events in Area 9; 14 of these were surface or above-ground shots. From aerial surveys, Fritzsche (1982) identified four major contaminated areas in the vicinity of events (1) WILSON, LASSEN, WHEELER, HOOD, OWENS, CHARLESTON, MORGAN, and RUSHMORE (balloon shots at the same or nearby sites); (2) GANNYMEADE; (3) VESTA; and (4) a waste dump. Radioisotopes identified in the surface soil at these sites include ^{60}Co, ^{152}Eu, and ^{132}Cs. As mentioned previously, the low-energy (60 keV) gammas from ^{241}Am appeared to be lost in the large gamma backgrounds from the other contaminants when aerial gamma radiation surveys were taken.

VESTA and JUNO were two surface safety experiments fired in surface structures (U.S. Department of Energy 1983). Only minor levels of radiation were detected following the JUNO event. According to Brown et al. (1961), the area around JUNO and VESTA was bladed; the top soil was pushed into windrows and fixed with hot road-oil spray. The events took place in 1958; the cleanup was undertaken by REECo in 1960. Cursory monthly inspections between 1960 and 1961 indicated that the oil seal in the windrows was satisfactory and did not need repair. Both loose, sandy loam and clay-gravel aggregate are typical soil types in Area 9.

2.1.4 Area 10

In Area 10 information was available for only the SEDAN event that took place on July 6, 1962; the 106-kt detonation resulted in a crater (Kordas and Anspaugh 1982). According to an aerial survey, the principal contaminants are ^{241}Am, ^{60}Co, ^{137}Cs, and ^{102}Rh (Fritzsche 1982).

Wallace and Romney (1975) quote the following from a REECo report by Brown et al. (1964):

> Following the SEDAN experiment, after decontamination of the road, a road blader was used to remove a thin layer of surface contaminated soil from the road shoulders. The blading operations progressed from the surfaced road edges toward the open fields on either side. To prevent resuspension of the dust and finely divided contaminant, a water truck was used to wet the surface ahead of the blading operation. The wet topsoil was accumulated into windrows, two feet high and three feet wide. The windrows were then sprayed with hot road oil to confine the contamination. Windrowing operations to confine and control contamination are quite straightforward. Only conventional road maintenance equipment—bladers, water tank trucks, and road-oil trucks—is required.

2.1.5 Area 11

A series of four nuclear safety shots was conducted in the "Plutonium Valley" portion of Area 11 as part of Project 56 (Kordas and Anspaugh 1982; Clark 1983). The tests were conducted on November 1, 3, and 5, 1955, and January 18, 1956, at Sites A, B, C, and D, respectively. Sites B, C, and D are contaminated with ^{241}Am and ^{239,240}Pu; Site A contains ^{235}U, and Site D also contains ^{137}Cs. Very little excess radiation is present at blast Site A. Gilbert (1977) estimates an inventory of 36 Ci (1.3×10^{12} Bq) of ^{239,240}Pu in the top 5 cm of soil in a 0.097-km^2 area encompassing Sites B, C, and D. The estimate is based on data obtained during a FIDLER (ground-based) survey. Clark (1983) indicates that values from aerial surveys tend to be three times higher than the corresponding ground-based measurements. He reports an inventory of 240 Ci (8.9×10^{12} Bq) of ^{239,240}Pu and 12 Ci (4.4×10^{11} Bq) of ^{241}Am in a 6.03 km^2 area. Only the ^{241}Am soil concentration was measured in the aerial survey. The values reported for ^{239,240}Pu are calculated from the plutonium to americium ratio (5.8) reported as a result of earlier soil sample studies.

In 1981 a cleanup and treatment test was conducted near Site C by REECo (Dunaway and Sorom 1982; Orcutt 1982; Clark 1983). The vacuum method of soil removal was tested to see if sufficient amounts of radioactivity could be removed at low costs and with minimum environmental damage. A 20-year-old Central Engineering Co. VAC-ALL model E5-16 vacuum truck was used as the soil collection unit. Pretest surface soil analyses indicated that ^{241}Am concentrations in this area ranged from 7 to 166 pCi/g (259 to 6142 Bq/kg) (Orcutt 1982).

Two experimental plots, each 12×102 m, were laid out near Site C. Vegetation was cleared from the plots. Soil was first loosened with a harrow and then moistened before vacuuming. The VAC-ALL removed 2.5 in. (6.4 cm) of top soil from each of the test plots. An estimated 5720 ft^3 (162 m^3) of contaminated soil was deposited in a nearby area and later removed to a waste disposal site. The EG&G IMP system, a tracked vehicle with an on-board electronic counting system and an intrinsic germanium detector extended away from the body of the vehicle by a boom, was used to make in situ measurements of the degree of ^{241}Am decontamination and to identify any remaining areas of localized contamination. Equipment malfunctions, the necessity to revacuum some areas, and problems with rough terrain are discussed by Orcutt (1982). The test plots were decontaminated to <10 pCi/g (<370 Bq/kg) of ^{241}Am in surface soil.

Problems may arise in the cleanup of this area. Although soil profile analyses indicate that most of the americium and plutonium activity is associated with the top 5.0 cm of soil, contamination is deeper in washes and mounds (Orcutt 1982). Essington et al. (1976) also indicate that for some locations in Area 11, substantial amounts of plutonium are found below the 5-cm level.

2.1.6 Area 13

Field decontamination experiments were first conducted by Test Group 57 at the NTS following a one-point chemical detonation (plutonium oxide dispersion) near Groom Lake, Nevada (Pinson et al. 1957; Baker et al. 1958; Dick and Baker 1967). The detonation resulted in contamination of the immediately surrounding desert soil and vegetation with plutonium and americium. In the studies described by Dick and Baker (1967), eleven 50×100 ft (15.2 by 30.5 m) test plots were established in the fallout area ~1,000 ft (305 m) downwind from ground zero. Methods of soil decontamination or fixation included oiling, spraying with fire-fighting foam, wetting, flooding, wetting with leaching agents and stablizing agents ($FeCl_3$), disking, plowing, and scraping.

Treatment plots were not duplicated. Equipment included a single-bottom farm plow, a disk harrow, a 1000-gal (3.8-m^3) water-sprinkling truck, an 850-gal (3.2-m^3) oil-distribution truck, and a U.S. Army roadgrader. The effectiveness of the decontamination methods was determined by measuring the air concentration of plutonium particles resuspended from the land surface before and after treatment. Resuspension was accomplished by driving a truck back and forth through the area. Decontamination efficiencies are listed in Table 1.

Plowing, oiling, and scraping were found to be the most effective methods of removing plutonium contamination from the land surface (Dick and Baker 1967). Plowing was most effective when the land surface was first moistened to keep surface dust from becoming suspended and then settling back on the plowed areas. Plowing was done to a depth of 12 in. (0.3 m). The top 2 in. (5 cm) of soil was scraped and hauled away for burial. Following the cleanup tests, the area was fenced off and has been monitored since that time.

Wallace and Romney (1975, 1977) inspected these test plots 17 years later with the purpose of evaluating vegetation recovery and comparing soil surface conditions. The plowed and scraped areas had recovered well with an estimated 25% of vegetation compared with adjacent nondisturbed areas. The area treated with road oil appeared to be no different from nontreated areas except for the residue of oil remaining. Wallace and Romney suggest that "... plowing might be an effective procedure for any additional decontamination needed at the Area 13 site, especially if road oil or another suitable agent were used after plowing to stablize the soil to prevent a dust bowl." They felt that more experimental work is needed to further test this combination of treatments. They also noted that the test group workers failed to document whether or not the original shrubs survived the treatments.

Hard surfaces, including concrete, asphalt, plate steel, aluminum, galvanized roofing, tar-paper roofing, painted and unpainted wood, glass, brick, stucco, and wood and asbestos shingles set up prior to the shot were also decontaminated by Test Group 57 (Pinson et al. 1957). In addition to the water distribution truck used in land decontamination, equipment included two "Tornado" vacuum cleaners, a steam jenny, and a sand blaster. Decontamination efficiencies are listed by method in Table 1. In separate tests, large highway asphalt, concrete, and wood float pads were decontaminated by the water-detergent hosing method. The efficiency of decontamination was 95.6% for the highway asphalt and 86.1% for the wood-float concrete.

Based on a FIDLER survey, Gilbert (1977) estimates an inventory of $^{239,240}Pu$ in the surface soil (0 to 5 cm depth) of 46 Ci (1.7×10^{12} Bq) covering a 4,017,000 m^2 area at this site. An aerial survey by Fritzsche (1979) resulted in an estimated inventory of 9.6 Ci (3.6×10^{11} Bq) of ^{241}Am. Based on a Pu/Am ratio of 9.4, the range of $^{239,240}Pu$ inventory is 62.1 to 90.5 Ci (2.30×10^{12} to 3.3×10^{12} Bq).

Using available summary data and contour or strata maps, Kinnison and Gilbert (1980) estimated the amount of soil removal necessary to decontaminate down to 160 pCi (5.9 Bq) of $^{239,240}Pu$, with removal of the top 15 cm of soil. This estimate is 180,000,000 kg of soil covering 269 acres (1.07 km^2). The authors stress that this is a rough estimate, and more accurate estimates could be obtained by applying Kriging techniques to available soil data. Soil profile studies by Essington et al. (1976) indicate that most of the $^{239,240}Pu$ in Area 13 is located in the top 5 cm of soil.

Based on a maximum dose rate of 1.5 rem/year to a "standard man" living at the site, Martin and Bloom (1977) estimated an "acceptable soil concentration" of $^{239,240}Pu$ for this site to be

~2800 pCi/g (103.6 Bq/g) in the surface soil. They obtained the 2800 pCi/g (103.6 Bq/g) limit by using a plutonium transport and dose estimation model developed explicitly for this site. They noted that only the stratum surrounding ground zero (stratum 6) has an average ^{239,240}Pu concentration exceeding 2800 pCi/g (103.6 Bq/g). Stratum 6 has an area of ~24,000 m^{2}d (Gilbert 1977), which is equivalent to ~4400 tons (4 × 10^6 kg) of soil cut to a 15-cm depth.

2.1.7 Area 20

Straume et al. (1977, 1978) report on the cleanup of a large area of rugged terrain following a spill of radioactively contaminated mud. Precleanup surveys indicated that ^{103}Ru and ^{106}Ru/Rh were the primary nuclides present, with total estimated activity at the time of release of 38 and 6 Ci (1.41 × 10^{12} and 2.22 × 10^{11} Bq), respectively. Because of the varied terrain, several decontamination methods were used; the effectiveness of each was assessed by determining the fraction of radioactivity remaining (FR) following cleanup. The most effective methods for each type of terrain are listed in Table 1. Fraction remainings (FRs) of 10^{-1} to 10^{-3} were achieved.

Decontamination down to 1 mrem/h at contact was achieved in most areas. Where this rate was not practically achievable by the described decontamination methods, the contamination was covered with sufficient amounts of clean soil to reach the 1 mrem/h exposure limit. Approximately 900 work-days were expended on this cleanup, and 2584 yd^3 (1975.6 m^3) of contaminated mud were removed and placed in a subsidence crater ~14 m below the surface ground level.

Some negative aspects to the cleanup methods and equipment need to be noted: the slowness of the vacuuming method and its impracticality in rugged, rocky areas; the slowness of hand shovels and bags and their impracticality where deep penetration has occurred; the possible recontamination by front-end loaders when drivers are unaware of problems with loader-use in rugged terrain; and the resultant deep penetration in gravel areas when flushing is used.

2.1.8 Nuclear Rocket Development Station (Area 24)

In 1965 an accident in Test Cell C at the Nuclear Rocket Development Station resulted in the contamination of approximately 5 acres (20,234 m^2) of land with reactor fission and activation products (Sanders 1966, cited in Wallace and Romney 1975). About 10^7 Ci (3.7 × 10^{17} Bq) of gamma-emitting radiation was released in the incident and about two months were required for decontamination of the land and buildings. Because of the buildings involved and the rocky terrain, large equipment was unsatisfactory for this type of cleanup operation. A small model vacuum cleaner and a small, remotely controlled mobile manipulator were used. Fuel pieces were picked up with tongs. Several inches of soil were removed from around the buildings, and oil was sprayed on piled soil to decrease wind suspension. The total cost of decontamination at this time was about $100,000.

