195
11-4-74

Dr-1041

UCLA 12—973

**LABORATORY OF NUCLEAR MEDICINE
AND
RADIATION BIOLOGY**

**UNIVERSITY OF CALIFORNIA
900 VETERAN AVENUE
LOS ANGELES, CALIFORNIA**

AEC CONTRACT AT(04-1) GEN-12

MASTER

**FEASIBILITY AND ALTERNATE PROCEDURES
FOR DECONTAMINATION AND POST TREATMENT
MANAGEMENT OF PU-CONTAMINATED AREAS IN NEVADA**

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

UCLA #12-973
UC-11 Environmental
and Earth Sciences

UNIVERSITY OF CALIFORNIA
LABORATORY OF NUCLEAR MEDICINE AND RADIATION BIOLOGY
900 VETERAN AVENUE
LOS ANGELES, CALIFORNIA 90024

FEASIBILITY AND ALTERNATE PROCEDURES
FOR DECONTAMINATION AND POST TREATMENT
MANAGEMENT OF PU-CONTAMINATED AREAS IN NEVADA

by

A. Wallace and E. M. Romney

September 1974

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

Prepared at the request of the Nevada Applied Ecology Group, USAEC
Nevada Operations Office, Las Vegas, Nevada.

Printed in the United States of America
Available from National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, VA 22151
Price: Printed copy \$5.45; Microfiche \$1.45

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

LEGAL NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

CONTENTS

ABSTRACT	v
I. INTRODUCTION	1
II. LAND AREA DECONTAMINATION EXPERIENCES	
A. <u>Incidents Involving Planned or Accidental</u> <u>Release of Pu in the Environment</u>	7
1. Safety Experiments at the Nevada Test Site	7
2. Palomares, Spain	23
3. Thule, Greenland	25
4. Rocky Flats, Colorado	26
B. <u>Problems Involving Fallout from Weapons Tests and Material</u> <u>from Industrial Processing which Relate to the Pu Cleanup</u> <u>Problem</u>	27
1. Coulomb C and Stonemann II Experiments	27
2. NTS-REECo Field Decontamination Procedures	28
3. NRDS Test Cell Decontamination Incident	31
4. USDA Farmland Decontamination Experience	31
5. Carlsbad Site Rollup Program	34
6. Tatum Dome Test Site Cleanup Operations	36
7. Mill Tailings Stabilization Programs	37
8. Bikini and Enewetak Experience	40
III. REVEGETATION AND LAND RECOVERY EXPERIENCES UNDER ARID CONDITIONS	
A. <u>Introduction</u>	42
B. <u>Revegetation Work at NTS in the Past</u>	52
C. <u>Israeli Studies on Revegetation in Microcatchment Basins</u>	52
D. <u>Revegetation Experiences in the Great Basin</u>	59
E. <u>Hydromulching as a Means of Revegetation</u>	63
F. <u>Trickle or Drip Irrigation in Revegetation of Arid Land Areas</u> ...	64
G. <u>Current Interest in Arid Land Revegetation</u>	67
IV. DECONTAMINATION AND LAND RESTORATION PROCEDURES WHICH MAY BE USEFUL IN NEVADA	
A. <u>Isolation with Permanent Fences</u>	69
B. <u>Removal of Surface Soil (2 to 4 inches as necessary) but</u> <u>Leaving Some Plants</u>	70
C. <u>Complete Removal of the Soil Surface (2 to 4 inches) with</u> <u>Subsequent Revegetation</u>	71
D. <u>Soil Stabilization with Metallic Iron, Kriilium, Oil or Other</u> <u>Materials to Decrease Resuspension of ²³⁹Pu</u>	72
E. <u>Covering with Asphalt or Road Oil</u>	73

F. <u>Deep Plowing and Other Farm Decontamination Procedures</u>	73
G. <u>Combination of Deep Plowing and Fencing</u>	74
H. <u>Commercially Available Soil Stabilizer Products</u>	75
V. RECOMMENDATION FOR EXPERIMENTAL WORK WHICH SHOULD BE DONE AT NTS	79
VI. SUMMARY AND CONCLUSIONS	80
VII. REFERENCES	82

ABSTRACT

This report was prepared under the auspices of the Nevada Applied Ecology Group in response to needs for determining the feasibility and environmental impact of cleaning up Pu-contaminated areas in Nevada. Instead of considering all aspects of radioactive decontamination, it deals primarily with findings from pertinent land area decontamination and post-management experiences which can be applied to solving Pu problems at the Nevada Test Site and the Tonopah Test Range. Previous experiences from accidental and planned releases of Pu in the environment are discussed along with those gained from nuclear fallout decontamination studies.

Considerable attention is given to problems concerning revegetation of arid lands. The fragile nature of the desert is such that any drastic alteration will result in a seriously damaged ecosystem. Revegetation by natural means is difficult, if not impossible, from a practical point of view. Post-treatment management of disturbed areas is almost always necessary to insure recovery. Correction of the damage may require greater efforts than the decontamination, and may have more far-reaching consequences than those concerned with the present status of the land.

Alternate procedures are discussed which may be useful in Nevada, providing the necessary experimental work is done to test the validity of the assumptions made. Many answers to pertinent questions can be obtained from investigations conducted outside of the Pu areas. Recommendations are made for experimental work that should be done to determine the best course of action before cleanup begins.

I. INTRODUCTION

The Nevada Applied Ecology Group (NAEG) has been involved in an intensive study of Pu-contaminated areas at the Nevada Test Site (NTS) and at the Tonopah Test Range (TTR). The purpose is compliance with requirements of the National Environmental Policy Act of 1969, Executive Order 11514 and AEC Manual Chapter 0510. There are seven specific objectives of the study (Romney and Davis, 1972):

1. Compile and evaluate information on the sources, characteristics, distribution and subsequent behavior of Pu that has been discharged into the environment from nuclear testing activities.
2. Inventory and document the distribution, amounts, characteristics and behavior of measurable Pu dispersed from testing activities at the NTS.
3. Describe the extent and conditions under which Pu on the NTS and its environs is redistributed, considering the routes and rates of movement and with emphasis on its availability to man.
4. Evaluate and document the potential impact on man from Pu that is deposited on the NTS and its environs.
5. Evaluate effects, if any, of Pu contamination in the environment on native plants, animals and ecological systems.
6. Evaluate methods for stabilizing and removing Pu from the environment and the impact of these measures on the ecology of the region.
7. Determine the need for removal of Pu from the environment.

The Nevada Operations Office (NVOO) has provided 18 contracts to individuals in other institutions and agencies to perform the needed studies. Some of the salient facts which have been developed from work in progress are as follows (Dunaway and White eds., 1974):

1. After up to 19 years some Pu has been moved down into the soil as much as 9 cm, but often to 4 cm.
2. The ^{239}Pu : ^{241}Am ratio is not constant in the presently existing soil and biological components.

FOOTNOTE: The use of trade names and names of industrial organizations in this document does not imply endorsement of products nor that the industrial organizations are the sole producers of products which may be useful.

3. The resuspension factor under natural conditions is lower than suspected and may be decreasing with time.

4. Man's activities (i.e., grazing, automobiles, etc.) may increase the resuspension and/or biological activity.

5. Not enough is yet known about the particle size effect on biological activity of Pu or if cementing agents in the soil (CaCO_3 and soil organic matter) are increasing the size of Pu-containing particles.

6. Revegetation and restoration of the sites involved in the Mojave Desert are extremely difficult.

Advisory and planning committees of the NAEG have recommended that more time should be taken to further explore these problems while the opportunity exists to work in Pu-contaminated areas where definitive studies can be made. Unambiguous answers can mean much to future generations.

Considerable confusion exists in establishing cleanup guidelines because of inadequacy of data on resuspension and attenuation factors under different environmental conditions. Mishima (1964) summarized several dozen resuspension values and concluded that many of them lie in the range of 10^{-5} to 10^{-7} m^{-1} for NTS conditions. Stewart (1964) adopted a value of 10^{-6} m^{-1} and Langham (1969) reported that a smaller value could be expected for vegetated areas.

Maximum permissible contamination levels for ^{239}Pu have been the subject of several studies. Two types of situations exist for which the permissible levels for ^{239}Pu would be greatly different - one is the one-time or infrequent exposure, while the other is the lifetime exposure. The latter situation is of most concern in the present study because the material is already deposited and has been so since 1955 in some cases. An early conclusion about this was that $100 \mu\text{g } ^{239}\text{Pu}/\text{m}^2$ ($700 \text{ pCi}/\text{cm}^2$) was safely inhabitable for a lifetime without decontamination (Langham, 1968; Dick and Baker, 1967). Data of the type given in Table 1 have been recently questioned, both because of more concern for safety and (on the other hand) favoring recently found low resuspension values (Dunaway and White eds., 1974; Volchok, 1971; Healy, 1974; Iranzo and Salvador, 1970). Upon reporting Test Group 57 experiences, Dick and Baker (1967) estimated that a person could spend unlimited time in an area contaminated as heavily as $500 \mu\text{g}/\text{m}^2$ if conditions

Table 1. Maximum permissible initial surface concentration levels for lifetime occupancy. (From Langham, 1968)

Conditions of resuspension	Resuspension factor	Permissible initial surface contamination level	
		$\mu\text{g}/\text{m}^2$	pCi/cm^2
Vehicular traffic (Nevada)	7×10^{-5}	10	70
British rescue operations (closed space)	4×10^{-5}	20	140
Dirty rural, suburban, and metropolitan air	7×10^{-6}	100	700
British rescue operations (in the open)	2×10^{-6}	360	2520

gave assurance of no resuspension forces beyond reasonable winds. Since, however, this test represented a special set of circumstances, they recommended clean up to at least the $1000 \mu\text{g}/\text{m}^2$ level. Langham (1968) pointed out that findings from the Plumbbob and other test series in Nevada have suggested that areas initially contaminated with around $7000 \text{ pCi } ^{239}\text{Pu}/\text{cm}^2$ may be safely inhabited after the acute inhalation hazard has ceased and all of the particulate matter has settled to the ground. The studies revealed, however, that there were a host of environmental factors which have a bearing on the conclusion including particle-size distribution (hence statistics of them), fallout cloud phenomena, time dependence of resuspension, natural disturbance, etc. The biological basis for action is more complicated than the physical basis, partly because the particle size of the contaminant becomes a problem. For example, Langham (1968) showed that by one method of calculation a lung burden of 5700 1-micron diameter $^{239}\text{PuO}_2$ particles would be within the maximum permissible body burden, but that three 2-micron particles would constitute an over-exposure, assuming the total lung as the critical organ. This implies that particle size as well as specific activity must be considered in the decision process.

Upon consideration of particle size distribution, resuspension phenomena, and a number of other environmental factors, Healy (1974) has made a very convincing case for the need of a lower interim standard for deriving

the upper limit of contamination of Pu in the soils of inhabited areas.

The areas of Pu-contamination specifically involved in the NAEG studies are test sites of one-point detonation in Area 5, 11, and 13 at the NTS, and the Double Track and Clean Slate 1, 2, and 3 sites at the TTR. Leavitt (1974) has made a brief soil survey of these areas. Gilbert and Eberhardt (1973) have reported some results for soil Pu-levels in these areas.

Some of the early assumptions behind the hazards evaluation of NTS tests with chemically detonated ^{239}Pu have been described by Langham et al. (1966). Calculated cloud dosages to the lung during fallout were very low and appeared not to constitute a hazard. ^{239}Pu and other alpha-emitting radio-nuclides do not constitute a health hazard to man so long as they are confined to a surface such as soil. If the resuspension factor was zero, then the health hazard would be zero no matter what the contamination level on the soil. It was assumed that the dry, hard surface of the desert soil was a surface from which resuspension would be very low. With time it could be expected that at least some of the Pu particles would become cemented with other material (CaCO_3 and soil organic matter) in the soil so that they would become too large for resuspension. This may still be a good assumption and its verification is one of the experimental projects of NAEG. Cementing does occur naturally in NTS soils insofar as bicarbonate-laden water does move across the soil. Upon its evaporation the bicarbonate forms poorly-soluble carbonates which cement around particles. A cemented "caliche" layer is formed with depth in the soil also, as a result of downward movement of the rainfall which moves bicarbonate downward. Carbonates form at the point in depth to which the moisture penetrates when the soil dries out. The Pu particles can become involved in the cementing process and the extent of this needs to be known, for it would greatly decrease the problem arising from the contamination.

Radioactive contamination incidents involving extensive decontamination efforts have occurred in areas which require vastly different procedures because of local geography, terrain, and climate. Although there have been some decontamination experiences under desert conditions even on a large scale, the final answers are not yet available from the effects of such activities. The desert, indeed, does present its own special problems which can be summarized into the concept that any drastic alteration of the desert

will result in a seriously damaged ecosystem. Correction of the damage may require greater efforts than the decontamination and may have more far-reaching consequences than those concerned with the present status of the land. Romney and Davis (1972) summarized this point of view: "Decontamination measures of the the kind used for agricultural land would not be very useful in wilderness areas because of subsequent soil erosion and water-shed control problems. Revegetation by natural means is difficult in many ecosystems, if not impossible, from a practical point of view. Replanting is sometimes possible, but not always economically feasible. Unquestionably, the denuding of a wilderness area of its natural vegetation would extract the greatest biological cost and should be considered only as a last resort. It should be remembered that, in most cases, the natural vegetation would not be destroyed even if an acute Pu inhalation hazard destroyed some wild animal life. Plant uptake of the residual Pu would be too low to cause any hazard (Romney et al., 1970) and the native vegetation cover would tend to lower the probability of resuspension. It appears then, from an ecological point of view, that low-level residual Pu contamination dispersed into wilderness areas might prove best left alone, and if they contain contamination levels greater than would be safe for lifetime occupancy, they should be restricted from public domain. Conceivably, these would be very small areas."

The criteria by which decisions are made concerning decontamination are not always uniform nor precise. Foremost are the radiological considerations, especially as they relate to human health and welfare. Next are political considerations which often involve our relationships at the international as well as local levels. The next, perhaps, are the esthetic and environmental considerations, particularly as they relate to consequences of the treatments for decontamination. The next, but still an extremely important factor, is the economics involved in any decontamination undertaking. Closely associated with the economic considerations are the logistics involved. Transportation, machinery, disposal of waste, etc. must be reckoned with if certain types of decontamination are undertaken.

"For which of you, intending to build a tower, sitteth not down first, and counteth the cost, whether he hath sufficient to finish it?" Luke 14:28

Decisions, hopefully, should be made on the basis of all possible considerations and not just on one of them. This report endeavors to first, review the criteria and experience of the past in decontamination of land areas, and second, to present possibilities with their ramifications for corrective action on sites in Nevada which have significant levels of Pu contamination. Much is known about hazards and toxicology of Pu (Blair and Thompson, 1974), but these subjects are not discussed herein. Moreover, it was not the purpose and scope of this report to include an extensive literature review concerning every aspect of radioactive decontamination which might relate to the Pu problem. There is an extensive list of reports in the literature on decontamination problems concerning nuclear reactors and industrial facilities, civil defense-related decontamination problems, and specialized situations such as cold weather decontamination problems. Some examples are: Bost (1959), Environmental Plutonium Data Base Group (1972), King and Bresee (1961), Maloney (1963), Miller (1958a, 1958b, 1959), Owen, et al. (1965, 1967), Owen and Sartor (1962), Price (1971), Raleigh (1965), and Sartor, et al. (1957).

Since there are fundamental questions and problems which are the same no matter what kind of contamination incident or area is involved, a brief review will be made of some of the more important world-wide land decontamination experiences. The questions common to all involve the following: (1) identification of source and extent of contamination, (2) development of a practical and economic means for removal of the contamination, (3) ascertaining and correcting any effects of alteration caused by the decontamination. Preferably the third item should be predicted and long-range plans made to handle subsequent effects before the decontamination is even started. In the case of the Pu-contaminated areas at the NTS that should be possible. Again, it is important to recognize that it is a prudent policy to avoid a cure worse than the original problem.

The decontamination experiences so far undertaken at the NTS have dealt with only a small part of that Pu which has been dispersed into the environment. The world-wide accumulation of fallout Pu amounts to over 300,000 Ci (Harley, 1971), but only about 100 Ci are involved at the one-point detonation sites in Nevada. Very small quantities per unit area (0 - 13 pCi/cm²) are found off the NTS (Bliss and Dunn, 1971). World-wide production

of Pu will probably increase at an accelerated rate over the next few decades (Harley, 1971) which means that background levels of Pu will probably increase. Even though the one-point detonation study sites at NTS represent just a small portion of the totally-dispersed Pu, they do present excellent opportunities for investigating the behavior of Pu in the environment.

II. LAND AREA DECONTAMINATION EXPERIENCES

A. Incidents Involving Planned and Accidental Release of Pu in the Environment

1. Safety Experiments at the Nevada Test Site

A series of formal environmental contamination experiments with Pu were conducted in order to evaluate safety characteristics of nuclear devices, study the behavior of released Pu in air, conduct biomedical experiments and perform decontamination and area monitoring studies (Stannard, 1973).

Field decontamination experiments were conducted by elements of Test Group 57 in the Pu-contaminated fallout pattern downwind from a one-point chemical detonation near Groom Lake, Nevada (Pinson et al., 1957; Baker et al., 1958; Dick and Baker, 1967). Effects of treatments were evaluated by pre- and post-treatment analysis of air and soil samples taken before and after resuspending the surface of study plots by repeatedly driving a truck back and forth through the area. The land area fixation and/or decontamination efficiencies from different treatments are shown in Table 2.

Greatest attenuation of Pu-activity was achieved by plowing and by oiling and scraping treatments.

