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Barrier Erosion Control Test Plan: Gravel Mulch, Vegetation, and Soil Water Interactions

W. J. Waugh
S. O. Link
Pacific Northwest Laboratory

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Westinghouse Hanford Company P.O. Box 1970 Richland, Washington 99352

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ABSTRACT

Soil erosion could reduce the water storage capacity of barriers that have been proposed for the disposal of near-surface waste at the U.S. Department of Energy's Hanford Site. Gravel mixed into the top soil surface may create a self-healing veneer that greatly retards soil loss. However, gravel admixtures may also enhance infiltration of rainwater, suppress plant growth and water extraction, and lead to the leaching of underlying waste.

This report describes plans for two experiments that were designed to test hypotheses concerning the interactive effects of surface gravel admixtures, revegetation, and enhanced precipitation on soil water balance and plant abundance. The first experiment is a factorial field plot set up on the site selected as a soil borrow area for the eventual construction of barriers. The treatments, arranged in a split-split-plot design structure, include two densities of gravel admix, a mixture of native and introduced grasses, and irrigation to simulate a wetter climate. Changes in soil water storage and plant cover are monitored with neutron moisture probes and point intercept sampling, respectively.

The second experiment consists of an array of 80 lysimeters containing several different barrier prototypes. Surface treatments are similar to the field-plot experiment. Drainage is collected from a valve at the base of each lysimeter tube, and evapotranspiration is estimated by subtraction. The lysimeters are also designed to be coupled to a whole-plant gas exchange system that will be used to conduct controlled experiments on evapotranspiration for modeling purposes.

This test plan was written in 1986 as an engineering support document. Publication has become necessary because of the need to reference the test plan in status reports and other documents scheduled for publication by the Protective Barrier Development Program. Any changes in the original experimental design, test procedure, or cost estimates will be documented in the latter reports.

EXECUTIVE SUMMARY

The *Final Environmental Impact Statement, Disposal of Hanford Defense High-Level, Transuranic, and Tank Wastes** includes alternatives for disposing of certain wastes near the surface. The near-surface disposal involves the use of a protective barrier that isolates these wastes from percolating soil water, biointrusion, and surficial erosion for time periods as long as 10,000 years. The conceptual protective barrier consists of coarse-rock and sand layers covered with a fine-textured soil that stores rainwater until it can be cycled back into the atmosphere by evaporation and plant transpiration. Erosion control is a critical issue. Significant erosion of the fine-soil layer and/or a reduction in plant transpiration would reduce barrier effectiveness.

Gravel mulch may be the answer. Engineering a gravel mulch analogous to desert pavements that have protected underlying soils for thousands of years may be possible. Several questions must be resolved before the use of gravel for erosion control can be defended. What is the optimum gravel size and volume for controlling projected wind and water erosion rates? How will plants respond? Can plant transpiration offset a gravel-induced increase in water infiltration and a decrease in evaporation? How much will freeze-thaw and shrink-swell action over the years alter the gravel mulch configuration? How sensitive will the system be to climatic variability? The *Protective Barrier and Warning Marker System Development Plan*** outlines several tasks for answering these questions.

Consistent with the barrier development plan, this document describes two experiments for testing hypotheses on the effects of gravel mulch, revegetation, and precipitation on soil water storage, water drainage through the barrier, and evapotranspiration (ET). In the first, a field-plot

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*DOE, 1987, *Final Environmental Impact Statement, Disposal of Hanford Defense High-Level, Transuranic, and Tank Wastes*, DOE/EIS-113, U.S. Department of Energy-Richland Operations Office, Richland, Washington.

**Adams, M. R. and N. R. Wing, 1987, *Protective Barrier and Warning Marker System Development Plan*, RHO-RE-PL-35 P, Rockwell Hanford Operations, Richland, Washington.

experiment, a statistical procedure known as analysis of variance will be applied to test the effects of 12 different combinations of gravel mulch, vegetation (and no vegetation), and precipitation (plus enhanced precipitation) on soil water storage and plant abundance. The split-plot layout selected for this experiment will produce more accurate estimates of the effects of gravel on soil water as compared to the effects of precipitation and vegetation. The field plots may also be more representative of the spatial heterogeneity in soil hydraulic properties and vegetation that will occur on real barriers, a source of variance not accounted for in lysimeter studies. This study will be located at McGee Ranch, a site near the intersection of State Highways 24 and 240 in Washington, which has been selected as a barrier topsoil quarry.

A second experiment will test, using lysimeters, whether or not a combination of gravel mulch and enhanced precipitation will increase soil water storage enough to cause the barrier to drain. A grid of 80 tube lysimeters will be constructed to test four levels of gravel mulch, two levels of precipitation, and two levels of vegetation representing 16 different treatment combinations, each replicated five times. Drainage (D) will be measured periodically by releasing a plug at the bottom of each lysimeter. Water storage changes (ΔS) will be inferred from changes in lysimeter weights between sampling periods. Treatment effects on ET will be measured by a subtraction method:

$$ET = P - D - \Delta S$$

where

P = Precipitation.