An aerial survey performed in 1976 indicated that the major radionuclides present in Area 25 are ^{60}Co and ^{137}Cs (Tipton 1979). These radionuclides are present around several test cells and a waste dump. The most heavily contaminated area is a radioactive materials storage facility, which lies about 2 km southwest of Test Cell C. The data are presented as gamma exposure rate isopleths (μR/h).

From 1974 to 1983 the REECo performed a radiological survey and cleanup of Area 25 (McKnight et al. 1984). Buildings and land area were decontaminated at a total cost of $1.6

million. Approximately 350,000 ft^3 (9910.9 m^3) of radioactive material—debris from buildings and land area and scraped soil—was removed for burial in radioactive waste management sites at the NTS. Methods of soil removal are not discussed; front end loaders and road blading machinery were used to remove two large piles of fuel element debris. The majority of Area 25 facilities and land areas have been returned to unrestricted use. The Area remains under Department of Energy control.

2.1.9 Tonopah Test Range

Four safety shot areas—DOUBLE TRACK and CLEAN SLATES 1, 2, and 3—on the Tonopah Test Range adjacent to the NTS are being considered for cleanup treatment. At each site a chemical explosive was detonated in close proximity to an assembly of plutonium and/or uranium (Jobst 1979, Rarrick 1972). Detonations 2 and 3 were bunker shots. Detonation dates were May 15, 25, 31, and June 6, 1963, for DOUBLE TRACK and CLEAN SLATES 1, 2, and 3, respectively. DOUBLE TRACK is ~8 km west of the Tonopah Test Range. The detonations yielded molten plutonium metal that combined with device materials, earth, concrete, and metal. Ground zero and most of the resultant fallout patterns are enclosed by a barbed wire fence with prominent radiation hazard warning signs.

No land decontamination experiments were reported, but the usual post-shot cleanup activities took place (Burnett et al. 1964; Rarrick 1972). Metal and concrete debris in the vicinity of each ground zero and fragments out to a range of 2500 ft (762 m) were collected and buried in a pit inside the fenced ground zero area. The contaminated surface around each ground zero and areas contaminated by jetting were scraped to a depth of several inches. The soil was placed in the pit or mounded, covered with dirt, compacted, and watered. Windrows were still intact 11 years later (Wallace and Romney 1975). Some areas had been bladed free of vegetation for use as balloon launching sites. The vegetation had partially recovered.

Both ground-based or FIDLER (Gilbert et al. 1975; Gilbert 1977; Kinnison and Gilbert 1980) and aerial (Jobst 1979) radiological surveys of the shot sites have been taken. While there is qualitative agreement between the FIDLER and aerial survey maps, some discrepancies, perhaps because of redistribution during the intervening years, are noted by Jobst (1979). Readily measurable concentrations of ^{241}Am were found outside the barbed wire fence. Some movement of plutonium, americium, and uranium into the soil has occurred at these sites (Essington et al. 1976). In soil profiles collected from CLEAN SLATES 1 and 2 and DOUBLE TRACK, a sizable fraction of the plutonium is found between 5 and 25 cm below the surface. Gilbert (1977) published estimates of inventories of ^{239,240}Pu in the top 5 cm of soil at the four sites. These are listed in Table 1.

Kinnison and Gilbert (1980) give rough estimates of the amount of soil that must be removed in order to decontaminate the surface soil down to 160 pCi/g (5.9 Bq/g) of ^{239,240}Pu (the only level for which there was sufficient data on which to base their estimates). Soil removal down to a depth of 15 cm was assumed, that being the typical minimum level achievable by heavy earth moving equipment. Soil volume was calculated by multiplying the area of land estimated to be >160 pCi/g by an average cleanup depth of 15 cm. Soil weight was calculated by multiplying this soil volume by the average density for the study site. Table 2 summarizes the area and weight results based on the ^{239,240}Pu data. The weight of soil involved is approximately 338,000 tons (3.07×10^8 kg).

Table 2. Rough estimates of the amount of soil removal necessary to decontaminate a 15-cm depth of soil down to 160 pCi of $^{239,240}Pu/g$

Site	Area (m^2)	Volume (m^3)	Soil (kg)
DOUBLE TRACK	62,000	9,200	10,000,000
CLEAN SLATE 1	177,000	27,000	24,000,000
CLEAN SLATE 2	236,000	36,000	33,000,000
CLEAN SLATE 3	1,730,000	260,000	240,000,000
Total	2,205,000	332,000	307,000,000

Source: Adapted with permission from R.R. Kinnison and R.O. Gilbert, *Estimates of Soil Removal for Cleanup of Transuranics at NAEG Offsite Safety-Shot Sites,* PNL-SA-8267, Pacific Northwest Laboratory, Richland, Wash., 1980.

2.1.10 Waste Consolidation Program

Where future use of contaminated land was indicated, surface debris was removed to a waste dump (Brown et al. 1964). The soil was wet down by a water truck, and the top few inches were scraped into windrows by a standard road grader. The moist, windrowed soil was then removed by a large earth mover boosted by D-8 Caterpillar tractors. The removed soil was mounded into soil dumps that were sprayed with a heavy application of road oil. The debris sites were fenced and posted with appropriate radiation warning signs.

In 1979, REECo began a Radioactive Waste Consolidation Program at NTS (Reynolds Electrical & Engineering Co., Inc., 1980, 1983). Original plans called for 25 sites to be cleaned over a period of 10 years. By the end of FY 1984, 16 sites in Areas 1 through 7, 9, and 16 had been cleaned. Procedures involved precleanup inspections; establishment of requirements for equipment, personnel, and radiological control; pre- and post-cleanup radiation surveys; and pre- and post-cleanup soil sample analyses. Debris was moved by dump truck to a radioactive waste management site. At some sites 1 ft (0.3 m) of soil was removed by bulldozers, front-end loaders, or hand excavation. A road grader was used to clean access roads. Complete wetting with water and mixing of the soil during excavating and loading were maintained. Trenches were backfilled with clean soil.

2.2 CLEANUP AT OTHER SITES

2.2.1 Enewetak Atoll

Detonation of 43 nuclear devices took place on Enewetak Atoll between 1946 and 1958. Because there was a desire for the Enewetak people to reestablish their villages in some areas, decontamination of some of the islands has taken place. In 1972 and early 1973, the Atomic Energy Commission made a radiological survey of the atoll (Defense Nuclear Agency 1975). The northeast islands of Runit (Yvonne), Enjebi (Janet), Aomon (Sally), and Eleleron (Ruby) were the most heavily contaminated. Radioactivity was found in the soil, sediment of the lagoon, shrubs and trees, birds, and fish. Cleanup methods tested and results for Yvonne island are summarized in Table 3. Soil was also excised from the surface of Sally, Pearl, Janet, and Irene islands (Barnes and Giacomini 1982).

Table 3. Cleanup methods at other sites

Site	Type of contamination	Decontamination method	Results	References
Enewetak Atoll				
Soil Removal Pilot Project: Sally (KICKAPOO Event)		Removal of vegetation	Bucket loader superior to bulldozer superior to road grader	Friesen 1982
		Soil removal	Bulldozer most rapid equipment for making windrows; bucket loader used to load windrowed soil into dump trucks	Friesen 1982
Plowing experiment: Janet 25 × 25 m plots		Plowing to 50 cm	Effective in mixing ^{241}Am at surface down to 50 cm; "hot spots" remained; suggested a follow-up of disking	Dunaway 1982
Soil removal: Yvonne	^{239,240}Pu, ^{241}Am, ^{60}Co, ^{155}Eu, ^{137}Cs, ^{90}Sr	Top 20 cm soil removed, (8,200 m^3), burial in crator, concrete capped. Follow-up of backblading and coverage with clean soil	The island is currently quarantined. The transuranics average radioactivity is 7.8 pCi/g (0.27 Bq/g) for southern YVONNE and 41 pCi/g (1.52 Bq/g) for northern YVONNE	Barnes and Giacomini 1982 Tipton et al. 1981
Carlsbad, New Mexico				
Project GNOME	^{3}H, ^{90}Sr, ^{137}Cs	Debris, soil removal; disposal into cavity, trenches	Final cleanup status—unrestricted use use on the surface, subsurface drilling is restricted. Some areas fenced; follow-up surveys	Wallace and Rommey 1975 Bicker 1981
Tatum Dome, Mississippi	^{125}Sb and other radionuclides	Soil excavation with front-end loaders, backhoes, draglines, trucks	Removal of >8410 m^3 soil; deposition into cavity or transport to NTS. Manual handling of large debris, clay	Bicker 1981
			Cost: $1,080,000 ($40/yd^3 or $30.5/m^3	Church 1974

Table 3 (continued)

Site	Type of contamination	Decontamination method	Results	References
Los Alamos, New Mexico				
Main Technical Area	Primarily ^{239}Pu	Soil removal. Soil loosened with ripper on back of crawler tractor; soil removed with front-end loaders; loaded into plastic-lined dump trucks. Garden hose used for water spray. Small spots: hand shovel and plastic bags	As low as reasonably achievable: approx. 16 hectares (40 acres) at cost of $769,000. 15,000 m^3 of material removed	Ahlquist 1977, 1981
Wasteline-townsite	Primarily ^{239}Pu	Removal of contaminated industrial wasteline with backhoe, plastic lined dump trucks	As low as practical	Gunderson and Ahlquist 1979
Wasteline leak	Variable radionuclide content	Soil removal with front-end loaders, plastic lined dump trucks	Cost $100,000 including cleanup/ repair of wasteline, spill containment, surveillence, sample analysis, excavation, restoration, waste disposal	Smith et al. 1977
Adjacent area	^{239}Pu	Contaminated soil removed with front-end loader alone or in conjunction with a road maintainer and/ or dozer. Hand excavation in some areas	Decontaminated down to less than 0.06 pCi/m^3 (2.2×10^{-3} Bq/m^3)	Barker 1982
Accidental release	Rocky Flats, Colorado, ^{239}Pu	Removal of contaminated soil and leaking oil drums Residual activity contained underneath asphalt and concrete pads	Effective containment	Wallace and Romney 1975
Savannah River Plant				
Nearby field	$^{238,239,240}Pu$	Disking and plowing	Resulted in little movement out of 0-5 cm depth	Corey et al. 1978

2.2.2 Nonweapon Detonations

As part of the Plowshare program a 3 kt nuclear device was detonated in bedded salt rock 30 miles (4.8 km) southeast of Carlsbad, New Mexico (GNOME Site). Radioactive mud and debris were either placed in the shaft or buried. A follow-up radiological survey disclosed that further cleanup was necessary (cleanup methods are summarized in Table 3).

Two nuclear test detection experiments, SALMON and STERLING, were conducted at the Tatum Dome Site near Hattiesburg, Mississippi. Problems encountered during the cleanup are discussed by Bicker (1981). These two sites may be of limited relevance to cleanup at NTS because the terrain, debris, and problems encountered are quite different from those at NTS.

2.2.3 Accidental Releases

Industrial processing of radioactive materials and leakage from waste storage sites have resulted in accidental releases. Soil cleanup methods used at these sites are also summarized in Table 3.

2.2.4 Weapons Accidents

Two accidents, both involving weapons-bearing B-52 bombers, dispersed plutonium over land areas. At Palomares, Spain, two nuclear weapons chemically detonated, dispersing plutonium over some 1200 acres (4.9 km^2) of ground (Langham 1968; Jordan 1971). Cleanup methods employed were determined by the radioactivity levels in the contaminated area. All crops were stripped from the fields and destroyed where readings above 0.35 $\mu Ci/m^2$ (13,000 Bq/m^2) were observed. The soils with readings between 0.35 and 35 $\mu Ci/m^2$ (13,000 and 1,300,000 Bq/m^2) were deep-plowed to at least 10 in. (0.3 m) deep to reduce the probability of resuspension. Areas with readings greater than 35 $\mu g/m^2$ were stripped of vegetation and topsoil, and the contaminated debris was shipped to the United States. Areas too rough to plow were turned under by hand. Following decontamination, air concentrations in the vicinity were the same as those expected from worldwide fallout of plutonium. Crop uptake was so low that consumption presented no hazard to consumers (Fowler et al. 1968; Buchholtz et al. 1971).