Table 2. Land area fixation and/or decontamination efficiencies. (From Dick and Baker, 1967)

Method	Mean initial (dpm/m ³)	Mean final (dpm/m ³)	Efficiency (percent)
Plowing	2630	55	97.9
Oiling and scraping	1240	55	95.6
0.3-inch water leaching and scraping	205	15	92.7
0.3-inch water FeCl ₃ leaching	1405	118	91.6
Disking	500	54	89.2
1.0-inch water leaching	515	65	87.4
Scraping	79	11	86.0
Oiling (RC-0 road oil)	121	37	69.4
0.3-inch water leaching	8133	3660	55.0
0.3-inch water-Alconox leaching	380	309	18.7

In the studies described by Dick and Baker (1967), there were eleven 50 x 100 ft test plots established about 1000 ft north of ground zero. The equipment used included a road grader, a single-bottom farm plow, a four-gang disk harrow, an 850-gallon oil-distribution truck, a 1000-gallon water-sprinkling truck, and two 400-gallon decontamination trucks. Among the treatments were road oil, foam from fire fighting equipment, flooding, disking, plowing, and scraping. The scraping was with and without road oil, and with water. In one treatment, an FeCl_3 solution was applied, supposedly to induce cementing of Pu particles and soil particles in order to decrease the probability of resuspension. This is one of the ideas which we suggest should be tested more completely in future decontamination studies.

Dick and Baker (1967) concluded that plowing and oiling were most effective and cheapest of the various treatments used. That may still be a valid and worthwhile conclusion. Water and fire-fighting foam treatments were effective for 1 hour in preventing resuspension and to a degree permanently because of pressure-induced mixing in the first few cm of soil. These can be looked upon as temporary decontamination measures.

The effects from the decontamination treatments were evaluated again at 3, 6, 12, and 18 months by the TG 57 group. We do not know if they were evaluated at later intervals, but inspection of them after 17 years, by Wallace and Romney in June 1974, showed many items of interest.

This inspection of the TG 57 test plots included an evaluation of the recovery of vegetation by species, an estimation of ground cover, and a comparison of soil surface conditions. Photographs also were taken and views of some of the test plots are shown in Figs. 1 - 5. Insofar as the present status of vegetation is concerned, the results are interesting and promising. The vegetation of the area is dominated by shadscale (Atriplex confertifolia) and the flora is a form of the Great Basin desert. Although the annual rainfall is only around 8 inches, which is sparse, the weather is cool enough for the natural revegetation process to be reasonably fast. The soil is sandy and of fairly good quality. Elevation is about 4800 feet. The plowed area (Fig. 1) has recovered well with an estimated 25% of plants compared with the adjacent non-plowed area. All three scraped areas have some vegetation (Figs. 2, 3, 4) which also is estimated to be around 25% of that of nonscraped areas. The

Fig. 1. The area in foreground was plowed 17 years ago as a decontamination test in Area 13 at the NTS. The plow depth was about 1 foot and it is not known if the plowing killed all the original vegetation. Recovery has been reasonable on this Great Basin Desert site although the cover is only about 25% of that of the undisturbed area.

Fig. 2. This area was bladed 17 years ago (1957) in a decontamination test at Area 13. Although recovery of vegetation has been good in this Great Basin Desert site, the amount of vegetation is about 25% that of the undisturbed area. We do not know if the plants in the test area have grown from seeds since then or if they were some plants not killed by the blading.

Fig. 3. The area in the foreground was first treated with hot, rapid-cure (RC) road oil to decrease resuspension and then the area was later scraped (see pile of scrapings in bottom of photograph) in a decontamination experiment conducted in Area 13, 17 years ago. Revegetation has been good (about 25%). (Photographed in June 1974)

Fig. 4. This site was part of the 1957 decontamination experiment in Area 13 (Great Basin Desert). It was first watered to decrease dust and resuspension (Pu was moved into the soil by the water spray). The area was later scraped. (Photographed in June 1974)

Fig. 5. Soil pieces varying from $\frac{1}{2}$ to 2 inches thick which were stabilized 17 years ago with hot, rapid-cure (RC) road oil in Area 13 at the NTS. Resuspension of ^{239}Pu from such soil would be extremely low. (Photographed June 1974)

disked area is not distinguishable from nontreated areas. The road oil-treated area seemed to be no different from nontreated areas except for the residue of oil remaining. The oil surface (Fig. 5) has broken up, but in most cases the soil remains stabilized in pieces from $\frac{1}{2}$ to 2 inches in thickness. The road oil does pose some advantages inasmuch as any Pu entrapped in those pieces of stabilized soil would not be subject to resuspension. There were no obvious effects from the iron chloride treatment.

These observations after 17 years, together with the earlier observations of Dick and Baker (1967) that plowing was 98% effective in decreasing Pu resuspension, indicate that plowing (1 foot depth) 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 stabilize the soil to prevent a dust bowl. Experimental work is needed to further test such combination of treatments. One question the 1957 workers failed to document was whether or not any of the original shrubs on the test plots survived the plowing, disking, or scraping treatments. It is assumed that fewer shrubs were killed by the disk-harrowing treatment since there were essentially as many shrubs on the disked plot as on the undisturbed area when surveyed in June 1974.

In addition to being effective in dealing with alpha contamination problems, plowing and disking can effectively provide protection from gamma radiation (Anonymous, 1960). When viewed 3 feet above ground, the shielding effect of mixing gamma isotopes with soil is as follows:

1/4 inch of soil	equals	56% of surface value
1/2 inch of soil	equals	44% of surface value
1 inch of soil	equals	32% of surface value

When mixtures of alpha, beta, and gamma-emitting contaminants are involved, plowing seems to be a prudent decontamination measure even though crop plants might take up some of the beta and gamma-emitting isotopes. There is a very important dilution process involved, and certain isotopes can be stabilized somewhat by carbonate and phosphate treatments (Kunishi and Taylor, 1972).

Apparently there were no land decontamination experiments in conjunction with the safety tests involving Pu in Area 11, although there were post-shot cleanup operations. These tests were conducted in 1955-56 at four

detonation sites which subsequently were disturbed by scraping, land burial and asphalt-covering operations.

The revegetation which subsequently has occurred on these earlier disturbed sites is of considerable importance. Area 11 is a transitional desert area having both Great Basin and Mojave Desert vegetational characteristics. It can be expected that revegetation in this area would be easier than in a purely Mojave Desert condition, but more difficult than in Area 13. Annual rainfall is around 6 inches. The few plants growing on or near the asphalt-covered ground zero pads of shot Sites A, B, C, D, (Figs. 6, 7) are large and healthy because of the extra water available (Wallace et al., 1972c). This is like the commonly observed roadside effect in which plants grow larger because of the greater amount of run-off water available to them (Fig. 8).

It should be noted that windrowing of fallout-contaminated areas has been very common as a means of decontamination at the NTS, and the history of the practice needs to be better documented. An important aspect is that the windrows can be picked up for disposal at any time, if necessary. A major difficulty of this procedure is the disturbance of vegetation which does not easily recover.

Some large land areas were bladed free of destructive vegetation for use as balloon launching sites in conjunction with four tests involving Pu at the TTR. No specific land decontamination experiments were reported during the Roller Coaster test series in 1963, but there were the usual kinds of post-shot cleanup activities around each ground zero. An investigation of these earlier bladed areas in June 1974 disclosed that the vegetation recovery after 11 years was as good, or better, than that which occurred during the 16-year period in Area 13. The sites on the TTR are more typically Great Basin Desert. Perennial vegetation recovery has reached about 25% of normal cover, and there also has been considerable grass invasion.

At each shot site, some 3 to 5 acres were scraped around ground zero, then the material was buried in a trench (Fig. 9). Other material was windrowed (Fig. 10), and the windrows are still intact after 11 years. The scraped and windrowed areas are fenced.

It should be noted at this point that all Pu-contaminated areas under study by NAEG are presently fenced with barbed wire - steel post and some

Fig. 6. Large Atriplex canescens in middle of asphalt pad at Site C in Area 11. The extra run-in water available resulted in the large growth of the plant. This illustrates how water manipulation with meager rainfall can result in revegetation with vigorous plants. (Photographed June 1974)

Fig. 7. "Roadside" effect on vegetation growing around the asphalt pad at Site C in Area 11. The water runoff from the asphalt cover stimulates plant growth due to the extra water available for each plant. Should it be necessary to disturb this land, it should be so manipulated to cause this to happen; otherwise revegetation will be very slow in this semi-Mojave Desert area.

Fig. 8. Roadside effect on Larrea tridentata along U.S. Highway 95 in Southern Nevada. The road cut serves as a contour basin with the run-in rain water resulting in vigorous plant growth. This general idea can be used for stimulating revegetation of disturbed land in the Mojave Desert. (Photographed June 1974)

Fig. 9. Shown in the photograph are two alpha-containing windrows made 11 years ago in a decontamination effort at Clean Slate 3 at the Tonopah Test Range. At the right of the picture is one of the fences used to isolate the area.

Fig. 10. Area scraped 11 years ago as part of a decontamination effort near ground zero of Clean Slate 1 at the Tonopah Test Range. The scraped soil was buried, but can be retrieved. (Photographed June 1974)

with cedar post reinforcement. Some are double fenced to further isolate zones of highest contamination. All fenced areas are on controlled access with radiological safety surveillance. The fence construction is durable for up to 50 years. These precautions which have been taken (fencing, scraping, windrowing, etc.) are sufficient to exclude need for undue haste in searching for more permanent solutions to the land contamination problems.

Because of its relevance to the safety experiments discussed above, the following section of Langham's (1969) report on feasibility of Pu-decontamination is given:

"Experience has shown that most Pu-contaminated surfaces can be restored and returned to normal use through application of appropriate decontamination methods by properly trained personnel. Accidents involving Pu contamination (King and Bresee, 1961; Dick and Baker, 1967; Baker et al., 1958) have illustrated the effectiveness of several plutonium decontamination methods. Additional information is contained in a number of publications (Raleigh, 1965; Phillip, 1966) concerning general decontamination procedures.

"The selection of an appropriate decontamination method will depend on contamination levels involved, surface characteristics, environmental conditions, economic considerations, and the intended future use of the area. Thus no single decontamination method is suitable for all situations, and under most conditions several methods would probably be utilized. Some of the methods that have been tested and corresponding decontamination efficiencies for various surfaces are listed below:

"**HARD SURFACES:** Decontamination of hard surfaces may be accomplished by the following methods:

"Water methods. A water truck capable of producing a water stream at a pressure of 200 to 400 pounds/in² is used for: (1) plain water hosing, (2) water hosing and scrubbing, (3) hosing with 1% (by weight) commercial detergent and water solution, or (4) detergent-solution followed by scrubbing and rinsing.

"Sandblasting. The surface is removed in this operation, and it should only be used when other methods are unsuccessful. The loose residue must be collected by some suitable means, such as vacuum cleaning.

"Vacuum cleaning. Vacuuming is suitable for situations where the use of water would not be practical. Suitable filters are placed over the exhaust to

Table 3. Percent efficiencies for various hard surface decontamination methods. (From Langham, 1969 and Dick and Baker, 1967)

Material	Method (% efficiency)						
	Vacuum	High pressure water	High pressure water with scrub	High pressure water and detergent	High pressure water and detergent with scrub	Sand blasting	Steam cleaning
Glass	98	99	97	100	99	100	97
Stucco	48	97	95	95	99	100	27
Painted wood	99	98	96	99	99	100	91
Unpainted wood	36	85	93	99	95	99	85
Aluminum	89	99	97	99	100	98	84
Plate steel	93	97	94	100	98	99	91
Asbestos shingles	61	99	98	96	99	100	63
Unpainted wood shingles	61	97	90	95	97	99	71
Brick	29	99	99	99	99	99	97
Tar paper	55	98	95	95	96	99	52
Corrugated galvanized roofing	69	99	97	99	99	100	85
Highway asphalt	32	99	96	99	99	99	44
Highway asphalt (10 ft ²)	72	92	94	98	96	92	22
Sealed asphalt	71	98	90	100	99	99	84
Sealed asphalt (10 ft ²)	64	90	82	96	97	90	48
Sealed trowel concrete	74	98	-	96	99	100	-
Steel trowel concrete (10 ft ²)	-	78	97	-	98	98	27
Wood float concrete	-	98	92	100	97	100	65
Wood float concrete (10 ft ²)	56	97	-	98	98	98	85
Average of all surfaces	66	96	94	98	98	98	67

prevent resuspension of the contaminant blowing through the cleaner.

"Steam cleaning. Greasy or oily surfaces may best be cleaned by the use of steam cleaners. Decontamination efficiencies for these methods on various surfaces are listed in Table 3.

"LAND AREAS: (Dick and Baker, 1967; Baker et al., 1958). Methods for fixation and/or decontamination of land areas include the following:

"Plowing. Plowing to a depth of 12 inches to insure adequate mixing and burial of the contaminant.

"Scraping. The top 2 inches of the soil are removed for subsequent disposition.

"Oiling. The oil treatment consists of spreading RC-O (rapid cure) oil over the area with an oil-distribution truck. This forms a semihardened surface within 24 hours.

"Oiling and scraping. Following the oiling operation as described above, the hardened oil crust can be scraped off for subsequent disposal.

"Wetting down with water and scraping. Wetting down with approximately 0.3 inches of water tends to temporarily fix the contaminant and permits removal by scraping without excessive resuspension of the contaminant.

"Flooding with water (1 inch). Flooding with large amounts of water will accelerate the natural weathering action and will tend to leach the contaminant into the soil, thereby reducing the amount of contaminant resuspended in the air.

"Decontamination efficiencies for land area methods are listed in Table 2 (this report). It should be emphasized that in all decontamination efforts, careful consideration must be given to proper disposal of contaminated waste."

2. Palomares, Spain

On January 16, 1966 an aerial refueling accident, involving a B-52 bomber carrying four nuclear weapons containing Pu, occurred near the Spanish village of Palomares (Langham, 1968; Jordan, 1971). Two of the weapons were recovered intact, but the high explosive component of the other two devices detonated, dispersing Pu over a restricted area. The cloud from one weapon spread across an irrigated agricultural area containing tomatoes and alfalfa ready for harvest. The other cloud drifted across more agricultural

land and through the northern third of the village.

Contamination contours were established and negotiations initiated regarding cleanup, although there were no realistic or official standards for determining a course of action (Langham, 1968). In the final agreement, all crops were removed from the field and destroyed where readings for ^{239}Pu were above $5\ \mu\text{g}/\text{m}^2$ ($35\ \text{pCi}/\text{cm}^2$) (Langham, 1968). All areas between 5 and $500\ \mu\text{g}/\text{m}^2$ ($3500\ \text{pCi}/\text{cm}^2$) were plowed to a depth of at least 10 inches to decrease the possibility of resuspension of the Pu-oxide particles. Langham reported (Carter and Placak, 1956) that mixing of Pu with just 1 cm of soil produces a dilution factor of 10^5 compared with the same amount of Pu on the surface. This is the basis for the disking, plowing, the windrowing procedures used at the NTS in the past to achieve decontamination of Pu on soil surfaces. In Palomares, those areas with contamination greater than $500\ \mu\text{g}/\text{m}^2$ were stripped of the contaminated soil and vegetation which was subsequently shipped to the U.S.A. for disposal. Top soil was removed from $5\frac{1}{2}$ acres which was subsequently plowed. The removed top soil was replaced with new top soil. Areas too rough to plow, but with contamination of $50\ \mu\text{g}/\text{m}^2$ ($350\ \text{pCi}/\text{cm}^2$) or greater, were cultivated by hand shovel to work the Pu into the soil (Langham, 1968).

Post study of the decontaminated area conducted 5 months after the incident (Fowler et al., 1968; Buchholtz et al., 1971) revealed that there was a wide range of Pu concentrations in the soil (0.2 to $4680\ \text{d}/\text{m}/\text{g}$ in the 0 to 5 cm depth), but some had been mixed down to 45 cm. The variability in the observed activity in the soil was a function of the particle size of the Pu. Aliquots from a single soil sample ranged from 0 to $778\ \text{d}/\text{m}/\text{g}$ with a mean of 195 . This was due to the wide range of particle size. Tomato fruit contained $0.0028\ \text{d}/\text{m}/\text{g}$ wet weight of fruit when the soil average was $27\ \text{d}/\text{m}/\text{g}$ dry soil (discrimination ratio of about 10^{-4}). This led to the conclusion that 1000 kg tomatoes per day per person could be ingested without harm (Fowler et al., 1968). The same procedure resulted in values of 28 kg maize per day per person and near the same value for beans which could be consumed without harm. The crops grown, including alfalfa (Buchholtz et al., 1971), seemed to present no health hazard.

One of the problems, subsequent to the plowing program at Palomares,

was that the agricultural land was on a delicately balanced salinity situation. Rainfall and irrigation had been sufficient to keep the excess of salts in the lower part of the profile, but the plowing brought excess of soluble salts to the soil surface, with adverse effects upon crop production. This illustrates one of the environmental dangers which may be encountered in any type of decontamination operation: the cure may be worse than the original disorder, therefore such problems should be ascertained before corrective action is taken.

3. Thule, Greenland

On January 21, 1968 a SAC B-52 bomber carrying four nuclear weapons crashed on the ice near Thule Air Force Base in Greenland (Langham, 1968; Jordan, 1971). The chemical explosive devices on each of the bombs were detonated so that over 3100 g Pu was spread over an area of $2.23 \times 10^5 \text{ m}^2$ (Langham, 1970). The distribution is shown in Table 4.

Table 4. Distribution of Pu on the surface in the vicinity of the crash exclusive of that picked up on aircraft debris. (From Langham, 1971)

Contamination boundary mg/m ²	Enclosed area m ²	Plutonium g	Deposition* %
380	1.97×10^3	845	27
112	1.10×10^4	2816	89
8	2.49×10^4	3014	96
2.4	3.90×10^4	3079	98
0.9**	5.97×10^4	3109	99
0.26	1.10×10^5	3135	99+
0.19	1.34×10^5	3140	99+
0.06	2.23×10^5	3151	100

* Total out to the specified boundary

**Edge of the blackened area

The Pu (Pu-oxide dust) was either deposited to shallow depths in the ice (usually less than 1 cm, but up to 10 cm where burning jet fuel had melted the snow which had refrozen with the Pu embedded in the snow) or was present on the aircraft wreckage. The 130 curies of tritium associated with the accident were judged as not constituting a hazard, although it was concentrated with the high level of Pu so that much of it was removed when the Pu was removed.