As in the field experiment, treatment effects will be compared using analysis of variance. The results will also comprise a portion of the data base for validation of UNSAT-H, a soil water balance code created to predict long-term barrier performance. The tube lysimeter array will be constructed at the Field Lysimeter Test Facility, which is located at the Hanford Meteorological Station.

At present, the plant-water relations components of UNSAT-H limit its usefulness for barrier performance assessment. Refinement of the code will require controlled experiments of plant processes. The lysimeters have been designed to be coupled to gas exchange chambers for measuring functional relationships between ET and environmental driving variables. The gas exchange system can control determinants of stomatal conductance such as vapor pressure, temperature, CO_2 concentrations, and convection. Gas exchange measurements on lysimeters, with and without vegetation, can be compared to estimate the net difference in ET with plants present. Although model development is beyond the scope of this document, future experiments based on this coupled lysimeter/gas exchange system, in concert with sampling for community-scale indexes of ET, will yield information needed to establish the parameters of predictive models of ET.

CONTENTS

Appendices:

LIST OF FIGURES

LIST OF TABLES

BARRIER EROSION CONTROL TEST PLAN: GRAVEL MULCH, VEGETATION, AND SOIL WATER INTERACTIONS

1.0 INTRODUCTION

The *Final Environmental Impact Statement: Disposal of Hanford Defense High-Level, Transuranic, and Tank Wastes* (HDW-EIS) (DOE 1987) compares four waste disposal alternatives: geological disposal, in-place stabilization and disposal, continued storage, and a reference alternative. The reference alternative combines elements of the geologic and in-place disposal alternatives. Implementation of any of these alternatives would include construction of a protective barrier. The purpose of the protective barrier is to impede biointrusion and water movement into the underlying waste zone. Preliminary field demonstrations (Cline et al. 1980; Phillips et al. 1985) and computer-aided simulations (Lu et al. 1982; Fayer et al. 1985, 1986) suggest that the protective barriers designed of layered earthen materials may be effective in limiting water movement, plant root intrusion, and animal burrowing for extended periods of time.

The conceptual protective barrier design consists of a layered rock and soil mound constructed over a waste disposal site (Figure 1-1). A layer of fine-textured soil overlying coarse sand and rock stores rainwater until it can be cycled back into the atmosphere by evaporation and plant transpiration. This design is based on a principle of soil physics called the outflow law (Richards 1950), which says, in effect, that water will not move from the fine-soil layer down into the coarse sand and rock until the soil at the layer interface is virtually saturated. Other attributes of this type of design include greater topsoil water retention, reduced gas emanation (Hartley et al. 1983), and enhanced evapotranspiration (ET) (Unger 1971).

The long-term performance of the layered earthen barrier depends, to a large degree, on (1) adequate topsoil hydraulic properties to reduce the likelihood of saturation at the layer interface and (2) vegetation for regular depletion of this reservoir by ET. Erosion of the topsoil layer or destruction of the plant cover could render the barrier inoperative. The *Protective Barrier and Warning Marker System Development Plan* (Adams and Wing 1987) specifies admixing pea gravel into the topsoil layer as an erosion control measure. Field and lysimeter experiments are proposed here for testing hypotheses on the effects of admix and other gravel mulch configurations on soil water storage, drainage, plant community dynamics, and ET. These data are also needed for the development and validation of predictive models of ET and water movement in barriers.

1.1 OBJECTIVES

The purpose of these investigations is to obtain field data as a basis for supporting or rejecting the use of gravel mulch for protective barrier erosion control. Results will be used for water balance model validation and, if applicable, selection of gravel mulch design specifications. Probabilistic inferences derived from the experiments described here will be pooled with those from companion experiments and measured against a set of barrier performance standards, thereby serving as a basis for design engineering. The following are some specific objectives of the proposed field and lysimeter experiments:

- Measure the combined effects of gravel mulch, vegetation, and precipitation on soil water storage and drainage
- Measure the combined effects of gravel mulch and increased precipitation on vegetation composition, abundance, and gas exchange
- Provide validation data for the UNSAT-H (unsaturated flow code)
- Determine functional relationships between ET and environment-driving variables for modeling purposes
- Demonstrate methods to accelerate initial plant community development on barriers.