Wallace and Romney (1975) discussed problems subsequent to the plowing program. The plowing brought an excess of soluble salts to the soil surface, with adverse effects on crop production.

The crash of a Strategic Air Command B-52 bomber near Thule Air Force Base in Greenland resulted in contamination of 238 km^2 with 3100 g of plutonium (Langham 1968; Jordan 1971; Wallace and Romney 1975). Road graders were used to windrow the frozen ice and snow. Mechanized loaders were used to place the contaminated material into boxes for shipment to the United States. An area of ~70 km^2 was cleared to a depth of 4 in. (0.1 m).

2.3 EXPERIMENTAL STUDIES

Two experimental studies are relevant to the cleanup problem at NTS. The Stoneman II Tests of Reclamation Performance investigated a variety of proposed decontamination procedures, each applicable to a specific simulated level of fallout contamination on various land target surfaces (Lee et al. 1959). A synthetic fallout labeled with ^{140}La was applied to four soil surfaces: (1) moist green grass; (2) moist tilled surface; (3) dry tilled surface; and (4) dry, hard surface with withered vegetation. Decontamination effectiveness was dependent on terrain type. Soil with deep cracks and fissures (in which contamination was deeper than the removed surface layer) and soils with non-cohesiveness were the most difficult to decontaminate during first pass. On all terrain types used in the experiments, decontamination ratios of ≤ 0.01 were obtained by successive cycle application of the scraper and grader plus scraper reclamation methods.

Experiments on the physical removal of radioactive surface contamination were also conducted at the U.S. Department of Agriculture Agricultural Research Center at Beltsville, Maryland (Menzel and James 1959). In the first part of the experiment, contaminated sod, standing crops, and straw mulch were removed. In the second series, more applicable to NTS, contaminated soil was removed from fields of silt loam and sandy loam. Surfaces were contaminated with ^{140}La or ^{32}P. The percentages of decontamination achieved by scraping with a road grader following the various pretreatments are indicated in Table 4. Scraping was done with a road grader with a 7-ft (2.1-m)-wide blade. Over 98% decontamination was achieved by scraping off 3–4 in. (0.08–0.1 m) of surface soil when the surface was relatively smooth before contamination. The use of asphalt coatings on the soil in conjunction with scraping was of no benefit.

2.4 EQUIPMENT

For ground-based in situ measurements of plutonium utilizing the gamma activity of ^{241}Am, EG&G employed IMP vehicles, tracked all-terrain vehicles manufactured by Thiokol Corporation. The monitoring system consists of a high-purity germanium detector mounted on the end of a retractable mast, an amplifier, a 4096-channel analyzer, and a computer for spectrum analyses and data recording (Giacomini and Miller 1981). IMPs were used to monitor cleanup activity at both NTS and Enewetak Atoll.

Cleanup equipment used at each site and manufacturer's name, where available, are listed in Table 5. Barbier (1981) lists existing machinery, used in other industrial operations, that could be used for large-scale outdoor decontamination operations. He lists vacuum trucks made by TYMCO and FMC. Other manufacturers of vacuum equipment are General Resource Corp., Drum Engineering, Inc., The Hayden Co., Super Products, ULTRAVAC-DP Way Corp., Peabody Myers, Vacuum Inductors, The Kleener Kleener Corp., AI Research, Inc., NFE International Ltd., Wm. W. Meyer & Sons, Inc., Rich Mac Systems, Vacuum Truck Equipment Co., Inc., and Huber Mfg. Co. In addition, earth moving equipment designed for other reclamation projects may be of interest for use at NTS. A 40-ft (12.2-m) Balderson blade mounted on a Caterpillar D-9 tractor was specifically designed for reclaiming area-mined coal spoil piles (Anonymous 1975). The scraper moves ~6000 yd^3/h (4587 m^3/h). A 24 ft (7.3 m) wide grading bar that mounts on a Caterpillar D-8 crawler tractor can be used to smooth level 7 acres/h (28,328 m^2/h).

2.5 CHEMICAL AND PHYSICAL METHODS

As alternative methods to soil removal and/or plowing, several chemical and physical methods for stabilizing, immobilizing, or removing radioactivity from soil have been proposed. With the exception of methods used at NTS, most of these methods have been tested only in the laboratory or on uranium mill tailings, the latter test encompassing smaller areas than those at NTS.

Early experiments at NTS involved the use of road oil on soil to decrease the probability of plutonium resuspension. According to Wallace and Romney (1975), the road-oil treated areas appeared to be no different from nontreated areas 17 years later, except for the remaining oil.

Table 4. Percentage of decontamination by scraping surface soil following various treatments

Number of cuts with grader	Asphalt spray	Soil preparation					
		Plowed		Disked		Seedbed	
		Rolled	Not rolled	Rolled	Not rolled	Rolled	Not rolled
		Sassafras sandy loam					
1	Yes	75	96	66	70	82	99
1	No	85	68	60	80	62	100
2	No	89	100	95	100	93	100
		Elkton silt loam					
1	Yes	91	69	88	89	99	92
1	No	98	84	91	91	94	96
2	No	87	91	100	86	100	100

Source: Reprinted with permission from R. G. Menzel and P. E. James, "Physical Removal of Radioactive Surface Contamination from Agricultural Land," pp. 45–59 in *Proceedings of the Thirty-fifth Annual Meeting of the National Joint Committee on Fertilizer Application*, National Plant Institute, Washington, D.C., 1959.

Although the oil surface had broken up, in most cases the soil remained stabilized in pieces from ½ to 2 in. (1.3 to 5.1 cm) in thickness.

In addition to road oil, a number of other substances can be used as fixatives, including asphalt, diesel oil, and MC-70 (Tawil and Bold 1983). Dust control materials include generic products such as calcium chloride, magnesium chloride, and calcium lignosulfonate and proprietary products such as Coherex and Compound SP. Road oil, MC-70, magnesium chloride, and calcium lignosulfonate have been used at NTS. Fixatives and the manufacturer's name, where available, are listed in Table 6. Several of the products have been used, or suggested, for stabilization of uranium mill tailings. Some of the products need to be evaluated in terms of their effects on plants and animals.

Soil decontamination by leaching was tested at NTS by Pinson et al. (1957). Leaching with 1 in. (2.5×10^{-2} m) of water, 0.3 in. (7.6×10^{-3} m) water containing $FeCl_3$, 0.3 in. (7.6×10^{-3} m) of water, and 0.3 in. (7.6×10^{-3} m) of water with Alconox detergent resulted in decontamination efficiencies of 85, 84, 33 and 3%, respectively.

Horton and Albenesius (1976) conducted a series of experiments to test the feasibility of separation of plutonium-contaminated soil into plutonium-rich and -depleted fractions. Water-scrubbing and washing of a sample of soil from the Savannah River Plant burial ground separated out a clay-silt fraction containing ~95% of the plutonium but constituting only one-third of the total soil.

The use of sorting and scrubbing to remove plutonium contamination from soils was reviewed by Stevens et al. (1982), who cite work at Rockwell International that has included wet and dry

Table 5. Equipment used for cleanup of radioactively contaminated sites

Equipment	Manufacturer
1. Nevada Test Site	
Vacuum cleaner: VAC/ALL, E5-16;	Central Engineering
small industrial model	Tornado
Scraper	R.G. LeTourneau
Harrow	Not given
Grader	Not given
Bulldozer	Not given
Motorscraper	Not given
Front-end loader	Not given
Remotely controlled small model vacuum cleaner and mobile manipulator	Not given
Road blader	Not given
Water truck (Air Force)	Not given
Road-oil truck (Air Force)	Not given
2. Carlsbad, New Mexico	
Front-end loader	Not given
Backhoe	Not given
3. Los Alamos, New Mexico	
Backhoe	International Harvester
Dump trucks	White, Chevrolet
Front-end loader	Not given
Crawler-tractor with ripper, blade	Not given
Water trucks	Not given
Scraper	Not given
Roller	Not given
4. Tatum Dome, Mississippi	
Front-end loaders	Not given
Clamshells	Not given
Backhoe	Not given
5. Enewetak	
Plow pulled by tractor: D-8K	Caterpillar
Bucket loader	Not given
Bulldozer	Not given
Road grader	Not given
6. Camp Stoneman, California	
Scraper (towed): Type III, Model LS	R.G. LeTourneau
Tractor: Tourna	Westinghouse LeTourneau
Motorgrader: Model No. 994	Austin-Western
Bulldozer tractor: Model D-7	Caterpillar
7. Beltsville, Maryland	
Road grader	Massey-Ferguson
Tractors	Massey-Ferguson
Sod cutter	Massey-Ferguson
Forage chopper	Massey-Ferguson
Side-delivery rake	Massey-Ferguson
Plow	Massey-Ferguson
Disc and section harrows	Massey-Ferguson
Sidewalk and corrugated rollers	Massey-Ferguson

Table 6. Soil stabilizers

Product	Manufacturer	References
Road oil (rapid cure)	Not given	Baker et al. 1958, Dick and Baker 1967
Diesel, bunker, and dust oils	Not given	Tawil and Bold 1983
MC (petroleum product)	Not given	Tawil and Bold 1983
Polyurethane foam spray	Dow Chemical Company	Hornbacher et al. 1971, Lindsay et al. 1973
Resins (Geo Tech)	Southwest Consultants	Wallace and Romney 1975
Iron chloride, iron oxide	Master Builders, Columbus, OH	Pinson et al. 1957 Baker et al. 1958, Dick and Baker 1967 Wallace and Romney 1975
Krilium (an organic agent)	Monsanto Chemicals Company	Wallace and Romney 1975
Asphalt emulsion	Not given	Hartley et al. 1980
Elastomeric polymer (DCA-70)	Union Carbide	Havens and Dean 1969, Wallace and Romney 1975
Calcium lignosulfonate (Norlig A, Lignosite, Polybinder)	American Can Co., GA Pacific, IIT-Rainier, Polychem International, Inc.	Havens and Dean 1969, Wallace and Romney 1975, Tawil and Bold 1983
Calcilox cement	Dravo Corp., Pittsburgh, PA	Martin 1979
Soil binders (TURCO 5833, PetroSet)	Turco Products, Inc., not given	McKinley and McKinney 1978
Coherex (petroleum resins)	Witco Co.	Tawil and Bold 1983
Compound SP (polymer)	Johnson March, Inc.	Tawil and Bold 1983
Calcium chloride	Dow Chemical Co.	Tawil and Bold 1983
Magnesium chloride	Not given	Tawil and Bold 1983

screening, attrition scrubbing, ultrasonic scrubbing, chemical oxidation, calcination, deliming, flotation, and heavy liquid density separation. They also assessed the effectiveness of three scrub solutions on transuranic-contaminated soils from five Department of Energy sites. Solutions tested included (1) aqueous NaOH, pH of 12.5; (2) 2N HCl; and (3) 2 vol % of concentrated HNO_3, 0.2 vol % of concentrated HF; 2 vol % of pine oil and 5 wt % of Calgon. The success of decontamination, which was by physical and chemical means, depended on the type of soil. All soils showed an enrichment of activity in the fine fraction after scrubbing with the pH 12.5 solution; it did not solubilize the actinide contamination. The 2N HCl reagent solubilized soil constituents, removing contamination that had migrated into mineral surfaces. The third solution solubilized particulate actinide and actinide dispersed on the surface of soil particles.

Lee and Tamura (1981) characterized the physicochemical properties of contaminated soil from Area 20 of NTS in order to evaluate potential decontamination methods. More than 90% of the total radioactivity was recovered in 25% of the total sample weight by a grinding-sieving process. Lee and Tamura further suggested that radioactive particles might be removed from the contaminated soil by (1) a controlled vacuum collector, (2) density separation, (3) grinding-sieving separation, or (4) a combination of these techniques based on the density and compressibility differences between radioactive and nonradioactive particles.