The smoke cloud from the burning aircraft rose over 830 m (Gjörup et

al., 1970). Some finer particles were spread over a distance of some 20 km (11 miles) and toward inhabited areas, but the deposition levels were found to be far below danger levels. The total amount of ^{239}Pu outside the well-defined crash site was estimated to be between 1 and 5 Ci, and concluded to constitute no biological hazard (Gjörup et al., 1970). In the area involved in the crash site, the concentration of ^{239}Pu rose to 3000 pCi/cm².

The crash site area was cleaned of contaminated snow and debris and over 600 containers of contaminated material were shipped to the U.S.A. for disposal (Otten, 1970). At the conclusion of the cleanup the scientific mission reported that there was no risk in the area for humans, marine, animal, or plant life.

A total of 67 tanks of 25,000-gallon size were used in the cleanup of snow and ice (Otten, 1970). This indicates that an area of about 70,000 m² and 4 inches (10 cm) deep would have been cleared. This would be approximately to the edge of the blackened area (Table 4) and would remove 99% of the contamination. The area cleaned up extended out to the 3000 pCi/cm² level of ^{239}Pu . The next 50,000 m² located outside of the cleaned-up zone averaged about 800 pCi/cm², but this area was not decontaminated. To have removed essentially 100% of the contamination would have more than tripled the amount of ice and snow which was removed.

A follow-up ecological program was initiated as had been done in Spain. One investigation (Aarkrog, 1972) showed that, although the levels in most samples had decreased since 1968, Pu was still present in concentrations above the fallout background. Samples of bottom sediments showed a vertical movement of Pu in the sediments down to a depth at least 10 cm. Bivalves as far as 30 km from the point of impact contained Pu from the accident.

4. Rocky Flats, Colorado

In 1969 deposition of concentrations of ^{239}Pu as high as 200 pCi/cm² were found off the Rocky Flats site (Krey and Hardy, 1970). The concentrations decreased greatly with distance from the plant. A total of about 2.6 Ci was involved. It was concluded that most of the contamination came from leaking barrels of ^{239}Pu -containing cutting oil located in the storage area from which Pu-contaminated soil subsequently became wind blown. It was determined that the 1967 fire caused little release of ^{239}Pu . The Pu had moved down into the

soil as much as 13 cm (60% of the total activity was below 5 cm). Removal of the contaminated oil drums and soil along with containment of residual activity underneath asphalt and concrete pads were effective decontamination methods employed at this site (personal communication). Most AEC installations where Pu has been processed have small quantities of Pu in the local environment (Corley et al., 1971; Hakonson et al., 1973) and these and other decontamination procedures have been used to decrease hazards.

A foam capable of hardening has been developed by Dow Chemical Company which can be quickly sprayed onto a contaminated soil to contain the contaminant until better conditions are available for its pick up (Hornbacher et al., 1971). A 2-inch (5 cm) layer of foam is sprayed on the soil. Lifting of the hardened foam is done easily by mechanical or manual means. The contaminated soil together with other soil particles becomes encapsulated in the foam which lasts for a period of about 2 years before it begins to seriously degrade. Its cost is about the same as that of asphalt (22¢/ft² in 1973).

One advantage of this material is that it can be quickly applied to a contamination spill or leak in order to prevent the spread of contamination to adjoining areas. One such emergency use was made of the material at Rocky Flats on an area involving about 4 m². About 85% of the activity was removed when the 2-inch (5 cm) layer of the foam was removed from the soil (Hornbacher et al., 1971).

B. Problems Involving Fallout from Nuclear Tests and Materials from Industrial Processing which Relate to the Pu Cleanup Problem

1. Coulomb C and Stoneman II Experiments

The Civil Effects Test Operation Exercise CEX-57.1, following operation Plumbbob, was carried out to obtain information on fallout decontamination procedures that could be used as radiological countermeasures (Miller, 1958). The test was conducted on D + 1 and D + 2 days after shot Coulomb C. Data were obtained on reclamation of land areas by scraping with a motorgrader, on fire-hosing, and scrubbing a concrete-slab roof, and on fire-hosing a composition roof. The decontamination effectiveness was computed in terms of the fraction of contamination remaining after the decontamination procedure. The findings from this exercise are probably not as significant as those from follow-up experiments in the Stoneman II series which this work prompted.

For the Stoneman II series of experiments, a synthetic fallout material was used to simulate a variety of conditions from which to develop radiological countermeasure information for use by the Armed Services, Civil Defense, and other agencies. Lee, Sartor, and Van Horn (1959) reported on one series of tests conducted to determine the influence of various soil surface characteristics and repeated method applications on the effectiveness of some basic land reclamation methods. Four soil surfaces were tested: a moist surface with green grass; a tilled moist surface, a dry tilled surface; and a dry, hard surface with withered vegetation. A synthetic fallout was produced and dispersed over the test surfaces then the performances in removing layers of soil with a scraper or a motorized grader plus scraper and remote-controlled bulldozer were evaluated. Soil surface characteristics, moisture content, and the technique in the application of the methods influenced the effectiveness of the reclamation methods. Decontamination ratios of 1% or less (greater than 99% removal) were obtained through one or more applications by the scraper and the grader plus scraper methods. Based upon the efficiency with which a method could achieve any effectiveness with the test range, scraping was the best decontamination method.

2. NTS-REECo Field Decontamination Procedures

During the above-ground test years at the NTS, there was considerable site preparation so that radioactive debris was piled, buried, and disked or graded into windrows. All were effective for specific needs, thus the history of many would be important documentation. All of these procedures were used before the 1969 National Environmental Policy Act so that some may not now be acceptable, at least without post-treatment procedures.

The Reynolds Electric and Engineering Company (REECo) has for many years been in charge of radiation safety and, therefore, necessary decontamination at the NTS. Within company files are several reports of this work on land decontamination (Brown et al., 1961, 1964). Special attention is given to the alpha decontamination problem.

Some important parts of the paper of Brown et al. (1964) are quoted:

"The widespread use of radioactive isotopes, the increasing transportation and storage of nuclear assemblies, and the expanding use of nuclear energy for generating power have, in combination, created a new problem for

the nuclear industry. In the event of a large-scale criticality accident or source spill, large land areas, or even heavily populated urban areas, may become contaminated. Procedures and plants should be developed to initiate practical, effective large-scale decontamination methods.

"Knowledge of the obstacles, and practical experience in effective methods used in the actual decontamination of large land areas, roadways and structures is limited. However, at the NTS, diverse, large area decontamination problems are not uncommon. The Radiological and Science Departments of the REEC Co has accumulated a wealth of unusual experience. REEC Co is the prime contractor supporting all Test Agencies that conduct nuclear experiments at the site.

"Land area decontamination techniques at the 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.

"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 are required.

"Following one test series in which low yield nuclear devices were detonated, approximately seven hundred acres of land were contaminated with long-lived alpha emitters. Four devices were detonated in the same general area. Contamination not only covered the detonation sites, but included several square miles in which there were four equipment parking pads, three miles of paved road, and four miles of auxiliary unsurfaced roads. The contaminated debris contained fragments of wood and metal which littered the entire contaminated area.

"In parts of the area where future use was indicated, all surface debris was removed to a contaminated waste dump. Then a small section of the area was wet down to suppress resuspension. Water trucks equipped for sprinkling preceded a standard roadgrader which scraped the top few inches of soil into windrows. The moist, windrowed soil was then removed by large earth movers, boosted by D-8 caterpillar tractors. In this case, the removed soil was accumulated in large piles outside the area of interest. These soil dumps were kept moist until the operation was completed. Then the completed mounds were sprayed with a heavy application of road oil.

"In parts of the area where use was not anticipated in the near future, the top few inches of soil after being wet down were bladed into windrows twenty to thirty feet apart. These windrows were sprayed with hot road oil to fix the contaminant and prevent wind and water erosion.

"Studies over a six-year period have shown that alpha-emitting contamination, unevenly dispersed over 700 acres of land, is effectively controlled and confined by oil-sealed windrows. The contaminated windrows can be removed any time the land be required for future tests.

"The decontamination of large areas requires skilled leadership. The combined efforts of health physicists, industrial hygienists, and equipment engineers should be enlisted to plan and expedite a large scale decontamination operation. Requirements may vary with circumstances. Therefore, the entire operation, including the removal and disposal of contaminated waste, should be carefully planned with appropriate provisions for long-range public safety. For example, the decontamination of an urban area and associated problems would vary greatly compared to decontamination requirements in a rural area.

"In summary, decontamination of facilities, roadways, and large land areas can be feasible and practical. Thorough planning, development of procedures, and careful execution is fundamental to the success of such an operation. Techniques are similar to those applied in normal decontamination operations, as are the tools and their uses. Intermediate confinement, control and storage of contaminants may be desirable in some situations. Permanent removal and disposal can then be undertaken with appropriate consideration of future public interest. Appropriate sampling, evaluation, and documentation of radiological data is essential, as are adequate records of procedures, costs,

and the description of new or unusual methods successfully applied to increase the fund of practical decontamination information." (This statement was prepared before Congress passed laws requiring environmental impact statements.)

3. NRDS Test Cell Decontamination Incident

In a 1965 accident in a Test Cell at the Nuclear Reactor Development Station at the NTS, some five acres became contaminated with radionuclides (Sanders, 1966). About 10^7 Ci of gamma radiation were released in the incident and about 2 months were required for the decontamination because of the buildings involved. The heavy earth scraping and loading equipment proved to be unsatisfactory for the type of cleanup necessary. A large vacuum cleaner also proved unsatisfactory because of the rocks in the area needing to be cleaned. A small model proved more satisfactory as did a small, remotely-controlled, mobile manipulator. Eventually man teams were allowed to pick up fuel pieces with tongs. Several inches of soil were removed and oil was sprayed on piled soil to decrease wind resuspension. The total cost of the decontamination effort on the 5 acres was about \$100,000. The employees involved in the cleanup received about 150 rem of radiation, but some received much less and a few received more. There was no concern at that time for the problem of vegetation removal during the decontamination or for the environmental impact.

4. USDA Farmland Decontamination Experiences

With deep plowing to effect a measure of decontamination, there are at least two different techniques or procedures. One of these is designed to bury the contamination at a sufficient depth to prevent its uptake by plants, its erosion by water, and its redistribution by animals. The other attempts to achieve a dilution of the contaminant throughout the entire plow depth so that its effective surface exposure is below the tolerance limit (USDA Handbook 395, 1971; USDA Tech. Bu. 1464, 1973; Menzel and James, 1959). The first technique has application for radionuclides which are biologically active in plant uptake. Inasmuch as roots of most plants easily penetrate two to three or more feet, success is not likely to be achieved, however, unless chemical means are used for fixing the radionuclides at the bottom of the plow depth. Otherwise, they would be readily available to plant roots and would be recycled to the soil surface if taken up by the plant. The second technique would be of value for radionuclides which are extremely inactive biologically. Plutonium may be

in this category.

If an area contained 7000 pCi/cm² of ²³⁹Pu uniformly distributed throughout 1 cm of soil, a plowing procedure which uniformly mixed it throughout a vertical depth of 1 meter would result in a surface contamination of 70 pCi/cm². Since most of the ²³⁹Pu is in the first cm of soil, uniform mixing to 1 meter could decrease the surface level to around 70 pCi/cm², a level from which resuspension to dangerous proportions would not be likely. Any erosion of ²³⁹Pu from heavy storms would be real, but at much lower levels than if all the ²³⁹Pu were on the soil surface. The feasibility of this as an operational procedure depends upon the information obtainable on the availability to plants from soil of the ²³⁹Pu when mixed into soil. Such experiments of plant availability of Pu in NTS soils are in progress and the analytical data will be available in the near future.

Some pertinent findings from experiments on decontamination of farm land discussed by Menzel and James (1959) and James and Menzel (1959, 1973) are quoted:

"Land that has been contaminated with radioactive materials may be treated to remove the contaminant or to reduce its entry into food products. Because these treatments usually require great effort, the objectives and feasibility of various treatments need to be carefully evaluated for each contamination incident. Indiscriminate use of ineffective treatments could be very costly without much reduction in the radiation hazard to the population.

"Treatment objectives may vary according to the type and extent of contamination. If accidental contamination is confined to a limited area, it may be removed to prevent its spread to other areas. In such cases an existing or potential radiation hazard may be removed without undue hazard to the decontamination workers. If the contamination is widespread radioactive fallout, it may be physically impossible to remove the entire hazard. Nevertheless, the proper choice of treatments, and land areas to be treated could reduce significantly the entry of radionuclides into the human food chain.

"Scraping off the surface soil is the most effective method of removing a surface deposit of radioactive material. More than 95% may be removed if scraping is carefully done. Scraping should be done before the contaminated soil has been cultivated. Even in favorable circumstances, about one hour of

equipment time per acre is required for soil removal and disposal. Scraping rough or stony soil, or that covered by coarse vegetation, is less effective and requires more effort. Various kinds of scraping machinery could be used, but those providing easy depth control and self-loading reduce the effort of soil removal and disposal. Scraping treatments may also be effective for contaminated snow surfaces.

"A rotary-brush street sweeper removes more than 75% of radioactive particles that have been deposited on a relatively hard, smooth soil surface. Two or three passages of the sweeper remove additional contamination and the amount of soil to be disposed of is much smaller than with scraping equipment. This treatment may also be effective on ice or frozen soil surfaces.

"Vegetative cover would intercept part of a deposit of radioactive material, and removing the vegetation might remove up to half of the radioactive material. Removal of vegetation might be necessary preliminary to a more effective treatment such as scraping. Conventional forage-harvesting machinery could be used to remove vegetation.

"Lime, fertilizer, or other amendments may reduce the entry of radionuclides from contaminated soils into crops. Use of lime and fertilizers for optimum economic return often gives the best reduction in radionuclide uptake. Hence, although the reduced uptake may be 70 or 80% of that with no treatment, it can be obtained at no cost. Some other amendments, including large applications of ammonium phosphate or sodium carbonate (the latter plowed deeply with the contaminated soil), may reduce radionuclide uptake much more effectively. However, the reduction in uptake is less than would be obtained by scraping a suitable soil surface, and the treatments would probably be more costly than scraping.

"Alternatives to decontamination and soil management should be considered, especially if the radioactive material is widespread, because of the great effort required for effective treatment of contaminated land. Some alternatives are growing crops that take up small amounts of radionuclides and removing radionuclides from milk and other products by treatment during processing. The treatment of contaminated land might then be limited to those areas needed for the production of certain vegetable or fruit crops.

"Methods were devised to simulate both wet and dry fallout. Distribution

methods of removal were also devised. The radioactivity eliminated from farmland by removal of various contaminated crops was measured. Following this, the effectiveness of removing contaminated top soil was determined.

"In a related study, the contaminated soil was treated with a concrete or asphalt coating before removal. Road graders, bulldozers, rotary and elevating scrapers as well as mechanized streetsweepers were used to remove the contamination.

"Further studies involved burying contaminated soil 3 feet deep with a large plow and measuring the uptake of radioactivity in various crops planted over it. Factors controlling uptake of radioactivity were compared.

"In removing radioactive fallout from farmland, there is no method which is best in all circumstances. Some methods seem to be better under a wider variety of conditions than others. The following conclusions are made from this research:

"Removal of contaminated crops is an ineffective method of decontaminating farmland.

"A power-driven streetsweeper or scraper cutting 2 inches deep removes about 90 percent of the contaminant.

"Decontamination should be accomplished before rainfall washes the radioactivity into low places where it is difficult to remove.

"Decontamination can be accomplished by a scraper with a 12-foot blade at the rate of 100,000 square feet (2.3 acres) in 3.3 hours.

"Application of a concrete or asphalt coating over the radioactivity is undesirable on farmland and only makes later pickup of radioactivity more difficult. (It is, however, an effective treatment if the land can be sacrificed.)

"Burying radioactivity 3 feet deep with a large plow is costly and ineffective in reducing the uptake of radioactivity.

"Planting through a contaminated surface which is then left untilled is an effective way to reduce the uptake of radioactivity.

"The species of the crop is a highly significant factor in the uptake of radioactivity."

5. Carlsbad Site Roll Up Program

The Carlsbad Test Site, located about 30 miles southeast of Carlsbad, New Mexico, was selected for the first scientific experiment in the Plowshare

Program. Project Gnome, the first attempt to use nuclear devices exclusively for peaceful purposes, was conducted on December 10, 1961. Upon completion of subsequent studies, the contaminated areas on the 640-acre Carlsbad site were decontaminated during the months of June through November 1968, and the area was restored for eventual release to public domain (Tappan and Lorenz, 1969). A great deal of contaminated material had to be handled in order to meet the objective of the cleanup program which was the removal and disposal of all surface contamination to whatever depth it was in excess of 0.1 mR/hr measured with an open shield GM-tube survey instrument.

The cleanup procedures generally involved: (1) locating contaminated materials (some of which had been previously buried in waste dump facilities), (2) removing the contaminated materials, and (3) disposing them into the mine shaft. Where dusty material, including soil, was involved, the area was wet down to eliminate air-borne debris during the disposal operations. After all contaminated materials were disposed of into the shaft, it was backfilled to within five feet of the surface and then capped off with a permanent concrete plug.