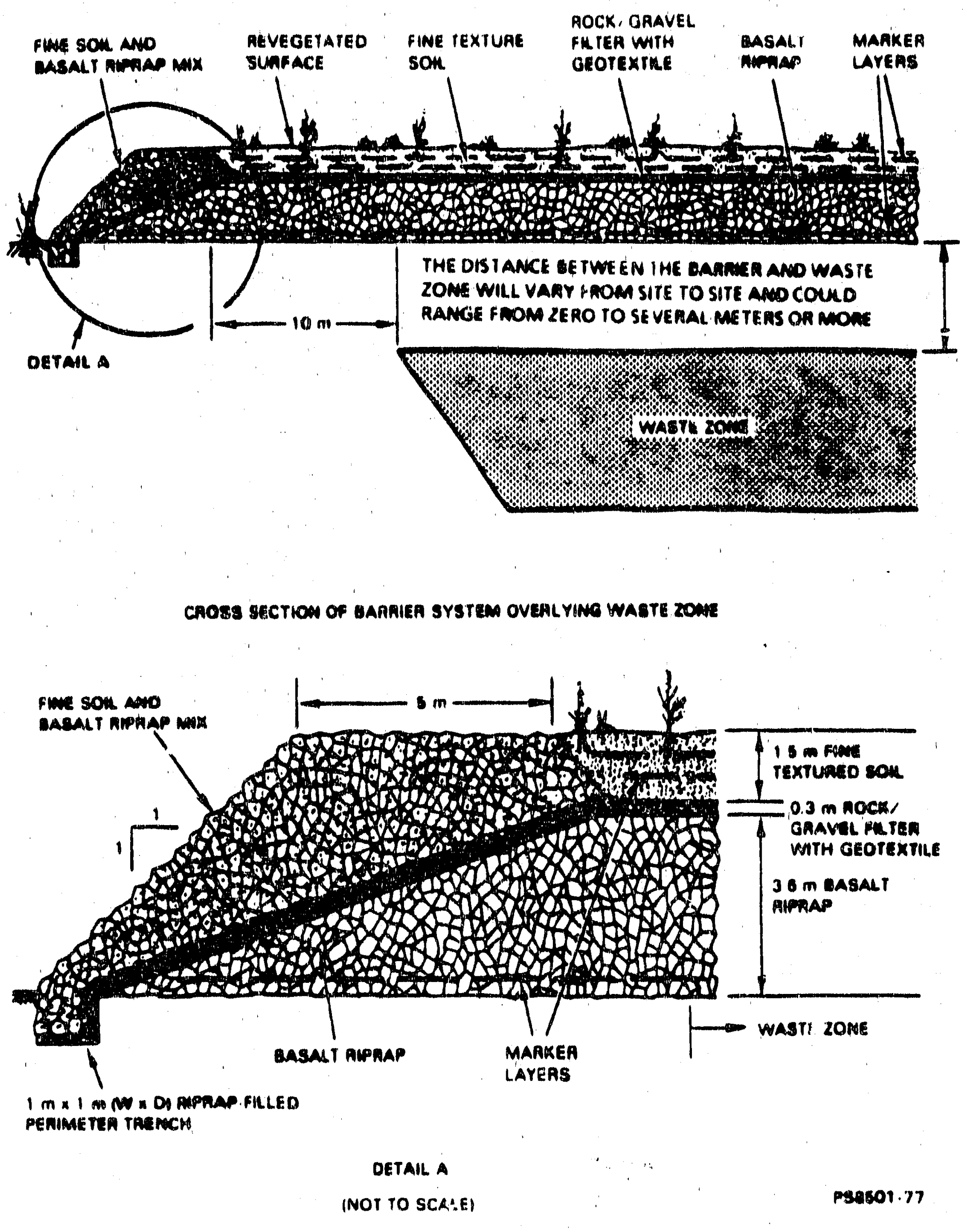

Figure 1-1. Hanford Defense Waste-Environmental Impact Statement Protective Barrier Concept (DOE 1987).

1.2 SCOPE

In addressing the above objectives, this document provides (1) an assessment of informational needs, (2) testable hypotheses that, if true, support the use of gravel mulch for protective barrier erosion control, and (3) experimental designs, treatment descriptions, sampling methods, construction plans, costs, schedules, and quality assurance for field and lysimeter experiments to test those hypotheses. The informational needs, hypotheses, and experiments described here are not all-inclusive. This test plan focuses on the interactions of gravel mulch, soil water storage, and ET. Other test plans will address deflation, runoff, and soil displacement by burrowing animals. Adams and Wing (1987) provide a comprehensive review of all technical issues and tasks associated with barrier erosion control (Table 1-1).

2.0 BACKGROUND INFORMATION

2.1 EFFECTS OF GRAVEL ON SOIL PROPERTIES AND VEGETATION

Incorporation of gravel into the upper 20 to 30 cm of the protective barrier topsoil is intended to mimic conditions that lead to the formation of desert pavements. Desert pavements form on soils dispersed with stones. Over time, the stones concentrate in the surface layer, thereby protecting the underlying soil from further erosion. If stones remain dispersed in the underlying soils, the pavement can be described as 'self-healing' following disturbances of the surface veneer.

Desert pavements typically occur on level or slightly inclined relief. Their formation has been attributed to three processes: (1) concentration of stones by wind deflation, (2) concentration of stones by runoff erosion, and (3) concentration by the upward migration of stones (Mabbutt 1977). If stones were dispersed uniformly in a soil, the amount of deflation could be estimated by subtracting the thickness of the veneer from the thickness of underlying soil

Table 1-1. Summary of Erosion Control Technical Issues and Tasks.