3. REPRESENTATIVE COSTS OF CLEANUP AND TREATMENT OF CONTAMINATED AREAS

3.1 ESTIMATING COSTS PER UNIT OPERATION FOR HAZARDOUS WASTE SITES

Cleanup consists of initial monitoring to establish the extent and type of contamination, planning and execution of cleanup procedures, disposal of contaminated wastes, stabilization of the site, and monitoring to ascertain the success of the cleanup. One attempt to develop a consistent cost methodology for cleanup is that described by Rishel et al. in a 1982 U.S. Environmental Protection Agency (EPA) report. Although their study was concerned with hazardous waste sites, and not with radioactive site cleanup, it does provide a description of how cost estimation methodologies can be developed. It may be possible, then, to adapt their methods to radioactively contaminated sites such as Nevada Test Site.

To arrive at a cost methodology that would be applicable to any type of hazardous waste cleanup, Rishel et al. 1982 examined such projects at some 35 uncontrolled landfill or impoundment disposal sites across the United States dividing them into comparable components and subcomponents for comparisons between sites, and costing each component separately. This procedure was developed so that costs for other projects could be estimated by identifying the components involved and consulting their cost-per-component data. Component costs for one site in Newark, New Jersey, were calculated, and U.S. upper and lower costs were estimated in order to provide a range of values for comparison. Price lists for labor, materials, transportation, etc. were compiled primarily from the Dodge and Means Guides (McMahon 1979; Robert S. Means Company 1979) for both English and metric units, and regionally adjusted using indices provided in the Dodge Guide. Costs for overhead and contingencies were not included in these total costs but were calculated by summing all the components within a unit operation to obtain a subtotal capital cost. From this subtotal capital costs, an overhead allowance (25%) and a contingency allowance (10 to 40%, depending upon the extent to which component requirements can be precisely estimated) were obtained. The subtotal capital cost plus overhead and contingency allowances represent the estimate of total unit operation cost. Tables B.1 through B.7 in Appendix B are taken from the EPA report by Rishel et al. 1982 and show the unit for which costs were estimated, costs per unit, sources of the cost data, U.S. upper and lower average costs per unit, and costs per unit at Newark, New Jersey, for the various components identified by the authors.

3.2 COSTS FOR SITE STABILIZATION, LONG-TERM CARE, AND WASTE RELOCATION

As a part of the process of developing information to support the preparation of standards covering decommissioning of nuclear facilities, the Nuclear Regulatory Commission undertook studies on the technology, safety, and costs of decommissioning reference nuclear facilities. One of these studies (Murphy and Holter 1980) involved the conceptual decommissioning of commercial low-level waste burial grounds. Two generic burial grounds, one located on an arid western site and the other on a humid eastern site, were used as reference facilities in the study. The climate, geology, and hydrology of the sites were chosen to be typical of western and eastern sites. Each reference burial ground was assumed to occupy ~70 ha and included 180 trenches with a total of 1.5×10^6 m^3 of radioactive waste. The basic options considered in the study are site/waste stabilization followed by long-term care of the site and waste relocation. Three plans were evaluated for each site: (1) a minimal plan includes site inspection, stabilization of trenches and damaged areas, and vegetation management; (2) a modest plan includes capping, revegetation, and vegetation management; and (3) the complex plan includes a subsurface rock layer with hard top, increased capping thickness, revegetation, and vegetation management. Estimated costs for each plan are found in Table 7. Long-term care for the reference site includes administrative control, environmental surveillance, and site maintenance. Costs for long-term care at an arid western site are estimated in Table 8. Information on costs estimates at a humid eastern site is included in the report by Murphy and Holter (1980). Waste relocation involves exhumation of the buried waste, repackaging the waste if necessary, and reburial of the waste at a deep geologic disposal site in a shallow-land burial ground, or in another trench on the same site. Cost estimates for waste relocation are found in Table 9.

Table 7. Estimated costs of site stabilization (arid western site)

	Cost of plan[a,b] ($ millions)		
Cost category	Minimal	Modest	Complex
Manpower			
Support staff	0.298	0.704	0.770
Decommissioning workers	0.066	0.360	0.859
Contractor's equipment	0.035	0.374	0.870
Material and expendable equipment	0.071	0.905	4.558
Contractor's fee[c]		0.188	0.565
Miscellaneous owner expense[d]	0.008	0.018	0.020
Environmental monitoring	0.008	0.023	0.028
Records maintenance	0.001	0.006	0.006
Total (rounded)	0.5	2.6	7.7

[a]Number of figures shown is for computational accuracy only and does not imply precision to the nearest thousand dollars.
[b]Costs include 25% contingency.
[c]Based on 8% of the sum of manpower, equipment, and material costs.
[d]Includes utilities, insurance, and taxes.

Source: Murphy, E. S. and G. M. Holter, *Technology, Safety and Costs of Decommissioning a Reference Low-Level Waste Burial Ground*. NUREG/CR-0570, Vol. 1, Pacific Northwest Laboratory, Richland, Wash., 1980.

Table 8. Summary of estimated long-term care costs

Stabilization plan preceding long-term care	Costs for time period[a,b] (millions of constant 1978 dollars) 0-5 Years after stabilization		6-25 Years after stabilization		26-200 Years after stabilization		Total costs for 200 Years (in millions of constant 1978 dollars)
	Annual	Total	Annual	Total	Annual	Total	
Minimal and modest plans for the western site	0.162	0.808	0.106	2.122	0.078	13.580	16.5
Complex plan for the western site	0.230	1.150	0.100	2.000	0.072	12.512	15.7

Source: Murphy, E. S. and G. M. Holter. *Technology, Safety and Costs of Decommissioning a Reference Low-Level Waste Burial Ground.* NUREG/CR-0570, Vol. 1, Pacific Northwest Laboratory, Richland, Wash. 1980.

3.3 COSTS FOR STABILIZATION OF FINE-SIZED MINERALS

The U.S. Bureau of Mines has issued a report (Dean, et al. 1974) on the estimated cost for stabilizing fine-sized mineral wastes at a reference uranium mill tailings site. These wastes represent the most difficult materials to stabilize. The principal methods for stabilization of these wastes include physical covering of the tailings with soil or other restraining materials, the chemical use of a material to interact with fine-sized minerals to form a crust, and the growth of plants in the tailings. Costs of these three methods plus a fourth which involves a combination of chemical reaction and revegetation are presented in Table 10. Note that the publication date for this report is 1974, and the cost estimates are more than 10 years out of date.

3.4 COSTS OF FIXATIVES

A Pacific Northwest Laboratory report (Tawil and Bold 1983) quotes 1983 price estimates for fixatives suitable for use on radioactively contaminated surfaces. The fixatives in Group 1 act by the formation of membrane layers over the surface and those in Group 2 act to bind particles by absorbing into them. Information on these fixatives is contained in Table 11.

Comments on the durability of these various fixatives are as follows:

1. Road oil is durable for 20 years or more.
2. Membranes formed with the MCs break under foot or vehicle traffic.
3. Emulsified asphalt produces reduced penetrating power compared with MCs and tends to ball up with vehicle traffic.
4. The first application of Coherex is durable for 6 months and successive applications for 1 year on surfaces with load.
5. SP-301 is durable for 1 year and SP-400 for 3 years.

Table 9. Estimated costs of relocation of all the waste from a conventional burial trench (western site)

Relocation procedure	Cost ($ millions)[a,b] Excavation from above the trench	Excavation from within the trench
Deep geologic disposal		
Exhumation	0.582	0.465
Waste management	43.280	43.280
Total (rounded)	43.9	43.7
Shallow-land burial		
Exhumation	0.582	0.465
Waste management	7.220	7.220
Total (rounded)	7.8	7.7
Reburial onsite		
Exhumation	0.582	0.465
Waste management	0.165	0.165
Total (rounded)	0.75	0.63

[a]Number of figures shown is for computational accuracy only and does not imply precision to the nearest thousand dollars.
[b]Costs include 25% contingency.

Source: Murphy, E. S. and G. M. Holter. *Technology, Safety and Costs of Decommissioning a Reference Low-Level Waste Burial Ground.* NUREG/CR-0570, Vol. 1; Pacific Northwest Laboratory, Richland, Wash., 1980.

6. Calcium chloride is durable for ~6 months but requires frequent moistening in arid climates.
7. Liquidow is durable for 1½ months, magnesium chloride for 3 months, polybinder for 3 months, and lignosite for 1 year.

3.5 COSTS OF URANIUM MILL TAILINGS STABILIZATION

The Uranium Mill Tailings Remedial Action Program produced a number of reports (FBDU 1981a-f) that include costs. Table 12 includes estimates for a few of these sites that are representative of those in arid regions and for which figures for tons of material to be relocated are available. The authors of the report do not consider stabilization with 3 m cover a viable option, but cost data for doing so are included for comparison with that of other methods.

Table 10. Cost comparison of stabilization methods for fine-sized minerals[a]

Type of stabilization	Effectiveness	Maintenance	Approximate cost per acre ($)
Physical			
Water sprinkling	Fair	Continual	
Slag (9-in. depth)			
By pumping	Good	Moderate	350–450
By trucking	Good	Moderate	950–1050
Straw harrowing	Fair	Moderate	40–75
Bark covering	Good	Moderate	900–1000
Country gravel and soil			
4-in. depth	Excellent	Minimal	250–600
12-in. depth	Excellent	Minimal	700–1700
Chemical			
Elastomeric polymer	Good	Moderate	300–750[b]
Lignosulfonate	Good	Moderate	250–600[b]
Vegetative			
4-in. soil cover and vegetation[c]	Excellent	Minimal	300–650
12-in. cover and vegetation[d]	Excellent	Minimal	750–1750
Hydroseeding	Excellent	Minimal	200–450
Matting[e]	Excellent	Minimal	600–750[b]
Chemical-vegetative	Excellent	Minimal	120–270[b]

[a]Based on average tailings, costs could be revised upwards for acidic requiring limestone or other neutralizing additives.

[b]The first data are derived bureau-industry costs, based upon cooperative stabilization efforts; the remaining cost data were obtained directly from industry.

[c]Generally used on pond areas rather than on dikes. Also, not as effective as 12-in. soil cover when tailings are excessively acidic or saline.

[d]Substantiated as the optimum economic depth of soil cover when reclaiming bauxite-mined lands with soil covers ranging from 6 to 24 in., although a lesser soil cover may be satisfactory on other types of waste materials.

[e]Based on placing 3-ft-wide matting at 3-ft intervals over the seeded area.

Source: Dean, K. C., Havens, R., and Glantz, M. V. *Methods and Costs for Stabilizing Fine-Sized Mineral Wastes.* U.S. Bureau of Mines Report of Investigations 7896, 1974.

Variation in the estimates for relocation over distances of from 1 to 30 miles (1.6 to 48.3 km) appears to depend upon already existing access roads, already excavated pits for disposal, and the availability and type of cover material.

Options for disposal listed in Table 12 provide for relocation of all debris and contaminated materials from tailings piles and off-site locations.

Table 11. Cost estimates for fixatives suitable for use on radioactively contaminated surfaces

Fixative	Manufacturer	Cost ($/m^2)
Group 1		
MC-100	Chevron	0.34
MC-70	Shell	0.07–0.39
MC-70	Representative	0.31
Emulsified asphalt	Chevron	0.134–0.185
Emulsified asphalt	Shell	0.27–0.29
Compound SP-301	Johnson March	0.23
Compound SP-400	Johnson March	0.425
Group 2		
Road oil	WA State DOT	0.31
Road oil	Chevron	0.32–0.37
Diesel	Chevron	0.215
Bunker oil	Chevron	0.148–0.213
Emulsifier dust oil	Chevron	0.149
Coherex	Witco	0.142
Calcium chloride (Pelladow)	Van Waters & Rogers	0.212
Liquidow	Dow	0.412
Magnesium chloride	Burris Oil	0.60
Polybinder	Burris Oil	0.239
Polybinder	Polychem	0.224
Lignosite	Georgia Pacific	0.06
Lignosite	Yakima Co.	0.05

Source: Tawil, J. and F. C. Bold, *A Guide to Radiation Fixatives*, PNL-4903, Pacific Northwest Laboratory, Richland, Wash., 1983.