A surface salt muck pile, formed during underground construction work, contained an estimated 27,000 cubic yards of partially solidified salt, salt-polluted soil, and miscellaneous debris. This dump formed a gently sloping hillside encompassing a surface area of about 350 x 450 feet, varying from 1 to 20 feet in depth. It was determined that the salt muck pile could contain radioactive debris resulting from the Gnome reentry operations, but subsequent investigations determined that any radioactivity within the mass was sufficiently contained so as to present no radiological or significant environmental problem. Therefore, the salt and soil dump was left intact after an additional precautionary measure of constructing a ditch and berm to divert any surface runoff away from the dump during heavy rainfall.

A follow-up radiological survey of the Carlsbad Site in late March 1972 disclosed that the salt muck pile had eroded appreciably during the three-year post-roll up period, exposing some radioactive material (Nevada Operations Office, 1973). In addition there were other areas where radioactivity could be detected with more sensitive survey instruments. Interim measures subsequently have been implemented pending final site disposal actions, including the

installation of fencing, cleanup and disposal of pieces of contaminated materials, and stabilization of eroding areas. Follow-up radiological and ecological surveys are continuing to determine if there are needs for further action before final return of the Carlsbad Site to Public domain.

6. Tatum Dome Test Site Cleanup Operations

Decontamination of the Tatum Dome Test Site near Hattisburg, Mississippi was undertaken to reduce to the lowest practicable level any radiation contamination which might be potentially hazardous to present and future human land use (Nevada Operations Office, 1972).

The cleanup was accomplished by, (1) sampling and analyzing soil, water, vegetation, and indigenous animal life from on-site work areas and contiguous off-site areas, (2) excavating and placing all contaminated soil (about 11,000 cubic yards) and pumping all contaminated water and other accumulated fluids into the Tatum Salt Dome nuclear cavity, (3) sealing the cavity by plugging all drilled entry holes with cement, (4) segregating, packaging and transporting for disposal at NTS all remaining solids, equipment, and debris either contaminated or suspected of contamination, and (5) demonstrating that the site has been decontaminated and restored so far as practicable to provide reasonable assurance that unrestricted use of the site surface will cause no concern in respect to radiological consideration.

In addition to follow-up radiological and hydrological monitoring, the Federal Government will retain exclusive rights to regulate and control access to the subsurface of the real property, whether by drilling or excavation, and the right to prevent removal of any materials whether solid, gaseous, or fluid from the real property below mean sea level.

A post-operation evaluation of the Tatum Dome cleanup experience was reported by Church (1973). The following paragraphs are quoted from a summary of recommendations which Church believes would enhance future cleanup operations.

"Sites and activity areas should not be allowed to remain in stand-by conditions for long time periods. Personnel change, conditions change, records are lost, and material of all types tend to become mobile. If operational sites and facilities are to remain idle for appreciable time periods, an interim cleanup should be completed to minimize effects of time.

"Along with the standard practice of recording locations of dumps, waste areas, description of operations, etc., reports should reflect names and positions of key operational personnel --- documentary photographs (particularly aerials) are a necessity to complete reports for historical purposes.

"The completion of pre-cleanup surveys is a must for planning a cleanup operation. An adequate pre-cleanup survey cannot be emphasized too much. The total logistical effort for a cleanup is based on the conclusions drawn from this survey. For example, this project (Tatum Dome Cleanup) was started expecting to excavate approximately 1500-2000 cubic yards of soil. Consequently, the disposal techniques, cost estimates, and excavating methods were planned and obtained for this estimated work load. However, as the cleanup progressed and soil volumes doubled and tripled, the methods and equipment became obviously inadequate. -----The necessity for this survey is even more obvious for isotopes difficult to quantify (i.e., ^{90}Sr , ^{239}Pu , ^{55}Fe , etc.).

"General criteria are needed before the pre-cleanup survey to enhance survey planning. Specific criteria are needed long before the field effort is started to enable reasonable assessment of the required logistics. The development of concentration guides for soil are necessary to assist management in planning for operations at the very inception of programs.

"-----the choice of excavating equipment can be crucial because it severely impacts on cost and time.

"The first-line supervisors instructing construction crafts and laborers need to be well trained and indoctrinated in handling contaminated material.

"Scrap dumps should be cleaned up periodically and not allowed to proliferate."

As an example pertinent to demonstrate that things change with time, invalidating predictions and the best of intentions, Church (1973) pointed out that when the disposal action at the Tatum Dome Site was considered, it was not expected that a nearby gas and oil field was to be rapidly developed and that very large quantities of brine were to be injected in the disposal zone, changing flow, hydrological pressures and flow directions.

7. Mill Tailings Stabilization Programs

An example of cleanup and restoration activities at an industrial processing site is found in reports concerning the Monticello Project (Grand

Junction Office, 1963; Paas, 1966). At this site nearly one million tons of mill tailings were accumulated and deposited over an area of some 49 acres during the mill operation in the period 1942 to 1960. Following shutdown of the mill, the site recovery operations included grading the gross tailings area to promote drainage and covering it to a depth of 12 to 24 inches with approximately 135,000 cubic yards of rock and soils. Radiation emitted from the tailings was reduced to negligible values by the attenuation effect of the soil and rock cover. After fertilizing, the area was seeded with grasses to establish a ground cover comparable to or exceeding that of the original area. The cost of this stabilization program based upon the deposition of up to 24 inches of cover soil and subsequent vegetative planting was \$4750 per acre (U.S. Dept. HEW, 1966).

An additional 80-acre ore storage area was cleaned to the extent that no visible evidence of ore remained. Processing, storage, and administrative buildings and contents were removed, destroyed, or buried concurrent with the mill tailings stabilization program. Subsequent evaluation of environmental samples of air, vegetation and water (Paas, 1966) showed no evidence of radioactive material transport from the tailings and ore storage areas. Although surface occupancy of this site could be permitted on a nonrestricted basis, the presence of subsurface contaminants at the stabilized tailings area require continued control to prevent human disturbance. Also there is continuing need to guard against disturbance by wind and water erosion at any of the stabilized uranium tailings sites.

In another industrial situation, acidic and basic uranium leach plant tailings located on the Navajo Indian Reservation, Tuba City, Arizona, were successfully stabilized against wind erosion using a relatively low-cost chemical method. An elastomeric polymer (DCA-70; Union Carbide) was applied to the dike areas and a calcium magnesium lignosulfonate to the beach areas of three tailing ponds. These water-soluble chemicals were applied with an automated sprinkling system at a cost of \$335 per acre for the 34.5-acre tract (Havens and Dean, 1969).

The Bureau of Mines and Kennecott Copper Corp. cooperated in stabilizing a 10-acre test plot of copper tailings (without adding soil cover) by a combined chemical and vegetative method at a cost of \$135 per acre (Dean et al., 1969). Arizona copper producers and HEW report that the costs for

placement of a 12-inch soil cover were about \$1100 per acre (U.S. Dept. HEW, 1966).

Another cleanup activity in an entirely different kind of ecosystem (Deciduous Forest) is represented by the decontamination of land adjacent to the AEC Niagara Falls Site (LOOW Survey Report, not dated). This land was previously part of the Lake Ontario Ordnance Works and was utilized during World War II for the storage of radium-bearing uranium refinery residue and contaminated building rubble from dismantled uranium processing buildings. The cleanup included an extensive radiological survey which defined that about 6.5 acres exceeded the acceptable criteria ($50 \mu\text{R/hr}$) for unrestricted use of the involved land. Contractor operations began on May 30, 1972, and were completed on June 23, 1972. About 8-10 acres of land finally were involved from which an estimated 15,000-20,000 cubic yards of soil, debris, etc., were removed from non-AEC property to the spoil area on AEC property. The work included cleanup of surface and below-surface contamination from storage areas, railroad beds, catch basins, burial dumps, creek areas, and drainage ditches. Contractor costs totalled about \$88,000.

The decontamination method of covering radioactive material with non-radioactive soil has certain practical applications as mentioned above. It is one of the control measures to be considered for Pu contamination problems, but, as pointed out by Hendricks (1974), any stabilized Pu and U areas have an uncommon problem, namely, the diffusion and concentration of radon from the uranium contaminant into new surface overburden. For this reason the practice of establishing plant cover (which in dry areas usually requires supplemental moisture) on soil-covered uranium tailings is now being questioned as a desirable method. Chemical or physical stabilization without vegetation may prove to be the soundest method. In any event, the desired objective is to obtain permanent stabilization against wind and water erosion at the lowest practical cost. Other problems relative to containment and stabilization of radioactive wastes are caused by burrowing animals and grazing animals. In the course of their living and feeding habits, certain radionuclides can be tracked by or distributed by fecal pellets in the contiguous areas surrounding waste disposal sites (Sill, 1973; O'Farrell et al., 1973). The main point of concern under these conditions is to prevent the growth of vegetation on sites where

radionuclides can be extracted through plant roots and subsequently redistributed by animals. Other methods of surface soil stabilization must be applied to such areas.

8. Bikini and Enewetak Experience

Rehabilitation of the Bikini Atoll following nuclear testing activities included the provision that the islands of Bikini and Eneu could be used for continuous occupancy and agricultural development sufficient to support the returning native population. The cleanup of these islands included: (1) the removal of all test-related debris with disposal at sea of all radioactive debris, (2) stripping of the vegetation cover to permit planting of coconuts, pandanus, breadfruit, etc., which was accomplished by cutting 20-foot wide swaths on 56-foot centers through the vegetation cover, (3) determining residual external radiation levels at each step of the clearing and stripping operations, and (4) continued monitoring of available food items for hazard evaluation. Radioactive scrap and test-related debris was removed from other islands (not inhabited by humans) since these islands may be used for the collection of birds, turtles and their eggs for human consumption (Smith and Moore, 1972).

Since there is desire and pressure for the Enewetak people to reestablish their villages in some locations on the atolls used for nuclear tests, considerable work is being done there on decontamination problems and policies. Of course the sociological, geographical, geological, and climatological characteristics are vastly different between Enewetak and Nevada; nevertheless, there are some important and pertinent relationships. Some of these from the Task Force Report (1974) on recommendations for decontamination and rehabilitation of Enewetak are as follows:

1. It may be possible to reduce the amount of material requiring disposal by removal of the Pu from the most highly contaminated soil only.
2. In the radiologically complex Enewetak atoll environment there are several options that may be considered for cleanup and rehabilitation of various islands.
3. Comments have been solicited from several federal agencies. Their suggestions have influenced the development of recommendations.
4. Choice of the best overall method for reduction of exposures to the lowest practicable level is a matter of judgment and opinion.

5. The adverse impact of various engineering actions on the atoll environment and the uncertainties regarding effectiveness have been viewed.

6. Estimates of dollar costs for cleanup actions are being prepared.

7. There are three basic questions to be addressed: (1) Is the radiation environment acceptable or can it be made acceptable for the Enewetak people to return to their atoll; (2) Is the radiation environment on Enjebi (JANET) acceptable or can it be made acceptable for the people to return; and (3) Are there islands which are not acceptable for people to conduct their normal agricultural and social activities, and if so, are there any actions that could be taken or restrictions imposed that would keep exposures within acceptable criteria?

8. Removal of 15 cm of soil would result in a theoretical reduction factor of 3 to 4 for ^{137}Cs and ^{90}Sr in the remaining top cm layer of soil. This is roughly the same theoretical effect as waiting 60 years for radioactive decay to take place.

9. Since the top soil on that island is charitably described as meager, such action as removing 15 cm of top soil would leave JANET a sand island. Heroic actions would be required to either reconstitute the remaining soil through use of fertilizers and other additives, or import quantities of top soil sufficient to support subsistence and commercial agriculture.

10. A period of time would be required, possibly as long as 8 to 10 years, or until test plantings of coconut, pandanus, and breadfruit are grown and analyzed for their radioactivity content, before a decision could be made to settle people at JANET. An additional period of 8 to 10 years would be required after a decision to plant subsistence and commercial crops in quantity before the island could support its inhabitants.

11. Removal of Pu soil concentrations greater than 400 pCi/g $^{239}, ^{240}\text{Pu}$ to any depth necessary would be undertaken. The justification is that Pu at some depth may one day be at the surface. Also, removal of sufficient contaminated soil to reduce surface levels to a value well below 40 pCi/g $^{239}, ^{240}\text{Pu}$ in order to keep air concentration of resuspended Pu to levels within acceptable standards.

12. Test plantings of agricultural crops should be made. As edible parts of these plants become available, their concentration of ^{90}Sr , ^{137}Cs , $^{239}, ^{240}\text{Pu}$ and any other significant radionuclides should be measured and compared with the Radiological Survey predictions and with standards.

These recommendations, of course, are based upon the assumption that the people returning to the islands would grow all their food crops in the soil on the sites. The most relevant of them concern the avoidance of haste and the need for time for experimentation and evaluation.

III. REVEGETATION AND LAND RECOVERY EXPERIENCES UNDER ARID CONDITIONS

A. Introduction

Considerable pressure has been exerted in the recent past for restoration of disturbed areas of the landscape to their original condition by whatever agency caused the disturbance rather than abandoning the area in its disturbed condition. In addition to this, new governmental environmental policies and regulations require statements concerning impact of activities on the environment and plans for restoring to the original condition, particularly if lands are to be returned to the public domain. These policies are considered relevant to any new radiation cleanup procedures undertaken in Nevada.

Desert environments present considerable difficulties for restoration once their vegetation has been destroyed (Figs. 11, 12, 13, 14, 15). Much more effort than in humid environments is required. The severe nature of the desert environment is largely responsible and the principles of succession do not operate as they do in more favorable environments. There are decided differences, for example, in vegetation recovery in the Great Basin portion of the NTS (Pahute Mesa) as compared with the Mojave Desert portion (Yucca and Frenchman Flat).

Rainfall is the dominant factor in revegetation success and it is generally considered that about 10 inches (25 cm) of rainfall per year is the minimum needed for reasonable revegetation without supplemental irrigation (Hull et al., 1964; Plummer et al., 1968; Tueller et al., 1972). Since the areas with which we are concerned at NTS normally have lower rainfall than this, an adjustment of the physical features of the terrain to concentrate moisture is vitally important, since supplemental irrigation is not easy to achieve. Where irrigation is available some marginal lands, for example saline and alkaline, can be reclaimed (Stuart et al., 1973). A general rule of thumb

Fig. 11. Old roadway unused for 17 years which goes into Site D in Area 11 at the NTS. This semi-Mojave Desert site recovers very slowly after disturbance. Unless water distribution is manipulated, such an area may not recover for many decades. (Photographed in June 1974)

Fig. 12. Remains of a road in Area 13 after 15 years of nonuse. Recovery is good in this Great Basin Desert area, but the effects of the road will remain for many decades. (Photographed in June 1974)

Fig. 13. Demarcation line between land scraped (right) 11 years ago at the Clean Slate 3 site at the Tonopah Test Range in Nevada and nonscraped land (left). The recovery of this Great Basin land has been reasonably good and grasses were favored. There are many bare areas remaining in the scraped area which may relate to the depth of scraping. (Photographed in June 1974)

Fig. 14. An example of 11 years of recovery following blading of an area in the Great Basin Desert (Clean Slate 1 at Tonopah Test Range). The area bladed was to the left of the line right of the center of the photograph. Actually the recovery of vegetation is reasonably good with a fair amount of grasses growing in the bladed area. (Photographed in June 1974)

Fig. 15. Another site bladed 11 years ago (at Clean Slate 2 at the Tonopah Test Range). A rectangular area of about 5 acres shown in the left part of the photograph was bladed. Again, the recovery has been fairly good with many grasses present. At the lower part of the photograph in the bladed area many Halogeton are growing. This poisonous plant is one of the problems associated with disturbed and over-grazed lands. (Photographed in June 1974)

is that where Artemisia tridentata (sage brush) grows, revegetation is reasonably successful. That shrub is normally a Great Basin Desert species. When annual rainfall is greater than about 10 inches, the natural revegetation process under Great Basin Desert conditions is sufficient to insure some success (Tueller et al., 1972). Parts of the Great Basin Desert and all of the Mojave Desert present a formidable challenge for revegetation because of sparsity of rainfall, high summer temperature, and adverse soil conditions. Adequate procedures for land rehabilitation should be available and tested before there is any large-scale destruction of native vegetation in these areas.

When Mojave Desert vegetation has been destroyed, several decades and often over a century are required before the area regains its natural or original plant cover largely because the rainfall is usually less than 10 cm (4 inches) per year. If a goal is adopted for returning disturbed Mojave Desert to its natural condition, considerable developmental effort is needed. It may be practical to propagate many kinds of desert plants (Wieland et al., 1971; Wallace et al., 1972). Development work, however, is needed on procedures for placing plants and/or seeds in the field in a manner which will insure survival. In some years this can probably be achieved by normal winter rainfall provided that proper types of catchment basins are mechanically constructed to concentrate sparse rainfall to the sites where plants are to grow. This has been accomplished successfully in other deserts (Evenari et al., 1971a). Workers found that small-sized microcatchment basins which cost about \$20 per hectare to construct were most useful in Israel. A most serious problem in revegetation efforts that needs solution is the destruction of new plants by animal activity. A series of studies with repellants and other procedures needs to be undertaken. The research goal should endeavor to restore areas to natural vegetation in an inexpensive manner and as rapidly as possible.

Natural reseeding of perennial shrubs under steady-state natural conditions is a statistical problem and related to combinations of favorable seasons of rainfall. Seedling survival is related to soil moisture and to micro soil conditions in part, but perhaps even more to animal activities. As mentioned, we have found that animals play an extremely important role in the regulation of survival of perennial shrubs. Animals eat off the new seedlings. This is so in both the Great Basin and Mojave Deserts. In areas such as Pahute Mesa

at the NTS where vegetation was killed in down-wind fallout patterns, sufficient Artemisia tridentata seedlings appeared to restore the area to its natural condition provided that the seedlings all survived. During the third year of recovery, a severe drought season resulted in destruction of many of the 3-year-old seedlings; however, the destruction was by rabbits rather than by the drought. Rabbits sought out young seedlings to compensate for the depletion of their normal forage (Wallace et al., 1972a).