Technical issue	Tasks[a]
1. Barrier erodibility--wind	1.1 Wind tunnel tests (EROD-2) 1.2 Bergmound field studies (EROD-3) 1.3 Blowout field studies (EROD-4) 1.4 Armor analog studies (NAT-4)
2. Barrier erodibility--water	2.1 Bergmound field studies (EROD-3) 2.2 Water erosion field study (EROD-5) 2.3 Armor analog studies (NAT-4)
3. Gravel mulch/water balance interactions	3.1 Simulation models (Fayer et al. 1985, 1986) 3.2 Field Lysimeter Test Facility (WTR-1) 3.3 Field and small lysimeter gravel mulch experiments (EROD-1) 3.4 Surface armoring analog studies (NAT-4)
4. Gravel mulch/vegetation interactions	4.1 Field and small lysimeter gravel mulch experiments (EROD-1) 4.2 Surface armoring analog studies (NAT-4)
5. Gravel mulch/animal burrowing interactions	5.1 Animal intrusion tests (BIO-1) 5.2 Barrier stress tests--animals (BIO-2)

[a]Task codes from Adams and Wing (1987) are in parentheses.

PST87-3337-1

containing an equivalent volume of stones (Symmons and Hemming 1968). Furthermore, if wind erosion essentially ceases when the surface area covered by stone reaches 50% (Mabbutt 1977), predicting deflation may be possible for various admix gravel layer configurations. On sloped surfaces, overland flow may be more effective than wind in removing fines. For slopes 9% and greater, Simanton et al. (1984) found that the rates of water erosion decreased exponentially with increasing percent cover of rock fragments.

The soils underlying many desert pavements are nearly stone-free; evidence that stones had migrated toward the surface. These soils are typically high in clays that swell when wet and shrink and crack when dry. The stones may shift upward as the soil swells. Fines fall into the cracks as the soil dries (Mabbutt 1977). Conversely, freeze-thaw action and soil mixing by animals over many years may result in the mixing of gravel initially applied as a surface mulch into the topsoil layer (Boul et al. 1980). Therefore, the balance of pedoturbation (soil mixing) and erosional processes operating on a gravel mulch over the long term may result in an equilibrium gravel mix morphology, regardless of how the mulch was initially configured.

Addition of gravel to the topsoil layer influences soil hydraulic characteristics and the type and abundance of vegetation. In general, gravel increases infiltration and percolation rates, reduces evaporation, alters soil temperature, and yields fewer grasses and more shrubs and forbs (Nichols et al. 1984). Kirkham et al. (1982) measured greater soil moisture and drainage in soils underlying a rock cover than in soils with no rock. Model simulations indicate that adding gravel to denuded soils lowers the storage capacity and, therefore, increases drainage (Fayer et al. 1985). In contrast, Beedlow (1984) found no significant difference in soil moisture for a soil with rock mulch compared to a soil without mulch when vegetation was well established. However, the rock cover caused a greater abundance of deep-rooted forbs and shrubs at the expense of grasses. Furthermore, crop yields are often higher on relatively deep soils with moderate rock fragment content than on similar soils with the rock removed (Saini and Grant 1980; Magier and Ravina 1984).

2.2 MANIPULATION OF PLANT COMMUNITY DEVELOPMENT

Vegetation is an essential component of the proposed protective barrier. A plant cover can reduce soil loss and may enhance deposition of wind-transported particles. The addition of organic matter over the years binds soil particles. Higher plants also feed and are fed by soil microorganisms that help drive plant succession, secondary mineralization, soil aggregation, and, hence, moisture retention and soil stability. Perhaps most critically, vegetation removes (transpires) infiltrated moisture.

Unlike other barrier components, an ideal plant community cannot be engineered. Plant communities are dynamic and, to a large degree, unpredictable. Even if vegetation criteria were developed to guide barrier construction, such criteria would become superfluous considering the requisite 10,000-yr barrier design life. Over time, regardless of what is initially planted on a barrier, the plant community will likely converge with the community that would have developed naturally.

In theory, the natural succession or recovery of a plant community following a disturbance leads to greater biomass (and initially, greater transpiration), slower rates of nutrient cycling, damped effects of macroenvironmental extremes (such as a buffering of extreme precipitation on soil water movement), and overall greater site stability (Odum 1969). Since these appear to be attributes of a desirable protective barrier state, a realistic revegetation goal may be to accelerate succession by manipulating the causal factors of plant community development. Such manipulations would expedite field tests of vegetation, gravel mulch, and soil water interactions, as well as become the final phase of barrier construction. An overview of revegetation concepts and practices is provided in Appendix A.

2.3 NEEDED INFORMATION

Knowledge of the effects of gravel mulch on erosional processes, soil water balance and vegetation establishment is inadequate at present to support operational-scale barrier construction.