Table 12. Estimated costs to move contaminated soil

Site	Acres	Tons material	Cost to move ($) 5 miles or less	5-15 miles	15 miles or more	Stabilization with 3-m cover
Spook, Wyoming	5	187,000	1,510,000	1,700,000	1,950,000	710,000
Tuba City, Arizona	22	800,000	21,600,000	22,300,000	23,100,000	17,800,000
Mexican Hat,	43	1,320,000				
Utah	25	880,000	29,900,000	34,600,000	45,500,000	15,200,000
Shiprock,	46	600,000	25,600,000	27,000,000	34,100,000	13,400,000
New Mexico	26	1,050,000		30,000,000	37,900,000	
Grand Junction, Colorado	61.3	1,900,000	23,000,000-28,500,000	39,500,000[a] 41,900,000[b]		
Monument Valley, Arizona	10	165,000	14,300,000	14,900,000	15,900,000	6,600,000
	20	935,000				

[a]Transportation by rail.
[b]Transportation by truck.

4. REFERENCES

Ahlquist, A. J. 1981. "Los Alamos Scientific Laboratory Experience in Decontamination of the Environment," pp. 46–60 in *Environmental Decontamination, Proceedings of a Workshop*, CONF-791234, Oak Ridge, Tenn.

Ahlquist, A. J., A. K. Stoker, and L. K. Trocki. 1977. *Radiological Survey and Decontamination of the Former Main Technical Area (TA-1) at Los Alamos, New Mexico*, LA-6887.

Anonymous. 1975. "Innovative Earthmoving Tools Make P&M Coal Reclamation Project More Economical," *Coal Age* (Nov.) 76–79.

Baker, T. P., B. B. Boecker, and J. L. Dick. 1958. *Aircraft Accidents Involving Plutonium Contamination*, AFSWC-TN-583.

Barbier, M. M. 1981. "Machine Technology: A Survey," pp. 243–53 in *Environmental Decontamination, Proceedings of a Workshop*, CONF-791234, Oak Ridge National Laboratory, Oak Ridge, Tenn,

Barker, C. J. 1982. *Removal of Plutonium-Contaminated Soil from the 903 Lip Area During 1976 and 1978*, RFP-3226, Rockwell International,

Barnes, M. G., and J. J. Giacomini. 1982. "Radiological Condition of Islands," pp. 203–341 in *Enewetak Radiological Support Project, Final Report*, ed. B. Friesen, NVO-213,

Bicker, A. E. 1981. "Site Decontamination," pp. 91–99 in *Environmental Decontamination, Proceedings of a Workshop*, CONF-791234, Oak Ridge National Laboratory, Oak Ridge, Tenn.

Brown, B. L., J. L. Gardner, K. H. Guinn, C. H. Johnston, and R. D. Scanlon. 1961. *Documentation of Alpha Contamination at the Nevada Test Site*, RRS-61-7, Reynolds Electrical and Engineering Co., Inc.

Brown, B. L., C. R. Penwell, W. E. Moore, F. J. Sanders, and O. W. Mullen. 1964. *Decontamination of Large Land Areas and Roadways at the Nevada Test Site*, RRS-64-3. (Cited in Wallace and Romney 1975).

Buchholz, J. R., W. H. Adams, C. W. Christenson, and E. B. Fowler. 1971. *More on the Pu Particle Size Problem*, Report LADC-12898. (Cited in Wallace and Romney 1975).

Burnett, W. D., H. L. Rarrick, and G. E. Tucker. 1964. *Health Physics Aspects of Operation Roller Coaster*, SC-4973(RR).

Church, B. W. 1974. "What Can Be Learned from the Cleanup of the Tatum Dome Test Site, Hattiesburg, Mississippi," pp. 727–64 in *Second AEC Environmental Protection Conference*, WASH-1332.

Church, B. W. 1981. "Nevada Operations Overview," pp. 61–70 in *Environmental Decontamination: Proceedings of a Workshop*, CONF-791234, Oak Ridge National Laboratory, Oak Ridge, Tenn,

Clark, H. W. 1983. *An Aerial Radiological Survey of Area 11 Nevada Test Site*, EGG-10282-1004.

Corey, J. C., J. E. Pinder, and D. C. Adriano. 1978. *Effect of Disking and Other Agricultural Practices on the Distribution of Surface Deposited Plutonium in Soil*, Environmental Transport and Effects Research Annual Report, DP-1526, Savannah River Laboratory, pp. 173–174.

Dean, K. C., R. Havens, and M. V. Glantz. 1974. *Methods and Costs for Stabilizing Fine-Sized Mineral Wastes*, U.S. Bureau of Mines Report of Investigations 7896.

Defense Nuclear Agency. 1975. *Environmental Impact Statement. Cleanup, Rehabilitation, Resettlement of Enewetak Atoll—Marshall Islands*, Vol. 3, Washington, D.C.

Dick, J. L. and T. P. Baker. 1967. *Monitoring and Decontamination Techniques for Plutonium Fallout on Large Scale Surfaces: Operation Plumbbob*, Report WT-1512. (Cited in Wallace and Romney 1975).

Dunaway, P. 1982. "Plowing Philosophy and Experiment," pp. 171–73 in *Enewetak Radiological Support Project, Final Report*, ed. B. Friesen, NVO-213.

Dunaway, P. B., and E. R. Sorom. 1982. "Experience in Cleanup of Old Radioactive Sites. 1. Cleanup Trial in the NTS Plutonium Valley," *Trans. Amer. Nucl. Soc.* **43**, 56.

Essington, E. H., E. B. Fowler, R. O. Gilbert, and L. L. Eberhardt. 1976. "Plutonium, Americium and Uranium Concentrations in Nevada Test Site Soil Profiles," *Transuranium Nuclides in the Environment*, IAEA-SM-199/76, pp. 175–73.

FBDU. 1981a. *Engineering Assessment of Inactive Uranium Mill Tailings, Grand Junction, Colo.*, FBDU 360-09, Ford, Bacon & Davis Utah, Inc., Salt Lake City, Utah.

FBDU. 1981b. *Engineering Assessment of Inactive Uranium Mill Tailings, Mexican Hat, Utah.* FBDU 360-03, Ford, Bacon & Davis Utah, Inc., Salt Lake City, Utah.

FBDU. 1981c. *Engineering Assessment of Inactive Uranium Mill Tailings, Monument Valley, Ariz.*, FBDU 360-04, Ford, Bacon & Davis Utah, Inc., Salt Lake City, Utah.

FBDU. 1981d. *Engineering Assessment of Inactive Uranium Mill Tailings, Shiprock Site, NM, FBDU 360-02, Ford, Bacon & Davis Utah, Inc., Salt Lake City, Utah.*

FBDU. 1981e. Engineering Assessment of Inactive Uranium Mill Tailings, Spook Site, Converse County, Wyo. FBDU 360-15, Ford, Bacon & Davis Utah, Inc., Salt Lake City, Utah.

FBDU. 1981f. *Engineering Assessment of Inactive Uranium Mill Tailings, Tuba City, Ariz.* DOE/UMT-0120, Ford, Bacon & Davis Utah, Inc., Salt Lake City, Utah.

Fore, C. S, R. A. Faust, and R. H. Brewster. 1982. *Cleanup and Treatment of Radioactively Contaminated Land Including Areas Near Nuclear Facilities: A Selected Bibliography*, ORNL/EIS-199, NVO/AEIC-243,

Fowler, E. B., J. R. Buchholz, C. W. Christenson, W. H. Adams, E. R. Rodriguez, J. M. Celma, E. Iranzo, and C. A. Ramis. 1968. *Soils and Plants as Indicators of the Effectiveness of a Gross Decontamination Procedure*, Report LA-DC-9544. (Cited in Wallace and Romney 1975).

Frieson, B. 1982. Pilot Soil Removal Project. In: B. Friesen (Ed.), Enewetak Radiological Support Project, Final Report. NVO-213.

Fritzsche, A. E. 1979. *An Aerial Radiological Survey of Area 13 Nevada Test Site*, EGG-1183-1752.

Fritzsche, A. E. 1982. *An Aerial Radiological Survey of Areas 1–10, 12, 15, and 17*, EGG-1183-1808.

Giacomini, J. J., and F. L. Miller, Jr. 1981. "Statistical Aspects of the Cleanup of Enewetak Atoll," pp. 100–103 in *Environmental Decontamination, Proceedings of a Workshop, CONF-791234, Oak Ridge National Laboratory, Oak Ridge, Tenn.*

Gilbert, R. O. 1977. "Revised Total Amounts of ^{239,240}Pu in Surface Soil at Safety-Shot Sites," pp. 423–29 in *Transuranics in Desert Ecosystems*, ed. M. G. White, P. B. Dunaway, and D. L. Wireman, NVO-181.

Gilbert, R. O., L. L. Eberhardt, E. B. Fowler, E. M. Romney, and E. H. Essington. 1975. *Statistical Design and Analysis of Environmental Studies for Plutonium and Other Transuranics at NAEG "Safety-Shot" Sites*, BNWL-SA-5505, CONF-751105.

Graves, A. W. 1981. "Soil Surface Decontamination and Revegetation Process," pp. 152–66 in *Environmental Decontamination, Proceedings of a Workshop*, Oak Ridge National Laboratory, Oak Ridge, Tenn.. CONF-791234.

Gunderson, T. C., and A. J. Ahlquist. 1979. *Formerly Utilized MED/AEC Sites Remedial Action Program: Removal of a Contaminated Industrial Waste Line,* Los Alamos Scientific Laboratory, Los Alamos, New Mexico, DOE/EV-0005/14.

Hartley, J. M., P. L. Koehmstedt, J. D. Esterl, H. D. Freeman, and R. L. Clark. 1980. "Applications of Asphalt Emulsion Salts to Uranium Mill Tailings," pp. 39–56 in *3rd Symposium on Uranium Mill Tailings Management*, CONF-801155.

Havens, R. and K. C. Dean. 1969. *Chemical Stabilization of the Uranium Tailings at Tuba City, Arizona*, U.S. Bureau of Mines Report of Investigations 7288.

Hornbacher, D. D., R. M. Saiki, and C. T. Illsley. 1971. *Status of Soil Stabilization Evaluation Program*, International Report of Dow Chemical Company, Golden, Colo. (Cited in Wallace and Romney 1975).

Horton, J. H., and E. L. Albenesius. 1976. "Volume Reduction of Plutonium-Contaminated Soil," *Nucl Tech.* **30**, 86–88.

Jobst, J. E. 1979. *An Aerial Radiological Survey of Clean Slates 1, 2, and 3, and Double Track, Tonopah Test Range, Central Nevada*, EGG-1183-1737.

Jordan, H. S. 1971. "Distribution of Plutonium from Accidents and Field Experiments," pp. 24–24 in *Proceedings of Environmental Plutonium Symposium*, LA-4756.

Kinnison, R. R., and R.O. Gilbert. 1980. *Estimates of Soil Removal for Cleanup of Transuranics at NAEG Offsite Safety-Shot Sites*, PNL-SA-8267.

Kordas, J. F. and L. R. Anspaugh. 1982. *Nevada Test Site Radionuclide Inventory and Distribution Plan—Project Operations Plan*, UCID-19413, Lawrence Livermore Laboratory.

Langham, W. H. 1968. *The Problem of Large-Area Plutonium Contamination*, Seminar Paper No. 002, National Center for Radiological Health Seminar, Rockville, Md.

Lee, H., J. D. Sartor, and W. H. Van Horn. 1959. "Stoneman II Test of Reclamation Performance," Vol. IV, Performance Characteristics of Land Reclamation Procedures, USNRDL-TR-337.

Lee, S. Y., and T. Tamura. 1981. "Distribution and Characterization of Radionuclides in Soils from the Nevada Test Site." *J. Environ. Qual.* **10**(2), 234–39.

Lindsay, J. W., D. E. Michaels, and J. A. Martinez. 1973. *Scavenging Contaminated Soil with Polyurethane Foam*, RFP-1949, Dow Chemical Company.

Martin, D. 1979. "Asphalt and Cement Promise Savings in Stabilization of Mill Tailings," *Nuclear Fuel* **4**(8), 13–14.

Martin, W. E. and S. G. Bloom. 1977. "Nevada Applied Ecology Group Model for Estimating Plutonium Transport and Dose to Man," pp. 621–706 in *Transuranics in Natural Environments*, NVO-178.