Another important factor influencing revegetation efforts, particularly where the soil surface has been removed, is a very low organic matter content characteristic of subsurface soils in the desert. Reseeding and plant growth in such soils without amendment is extremely slow. Experience has shown that Mojave Desert areas do not naturally return to their original condition even in 100 years when the native vegetation is destroyed (Wells, 1961; Wallace et al., 1972a). To do it in considerably less time will require agronomic and engineering input to overcome adverse soil and moisture conditions.

We have collected seed and successfully germinated and grown about 100 species of plants from the NTS (Wallace et al., 1972b). We have also vegetatively propagated about 40 species of plants from the NTS and successfully grown some of them even in the field at NTS. For some species we have routine procedures with which we have produced hundreds of cuttings for testing use. The procedures can be used to produce thousands for widespread testing. We have transplanted some of these materials in the field at the NTS and concluded from the results that it is possible to successfully encourage revegetation of disturbed areas provided that animals can be kept from destroying the new plants, and provided that soil moisture is adjusted. These points need be studied additionally on a large-scale basis.

Considerable revegetation occurs along roadside cuts in Nevada and other arid areas. Larrea tridentata not only grows well on the bladed cuts, but also establishes itself very successfully even under adverse conditions so far as soil is concerned (Fig. 16).

We propose that a pilot program be established to further test the feasibility of encouraging revegetation at NTS on disturbed lands by artificial means. Seed of adapted species, especially of grasses, needs to be collected. We suggest that a series of animal repellent compounds be tested together with

Fig. 16. *Larrea tridentata* growing along U.S. Highway 95 in Southern Nevada. The plants are new seedlings growing in adverse conditions (almost out of the black top). This illustrates that Mojave Desert species can re-establish themselves on disturbed areas if sufficient moisture is present. In this case the runoff from the highway provides the needed moisture. (Photographed in June 1974)

transplanting procedures during the months when soil moisture is present at reasonable levels. Seeding and transplanting procedures will both be used. This has been successfully done in Israel for some species, especially when microcatchment basins were constructed (Evenari et al., 1971a).

Perennial shrubs ordinarily occur in groups or clumps in the Mojave Desert. There may be several hundred clumps per acre with a few thousand individual plants per acre. We calculate that in denuded areas, if we can successfully reestablish as many as 50 to 100 clumps per acre, there would be enough seed for natural reseeding. We would endeavor to establish about 50 to 100 clumps per acre on an experimental basis on some land by combination of seeds, particularly of grasses, and cuttings of woody plants. We would make these in micro water-catchment basins (simulating Evenari's catchment irrigation systems in Israel) made either by shovel or machine to conserve and accentuate the amount of rainfall. Experiments with various types of seeding will also be conducted in these catchment basins. We would fertilize slightly to favor establishment. We would test animal repellants and the effects of protecting plants with inexpensive wire cloth enclosures. It is expected also that the establishment of 50 to 100 clumps per acre as a start would greatly improve the appearance of an area which had been denuded.

Some explanation for the presence of animals (rabbits and rodents) in denuded areas in sufficient numbers to severely regulate revegetation is in order. Introduced annual plant species, mostly Salsola sp. and Bromus rubens, grow abundantly on disturbed soils and provide abundant seasonal animal feed. Animals (rodents particularly) also are attracted by the loose soil present in some denuded areas. New shrub seedlings, unfortunately, are part of their preferred diet.

Revegetation techniques differ considerably for the Great Basin Desert compared with the Mojave Desert. Procedures have been developed for revegetation in range areas under Great Basin conditions (Plummer et al., 1955; 1968). Reseeding, especially to grasses, can be successful, but only when rainfall is sufficient. Seasonal distribution of rainfall is also important.

Other important factors are selection of adapted species, the availability of seed, correct seeding procedures, adjustment of competition from both plants and animals, and manipulation of terrain.

Some pertinent points which have been mentioned only briefly are discussed in greater detail below.

B. Revegetation Work at NTS in the Past

Wherever vegetation has been destroyed at the NTS as the result of nuclear testing activities, Salsola (Russian thistle) species and native annual species and grasses have grown abundantly in subsequent years on those areas. Experience indicates, as mentioned in the introduction to this section, that decades of time are necessary for the perennial shrub vegetation on a disturbed site to return to its original state. In disturbed areas of the Great Basin Desert portion of NTS, germination and survival of native shrub seedlings have been sufficient to eventually return those areas to their native condition. After severe drought periods, many new seedlings have disappeared, not directly because of drought, but because of browsing animal activity. In the Mojave Desert portion of the NTS, the germination and survival of shrub seedlings have been much slower on disturbed sites than in the Great Basin Desert. Animals have destroyed virtually all shrubs which we have transplanted into disturbed areas of the Mojave Desert. Nevertheless, transplanting has been successful when plants are protected from browsing animals and initially supplied supplemental moisture.

Under natural conditions, revegetation in desert areas usually occurs in the relatively fertile islands created in the desert by colonies of shrubs which occupy a site for decades or centuries with turnover within the site. Organic matter build-up and concentration of nutrients by cycling make these zones of high fertility (Tables 5 and 6). Destruction of these sites makes revegetation difficult. Some field test results for revegetation attempts by propagated plants are given in Tables 7 and 8 (Romney et al., 1971; Wallace et al., 1972).

C. Israeli Studies on Revegetation in Microcatchment Basins

Evenari et al. (1971a) in Israel have discovered ancient land runoff irrigation systems near Avdat in which large farms were irrigated from the induced runoff. Many of these farms have been reconstructed (Evenari et al., 1971b) with impressive results (Evenari et al. 1971c).

Table 5. Yields and element composition of plants grown in bare desert soil as compared to plants grown in soil from underneath shrubs. The data here illustrate poor plant growth with nitrogen deficiency plus other nutrient element disorders of plants grown in bare area soil.

Yield and composition of Hilaria rigida

(dry weight basis)

	Shrub area	Bare area
Yield, mg/plant	1398	644
N, %	2.87	1.32
P, %	0.24	0.33
Si, %	0.92	2.07
K, %	3.03	1.85
Mg, %	0.29	0.27
Ca, %	0.51	0.60
Mn, ppm	18	61
Fe, ppm	74	51
Cu, ppm	12.2	24.6
Mo, ppm	5.8	13.0
B, ppm	37	41

Table 6. Soil properties of the bare-area soil in which it is exceedingly difficult to reestablish plants and of the fertile, interspersed shrub-area soil which supports vegetation.

Soil properties	Shrub area	Bare area
EC, mmho/cm	1.63	0.39
Soluble Na, me/l.	0.68	0.31
Soluble K, me/l.	3.20	0.92
Soluble Ca, mc/l.	6.44	4.16
Soluble Mg, me/l.	13.25	0.29
Soluble B, ppm	1.50	0.90
Organic C, %	1.45	0.43
Organic N, %	0.15	0.04
HCO ₃ ⁻ Sol. P, ppm	2.06	0.32
DTPA-ext. Fe, ppm	1.00	0.30
DTPA-ext. Zn, ppm	1.05	0.62
DTPA-ext. Mn, ppm	4.05	1.40
DTPA-ext. Cu, ppm	0.15	0.15

Table 7. Survival of potted desert plants 15 months after transplanting them into the field in Frenchman Flat (in a disturbed area). The "Z.I.P." is an animal repellant; "wire" is an individual 1-inch mesh-wire enclosure for protection against rabbits; "open" means no protection against animals. These plants were irrigated monthly during the first six months after transplanting. Test duration: 2/16/72 - 5/31/73

Species	Treatment			Total survival %
	Z.I.P. %	Wire %	Open %	
<u>Ambrosia dumosa</u>	83	83	67	78
<u>Atriplex canescens</u>	67	83	50	78
<u>Artemesia tridentata</u>	67	100	67	78
<u>Eurotia lanata</u>	78	78	50	72
<u>Grayia spinosa</u>	33	33	0	22
<u>Larrea tridentata</u>	89	94	56	83
<u>Lycium andersonii</u>	67	67	50	62
<u>Lycium pallidum</u>	0	100	0	33

Table 8. Survival of potted desert plants 30 months after transplanting them into the field in central Yucca Flat. Test duration: 12/8/71 - 5/31/73

Species	% survival	Species	% survival
<u>Artemisia ludoviciana</u>	60	<u>Grayia spinosa</u>	27
<u>Artemisia tridentata</u>	92	<u>Larrea tridentata</u>	0
<u>Atriplex canescens</u>	32	<u>Yucca brevifolia</u>	33
<u>Eurotia lanata</u>	40	<u>Encelia virginensis</u>	0

Those investigators have extensive experiments in which the idea has been extended to small plots (15 m² to 1000 m²) called either microcatchment basins or "negarin" (Evenari et al., 1971d). The tremendously difficult problem of revegetation in arid desert areas such as the Mojave Desert may yield to techniques such as this. First, a description of the Israeli experience should be given.

Under arid conditions and within certain limits, the smaller the catchment the higher the relative water yield per unit area. Another great advantage of microcatchments over the large runoff farms is the much lower cost of installing and maintaining them.

In a search for optimum size, an area was subdivided into 117 microcatchments ranging in size from 1/10 hectare (1000 square meters) to 1/640 hectare (15.6 m²; Table 9). A check border 15 - 20 centimeters high was raised around each plot. A planting basin was dug at the lowest point of each microcatchment to insure the flow of water to the center. Trees and shrubs were planted in each basin.

Table 9. Area and number of microcatchment "negarin" installations. (Adapted from Evenari et al., 1971d)

ha	m ²	Number/acre
1/10	1000	4
1/20	500	8
1/40	250	16
1/80	125	32
1/160	62.5	65
1/320	31.2	130
1/640	15.6	261

The fact that the 500 m² plots produced the maximum runoff and that smaller plots yielded less led to the conclusion that there is an optimum size for maximal runoff. In short, when the plot size is reduced below the optimal, the runoff yields decrease.

Average runoff from seven small farm-sized watersheds was less than 10%. In contrast, that of the microcatchments was 45 to 50% (Table 10). This rainfall which was too light and ineffective to provide runoff on the large farm, was effective on the microcatchments.

Table 10. Runoff measured during six rainy seasons from small negarin runoff plots (A, 20 m²) and from the larger runoff plots near the farm (B, 80 m², 10% slope with natural stone cover). (Adapted from Evenari et al., 1971d)

Year	Plot	Rainfall (mm)	Runoff (%)
1962-63	A	29.5	12.3
	B	29.5	6.0
1963-64	A	158.2	58.7
	B	169.2	27.1
1964-65	A	153.1	53.5
	B	159.8	30.2
1965-66	A	89.0	53.6
	B	90.7	27.2
1966-67	A	79.4	25.5
	B	85.0	14.7
1967-68	A	85.1	62.0
	B	86.2	22.0

In the negarin were planted pomegranates (Table 11), apricots, almonds, carobs, olives, and grape vines. Salt bush (*Atriplex halimus*), a promising highly salt-resistant pasture plant from Australia, was reserved for the 15.6 to 250 m² plots. The fruit trees were placed on plots of 125 to 1000 m².

Under the rainfall and flood conditions of Avdat, 20 to 40 pomegranate trees could be planted per hectare (8 to 18 per acre) if the negarin method was used. This is true also for other trees. The vines, being shrub-like rather than tree-like, can apparently do with smaller catchments (80 to 100 per hectare or 32 to 40 per acre).

Of all the negarin test plants, the saltbush was the only one planted also without catchment ("zero catchment") on the open loessial plain. None of the zero-catchment plants planted in 1961 survived in spite of being given 50 liters per plant of supplementary water at the planting date. A second zero-catchment planting late in 1962 was also unsuccessful. Zero-catchment salt bushes planted in 1963 survived in a very stunted state. The 15.6 m² catchment plants all became well established, but 60% succumbed to the 1962-63 drought. These too

Table 11. Growth of pomegranite trees in negarin of various sizes. The cross-sectional area was measured on 1 January of each year at the marked measuring point. All the trees were planted in the 1962-1963 season.

Year	Cross-sectional area of trunk (mm ²)	Relative growth	Height (cm)
1000 m ² microcatchment			
1965	685	1	210
1966	1300	1.89	
1967	2565	3.74	
1968	4140	6.04	
1969	5880	8.58	
500 m ² microcatchment			
1965	1067	1	222
1966	3120	2.92	
1967	4130	3.87	
1968	5670	5.31	
1969	8210	7.69	
250 m ² microcatchment			
1965	773	1	183
1966	1570	2.03	
1967	3080	3.98	
1968	4440	5.74	
1969	5970	7.72	

were replanted in 1963 and since then have grown well. Establishment of all saltbush plants in all other catchments was excellent (94%) on the first planting in 1963.

Over the years of experiments, many "volunteer" saltbush plants germinated, grew, and established themselves around the edges of the planting basins. These volunteers appeared only on the microcatchment basins larger than 15.6 square meters. Even on the larger catchments, no volunteers ever developed on the runoff slope area, but only in and around the planting basins. This fact again shows that on the loessial plain the saltbush finds conditions permitting establishment and growth in habitats only where runoff collects in sufficient quantities. All these data prove that zero-catchment planting is

doomed to failure under Avdat conditions. But microcatchments from 31.2 square meters upward guarantee successful establishment and subsequent growth even during bad drought years. This means that at least 320 saltbush plants could be grown successfully per hectare (130 per acre).

When yields per plant are converted into yields per hectare without taking into account the volunteer plants, the picture is changed. The higher yields of single plants in the larger catchments are largely offset by the greater number of plants per unit area in smaller catchments, and the optimal yields (312 plants per hectare) are then produced by the 31.2 m² catchments.

This technique of Evenari et al. (1971) has been tried in Southern Arizona (Morin et al., 1973). "Yields of grain sorghum averaged 1600, 2000, and 500 kg/ha for rainfalls of 190, 246, and 137 mm."

In revegetation of coal strip mine areas in Kentucky, the microplot catchment has been successful (Powell and Barnhisel, 1973). "The land preparation treatments in which a microrelief had been produced by subsoiling yielded at least two times more dry matter than plots which were reclaimed by the conventional method. The creation of a microrelief provided small depressions in which water could be temporarily stored to offset the slow infiltration rate of the spoil materials."

A microcatchment basin formed accidentally at a site in Area 11 shows revegetation as a result of the extra water (Fig. 17).

The cost of constructing microcatchments was very low in Israel due to the use of inexpensive hand labor — between \$5 and \$20 per hectare, depending on catchment size. The crucial problem is still the optimal size of the microcatchment for each species and each soil under given rainfall conditions. Other problems concern optimal depth and the size of the basin in relation to the size of the catchment area.

D. Revegetation Experiences in the Great Basin

Plummer et al. (1968) have considerable experience in revegetation under Great Basin Desert range land conditions. They have discussed several principles and procedures for success in establishing vegetation under Great Basin conditions which generally are more favorable than Mojave Desert conditions. Their ten ideas are briefly outlined and discussed, since each has some bearing on revegetation problems at the NTS.

Fig. 17. A water catchment basin unintentionally constructed at Site B in Area 11 in which new perennial plants have become better established than in the surrounding area all of which was disturbed due to testing. Note the water run-in channel at the bottom of the photograph. Basins such as this can be constructed in disturbed areas to concentrate the sparse rainfall to insure adequate revegetation on at least part of the disturbed area. (Photographed in June 1974)

1. Change must be desirable. There must be a reason for the effort expended to achieve the growth of new plants.

2. Terrain and soil type must be suitable, or it is futile to attempt to induce new vegetation. Steep slopes, coarse soil texture, proximity to bedrock, stoniness, etc. have a great effect on the outcome of revegetation efforts.

3. Precipitation must be adequate to assure establishment and survival of planted species or supplemental irrigation is needed. Amount of precipitation and occurrence of indicator plants are the most important guides to what species may be seeded successfully. As the amount of precipitation increases, a greater variety of species may be successfully established.

4. Competition from other plant species, especially those unwanted, must be low enough to assure that the desired species can become firmly established. Bromus sp. and Salsola sp., for example, are very troublesome on disturbed lands and may need control.

5. Only species and strains of plants adapted to the area should be planted. Fourwing saltbush (Atriplex canescens), a highly desirable species, develops nearly as rapidly as other brush species, but initial establishment is weaker; also, rabbits and rodents prefer its seedlings and destroy many of them. Plummer et al. (1968) obtained good stands of many shrubs on 5,000 acres by serial-broadcast seeding in winters when the cycle of rabbit population was low.

In addition to selecting appropriate species, it is necessary to make sure that only adapted sources or strains are used. Ordinarily, seed from sources having greatly different soils or very different climate is much less likely to produce good stands than seed from sites similar to those where it is to be planted. Species from cooler climates generally can adapt themselves to warmer climates more successfully than the reverse, especially if frost is involved.

Adaptability is especially important for shrubs. Differences between strains of several species have been observed. For example, seed of antelope bitterbrush (Pursia tridentata) collected from acid, granitic soils has produced chlorotic, unhealthy plants when planted in basic soils originating from limestone or shale. Seedlings from fourwing saltbush seed collected in stands of the warmer blackbrush type in Southwestern Utah failed to survive when moved only 50 miles into a higher mountain brush type. This species exhibits a high degree of adaptation to specific sites.

Good stands of Indian ricegrass (Oryzopsis hymenoides) from salt-desert shrubland have completely died out in the climates of nearby mountain brush and upper juniper-pinyon. Plants from seed of Indian ricegrass from cool, moist areas can survive in warmer areas, but not the reverse. Fourwing saltbush, antelope bitterbrush, big sagebrush (Artemisia tridentata), rubber rabbitbrush (Chrysothamnus nauseosus), and winterfat (Eurotia lanata) vary greatly in the characteristics noted above.

6. Mixtures of plant types rather than single species should be planted in areas being revegetated. Mixtures provide four major advantages. Site characteristics change radically, often within a few feet. Seeding several species in mixtures takes advantage of this diversity. Mixtures provide variety for animals; hence, there is less likelihood that animals will kill all of the new species by overgrazing them. Another major advantage in use of mixtures of species is that they produce better overall ground cover than single species.