An understanding of the roles of pedogenic soil-mixing processes at the Hanford Site is also lacking. Modeling and experimentation will be necessary to fill the gaps. Informational needs include answers to the following questions.

- Will gravel mulch adequately impede surficial soil erosion for the intended design life of the reference barrier? What is the optimum depth and size of gravel mulch for erosion control?
- Will gravel mulch reduce ET and increase water infiltration and drainage through the barrier? What is the optimum mulch configuration relative to water balance? How will climatic variability impact the soil-water balance?
- What long-term impacts will animal burrowing, plant physiognomy, freeze-thaw, and shrink-swell processes have on the distribution of gravels and on the microtopography of the barrier surface?
- What type of plant community will develop on a gravel-veneered soil. How will the community respond to changes in climate? How predictable is plant succession at the Hanford Site?
- Can the plant community development be manipulated so as to accelerate initial succession in an admix gravel layer? What type of plant community would provide the highest sustained transpiration? How stable would it be, how resistant to disturbances such as fire, and how resilient following a disturbance?

The experiments described in the following sections were designed to help satisfy some of these informational needs. These experiments focus on gravel mulch, vegetation, and soil water interactions. Other erosion control test plans will address issues such as wind deflation rates, runoff, climate change impacts, pedoturbation, and plant succession.

3.0 EXPERIMENTAL APPROACH

Perhaps an ideal experiment for measuring the response of soil water parameters to different combinations of gravel mulch and vegetation would consist of multiway comparisons in a network of large weighing/ drainage lysimeters. This ideal experiment would have the following attributes:

- A treatment structure comprising a full range of factor combinations including climatic variability
- Lysimeters containing full-scale contiguous barriers, not just design components
- Instrumentation capable of high-precision measurements of water storage and drainage across critical layer interfaces
- Adequate treatment replications to make experimental error manageable
- Lysimeters of sufficient size to contain the degree of heterogeneity in soil hydraulic properties and vegetation that would occur over time within and on the surface of actual barriers.

Most readers would recognize that this ideal experiment is unrealistic. An attempt to test all combinations of barrier designs and environmental conditions of concern, experimentally, would prove futile. An alternative approach has been adopted combining simulation modeling, lysimeter experiments, and field experiments.

Soil water balance terms for a broad range of simulated barrier designs and environmental conditions will be solved with mathematical models (Fayer et al. 1985, 1986). Two lysimeter studies and one field-plot study have been designed to test a range of surface covers under varying environmental conditions and to provide a data base for water balance model validation. High-precision measurements of drainage and soil water storage changes, essential for model validation, will be obtained in a few large drainage and weighing lysimeters (Kirkham et al. 1987). Optimizing the barrier surface cover for adequate erosion control without compromising drainage control will require many experimental units (lysimeters) for making multiple comparisons. These experiments will be conducted in a grid of small, possibly less precise, but less expensive weighing/drainage lysimeters (Section 5.0 of this document). Finally, large field-plot experiments (Section 4.0) are needed to account for the variance in water storage changes that may be attributable to nonuniform soil hydraulic properties and/or plant distribution patterns.

These four studies (field-plot experiment, small-tube lysimeter experiments, large lysimeter experiments, and model development) encompass all of the attributes of the ideal experiment (Table 3-1). However, the efficacy of this approach will depend on the level of agreement among studies. To obtain some measure of agreement, the demonstrations and experiments have been designed so that at least one level of each treatment factor is common to all.

4.0 FIELD EXPERIMENT DESCRIPTION

A factorial field-scale experiment has been designed to measure the effects of gravel mulch, vegetation, and precipitation on soil water storage, plant abundance, and ET. The experiment was designed to test the following four null hypotheses.

H1 Volume of gravel admix will not affect soil water storage below the root zone.

H2 Twice the annual precipitation will not increase soil water storage below the root zone.

H3 Addition of gravel admix will not decrease plant abundance.

H4 Addition of gravel admix will not decrease ET rates.

Acceptance of these hypotheses would support inclusion of gravel mulch in the protective barrier design. Results from this, the lysimeter experiments (Section 5.0), and other experiments and demonstrations (Section 1.0) will be pooled in the development of protective barrier design specifications.

4.1 STUDY AREA LOCATION AND DESCRIPTION

Given the high variability in model-simulated effects of different types of gravel and soil mixtures on water drainage (Fayer et al. 1985), field and lysimeter experiments will require soil having the same hydraulic characteristics as the soil selected for barrier construction. The gravel mulch field experiment

Table 3-1. Attributes of a Hypothetical Ideal Test of Gravel Mulch, Vegetation, and Soil Water Interactions Encompassed by the Combination of Simulation Modeling, Large Lysimeter, Small-Tube Lysimeter, and Field-Plot Experiments.