McKinley, K. B., and J. D. McKinney. 1978. *Early Waste Retrieval Interim Report*, TREE-1265.

McKnight, R. K., C. E. Rosenberry and J. A. Orcutt. 1984. *Nevada Test Site Area 25 Radiological Survey and Cleanup Project, 1974–1983, Final Report.* DOE/NV/10327-5.

McMahon, L. A. 1979. *1980 Dodge Guide to Public Works and Heavy Construction Costs*, McGraw-Hill, N.Y.

Menzel, R. G. and P. E. James. 1959. "Physical Removal of Radioactive Surface Contamination from Agricultural Land." pp. 45–59 in *Proceedings of the Thirty-fifth Annual Meeting of the National Joint Committee on Fertilizer Application*, National Plant Institute, Washington, D.C.

Miller, C. F. 1958. *The Radiological Assessment and Recovery of Contaminated Areas*, CEX-57.1.

Murphy, E. S., and G. M. Holter. 1980. *Technology, Safety and Costs of Decommissioning a Reference Low-Level Waste Burial Ground*, NUREG/CR-0570, vol. 1, Pacific Northwest Laboratory, Richland, Wash.

Orcutt, J. A. 1982. *Cleanup and Treatment (CAT) Test: A Land Area Decontamination Project Utilizing a Vacuum Method of Soil Removal*, DOE/NV/00410-70.

Pinson, E. A., R. F. Merian, B. B. Boecker, and J. L. Dick. 1957. *Operation Plumbob—Test Group 57, Program 73, Monitoring and Decontamination Techniques for Plutonium Fallout on Large-Area Surfaces*, ITR-1512-DEL.

Rarrick, H. L. 1972. "Weapons Effects Tests--Planned Emergencies," pp. 1573–80 in *Health Physics Operational Monitoring*, eds. C.A. Willis and J.S. Handloser, CONF-690103.

Reynolds Electrical & Engineering Co., Inc. 1980. *Nevada Test Site Radioactive Waste Management Consolidation Plan*, Completion Report, Fiscal Year 1980.

Reynolds Electrical & Engineering Co., Inc. 1983. *Nevada Test Site Radioactive Waste Consolidation Plan*, Completion Report, Fiscal Year 1983.

Rishel, H. L., T. M. Boston, and C. J. Schmidt. 1982. *Costs of Remedial Response Actions at Uncontrolled Hazardous Waste Sites*, EPA-600/2-82-035, SCS Engineers, Long Beach, Calif., pp. 22–25, and Tables, pp. 125–44).

Robert S. Means Company. 1979. *Building Construction Cost Data 1980*, Duxbury, Miss.

Sanders, F. 1966. *Decontamination of Test Cell C at the Nuclear Rocket Development Station*, Report LA-3633-MS, (Cited in Wallace and Romney 1975).

Smith, W. J., E. B. Fowler, and R. G. Stafford. 1977. *Experience in the Cleanup of Plutonium-Contaminated Land*, LA-6731-MS.

Stevens, J. R., R. L. Kochen, and D. W. Rutherford. 1982. *Comparative Scrub Solution Tests for Decontamination of Transuranic Radionuclides from Soils*. Rockwell International Report RFP-3161.

Straume, T., C. R. Kellner, and K. M. Oswald. 1977. *Cleanup of Radioactive Mud Spill U20aa Postshot Drilling Site, NTS*, UCID-17423.

Straume, T., C. R. Kellner, and K. M. Oswald. 1978. "Radioactive Decontamination Methods and Their Effectiveness as a Function of Terrain," *Health Physics* **35** 309–14.

Tawil, J. and F. C. Bold. 1983. *A Guide to Radiation Fixatives*, PNL-4903, Pacific Northwest Laboratory, Richland, Wash.

Tipton, W. J. 1979. *An Aerial Radiological Survey of Areas 25 and 26, Nevada Test Site*. EGG-1183-1745, EG&G Energy Measurements Group.

Tipton, W. J., A. A. Fritzsche, R. J. Jaffe, and A. E. Villaire. 1981. *An in situ Determination of ^{241}Am on Enewetak Atoll*, EGG-1183-1778, EG&G Energy Measurements Group.

Wallace, A. and E. M. Romney. 1975. "Feasibility and Alternate Procedures for Decontamination and Post-Treatment Management of Pu-Contaminated Areas in Nevada." UCLA-12-973 (1974). pp. 251–337 in *The Radioecology of Plutonium and Other Transuranics in Desert Environments*, eds. M. G. White and P. B. Dunaway, NVO-153.

Wallace, A., and E. M. Romney. 1977. "Initial Land Reclamation Procedures Related to Possible Pu-Cleanup Activities at the Tonopah Test Range." UCLA-12-1054, and pp. 65–77 in *Environmental Plutonium on the Nevada Test Site and Environs*, NVO-171.

U.S. Department of Energy. 1983. *Announced United States Nuclear Tests*, NVO-209.

APPENDIX A
ADDITIONAL PUBLICATIONS CONTAINING COST DATA

An extensive search was made for cost data of use to those who will be cleaning up radioactively contaminated sites. In addition to reports listed in the bibliography, some cost data were found in the following publications:

Ahlquist, A. J., A. K. Stoker, and L. K. Trocki. 1977. *Radiological Survey and Decontamination of the Former Main Technical Area (TA-1) at Los Alamos, New Mexico*, LA-6887, Los Alamos Scientific Laboratory, Los Alamos, N.M.

Bechtel National, Inc. 1984. *Final Report on Remedial Action at the Acid/Pueblo Canyon Site Los Alamos, New Mexico,* Advanced Technology Division, DOE/OR/20722-15, Oak Ridge National Laboratory, Oak Ridge, Tenn.

Bengson, S. A. 1979. "Irrigation Techniques for Tailing Revegetation in the Arid Southwest," ASARCO, Inc., Mission Unit, Sahuarita, AZ, *Tailing Disposal Today*, Vol. 2, G. O. Argall, Jr. (Ed.), Proceedings of the Second International Tailing Symposium, Denver, Colo. May 1978, (pp. 487–503). Miller Freeman Publications, Inc., San Francisco, Calif.,

Chapin, J. A. 1979. *Characterization of the TAN-TSF Outside Areas, Final Report*, PR-W-79-031, EG&G Idaho, Inc., Idaho Falls, Idaho,

Church, B. W. 1981. "Nevada Operation Overview," Nevada Operations Office, US ERDA, Las Vegas, NV, CONF-79123; *Environmental Decontamination, Proceedings of a Workshop,* Oak Ridge National Laboratory, Oak Ridge, Tenn., December 4–5, 1979, pp. 61–6),

Dean, K.C., R. Havens, and K.T. Harper. 1969. *Chemical and Vegetative Stabilization of a Nevada Copper Porphyry Mill Tailing,* U.S. Bureau of Mines Report of Investigations 7261, Salt Lake City Metallurgy Research Center, Salt Lake City, Utah.

FBDU 1981. *Engineering Assessment of Inactive Uranium Mill Tailings, New and Old Rifle Sites, Rifle, Colorado,* DOE/UMT-0108, Ford, Bacon & Davis Utah, Inc., Salt Lake City, Utah.

FBDU 1981. *Engineering Assessment of Inactive Uranium Mill Tailings, Bowman Site, Bowman, N.D.*, DOE/UMT-0121, Ford, Bacon & Davis Utah, Inc., Salt Lake City, Utah.

FBDU 1981. *Engineering Assessment of Inactive Uranium Mill Tailings, Durango, Site, Durango, Colorado,* DOE/UMT-0103, FBDU 360-06, Ford, Bacon & Davis Utah, Inc., Salt Lake City, Utah.

FBDU 1981. *Engineering Assessment of Inactive Uranium Mill Tailings, Green River Site, Green River, Utah,* FBDU 360-14, Ford, Bacon & Davis Utah, Inc., Salt Lake City, Utah.

FBDU 1981. *Engineering Assessment of Inactive Uranium Mill Tailings, Gunnison Site, Gunnison, Colorado*, DOE/UMT-0107, FBDU 360-12, Ford, Bacon & Davis Utah, Inc., Salt Lake City, Utah.

FBDU 1981. *Engineering Assessment of Inactive Uranium Mill Tailings, Maybell Site, Maybell, Colorado,* DOE/UMT-0116, FBDU 360-11, Ford, Bacon & Davis Utah, Inc., Salt Lake City, Utah.

FBDU 1981. *Phase 2—Title 1 Engineering Assessment of Inactive Uranium Mill Tailings New and Old Rifle Sites, Rifle, Colorado*, GJT-10, FBDU 130-10, Ford, Bacon & Davis Utah, Inc., Salt Lake City, Utah.

Hartley, J. N., G. W. Gee, E. G. Baker, and H. D. Freeman. 1983. *1981 Radon Barrier Field Test at Grand Junction Uranium Mill Tailings Pile*, DOE/UMT-0213, PNL-4539, Pacific Northwest Laboratory, Richland, Wash.

Havens, R., and K. C. Dean. 1969. *Chemical Stabilization of the Uranium Tailings at Tuba City, Arizona*, U.S. Bureau of Mines Report of Investigations 7288, Salt Lake City Metallurgy Research Center, Salt Lake City, Utah,

Miller, R. L., W. F. Downs, and J. E. Flinn. 1979. *Preliminary Assessment for Decontamination of Idaho National Engineering Laboratory Radioactive Soils Using Chemical Extraction Processes*, RE-M-79-012, EG&G Idaho, Inc., Fuels and Materials Division, Las Vegas, Nev.,

Murray, D., and D. Moffert. 1977. *Vegetating the Uranium Mine Tailings at Elliot Lake, Ontario*, Canada Centre for Mineral and Energy Technology, Mining Research Laboratories. Elliot Lake Laboratory, Elliot Lake, Ontario, Canada, *Soil and Water Conservation* 32(4):171–174.

Smith, W.J., II, E. B. Fowler, and R. G. Stafford. 1977. *Experience in the Cleanup of Plutonium-Contaminated Land*, LA-6731-MS, Los Alamos Scientific Laboratory, Los Alamos, N.M.,

APPENDIX B
COMPONENT COST DATA FOR LANDFILL AND SURFACE IMPOUNDMENT OPERATIONS

Tables included in this appendix are taken from a 1982 U.S. Environmental Protection Agency report (EPA-600/2-035) prepared by Rishel et al. The tables contain a description of each component, with cost data for that component and costs for geographical areas in the United States (U.S. low and U.S. high) that were computed from the source data. Regional adjustments for costs were made using adjustment indices in the Dodge Guide (McMahon 1979). No regional adjustment index was available for equipment costs, so it was assumed that these costs are the same around the nation.

Table B.1 includes landfill capital cost component data. Overhead and maintenance costs for landfill operations are found in Table B.2. Tables B.3 and B.4 provide similar data for surface impoundment operations.

These cost data are provided as an example of component cost computation. It is suggested that the reader consult the EPA report for a more detailed description of the actual costing methodology.