Occasionally the environment is suitable for establishing only a single species. Seeds of slow-growing shrubs should be segregated from seeds of herbs in order to reduce competition.

7. Sufficient seed of acceptable purity and viability should be planted to insure getting a stand. Dormancy of most seeds is broken by subjecting them to temperatures between 32° and 40°F for a period of 6 to 20 weeks in moist sand, peat moss, or moist newspaper. Fall and winter plantings take advantage of the cool temperatures and thus break dormancy naturally in some winters at NTS. For many species scarification by sulphuric acid treatment or mechanical rubbing helps to overcome dormancy for seed germination.

8. Seed must be covered sufficiently with soil, but not too deeply. Seeds must have a light covering of soil — usually 1/4 to 1/2 inch.

9. Planting should be done in a season that gives promise of optimum conditions for establishment. Some shrubs can be propagated satisfactorily by transplanting and best success has come from transplanting in the spring, especially if adequate soil moisture is present and if some precipitation is likely after the transplanting.

Direct seeding in late fall and throughout the winter gives good stands of most species. Four major advantages of fall or winter seeding over spring seeding are:

- (a) It overcomes inherent seed dormancy.
- (b) Cold winter temperatures stimulate seedlings into more rapid growth.
- (c) The longer period of available adequate moisture produces larger seedlings, which can better withstand heat and drought in summer.
- (d) Loss of seed to seed collecting animals is reduced because many of these animals hibernate.

Seed that must be seeded directly in the spring should be treated with a 3% solution of thiourea for 3 to 15 minutes to overcome dormancy and to improve both emergence and establishment.

Transplanting of nursery stock, seedlings and wildings is usually most successful when completed while the ground is still moist from snow melt or from winter rain.

10. The planted area must not be overgrazed or subjected to excess animal activity. Where pressure is heavy, the number of excess animals should be appropriately reduced. In Utah 400-acre areas have usually been a satisfactory critically large enough area to prevent damage from animals.

Newly planted areas are subject to damage from rabbits, rodents, and insects; but several effective control measures are available. Strychnine hay or poisoned grain effectively controls rabbits, especially if the population cycle is high. Strychnine salt put into holes bored in wood slabs is effective in spring and summer where herbage is succulent. Mice, chipmunks, kangaroo rats, and ground squirrels can cause devastation. The scattering of "1080" or strychnine-poisoned grain effectively controls damaging populations of these rodents.

E. Hydromulching As a Means of Revegetation

Hydromulching or hydroseeding is a method of application of seed into soil by high-pressure water spraying (Baciu, 1967). Seed, fertilizer, and organic materials are mixed together in a slurry. It has become a highly developed procedure in recent years with special machines built for particular conditions. The procedure is adapted to all kinds of terrain, but, although simple, efficient, and fast, costs have been high because most of the work has been done by contractors who have developed a specialty business. It is a very popular method

for seeding steep roadside cuts where solid ground cover is desired.

Most of the use to date has been in sowing grass seed. This is done with hydro-seeding machines which have been built on several different carriers. Some small ones are built on two-axle truck chasses while others are built on trailers and semi-trailers. The tanks in which the slurry is mixed and the high pressure pumps are of different sizes. The tanks hold enough mix to cover a given number of acres with so much ground straw or hay, held together with oil or thin asphalt. Some companies make a wood fiber mulch that holds together very well with satisfactory moisture-retaining power. A relatively new mulch is fiberglass plus a light resin.

Many new highway slopes are being seeded by this relatively new method, largely because of the ease, speed, and efficiency with which the job can be done. Actual planting time per acre is about 10 minutes, plus the time for mixing a new batch of slurry, and the time for cleaning equipment at the end of the day.

Research will need to be done to determine if hydromulching could be useful at the NTS.

F. Trickle or Drip Irrigation in Revegetation in Arid Land Areas

Trickle irrigation was developed in Israel as a means by which the water requirements of trees and vines could be met by relatively small amounts of water and by water too saline for normal irrigation. It involves use of plastic pipe fitted with drippers so that water would be applied a drop at a time in a point source often below ground. Although there has been considerable success with the method, it is generally considered too expensive for routine use where labor costs are high.

Tueller (1974) has made effective use of the technique in grassland revegetation studies in Central Nevada. More studies of its use in revegetation of native shrub species under arid conditions are warranted.

Some agricultural experiences with the drip and trickle irrigation technique are given here to illustrate its effectiveness on cultivated crops under arid conditions.

1. A study was made to compare drip irrigation with other systems for both low-salt and high-salt (brackish) water (Bernstein and Francois, 1973). When the same amount of low-salinity water (450 mg/l total salts) was applied by three methods of irrigation in the first experiment, the drip-irrigated plots

out-produced the furrow- and sprinkler-irrigated ones by about 50%. Brackish irrigation water (2450 mg/l total salts) caused only a 14% reduction in yield of bell pepper with drip irrigation, but caused 54% and 94% reductions in yield for furrow- and sprinkler-irrigated plots, respectively. When the irrigation frequency was increased for furrow and sprinkler treatments in the second experiment, however, yield differences decreased markedly, virtually disappearing with the low-salinity water, while the brackish water caused 18% and 59% yield reductions for the furrow- and sprinkler-irrigated plots, respectively.

With drip irrigation, salts accumulated in the surface soil midway between drip orifices and the perimeter of the wetted zone. Surface soil salinity midway between drip orifices may cause plant injury if rain washes the salt into the underlying root zone. Many fine roots of drip-irrigated plants are found in the surface 2.5 cm of soil except where salt accumulation inhibits root development.

Drip irrigation required about one-third less water than furrow irrigation for maximum yield of the annual bell pepper crop. The saving of water occurred while the crop was young. With lower efficiencies of furrow irrigation under field conditions, water savings would be correspondingly greater. For mature crops, water requirements by the three methods of irrigation are similar and water saving by drip irrigation would depend largely on the inefficiency of the method it replaces.

2. A study was made in a desert region in Israel where a constant amount of irrigation water was used for each of three methods (Shmueli and Goldberg, 1971). In comparison of sprinkle, furrow, and trickle irrigation applied during the growing season from August to December to muskmelon (Cucumis melo L. cv. Haogen-2), vegetative growth was found more rapid and yields were earlier and higher with the trickle method. No yield differences were detected between sprinkle and furrow irrigation. Salt accumulation on the leaves was greater with sprinkling than with the other two methods which do not wet the foliage. This experiment indicated water conservation value for trickle irrigation, but did not evaluate economics.

3. Pepper plants (Capsicum annuum L. cv. California Wonder) were sprinkle and trickle-irrigated, each at two different frequencies, during the growing season from September to April (Goldberg and Shmueli, 1971). Total

water application was constant for each method. Yield, leaf growth, and root development were all greater with trickle- than with sprinkle-irrigation. Frequency of water application had a slight, but nonsignificant, effect. Yield tended to decrease when the plants were sprinkle-irrigated daily. With trickle irrigation, the infrequent interval, every 5 days, tended to reduce the yield. The plant species involved in this study was not a drought-resistant desert plant, however, such would be used in revegetation work at the NTS.

4. All irrigation in another study was with the trickle system (Shmueli and Goldberg, 1972). Pepper plants were irrigated by trickling at a constant frequency of 1 to 2 days with four different amounts of water based on evaporation from a Class A pan. The amounts applied were 0.82, 0.95, 1.33, and 1.75 of the pan evaporation. Since annual total pan evaporation was 12.8 cm, the irrigation levels used were relatively low. An optimum curve was obtained for the relation between yield and water application, with a maximum yield resulting from use of the 1.33 factor. Determinations of salt content in the soil and plants, and measurements of soil moisture showed that even the smallest water application was adequate to leach the root zone and to maintain a low and almost constant soil moisture tension. The systems, therefore, were very efficient in terms of effectiveness and in water conservation.

5. In an established vineyard on sandy clay soil in Israel, the effect of trickle irrigation interval on soil moisture and salt distribution and relative water use efficiency was examined (Goldberg et al., 1971). The distribution of soil moisture and salinity resulting from this irrigation method was two dimensional, with high moisture contents along and beneath the row and decreasing laterally.

The main active soil layer supplying water to the roots was found to be restricted to a strip approximately 2 m wide and 120 cm deep beneath the rows, whereas the total distance between rows was 3 m. The effect of the shorter irrigation intervals, with proportionally smaller amounts of water applied in a single irrigation, was to decrease the variations of moisture regime. Salts were concentrated in a surface pocket and a deep layer with a leached zone between them. The relative position of the concentration layers was determined by the amount of water applied in a single irrigation.

Relative water use efficiency was positively affected by shorter irriga-

gation intervals.

6. The objective of another investigation was to determine experimentally the soil-water potential and salt patterns in uniform soil profiles as a result of four different water management treatments (Tscheschke et al., 1974). Under these treatments cherry tomato plants were irrigated (a) daily with a volume of water equal to that used by the plant on the previous day, (b) every other day with volumes of water equal, (c) below, and (d) above the water evapotranspired.

In general, the soil-water potential decreased in the soil profile, as a result of salt accumulation, with increased distance from the trickle source. In the profiles where the wetting fronts reached the mid-region between the emitters, much lower soil-water potentials were measured near the soil surface. The highest salt concentration occurred in the profiles irrigated with volumes of water below that evapotranspired by the tomato plants, indicating the importance of avoiding under-irrigation whenever highly saline water is used with trickle-irrigation. Higher soil-water potentials and higher yields resulted from irrigating with volumes above the evapotranspiration. This implies that irrigation water is not as efficient as rainwater. If the trickle system is to be used only for 1 year as plants are being established under arid conditions, the salt problem would be relatively unimportant. The cost for 1-year use only, however, may be too high.

These six reports do indicate promise for the trickle irrigation system on arid lands. Installation costs can be high, but if irrigation water is available, even if slightly saline, it probably can be used to bridge the gap from planting of seeds or transplants to the point of establishment. In the Mojave Desert virtually every year under natural conditions is unfavorable for establishment of seedlings of new shrubs, or at least of very many of them, and so supplemental moisture is an absolute necessity. The trickle method is one method for supplying this supplemental soil moisture. If no more than 100 plants per acre are involved, the cost of installation may not be formidable to some revegetation problems. Certainly the method warrants consideration.

G. Current Interest in Arid Land Revegetation

The energy crisis, intensified by the most recent Middle East war, has greatly stimulated interest in alternative sources of energy. Throughout many of the Western States there are large coal reserves which can be strip-mined, and

also large deposits of oil-shale which may be dug out in huge strip-mining operations. Congress will not permit mining in some areas until adequate means for land reclamation are developed. All disturbed lands must, by Federal law, be restored reasonably to their original condition (Anonymous, 1973).

The federal impact upon land restoration for ecological and esthetic reasons has been in effect for sufficient time to develop considerable experience in revegetation, particularly of mine tailing areas under semi-arid conditions. In 1973 the Western Society of Soil Science sponsored a symposium on land revegetation during its annual meeting in Salt Lake City, Utah. There were ten reports at that meeting dealing largely with land reclamation under semi-arid conditions:

1. Revegetation of forest cutover and surface-mines lands, Packer (1973).
2. Problems with vegetation on copper tailings, Nielson (1973).
3. Reactions of copper sulfide minerals with chlorine in an aqueous system, Groves and Smith (1973).
4. Coal spoil pile reclamation in the Four Corners area, Hale (1973).
5. Properties of coal mine spoils affecting revegetation, Power et al. (1973).
6. Vegetation stabilization of mineral wastes, Dean and Havens (1973).
7. Soil compaction control on the Malheur National Forest, Armstrong (1973).
8. Revegetation of subalpine areas denuded by human impact, Ahlstrand and Campbell (1973).
9. Revegetation in areas damaged by close-in fallout from nuclear detonations at the NTS, Romney, Wallace, and Childress (1973).
10. Revegetation potentials on Southern Utah's forest and range land, Tew (1973).

Another revegetation project of interest is concerned with the microbiological changes in alkaline copper and iron mine tailings upon regeneration. Mycorrhizae development from plants established on these areas showed that numbers of microorganisms in fresh tailings initially were low, but that the microbial populations generally increased as vegetation became established. Changes, both in the tailings and in the rhizosphere, were related to the success of revegetation, (Lennox et al. 1973). Other studies of revegetation of mine

tailings include those of Shetron (1973) and Smalley (1973).

The interest in revegetation and land restoration is continuing to increase and research projects are being started in most of the Western States (Herbel et al., 1973). It is possible that any such studies undertaken at the NTS will be with the most arid conditions of any of the studies done in the Western States. The Nevada studies would have far-reaching consequences. Among the agencies involved, or to be involved in various revegetation studies, are the U.S. Bureau of Mines, the U.S. Forest Service, the Bureau of Land Management, and many private utilities and industrial companies. As many as 100,000,000 acres in the Western States could become involved (Copeland and Packer, 1972).

IV. DECONTAMINATION AND LAND RESTORATION PROCEDURES WHICH MAY BE USEFUL IN NEVADA

If the decision is made that Pu should be removed from certain areas in Nevada, the various approaches should be considered along with their environmental impact. Listed below are several alternate procedures which could be used in those areas which are contaminated with Pu at sufficiently high levels to warrant cleanup and post-treatment.

A. Isolation with Permanent Fences

Procedure: Chain link fencing 6 to 10 feet high can be placed, where necessary around dangerously contaminated areas (adequate fencing for 25 to 30 years exists already).

Advantages:

1. Area can be isolated from people and livestock.
2. Less costly than burial of contaminated soil after removal.
3. Revegetation not needed.
4. At some future date, new technology not yet developed could be used to solve the problems.

Disadvantages, Including Environmental Impact:

1. Contaminating material would still be subject to some erosion by wind and water although there could be periodic stabilization of soil with light coverings of road oil.
2. Areas would not be available to the public.
3. Areas would not be available to large mammals.

B. Removal of Surface Soil (2 to 4 inches as necessary), But Leaving Some Plants

The soil would be removed leaving in place and intact at least 100, but preferably 400 or more, shrubs per acre.

Procedure: Existing kinds of land scraping and hauling equipment are adequate to remove and load the soil. A vacuum-type cleaner may be preferable in certain areas after soil has been loosened to required depth by another instrument. The plant material need not be hauled away since it contains little ^{239}Pu , but could be shredded and left on the soil.

Some shrub species may not tolerate the removal of contaminated soil from under and around them. Such species must be identified by empirical research methods. The number of plants per individual clump may have to be decreased in this procedure to facilitate removal of contaminated soil.

Possible storage sites for the contaminated material are the bottoms of one or more of the old test craters at NTS.

When there are no shrubs available, a native grass or barley could be planted in some catchment basins as a start of the revegetation process.

The procedure of leaving 100 or more plants per acre presents several important advantages and only minor disadvantages.

Advantages:

1. Decades will not be required for revegetation of the area by natural means because some plants were left in their native, fertile shrub sites.
2. The remaining plants not only provide seed pressure for continued revegetation, but also partially preserve the fertile shrub site in which new seedlings can become established with the favorable association with other species.
3. Protection and feed are assured for maintenance of native animal populations.
4. The costs of revegetation are largely avoided.
5. The area does not become a dust bowl, especially if rapid cure road oil is used to stabilize the area between remaining shrubs.
6. The area is reasonably environmentally and asthetically acceptable.

Disadvantages Including Possible Environmental Impact:

1. The clean up process will be more costly than one of complete removal of surface soil.
2. Clean up may not be 100% effective because of the shrubs which are permitted to remain. It can be 95% effective, however.
3. Enormous dust problems may arise when the soil is loaded and transferred to containers unless it is sprayed with water or oil.
4. Ground cover would be less than the original (Wallace et al., 1972) although the primary productivity may not be greatly decreased.
5. Erosion from rainfall could be accelerated unless soil were stabilized with road oil.

Preliminary work needed:

1. Development of equipment for removing soil around shrubs without destroying them.
2. Identification of plant species difficult to clean around.
3. Pilot test to ascertain wind effects on erosion after such manipulation.

C. Complete Removal of the Soil Surface (2 to 4 inches) with Subsequent Revegetation

Procedure: Shrubs can be shredded for ease of handling, but they could be left in the area or stirred into the remaining soil. Soil stabilization would be necessary upon complete removal of the surface material by conventional scraping and hauling equipment.

Advantages:

1. Less costly than leaving shrubs growing in place.
2. 100% clean-up, or nearly that can be obtained.
3. The operation can be done very rapidly.

Disadvantages, Including Environmental Impact:

1. Revegetation would be extremely difficult although, during the clean-up process, about 400 micro depressions per acre could be formed for revegetation on sites previously occupied by shrubs. These areas could be used for replanting of native plant species.
2. Dust-bowl conditions would exist until soil is stabilized and shrubs again are growing.
3. Fertilizer and organic matter might be required to replace

fertile surface soil removed around shrubs.

4. Native animals would be lost although they would be replaced from adjoining areas.

Experimental Work Needed:

Construction of microcatchment depressions to collect and concentrate runoff and development of seeding and transplanting techniques for revegetation in the catchment basins.

D. Soil Stabilization with Metallic Iron, Krilium, Oil, or Other Materials to Decrease the Resuspension of ^{239}Pu

The finer particles of soil (clay) tend to become cemented together by natural processes. The natural structure of soil depends upon the extent of cementing processes. Soils with a large amount of cementing due to soil organic matter are not only fertile soils, but also are less subject to erosion than are highly dispersed soils. The agents which tend to cause soil particles to aggregate are called flocculating agents. In addition to soil organic matter, carbonate precipitations and iron oxide formations cause flocculation. Soluble calcium is an example of an agent causing aggregation of soil particles. Soluble sodium, soluble hydroxides and sodium carbonate are deflocculating agents which tend to destroy soil structure.