Attributes of ideal experiment	Planned tests			
	Simulation models	Large lysimeter experiments	Small-tube lysimeter experiments	Field-plot experiments
Multiple barrier/environment combinations	X	--	--	--
Contiguous barrier design tested	X	X	--	--
Drainage measured directly	--	X	X	--
Water storage changes measured directly	--	X	X	--
Controlled plant gas exchange treatments	--	--	X	--
Multiple treatment combinations	--	--	X	X
Soil and vegetation heterogeneity	--	--	--	X

PST87-3337-2

will be located at McGee Ranch (Figure 4-1), the site that has been selected for a barrier topsoil quarry. McGee Ranch lies directly northwest of the Yakima Barricade in Section 30, T. 13 N., R. 25 E., and is bordered on the south and east by State Highways 24 and 240, respectively.

4.1.1 Soils

Hajek (1966) classified the McGee Ranch soil type as Warden silt loam. Silt loam soils may contain up to 50% sand, 50% to 80% silt, and up to 20% clay fractions (Soil Survey Staff 1975). Using U.S. Comprehensive Soil Classification System nomenclature (Soil Survey Staff 1975), the McGee Ranch soil is classified as an andic mollic camborthid; a dry, grayish-brown, wind-laid silt mixed with small amounts of volcanic ash, with a very weak eluvial clay horizon and often a calcareous horizon at about 50 cm. Warden silt loam grades into Ritzville silt loam at higher elevations.

4.1.2 Vegetation

The study site lies in an abandoned agricultural field that at one time was flood irrigated. Irrigation rills transecting the site from the northwest to the southeast are still visible. Although the plant canopy of an adjacent, undisturbed parcel consists primarily of sagebrush (*Artemisia tridentata*) and hopsage (*Grayia spinosa*), the old field remains dominated by cheatgrass (*Bromus tectorum*). This evidence contradicts a common assumption that plant succession on barriers will lead to a community similar to that found on the undisturbed soil quarry. Because of the introduction of cheatgrass, a Eurasian annual, sagebrush-dominated communities of the Columbia Basin may not be as resilient now as they once were (Rickard 1985).

4.2 EXPERIMENTAL DESIGN

The field experiment was designed to test the effects of gravel admix, vegetation, and precipitation on soil water storage, plant abundance, and ET. The three-way factorial treatment structure is shown in Table 4-1. Twelve different experimental conditions will be compared to test the hypotheses defined in Section 4.1. Each condition will be replicated three times, totaling 36 experimental units, or plots, on which soil water storage, plant abundance, and ET indexes will be measured.

The plot layout is a classic example of a split-split-plot design structure (Figure 4-2). Each of six large (10-m by 15-m) whole plots contains six (5-m by 5-m) subplots arranged in a two by three grid. Irrigation, vegetation, and gravel mulch are assigned to the subplots according to the following hierarchy: each whole plot receives a level of irrigation (the whole-plot treatment); a level of vegetation is randomly applied to half of a whole plot (the split-plot treatment); and the levels of gravel are randomly assigned to the subplots within the split plots (the split-split-plot treatment).

Table 4-1. Treatment Structure for the Gravel Mulch Field Experiment.

Factor	Levels	Treatment description*
Gravel mulch	3	1. 15% by weight gravel admix to a depth of 20 cm.
		2. 30% by weight gravel admix to a depth of 20 cm
		3. Control--no gravel mulch
Vegetation	2	1. Native and exotic grass/shrub seed mix
		2. Control--bare soil (herbicide)
Water	2	1. Doubled normal monthly precipitation
		2. Control--no supplemental water

*12 treatment combinations x 3 replications = 36 experimental units.