Table B.1 Landfill capital cost components

Component	Subcomponent	Definition	U.S. Dollars			
			Metric units	Source cost	U.S. low	U.S. high
Apply stabilized	Installation	Hauling and spreading, 10 miles (16 km), round-trip	m^3	8.76	5.52	11.5
Area preparation	Labor	Rake and cleanup, average	ha	741	469	963
Area preparation	Equipment	Rake and cleanup, average	ha	222	222	222
Backfill	Labor	Dozer and sheepsfoot roller	m^3	0.51	0.32	0.64
Backfill	Equipment	Dozer and sheepsfoot roller	m^3	1.44	1.44	1.44
Bentonite, delivered	Materials/ shipping	Shipment of bentonite by rail	tonne	66.4	177	166
Berm construction	Materials/ installation	Use scraper	m^3	0.50	0.35	0.60
Blower	Materials/ installation	Blower, air	each	1,150	800	1,360
Butterfly valves, 6 in.	Materials/ installation	PVC valve	each	192	135	230
Butterfly valves, 8 in.	Materials/ installation	PVC valve	each	304	213	360
Cement pipe, 4 in. perforated	Labor	Asbestos, Class 4000 underdrain	m	3.00	1.90	3.18
Cement pipe, 4 in. perforated	Materials	Asbestos, Class 4000 underdrain	m	5.08	3.91	5.38
Cement pipe, 6 in. perforated	Labor	Asbestos, Class 4000 underdrain	m	3.10	1.95	4.06
Cement pipe, 6 in. perforated	Materials	Asbestos, Class 4000 underdrain	m	8.00	6.16	8.48
Cement pipe, 6 in.	Labor	Cement pipe, nonperforated	m	3.54	2.23	4.63
Cement pipe, 6 in.	Materials	Cement pipe, nonperforated	m	6.23	4.80	6.60
Chemicals	Materials	Treatment chemical, sodium hypochlorite (NaC10)	L	0.16	0.12	0.17
Deep wells, 6 in.	Materials/labor	Drilled and cased	m	20.9	14.6	25.1
Dewatering system	Materials/labor	For cost breakdowns, see "Discharge pipe," "Submersible pump," "Deep wells"				
Discharge pipe, 4 in.	Labor	PVC plastic, Schedule 40	m	22.0	13.9	28.8
Discharge pipe, 4 in.	Materials	PVC plastic, Schedule 40	m	9.15	7.05	9.70
Discharge pipe, 8 in.	Labor	PVC plastic, Schedule 40	m	34.1	21.5	44.7
Discharge pipe, 8 in.	Materials	PVC plastic, Schedule 40	m	27.4	21.1	29.0
Diversion ditch, construction	Installation	Construction and maintenance/ repair	m	2.78	1.75	3.63
Drilled holes, 2.5 in.	Materials/ installation	Drilled and cased with pipe	m	18.3	11.6	24.1

Table B.1 (continued)

Component	Subcomponent	Definition	U.S. Dollars			
			Metric units	Source cost	U.S. low	U.S. high
Drilled holes, 6 in.	Materials/ installation	Drilled and cased with pipe	m	22.3	15.6	26.4
Drill rig	Rental (equip./labor)	Crew and light-duty rig, and grading	day	400	280	470
Excavation, drainage trench	Labor	Use backhoe loader	m^3	2.65	1.70	3.50
Excavation, drainage trench	Materials	Use backhoe loader	m^3	1.60	1.20	1.70
Excavation/grading, soil	Labor	Excavation/grading, soil, common borrow, 1000-ft (305-m) haul	m^3	0.22	0.14	0.29
Excavation/grading, soil	Equipment	Excavation/grading, soil, common borrow, 1000-ft (305-m) haul	m	0.76	0.76	0.76
Excavation, grading, and recontouring of site	Labor	300-ft (90-m) haul, dozer and truck	m^3	0.37	0.23	0.48
Excavation, grading, and recontouring of site	Equipment	300-ft (90-m) haul, dozer and truck	m	1.35	1.35	1.35
Exploratory boring	Materials/ installation	Test strata in or below landfill, and to apply chemical injection, 4-in. (0.03-m)-diam holes	m	19.7	13.8	23.2
Flow meters, 6 in.	Materials/ installation	Measures rate of flow of landfill gas to blower	each	880	550	1,150
Flow meters, 8 in.	Materials/ installation	Measures rate of flow of landfill gas to blower	each	1,040	650	1,360
Geotechnical investigation	Labor/materials	Includes exploratory holes, surveying, mobilization, drilling addition, pump test, and report	site	5,500	3,850	6,520
Gravel	Labor	One dozer operator, one truck driver	m^3	2.48	1.5	3.25
Gravel	Materials	3/4 in. screened gravel	m^3	7.20	5.54	7.63
Grout curtain	Labor	Two grid—phenolic resin (also for grout bottom seal)	m^3	262	165	343
Grout curtain	Materials	Two grid—phenolic resin (also for grout bottom seal)	m	56.2	43.3	59.6
Header pipe, 8 in.	Materials	PVC Schedule 40	m	27.4	21.1	29.0
Header pipe, 8 in.	Installation	PVC Schedule 40	m	34.1	21.5	44.7
Hydroseeding	Labor	Includes seed and soil supplements	ha	171	108	224

Table B.1 (continued)

Component	Subcomponent	Definition	Metric units	U.S. Dollars Source cost	U.S. low	U.S. high
Hydroseeding	Materials	Includes seed and soil supplements	ha	877	675	929
Hydroseeding	Equipment	Includes seed and soil supplements	ha	124	124	124
Liner	Labor/materials	30 mil., bracketed with heavyweight geotextile fabric, Hypalon	m^2	6.22	4.35	7.37
Materials testing	Materials/ installation	For costing, see "Exploratory boring"				
Moisture traps	Materials/ installation	Removes water from gas control system	each	480	335	570
Monitoring equipment	Equipment	Gas detection instrumentation to monitor gas control systems (MSA Model 53 Gascope)	each	500	500	500
Monitoring wells, gas	Materials	0.5 in. (1.3 cm), 12 ft (3.6 m) deep for landfill gas monitoring	m	1.34	1.03	1.42
Monitoring wells, gas	Installation	0.5 in. (1.3 cm), 12 ft (3.6 m) deep for landfill gas monitoring	m	8.82	5.55	11.5
Mulching	Labor	Hay mulching	ha	85.2	53.7	111
Mulching	Materials	Hay mulching	ha	210	162	223
Mulching	Equipment	Hay mulching	ha	57.3	57.3	57.3
Pipe, PVC (elbows), 6 in.	Materials	90 in. fitting	each	27.0	20.8	28.6
Pipe, PVC (elbows), 6 in.	Installation	90 in. fitting	each	28.0	17.6	36.7
Pipe, PVC (elbows), 8 in.	Materials	90 in. fitting	each	52.0	40.0	55.1
Pipe, PVC (elbows), 8 in.	Installation	90 in. fitting	each	39.0	24.6	51.1
Pipe, PVC (Tees), 6 in.	Materials	T-fittings for gas wells	each	37.0	28.5	39.2
Pipe, PVC (Tees), 6 in.	Installation	T-fittings for gas wells	each	46.0	29.0	60.3
Pipe, PVC (Tees), 8 in.	Materials	T-fittings for gas wells	each	75.0	57.8	79.5
Pipe, PVC (Tees), 8 in.	Installation	T-fittings for gas wells	each	59.0	37.2	77.3
Pipe, PVC, laterals, 8 in.	Materials	For gas extraction wells Schedule 40 (includes $4.92/m for perforations)	each	29.20	22.5	30.9
Pipe, PVC, laterals, 8 in.	Installation	For gas extraction wells, Schedule 40	m	9.65	6.08	12.6
Pipe, PVC, laterals, 12 in.	Materials	For gas extraction wells, Schedule 40 (includes $4.92/m for perforations)	m	41.0	31.6	43.7
Pipe, PVC, laterals, 12 in.	Installation	For gas extraction wells, Schedule 40	m	15.4	11.9	16.4

Table B.1 (continued)

Component	Subcomponent	Definition	Metric units	U.S. Dollars Source cost	U.S. low	U.S. high
Pipe, PVC, risers, 4 in.	Materials	For gas extraction wells, Schedule 40	m	9.15	7.05	9.70
Pipe, PVC, risers, 4 in.	Installation	For gas extraction wells, Schedule 40	m	22.0	13.9	28.8
Pipe, PVC, risers, 6 in.	Materials	For gas extraction wells, Schedule 40	m	16.4	12.7	17.4
Pipe, PVC, risers, 6 in.	Installation	For gas extraction wells, Schedule 40	m	25.7	16.2	33.7
Pump, centrifugal	Equipment/ installation	3/4-hp pump	each	1,600	1,600	1,600
Pump, submersible	Labor	1 hp—4 in., submersible	each	344	220	450
Pump, submersible	Materials	1 hp—4 in., submersible	each	424	330	450
Recharge trench	Materials/ installation	Excavation of trench	m^3	1.60	1.12	1.90
Sand	Materials/ installation	For well point casing backfill	bag	5.80	4.06	6.87
Sheet piling	Materials	Steel sheet, PMA-22 (22 lb/ft^2)	tonne	507	390	537
Sheet piling	Installation	Install steel sheet, PMA-22 lb/ft^2)	tonne	100	63	131
Slurry trench excavation	Materials/ installation	Includes installation of bentonite slurry	m^3	46.0	32.2	54.5
Spread excavated material	Labor	One equipment operator, five laborers	m^3	0.21	0.13	0.25
Spread excavated material	Equipment	Spread by dozer, no compaction	m^3	0.51	0.51	0.51
Surface seal, bituminous concrete	Installation	3 in.—(0.08-m)—thick cap	m^2	1.05	0.66	1.37
Surface seal, bituminous concrete	Materials	3 in.—(0.08-m)—thick cap	m^2	3.00	2.31	3.18
Surface seal, clay cap	Materials/ installation	6 in. (15-cm) clay cap, includes 18 in. (46-cm) soil cover	m^2	4.82	3.50	6.41
Surface seal, clay cap	Materials/ installation	18 in. (46-cm) clay cap includes 18 in. (46-cm) soil cover	m^2	6.18	4.51	8.22
Surface seal, fly ash cap	Materials/ installation	12 in. (30-cm) fly ash cap includes 18 in. (46-cm) soil cover	m^2	4.65	3.40	6.18
Surface seal, fly ash cap	Material/ installation	24 in. (60-cm) fly ash cap, includes 18 in. (46-cm) soil cover	m^2	6.27	4.49	8.36
Surface seal, fly ash cap	Material/ installation	5 in. (13-cm) lime-stabilized cap, includes 18 in. (46-cm) soil cover	m^2	6.05	5.24	8.04
Surface seal, PVC membrane cap	Materials/ installation	30 mil PVC membrane cap, includes 18 in. (46-cm) soil cover	m^2	10.8	9.7	14.4

Table B.1 (continued)

Component	Subcomponent	Definition	U.S. Dollars: Metric units	Source cost	U.S. low	U.S. high
Surface seal, soil-cement cap	Materials/ installation	5 in. (13-cm) soil-cement cap, includes 18 in. (46-cm) soil cover	m^2	6.05	5.24	8.04
Surveying	Labor	Labor cost/day, establish surface topographic profile	d	220	150	260
Tipping fees	Unit costs	Dumping and grading wastes at new site	tonne	110	110	110
Transportation	Labor/ equipment	30-ton dump truck/dump/driver, based on one-way hauling distance, return trip included	tonne-km	0.096	0.060	0.128
Transportation	Labor/ equipment	15-ton dump truck/driver, based on one-way hauling distance, return trip included	tonne-km	0.110	0.069	0.145
Treatment system	Unit costs	Typical costs—interpolated @ 0.12 MGD (440,000 L/D)	each	580k	406k	687k
Trench excavation	Labor	One equipment operator/one laborer	m^3	0.22	0.17	0.35
Trench excavation	Equipment	Tractor or hydraulic backhoe to excavate trench, sloped 1/2 to 1	m^3	1.16	1.16	1.16
Well points, 2.5 in. (6.4-cm) diam	Materials/ installation	PVC, 25 dt (7.6 m)	m	59.3	41.5	70.3
Well-point fittings	Materials/	Fittings and accessories	well	12.0	8.40	14.2

Source: Adapted with permission from H. L. Rishel, T. M. Boston, and C. J. Schmidt, *Costs of Remedial Response Actions at Uncontrolled Hazardous Waste Sites,* EPA-600/2-82-035, SCS Engineers, Long Beach, Calif., 1982.