The objective of this alternate procedure is to add agents to the soil which will promote flocculation or cementing processes which conceivably could involve the Pu particles and make them less available for resuspension. Early test site experiments involved use of road oil on soil as well as iron chloride additions to stabilize the soil. It was expected that iron chloride would result in the formation of insoluble iron hydroxides, which in essence would coprecipitate the Pu. In addition to road oil and iron (Master Builders of Columbus, Ohio has a commercially available source of metallic iron-iron oxide powder), krilium (an organic agent which binds particles of clay together) should be tested. Krilium was manufactured by Monsanto Chemicals Co. in the 1950's for use in soil stabilization. The past work on road oil at NTS has shown it to be a highly successful agent for a number of years to prevent soil erosion by wind and water. It also appears to have little adverse effect upon the native vegetation.

Advantages:

1. No contaminated soil to store.

Disadvantages, Including Environmental Impact:

1. ^{239}Pu remains in environment, although stabilized.
2. May be costly (equipment and initial research to develop methods).
3. May not last over 25 to 100 years.
4. Rainfall runoff may be increased.

Experimental Work Needed:

Methodology is needed for the formation of small rock-like pellets with iron compounds in the field. Some cementation may occur without the need for forming individual pellets. Humid climates or moisture tend to increase the processes by which particles become cemented into larger units (Langham, 1969). The moisture available during winter months have some effect in cementing soil particles. The effect of soil moisture on ^{239}Pu particle cementing at the NTS should have adequate research.

E. Covering with Asphalt or Road Oil

Procedures: Use standard asphalt covering techniques. Some, or most, of the perennial vegetation can be retained, although that not retained would have to be removed or shredded before covering.

Advantages:

1. No wind-blown material. Most plants can remain.
2. May be less expensive than other methods.

Disadvantages, Including Environmental Impact:

1. Land is almost useless for the period which it is covered.
2. Drainage needed. Water would not penetrate.
3. Not permanent, but does last many years.
4. Costly if asphalt is used. Road oil is less expensive.
5. Not conducive to much animal life.
6. ^{239}Pu remains underneath covering requiring constant vigilance.

Experimental Work Needed:

Sufficient information is probably available from tests made in the past, although shrub survival with asphalt cover should be studied.

F. Deep Plowing and Other Farm Decontamination Procedures

Procedures: A plow capable of plowing as deep as 3 feet is available. A

DC-10 caterpillar probably would be needed to pull it. If the Pu-contaminated areas were plowed to a depth of 3 feet, the Pu would be contained for as long as weathering cycles would take to weather 3 feet of soil, and provided that there were no man-made excavations in the area. Rodent activity generally is within the first 2 feet of soil, thus it is not likely that rodents would stir the Pu from as deep as 3 feet. Erosion rates for soil are highly dependent upon the terrain as well as upon the material being eroded. From a nearly level surface, the erosion rate would be virtually zero with the average rainfall conditions at the NTS. The occasional large floods do move considerable soil. For example, the 10-inch (25 cm) rain which occurred at the NTS in 1969 appeared to have moved 1/2 inch (1.25 cm) of surface soil in some places. If rainfall of that intensity came once every 20 years, it would take 1440 years for the soil to erode to the 3-foot point.

Advantages:

1. Pu availability to plants and animals would be greatly decreased.

Disadvantages, Including Environmental Impact:

1. Radionuclides are still available to plants although they are greatly diluted.
2. Revegetation is needed and would be sparse for decades.
3. Dust bowl conditions would exist initially unless stabilized with road oil, etc.
4. Not useful for extremely high levels of contamination.

Experimental Work Needed:

1. Each site would need experimentation to determine if plowing could be done. Rocks and impervious caliche layers in some areas would make it difficult.
2. Revegetation experiments would be needed.

G. Combination of Deep Plowing and Fencing

Procedures: A combination of above procedures.

Advantages:

1. None over either procedure singly.

Disadvantages, Including Environmental Impact:

1. Costs must be borne for plowing, fencing, and revegetation.
2. Only good if levels are below a given permissible activity.

Experimental work needed:

Same as for both procedures separately.

H. Commercially Available Soil Stabilizer Products

Included here are some of several available commercial products which are formulated for use as soil stabilizers and which might have application to the Pu problem at NTS and elsewhere. Name brands mentioned here should not be considered to be an endorsement of a particular product.

Geo Tech products are commercially made and available for soil stabilization work (Southwest Consultants Bul. GTS-100). These, or similar, products could be used for soil stabilization of the contaminated areas to decrease resuspension and erosion. The material actually coats the soil particles. The following information is abstracted from Southwest Consultants' Bul. GTS-100:

Descriptions: Geo Techs are a specially-compounded clear nonflammable, nontoxic, resin which, when applied correctly, stabilize surface soils against wind and water erosion.

Geo Tech Compounds Available:

Class I: Single Component Systems

GTS 1104-medium water resistance

GTS 1105-good water resistance

Class II: Three component systems

GTS U-58 superior erosion control and resistance to weather degradation

Purpose and Use: Geo Tech compounds have been formulated so as to coat individual soil particles with an invisible film, bonding them together as a protective layer and isolating the sub soil from erosion due to wind, rain, sprinkling, or irrigation.

When applied as a dust and sand erosion suppressive and not exposed to mechanical damage, Geo Tech will allow moisture to pass through without sacrificing its integrity as an erosion control agent when dry.

If insecticides, fungicides, or herbicides are to be used, these control agents may be combined as a single application with Geo Tech solution providing that the additive water dispersion is neutral or mildly acid. Chlordane, Fermate, Manate, and Parzate are typical insecticides and fungicides which are compatible with Geo Tech compounds.

Geo Tech solutions are excellent for controlling large open areas such as construction sites and during grading and sloping of roadways.

Geo Tech is also useful to highway maintenance departments in that the need for redress blading is extended 200-300% and where desired, plant life will grow through the stabilized soil.

For the above-mentioned applications, Class I or II can be used; for more severe problems Class II is recommended. As an example, high density walkways and bicycle paths to roadways that will support auto and pickup truck traffic. Such facilities are built on the bare soil using native components and are ready for use as soon as Geo Tech has been applied and allowed to cure.

Application: Geo Tech solutions should be applied as a spray, and just heavily enough to penetrate the surface soil approximately 1/4 inch. Flooding or penetration greater than 1/2 inch is not recommended due to excessive solution consumption without additional benefits.

For quantities above 5 gallons, a mechanical mixer should be used for thorough blending.

Typical equipment recommended for application is:

Large areas: Tank truck/recirculating systems, equipped with spray bar.

Smaller areas: Conventional orchard-type spray unit.

300 - 500 sq. ft. can be easily covered manually using an ordinary garden variety hand spray unit (2-3 gal. capacity).

Precautions:

1. Soil temperature must be 55°F or warmer to permit Geo Tech to coalesce into a continuous film.
2. Do not apply to soil with residual or pooled surface moisture.
3. Class II system (GTS-U-58) is a reactive mixture and should be used at once after mixing.
Note: 2 hrs. Pot life at 75°F (solution temp)
1 hr Pot life at 90°F (solution temp)
4. All equipment must be flushed thoroughly after use to prevent accumulation of Geo Tech film in system and spray heads.
5. Stored materials in bulk or barrels should not be exposed to sub-freezing temperatures. (Freezing extracts components from suspension)

Typical Coverage: The following can be used as a General Selection Guide for Erosive Conditions:

1. Severe Erosion:
 - a. 1 Gal. Geo Tech Resin/500-100 sq. ft. surface area.
2. Moderate Erosion:
 - a. 1 Gal. Geo Tech Resin/100-200 sq. ft. surface area.
3. Sand and Dust Suppression:
 - a. 1 Gal. Geo Tech Resin/300-400 sq. ft. surface area.

Toxicity: The cured Geo Tech compound will not harm plant or animal life. Plants will grow through stabilized soils unless herbicides are being used. However, some precautions are necessary when handling uncured Geo Tech resins.

1. Overspray. If spray equipment produces a fine mist, personnel should wear protective masks and keep windward of spray.
2. Streams, lakes, ponds, or other open bodies of water should not receive uncured Geo Tech solutions. Filming will adhere to gills of fish.
3. GTS-U-58 contains 1% formaldehyde. Formaldehyde is a strong sensitizer. Skin contact with uncured GTS-U-58 should be washed with clear water as soon as possible to prevent skin irritation.

Data from some field tests of Geo Tech products are given in Table 12.

These materials, obviously, have many advantages and should be tested experimentally. They surely would decrease the resuspension value for ^{239}Pu (if that is needed). Although undoubtedly excellent for stabilizing contamination sites where the need is temporary, little, if anything, is known of the permanence of material. Obviously, the surface does begin to break as a result of weathering in 1 year, but that mixed below the soil surface and not exposed to sunshine could last much longer.

Another advantage is that this material could be applied without injury to, or removal of, any of the existing vegetation. Even if new applications had to be made every decade or two for continued stabilization, the procedure would probably be worthwhile.

If vegetative uptake of ^{239}Pu were low, cattle uptake of the ^{239}Pu would probably be low also in areas treated with Geo Tech because dust would be greatly decreased. Damage to the fixed surface by grazing cattle needs to be tested and evaluated.

The cost of applying this kind of soil stabilization material is given at around \$400 per acre.

Table 12. Outdoor exposure tests (from Southwest Consultants' Bul. GTS-100).

Stabilizer	Application rate and strength (%) of water mixture		Date test started	Remarks
	g/yd ²	%		
Control	0	0	11-23-71	Considerable erosion; test terminated after 3 months. Soil weight loss was 7.3 lbs/ft ² .
EA-9478	0.125	50	10-6-72	Rain damage at 7 months. Additional erosion from hail at 8 months. Test terminated at 10 months. Soil weight loss 2.0 lbs/ft ² .
EA-9478	0.4	50	10-6-72	Slight erosion around edges of sample at 1 yr.
U stabilizer	0.125	50	10-6-72	Rain and hail damage at 8 months. Considerable erosion at top of sample at 1 year.
U stabilizer	0.4	50	10-7-72	Good condition after 1 year
EA-11-004	0.125	33	10-10-72	Slight erosion noted at top and bottom of sample at 8 months.
EA-11-044	0.4	33	10-10-72	Good condition after 1 year.
SA-117-58 plus U stabilizer 1:1 ratio	0.75	15	1-12-73	Good condition after 10 months.

V. RECOMMENDATIONS FOR EXPERIMENTAL WORK WHICH SHOULD BE DONE AT NTS

1. Due to the fragile nature of desert lands, some experiments involving alternate procedures outlined in Section IV should be conducted in order to develop techniques for clean-up and post-treatment soil stabilization. This is necessary to prevent the disturbed area from becoming a dust bowl or a source of easily-eroded material, and also to develop effective revegetation procedures. These experiments initially need not be done in Pu-contaminated areas; however, these areas in Nevada should continue to be used for much needed research on other aspects of the Pu problem until the most practical and effective methods of clean up and post-treatment management have been determined.

2. The environmental consequences of plowing followed by oiling of the shadscale ecosystem in the ^{239}Pu -contaminated areas of NTS seem to be minimal. Research on feasibility and costs for this treatment should be undertaken in Area 13 after experimental work is done to ascertain the true effects of plowing and oiling on revegetation. This should be done before any large areas are plowed with an aim to answering the following questions: Can deep plowing be achieved to turn under the ^{239}Pu to a depth of 1 to 3 feet? If the ^{239}Pu were mixed into soil uniformly to 3 feet, would subsequent erosion result in a re-concentration of Pu on the soil surface?

3. Scraping experiments should be conducted to answer the following questions: What are the most effective methods for stabilizing scraped soil? If the surface 2 to 4 inches of soil were scraped off leaving standing from 100 to 400 shrubs (out of about 5000/acre), how well would they survive and what would be their response to the increase in soil moisture available per plant? Could shrub clump sites which are high in nutrients and organic matter be marked during any scraping operation so that they could be subsequently used for reseeding grasses or transplanting shrubs? Will herbicide and oil sprays prohibit troublesome weeds (*Salsola* sp. etc.) from invading scraped areas, and would this treatment adversely affect returning the land to its native condition? What plant species can be satisfactorily cleaned underneath by scraping equipment without destroying the shrub?

4. The feasibility of developing small catchment basins for plant revegetation after land has been disturbed should be studied before any large areas are

denuded. Various procedures for establishing new plants should be investigated. Since Atriplex species and grasses are the most valuable of native vegetation for grazing, it should be determined if revegetation with these plants is easiest and most acceptable under Nevada conditions. It should be possible to develop close to a dry-farm procedure for revegetation of disturbed areas.

5. Extensive and intense studies should be made with the uses of, effect of, and physics and chemistry of road oil stabilization of NTS soil since it appears to be a highly useful material to decrease resuspension, and since it may not be an overly expensive method. Alternate methods of soil stabilization (cementing agents, foams, resins, etc.) should be evaluated in revegetation studies on disturbed soils together with their impact on plant and animal activity.

6. Seed collection, germination studies, and plant propagation trials should be intensified. Alternate methods of irrigation and of seeding should be evaluated in revegetation programs. Reasonable facilities for these studies should be developed at the NTS.

VI. SUMMARY AND CONCLUSIONS

Four areas in Nevada have been contaminated with sufficient ^{239}Pu to cause serious consideration of some clean-up procedures. The total area where the surface contamination level is above roughly 1000 pCi/cm^2 is about 300 acres. Only a few acres are above 7000 pCi/cm^2 , the level where clean up in the past has been done. Much has been learned about Pu contamination during the last 4 years that NAEG has been studying these areas. More can yet be learned from the areas since they present an opportunity for solving many problems. If at all possible, the areas should be preserved at least until the necessary research is accomplished.

Although we are reluctant to recommend land disturbance before pilot experiments are conducted at NTS, an ideal clean-up and post-treatment procedure for areas of contamination exceeding tolerance limits may be to: (a) remove the contamination, (b) retain some of the native vegetation with sufficient soil fertility for its maintenance, and (c) stabilize the disturbed soil to protect it from wind and water erosion. A combination of techniques may achieve all three features. Soil would be removed to a depth of 2 to 4 inches, as needed. One hundred shrubs, more or less, would be left per acre. The clean-up

procedures could be engineered to favor water run-in to the remaining sites. The bared soil can be road oil treated (rapid cure oil) to prevent its erosion over a period of several years. It is expected that the oiling would decrease the tendency for the disturbed lands to be invaded by undesirable tumbleweeds (Salsola sp.) and cheatgrass (Bromus rubens). An experimental area, or series of areas, should be set up immediately to experimentally test the validity of the assumptions made.

Of the several alternative clean-up procedures, the next most attractive, perhaps, is that of deep plowing with the intention of uniformly mixing the ^{239}Pu throughout 1 to 3 feet depth of soil so that the Pu would be greatly diluted in the soil mass. This procedure may require a total revegetation and soil stabilization program which could be costly unless inexpensive road oil were used for the soil stabilization and if the plowing did not kill all of the present plants in the area. There is some indication from past experiences that such is the case. Experimental work is needed to provide answers for these points.

Another alternative for handling of contaminated areas is that of a permanent fencing program which could be used until some future technological development dictated a simpler procedure. Such development may occur several decades from now. The areas of high Pu contamination are already fenced.

Another alternative procedure (perhaps the best of all) which appears to be feasible is application of road oil every 5 to 10 years to decrease resuspension. The procedure would be relatively inexpensive and could even permit cattle grazing since the oil seems to have little effect on native vegetation. Again, experimental work such as recommended in Section V of this report should be undertaken to provide additional answers.

VII. REFERENCES

- Aarkrog, B. 1972. Reexamination of plutonium at Thule, Greenland in 1970. Proc. Internatl. Symp. on Radioecology Applied to the Protection of Man and His Environment, Vol. 2:1213-1219. Rome, Italy, Sept. 7-10, 1971.
- Ahlstrand, G. M. and G. S. Campbell. 1973. Revegetation of subalpine areas denuded by human impact. Western Soc. Soil Sci. Meetings, Salt Lake City, Utah.
- Anonymous. 1960. External gamma doses and dose rates from the fallout from nuclear explosions. Fallout Studies Branch, DBM, USAEC.
- Anonymous. 1973. Water scarcity may limit use of western coal. Science 181:525.
- Armstrong, C. R. 1973. Soil compaction control on the Malheur National Forest. Western Soc. Soil Sci. Meetings, Salt Lake City, Utah.
- Baciu, E. 1967. Hydro-seeding. Proc. Internatl. Plant Propagators' Soc. 17:110-111.
- Baker, T. P., Jr., B. B. Boecker, and J. L. Dick. 1958. Aircraft accidents involving Pu contamination. Report AFSWC-TN-58-3.
- Beatley, Janice C. 1973. Russian thistle (Salsola) species in Western United States. J. Range Management 26(3):225-226.
- Bernstein, L. and L. E. Francois. 1973. Comparisons of drip, furrow, and sprinkler irrigation. Soil Sci. 115 (1):73-85.
- Blair, W. J. and R. C. Thompson. 1974. Plutonium: biomedical research. Science 183:715-722.
- Bliss, W. and L. Dunn. 1971. Measurement of plutonium in soil around the Nevada Test Site. In: Fowler, et al. (eds.) Proc. of Environmental Plutonium Symposium, LASL, Report LA-4756:89-92.
- Bost, W. E. 1959. Radioactive Decontamination: A Literature Search. Report TID-3535.
- Brown, B. L. et al. 1961. Documentation of alpha contamination at the Nevada Test Site. Report RRS-61-7.
- Brown, B. L. et al. 1961. Decontamination of large land surface areas following nuclear detonations. REECo, Inc., Mercury, Nev. 2 p.