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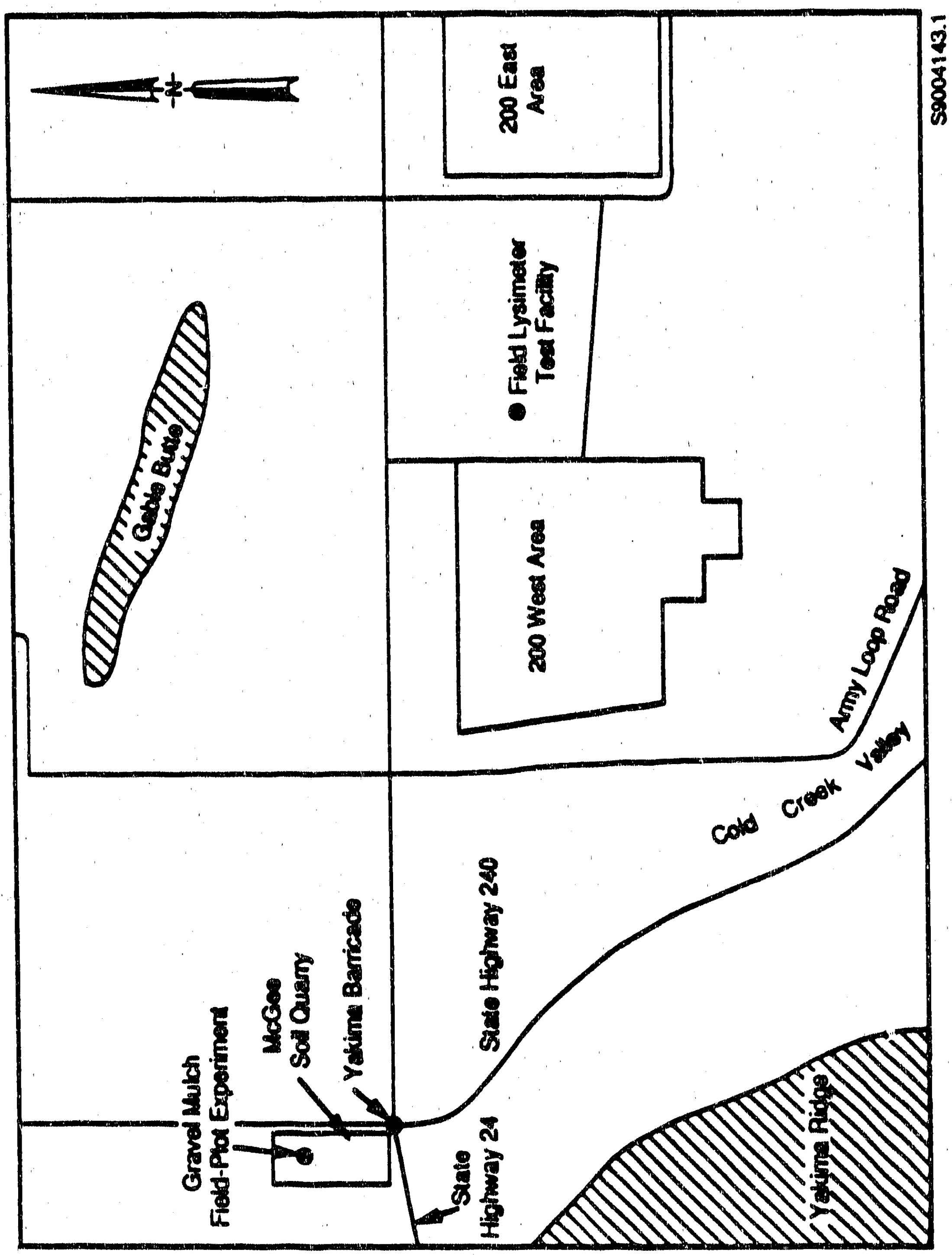

Figure 4-1. Locations of the Gravel Mulch Field-Plot Experiment and the Lysimeter Test Facility.