Table B.2. Landfill O&M cost components

Component	Subcomponent	Definition	U.S. Dollars: Metric units	Source cost	U.S. low	U.S. high
Chemicals	Materials	Wastewater/leachate treatment plant chemicals	L/d (influent)	0.025	0.025	0.025
Electricity	Power costs	For water treatment plant, extraction, injection, and gas control well/pumps	kwh	0.05	0.05	0.05
Grubbing	Labor/ equipment	Assume annual grubbing (clearing) of brush	m^2	0.19	0.12	0.25
Maintenance/repair diversion ditch	Installation	Assume diversion ditch needs needs rebuilding 2 times/ year after major storms	m^3	2.75	1.73	3.60
Monitoring	Labor	For gas monitoring at active and passive gas control installations	hr	12.5	7.88	16.6
Monitoring (analysis)	Laboratory costs	For ground water/leachate monitoring from monitoring wells	sample	330	330	330
Monitoring (sampling)	Labor	For ground water/leachate monitoring from monitoring wells	hr	12.5	7.88	16.6
Grass mowing	Labor/ materials	Use 58 in. power ride mower, one operator	ha	93.9	66.7	111
Operating cost	Labor	For water treatment plant operating personnel	hr	10	6.30	13.10
Operating cost	Labor	For gas collection system operating personnel	hr	15	9.45	19.95
Refertilization	Labor/ materials	Assume refertilization once per year	ha	341	247	395
Water	Materials	Industrial process water	kl	0.92	0.92	0.92

Source: Adapted with permission from H. L. Rishel, T. M. Boston, and C. J. Schmidt, *Costs of Remedial Response Actions at Uncontrolled Hazardous Waste Sites,* EPA-600/2-82-035, SCS Engineers, Long Beach, Calif., 1982.

Table B.3. Surface impoundment of capital cost components

Component	Subcomponent	Definition	U.S. Dollars			
			Metric units	Source cost	U.S. low	U.S. high
Area preparation	Labor	For area preparation, rake and cleanup, average	m^2	0.074	0.047	0.096
Area preparation	Equipment	For area preparation, rake and cleanup, average	m^2	0.022	0.022	0.022
Bentonite, delivered	Materials/ shipping	Shipment of bentonite by rail near job site, includes materials and delivery	tonne		66.4	177
Cement pipe, 6 in.	Materials	Class 4000, perforated, asbestos	m	8.00	6.16	8.48
Cement pipe, 6 in.	Installation	Class 4000, perforated, asbestos	m	3.10	1.95	4.06
Discharge trench	Labor	Including backfill 3 ft (1 m) deep	m^3	1.97	1.24	2.58
Discharge trench	Equipment	Including backfill 3 ft (1 m) deep	m^3	1.57	1.57	1.57
Diversion ditch	Installation	Construction and maintenance/repair	m^3	2.78	1.75	3.63
Drilled holes, 6 in.	Materials/ installation	Drilled and cased with pipe	m	22.3	15.6	26.4
Drill rig	Rental (Equipment/labor	Crew and light-duty rig	d	400	280	470
Excavation	Labor	One equipment operator	m^3	0.16	0.10	0.21
Excavation	Equipment	Front-end loader	m^3	0.65	0.65	0.65
Excavating/grading,	Labor soil	Common borrow (earth), 1000-ft (305-m) haul	m^3	0.22	0.14	0.29
Excavating/grading,	Equipment soil	Common borrow (earth), 1000-ft (305-m) haul	m^3	0.76	0.76	0.76
Geotechnical investigation	Unit costs	Includes surveying, test borings, equipment mobilization, monitoring wells, pump tests, report	each	14,500	9,500	19,500
Geotechnical investigation	Unit costs	Slurry well testing	each	2,000	1,260	2,260
Gravel	Labor/ installation	3/4 in. screened gravel, one dozer operator, one truck driver	m^3	2.48	1.56	3.25
Gravel	Materials	3/4 in. screened gravel, one dozer operator, one truck driver	m^3	7.20	5.54	7.63
Grout curtain	Labor	Chemical grout, phenolic resin, 2-grid	m^3	262	165	343
Grout curtain	Materials	Chemical grout, phenolic resin, grid	m^3	56.2	43.3	59.6

Table B.3 (continued)

Component	Subcomponent	Definition	Metric units	U.S. Dollars Source cost	U.S. low	U.S. high
Header and discharge pipe, 8 in.	Materials	PVC class 150 pipe, laid in trench	m	24.2	18.6	25.6
Header and discharge pipe, 8 in.	Installation	PVC class 150 pipe, laid in trench	m	9.61	6.05	12.6
Hydroseeding	Labor	Seed and soil supplements/ amendments	m^2	0.0171	0.0108	0.0224
Hydroseeding	Materials	Seed and soil supplements/ amendments	m^2	0.0877	0.0675	0.0929
Hydroseeding	Equipment	Seed and soil supplements/ amendments	m^2	0.0124	0.0124	0.0124
Mulching	Labor	Mulching hay	m^2	0.0085	0.0054	0.0112
Mulching	Materials	Mulching hay	m^2	0.0210	0.0162	0.0223
Mulching	Equipment	Mulching hay	m^2	0.0057	0.0057	0.0057
Pump, centrifugal	Equipment/ installation	3/4-hp pump	each	1,600	1,600	1,600
Pump, submersible	Labor/ installation	1 hp, 4 in., including wiring	each	344	220	450
Pump, submersible	Materials	1 hp, 4 in., including wiring	each	424	330	450
Sheet piling	Labor/ equipment/ installation	PMA-22 steel sheet piling	tonne	100	63	131
Sheet piling	Materials	PMA-22 steel sheet piling (22 lb/ft^2)	tonne	507	390	537
Slurry wall, installation	Installation	Install slurry compound in excavated trench	m^3	45.9	32.2	54.5
Slurry wall testing	Unit cost	See "Geotechnical investigation," "slurry wall testing"				
Soil compacting	Labor	With sheepsfoot roller	m^3	0.63	0.40	0.83
Soil compacting	Equipment	With sheepsfoot roller	m^3	0.86	0.86	0.86
Sump	Labor/ equipment	16-ft (5-m)-deep × 8 in. (20-cm)-thick concrete, cast in place	each	820	516	1,074
Sump	Materials	16-ft (5-cm)-deep × 8 in. (20-cm)-thick concrete, cast in place	each	750	577	795
Surface seal, bituminous concrete	Labor/ equipment	3 in.-(0.08-m)-thick cap	m^2	1.05	0.72	1.24
Surface seal, bituminous concrete	Materials	3 in.-(0.08-m)-thick cap	m^2	3.00	2.31	3.18
Surface seal, clay cap	Materials/ installation	6 in. (15-cm) clay cap, includes 18 in. (46-cm) soil cover	m^2	4.82	3.50	6.41

Table B.3 (continued)

Component	Subcomponent	Definition	U.S. Dollars: Metric units	Source cost	U.S. low	U.S. high
Surface seal, clay cap	Materials/ installation	18 in. (46-cm) clay cap, includes 18 in. (46-cm) soil cover	m^2	6.18	4.51	8.22
Surface seal, fly ash cap	Materials/ installation	12 in. (30-cm) fly ash cap, includes 18 in. (46-cm) soil cover	m^2	4.60	3.40	6.18
Surface seal, fly ash cap	Materials/ installation	24 in. (60-cm) fly ash cap, includes 18 in. (46-cm) soil cover	m^2	6.28	4.49	8.36
Surface seal, lime-stabilized cap	Materials/ installation	5 in. (13-cm) lime-stabilized cap, includes 18 in. (46-cm) soil cover	m^2	6.05	5.24	8.04
Surface seal, PVC membrane cap	Materials/ installation	30-mil PVC membrane cap, includes 18 in. (46-cm) soil cover	m^2	10.8	9.72	14.4
Surface seal, cement cap	Materials/ installation	5 in. (13-cm) soil cement cap, includes 18 in. (46-cm) soil cover	m^2	6.05	5.24	8.04
Surveying	Labor	Labor costs/day	d	220	150	260
Tipping fee	Unit costs	Fee paid at secure landfill	tonne	110	110	110
Transportation	Labor/ equipment	30-ton dump truck/driver, based on one-way hauling distance, return trip included	tonne/km	0.096	0.060	0.128
Transportation	Labor/ equipment	15-ton dump truck/driver, based on one-way hauling distance return trip included	tonne/km	0.110	0.069	0.145
Treatment plant	Unit costs	Costs interpolated from Dodge Guide 1980, with SCS estimate	L/d	0.89	0.70	1.18
Trench excavation	Labor	16 ft (5 m) deep × 3 ft (1 m) wide, one equipment operator, one laborer	m^3	0.22	0.17	0.35
Trench excavation	Equipment	16 ft (5 m) deep × 3 ft (1 m) wide, backhoe excavator, sloped 1/2:1	m^3	1.16	1.16	1.16
Well fittings, 8 in.	Materials	PVC	well	127	97.8	134.6
Well fittings, 8 in.	Installation	PVC	well	98	61.4	128.4
Well points	Materials/ installation	16 ft (4.9 m) long	m	59.3	40	70
Well-point fittings	Unit costs	Fittings and accessories	well	12.0	8.40	14.2

Source: Adapted with permission from H. L. Rishel, T. M. Boston, and C. J. Schmidt, *Costs of Remedial Response Actions at Uncontrolled Hazardous Waste Sites,* EPA-600/2-82-035, SCS Engineers, Long Beach, Calif., 1982.

Table B.4. **Surface impoundment of overhead and maintenance**

Component	Subcomponent	Definition	U.S. Dollars			
			Metric units	Source cost	U.S. low	U.S. high
Chemicals	Materials	Wastewater/leachate treatment plant chemicals	L/d (influent)	0.025	0.025	0.025
Electricity	Power costs	For water treatment plant or extraction, injection, and gas control wells/pumps	kwh	0.05	0.05	0.05
Refertilizing	Labor/materials	Assume fertilizing once/year	m^2	0.0060	0.0046	0.0064
Grass mowing	Labor/equipment	Assume grass mowing 6 times/ year, minimum $10/visit	m^2	0.0015	0.00097	0.002
Grubbing	Labor/equipment	Assume annual grubbing (clearing) of brush	m^2	0.19	0.12	0.25
Maintenance/repair, diversion ditch	Installation	Assume twice annual ditch repair	m^3	2.78	1.75	3.63
Monitoring (analysis)	Laboratory costs	For ground water/leachate monitoring from monitoring wells	sample	330	330	330
Monitoring (sampling)	Labor	For ground water/leachate monitoring from monitoring wells	h	12.5	7.88	16.6
Operator personnel	Labor	For operation of water treatment plant and sampling for monitoring	h	12.6	7.92	16.3

Source: Adapted with permission from H. L. Rishel, T. M. Boston, and C. J. Schmidt, *Costs of Remedial Response Actions at Uncontrolled Hazardous Wastes Sites*, EPA-600/2-82-035, SCS Engineers, Long Beach, Calif., 1982.

ORNL-6317

INTERNAL DISTRIBUTION

1. B. D. Chilton
2. J. T. Ensminger
3. S. V. Kaye
4. C. J. Oen
5. P. T. Owen
6. H. A. Pfuderer
7. D. E. Reichle
8. S. S. Talmage
9. T. Tamura
10. P. J. Walsh
11. Central Research Library
12–13. Information Research and Analysis
14–15. Laboratory Records Department
16. Laboratory Records ORNL-RC
17. ORNL Patent Office
18. ORNL Y-12 Technical Library

EXTERNAL DISTRIBUTION

19–22. L. R. Anspaugh, Lawrence Livermore National Laboratory, P.O. Box 5507, Livermore, CA 94596
23–27. B. W. Church, Nevada Operations Office, U.S. Department of Energy, P.O. Box 14100, Las Vegas, NV 89114
28. G. R. Eisele, Medicine and Health Science Division, ORAU, P.O. Box 117, Oak Ridge, TN 37830
29. E. H. Essington, Los Alamos National Laboratory, Environmental Sciences LS-6, 118 Balboa Drive, Los Alamos, NM 87544
30. R. O. Gilbert, Pacific Northwest Laboratory, P.O. Box 999, Richland, WA 99352
31. W. A. Howard, Nevada Operations Office, U.S. Department of Energy, P.O. Box 14100, Las Vegas, NV 89114
32. R. R. Kinnison, Pacific Northwest Laboratory, P.O. Box 999, Richland, WA 99352
33. E. M. Romney, University of California, Laboratory of Biomedical and Environmental Sciences, 900 Verteran Ave., Los Angeles, CA 90066
34. J. H. Shinn, Lawrence Livermore National Laboratory, P.O. Box 5507, L-524, Liveremore, CA 94550
35. Office of Assistant Manager, Energy Research and Development, U.S. Department of Energy, Oak Ridge Operations Office, Oak Ridge, TN 37831
36–37. Office of Scientific and Technical Information, U.S. Department of Energy, P.O. Box 62, Oak Ridge, TN 37831

CRL