- Brown, B. L., C. R. Penwell, W. E. Moore, F. J. Sanders, and W. O. Mullen. 1964. Decontamination of large land areas and roadways at the Nevada Test Site. Report RRS-64-3.
- Buchholz, J. R., W. H. Adams, C. W. Christenson, and E. B. Fowler. 1971. More on the Pu particle size problem. Report LADC-12898.
- Buchholz, J. R., W. H. Adams, C. W. Christenson, and E. B. Fowler. 1971. Summary of a study on the uptake of ^{239}Pu by alfalfa from soils. Report LADC-12897.
- Carter, M. W. and O. R. Placak. 1956. Plutonium contamination found off site following one-point detonations. In Dunning and Hilcken (eds.), Proc. of Symposium the Shorter-term Biological Hazards of a Fallout Field, p. 185-187. Washington, D.C. Dec. 12-14, 1956.
- Church, B. W. 1973. "What can be learned from the cleanup of the Tatum Dome Site Hattisburg, Mississippi?" 2nd Annual Environmental Pollution Control Conference, Albuquerque, New Mexico, Apr. 16-19, 1973.
- Copeland, O. L. and P. E. Packer. 1972. Land use aspects of the energy crisis and western mining. Jour. of Forestry 70(11).
- Corley, J. P., D. M. Robertson, and F. P. Brauer. 1971. Plutonium in surface soil in Hanford plant environs. In Fowler, et al. (eds.), Proc. Environmental Plutonium Symposium. LASL, Report LA-4756:85-88.
- Dean, K. C. and R. Havens. 1973. Vegetative stabilization of mineral wastes. Western Soc. Soil Sci. Meetings, Salt Lake City, Utah.
- Dean, K. C., R. Havens, and K. T. Harper. 1969. Chemical and vegetation stabilization of a Nevada copper porphyry mill tailing. U. S. Bureau of mines Report of Invest. 7261.
- Dick, J. L. and T. P. Baker, Jr. 1967. Monitoring and decontamination techniques for plutonium fallout on large-scale surfaces. Operation Plumbbob. Report WT1512.
- Dunaway, P. B. and Mary G. White, editors. 1974. The dynamics of plutonium in desert environments. USAEC Nevada Operations Office, NAEG Progress Report NVO 142.
- Environmental Plutonium Data Base Group. 1972. Environmental Aspects of Plutonium and Other Elements: A selected, annotated bibliography. Report ORNL-EIS-74-21 (with supplements).

- Evenari, M., L. Shannan, and N. Tadmor. 1971a. The Negev. Oxford Univ. Press, London.
- Evenari, M., L. M. Shannan, and N. Tadmor. 1971b. The Negev, p. 175. Oxford Univ. Press, London.
- Evenari, M., L. Shannan, and N. Tadmor. 1971c. The Negev, p. 191-207. Oxford Univ. Press, London.
- Evenari, M., L. Shannan, and N. Tadmor. 1971d. The Negev, p. 220. Oxford Univ. Press, London.
- 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.
- Gilbert, R. O. and L. L. Eberhardt. 1973. Statistical analysis of Pu in soils at NTS - some results. Report BNWL-SA-4815.
- Gjörup, H. L. et al. 1970. Investigation and evaluation of contamination levels. USAF Nuclear Safety 65(2):57-63.
- Goldberg, D. and M. Shmueli. 1971. Sprinkle and trickle irrigation of green pepper in an arid zone. Hort. Science 6(6):559-562.
- Goldberg, S. D., M. Rinot, and N. Karu. 1971. Effect of trickle irrigation intervals on distribution and utilization of soil moisture in a vineyard. Soil Sci. Soc. Amer. Proc. 35(1):127-130.
- Grand Junction Office, AEC. 1963. Monticello Mill Tailings Erosion Control Project, Monticello, Utah. Report RMO-3500.
- Groves, R. D. and Paulette B. Smith. 1973. Reactions of copper sulfide minerals with chlorine in an aqueous system. Western Soc. Soil Sci. Meetings, Salt Lake City, Utah.
- Hakonson, T. E., J. W. Nyhan, L. J. Johnson, and K. V. Bostick. 1973. Ecological investigation of radioactive materials in waste discharge areas of Los Alamos. Report LA-5282-MS.
- Hale, V. Q. 1973. Coal spoil pile reclamation in the 4-corners area. Western Soc. Soil Sci. Meetings, Salt Lake City, Utah.
- Harley, J. H. 1971. Worldwide plutonium fallout from weapons tests. Report LA-4756.
- Havens, R. and K. C. Dean. 1969. Chemical stabilization of the uranium tailings at Tuba City, Arizona. U.S. Bureau of Mines Report of Invest. 7288.

- Healy, J. W. 1974. A proposed interim standard for plutonium in soil. Report LA-5483-MS.
- Hendricks, W. W. 1974. Personal communication to E. M. Romney.
- Herbel, C. H., G. H. Abernathy, C. C. Yarbrough, and D. C. Gardner. 1973. Root plowing and seeding arid rangelands in the Southwest. *J. Range Management* 36(3):193-197.
- Hornbacher, D. D., R. M. Saiki, and C. T. Ilsley. 1971. Status of soil stabilization evaluation program. Internatl. Report of Dow Chemical Co., Rocky Flats Div., Golden, Colo.
- Hull, A. E., Jr. and R. C. Holmgren. 1964. Seeding Southern Idaho Rangelands. U.S. Forest Service Research Paper, INT-10, 31 p.
- Iranzo, E. and S. Salvador. 1970. Inhalation risks to people living near a contaminated area. 2nd Internatl. Cong. of the Internatl. Radiation Protection Assoc., Brighton, England.
- James, P. R. and R. G. Menzel. 1959. Radioactive fallout. What's being done about it. Part II. How soils are decontaminated. *Plant Food Rev.* 5:32-33.
- James, P. R. and R. G. Menzel. 1973. Research on removing radioactive fallout from farmland. USDA, ARS, Tech. Bull. No. 1464.
- Jordan, H. S. 1971. Distribution of plutonium from accidents and field experiments. In: Fowler, et al. (eds.) *Environmental Plutonium Symp.* LASL Report LA-4756:21-24.
- King, J. L. and J. C. Bresee. 1961. Plutonium release incident at Oak Ridge National Laboratory (Oak Ridge, Tenn.), presented at the ANS winter meeting, San Francisco, Calif. CF60-9-57.
- Krey, P. W. and E. P. Hardy. 1970. Plutonium in soil around the Rocky Flats plant. Report HASL-235.
- Kunishi, H. M. and A. W. Taylor. 1972. Immobilization of radiostrontium in soil by phosphate addition. *Soil Sci.* 113(1):106.
- Langham, W. H. 1959. Physiology and toxicology of plutonium-239 and its industrial medical control. *Health Physics* 2:172-185.
- Langham, W. H. 1968. The problem of large-area plutonium contamination. Seminar Paper No. 002, National Center for Radiological Health Seminar, Rockville, Md.

- Langham, W. H. 1969. Biological considerations of nonnuclear incidents involving nuclear warheads. Report UCRL-50639.
- Langham, W. H. 1970. Technical and laboratory support. USAF Nuclear Safety 65(2):36-41.
- Langham, W. H. 1971. Plutonium distribution as a problem in environmental science. In: Fowler et al. (eds.) Proc. Environmental Plutonium Symposium, LASL, Report LA-4756:3-11.
- Langham, W. H., P. S. Harris, and T. L. Shipman. 1966 (revised). Plutonium dispersal by accidental or experimental low-order detonation of atomic weapons. Report LA-1981 (rev.).
- Lee, H., J. D. Sartor, and W. H. Van Horn. 1959. Stoneman test of reclamation performance. Vol. IV. Performance characteristics of land reclamation procedures. Report USNRDL-TR-337.
- Lennox, L. K., M. M. Harris, and M. F. Jurgensen. 1973. Establishing vegetation on alkaline iron and copper tailings. II. Microbiological aspects of alkaline iron and copper tailings. Amer. Soc. Agron. Absts. Ann. Meet. 177.
- Leavitt, V. D. 1974. Soil surveys of five plutonium contaminated areas on the test range complex in Nevada. Report NERC-LV-539-28.
- Lindsay, J. W., D. W. Michels, and J. A. Martinez. 1973. Scavenging contaminated soil with polyurethane foam. Dow Chemical Co., Report RFP-1949.
- LOOW Survey Report, not dated. Radiation survey and decontamination report of the Lake Ontario Ordnance Works Site. USAEC Oak Ridge Operations, Oak Ridge, Tenn.
- Maloney, J. C. 1963. Cold weather decontamination. In: Symposium on Radiation Emergencies in Medicine, Research and Industry, Chicago, Ill. Dec. 1963. 12 p. (CONF-277-10).
- Mann, L. D., D. D. Focht, H. A. Joseph, and L. H. Stolzy. 1972. Increased denitrification in soils by additions of sulfur as an energy source. J. Environ. Qual. 1(3):329-332.
- Menzel, R. G. and P. E. James. 1959. Physical removal of radioactive surface contamination from agricultural land. Proc. of Thirty-fifth Ann. Meeting of the National Joint Committee on Fertilizer Application, Cornell Univ., p. 45-59.

- Miller, C. F. 1958a. The radiological assessment and recovery of contaminated areas. Report CEX-57.1.
- Miller, C. F. 1958b. Theory of decontamination, Part I. Report USNRDL-460.
- Miller, C. F. 1959. Analysis of radiological decontamination data obtained from field tests. Report USNRDL-TR-321.
- Mishima, J. 1964. Review of research on plutonium releases during overheating of fires. Report HW-83668.
- Morin, G. C. A., W. G. Matlock, and A. W. Warrick. 1973. Desert strip farming - use of water harvesting techniques in Southern Arizona's deserts. Amer. Soc. Agron. Absts. Ann. Meet. Las Vegas, NV.
- Nevada Operations Office. 1972. Cleanup Summary Report: Tatum Dome Test Site, Mississippi. Report NVO-129.
- Nevada Operations Office. 1973. Gnome/Coach Site Disposal Options. Report NVO-131.
- Nielson, R. F. 1973. Problems with vegetating copper tailings. Western Soc. of Soil Sci. Meetings, Salt Lake City, Utah.
- O'Farrell, T. P., R. E. Fitzner, and R. O. Gilbert. 1973. Distribution of radioactive jackrabbit pellets in the vicinity of the B-C cribs, 200 East Area, USAEC Hanford Reservation. Report BNWL-1794.
- Otten, L. J., Jr. 1970. Removal of debris from Thule. USAF Nuclear Safety 65(3):87-95.
- Owen, W. L., W. C. Cobbin, and W. E. Shelberg. 1967. Radiological Reclamation Performance Summary Vol. II. Evaluation and Condensation of Data for Preplanning of Recovery Operations. Report USNRDL-TR-68-71 (AD-674863).
- Owen, W. L., F. K. Kawahara, and L. L. Wiltshire. 1965. Radiological Reclamation Performance Summary Vol. I. Performance Test Data Compilation. Report USNRDL-TR-967.
- Owen, W. L. and J. Sartor. 1962. Radiological recovery of land target components - complex I and complex II. Report USNRDL-TR-570.
- Paas, H. J., Jr. 1966. Radiological appraisal of the Monticello Project, San Juan County, Monticello, Utah. Report IDO-12049.
- Packer, P. E. 1973. Revegetating forest cutover and surface mined lands. Western Soc. Soil Sci. Meetings, Salt Lake City, Utah.

- Phillip, H. 1966. Bibliographies in Nuclear Science and Technology, Sec. 13: Decontamination, Zentralstelle fuer Atomkernenrgie-Dokumentation, Gmelin-Institut fuer Anorganisch Chemie und Grenzbebiere, Frankfurt an Main, West Germany, Report AED-C-13-04.
- Pinson, E. A., R. F. Merion, B. B. Boecher, and J. L. Dick. 1957. Monitoring and decontamination techniques for plutonium fallout on large-area surfaces, Report ITR-1512 (Del.).
- Plummer, A. P., et al. 1955. Seeding rangelands in Utah, Nevada, Southern Idaho, and Western Wyoming. USDA Handbook #71.
- Plummer, A. P., D. R. Christenson, and S. B. Monsen. 1968. Restoring big-game range in Utah. Utah Div. of Fish and Game. Publication No. 68-3.
- Powell, J. L. and R. I. Barnhisel. 1973. Reclamation of coal strip-mine spoils in Western Kentucky. Amer. Soc. Agron. Absts. Ann. Meeting, Las Vegas, NV.
- Power, J. F., F. M. Sandoval, J. J. Bond, and W. O. Willis. 1973. Properties of coal mine spoils affecting revegetation. Western Soc. Soil Sci. Meetings, Salt Lake City, Utah.
- Price, K. R. 1971. A critical review of biological accumulation, discrimination and uptake of radionuclides important to waste management practices 1943-1971. Report BNWL-B-148.
- Raleigh, H. D. 1965. Radioactive Decontamination. A literature search. Report TID-3535 (Suppl. 1).
- Romney, E. M. and J. J. Davis. 1972. Ecological aspects of plutonium dissemination in terrestrial environments. Health Physics 22:551-557.
- Romney, E. M., H. M. Mork, and K. H. Larson. 1970. Persistence of plutonium in soil, plants, and small animals. Health Physics 19:487-490.
- Romney, E. M., A. Wallace, and J. D. Childress. 1971. Revegetation problems following nuclear testing activities at the Nevada Test Site. Proc. 3rd National Symposium on Radioecology, Oak Ridge, Tenn. 2:1015-1022.
- Romney, E. M., A. Wallace, and J. D. Childress. 1973. Revegetation in areas damaged by close-in fallout from nuclear detonations at the Nevada Test Site. Western Soc. of Soil Sci. Meetings, Salt Lake City, Utah.
- Sanders, F. 1966. Decontamination of Test Cell "C" at the Nuclear Rocket Development Station. Report LA-3633-MS.

- Sartor, J. D., H. B. Curtis, H. Lee, and W. L. Owen. 1957. Cost and effectiveness of decontamination procedures for land targets. Report USNRDL-TR-196.
- Shetron, S. G. 1973. Establishing vegetation on alkaline iron and copper tailings: III Treatment of alkaline iron and copper tailings to promote vegetation. Amer. Soc. Agron. Absts. Ann. Meeting, Las Vegas, NV.
- Shmueli, M. and D. Goldberg. 1971. Sprinkle, furrow, and trickle irrigation of muskmelon in an arid zone. Hort. Science 6(5):557-559.
- Shmueli, M. and D. Goldberg. 1972. Response of trickle-irrigated pepper in an arid zone to various water regimes. Hort. Science 7(3):241-243.
- Sill, C. W. 1973. Personal communication to E. M. Romney.
- Smalley, G. H. 1973. Stabilization of copper mine tailings and overburden waste dumps in Eastern Nevada. M.S. Thesis, University of Nevada.
- Smith, A. E. and W. E. Moore. 1972. Report of the radiological clean-up of Bikini Atoll. Report SWRHL-111r.
- Stannard, J. N. 1963. Plutonium in the environment. Handbook of Experimental Pharmacology. xxxvi:669-688.
- Stewart, K. 1964. The resuspension of particulate matter from surfaces. International Symposium on Surface Contamination, Gatlinburg, Tenn.
- Stuart, D. M., R. E. Eckert, Jr., A. S. Dylla, and G. E. Schuman. 1973. Seeding Coppice Dune Areas in Northern Nevada. USDA, ARS, Report T-11.
- Southwest Consultants. Geo Tech Systems, Soil Erosion and Stabilizer products. Bul. GTS-100.
- Tappen, J. T. and J. J. Lorenz. 1969. Carlsbad Site roll-up program: On site radiological safety report. Report NVO-410-2.
- Task Force Report. 1974. Recommendations for cleanup and rehabilitation of Enewetak Atoll.
- Tew, R. K. 1973. Revegetation potentials on Southern Utah's forest and range land. Western Soc. of Soil Science Meetings, Salt Lake City, Utah.
- Tscheschke, P., J. Alfaro, J. Keller, and R. J. Hanks. 1974. Trickle irrigation soil-water potential as influenced by management of highly saline water. Soil Sci. 117(4):226-231.
- Tueller, P. T., A. D. Bruner, and J. V. Davis. 1972. Ecology of Hot Creek

- Valley - vegetation - and soil response to underground detonation. Report NVO-409-1.
- Tueller, P. T. 1974. Personal communication to A. Wallace.
- USDA. 1973. Research on removing radioactive fallout from farmland. USDA, ARS, Tech. Bull. 1464.
- USDA. 1971. Treatments for farmland contaminated with radioactive material. USDA, ARS, Agriculture Handbook No. 395.
- US Dept. HEW. 1966. Disposition and control of uranium mine tailings in the Colorado River Basin. Fed. Water Poll. Control Admin., Region VIII, Denver, Colo.
- Volchok, H. L. 1971. Resuspension of plutonium-239 in the vicinity of Rocky Flats. Report LA-4756.
- Wallace, A., E. M. Romney, and Collaborators. 1972. Radioecology and Ecophysiology of Desert Plants at the Nevada Test Site. Report TID-25954.
- Wallace, A., E. M. Romney, and Collaborators. 1972a. Revegetation in areas damaged by close-in fallout from nuclear detonations, p. 75-79. In Radioecology and Ecophysiology of Desert Plants at the Nevada Test Site. Report TID-25954.
- Wallace, A., E. M. Romney, and Collaborators. 1972b. Seed germination of some Northern Mojave and Southern Great Basin plant species, p. 279-282. In: Radioecology and Ecophysiology of Desert Plants at the Nevada Test Site. Report TID-25954.
- Wallace, A., E. M. Romney, and Collaborators. 1972c. Characteristics of Larrea divaricata (creosote bush), p. 115-132. In: Radioecology and Ecophysiology of Desert Plants at the Nevada Test Site. Report TID-25954.
- Wells, P. V. 1961. Succession in desert vegetation on streets of a Nevada ghost town. Science 134:670-671.
- Wieland, P. A. T., E. F. Frolich, and A. Wallace. 1971. Vegetative propagation of woody shrub species from the Northern Mojave and Southern Great Basin Deserts. Madrono 21(3):149-152.