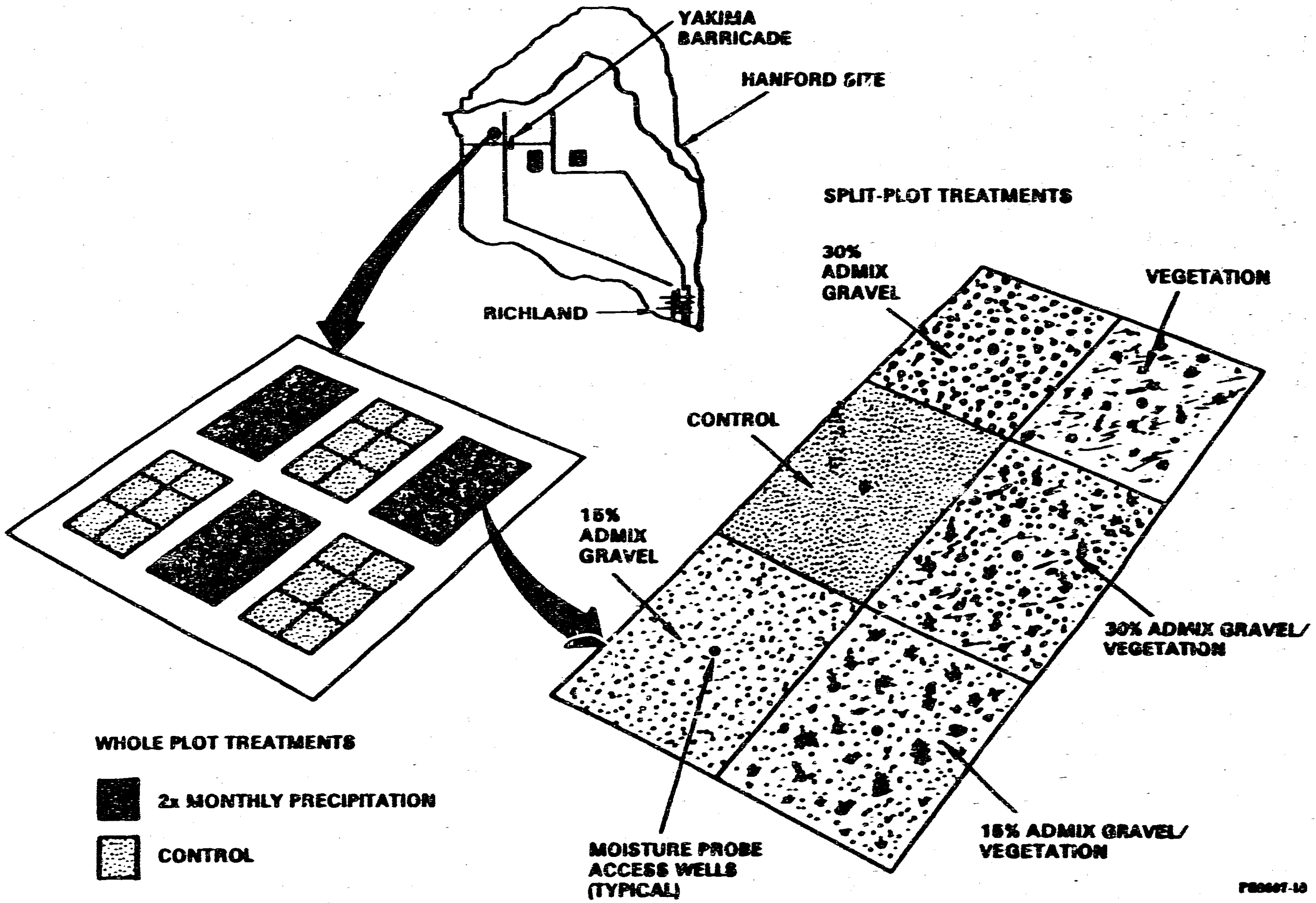

Figure 4-2. Split-Split Plot Design Structure for the Gravel Admix Field Experiment.

The split-split-plot design structure was selected because of the logistic problems associated with irrigating and drill-seeding small parcels of land. Furthermore, this design structure will produce more accurate estimates of the effect of gravel, the factor of greatest interest in this experiment, as compared to the effects of vegetation and precipitation. After data are obtained, a statistical procedure known as analysis of variance (ANOVA) will be applied to the data and a decision to reject or not to reject the above hypotheses will be based on an F-test. A discussion of appropriate ANOVA models and critical values of the F-test for each of the four hypotheses is provided in Appendix B.

4.3 TREATMENT DESCRIPTIONS

4.3.1 Gravel Mulch

Three levels of gravel mulch will be compared. Level 1, 15% by weight of 1.0-cm (3/8-in.) pea gravel mixed with soil, was the only level modeled for water drainage by Fayer et al. (1985). On bare soil, 15% gravel in Ritzville silt loam caused 1.7-cm (0.67-in.) drainage, compared to no drainage without it. No drainage occurred in admix gravel simulations when vegetation was included, regardless of soil type.

The percentage of gravel will be doubled for the second treatment level (30%). A higher percentage may be preferred for erosion control if no adverse effects on water storage are expected. Gravel will be mixed into the top 20 cm of soil for both treatment levels. Depth of admix will not be tested in the field experiment for two reasons: (1) simulations indicate that depths greater than 7.5 cm do not increase drainage proportionately (Fayer et al. 1985) and (2) 20 cm is the average mixing depth that can be achieved with available equipment. The control level is no gravel.

Given a soil bulk density of 1.4 g/cm^3, approximately 0.61 m^3 (0.8 yd^3) of pea gravel will be added per 25-m^2 (270-ft^2) plot to obtain 15% admix gravel in the top 20 cm (8 in.). About 1.2 m^3 (1.6 yd^3) will be mixed per plot for 30% gravel. A total of 23 m^3 (30 yd^3) of pea gravel will be purchased to construct the 12 replications of each treatment level. Following application of the gravel admix treatments, the surface material will be sampled randomly to ascertain the gravel content and depth achieved.

4.3.2 Vegetation

Bare soil and a mixed stand of grass and shrub species will comprise the two levels of vegetation. An appropriate revegetation practice for the barrier surface was conjectured from the literature and Hanford Site experience. Descriptions of the species, planting methods, fertilizer application, and other cultural practices follow. Comparisons of different treatment levels for these factors before operational construction of barriers would prove useful, but such comparisons are beyond the scope of the present experiment.

4.3.2.1 Species Selection. Species to be seeded and/or transplanted and seeding rates are shown in Table 4-2. This mixture of native and exotic grasses and shrubs was chosen for the following reasons: (1) it includes indigenous species found in mature plant communities at McGee Ranch and surrounding the 200 Areas, (2) it includes commercially available cultivars that are most like certain native species for which cultivars are not available, and (3) it includes relatively easy-to-establish cultivars having characteristics similar to native species that are difficult to establish in the Pasco Basin. The varieties and seeding rates generally conform with erosion control recommendations for sites with loamy or sandy soils in eastern Washington and with an annual precipitation of less than 30 cm (WSU 1983). Containerized shrub seedlings may be transplanted if drilled shrub seed fails to establish. Species descriptions follow.

Four shrub species will be seeded and/or transplanted: big sagebrush, hopsage, rabbitbrush, and bitterbrush. Basin big sagebrush (*Artemisia tridentata* ssp. *tridentata*) is fairly aggressive, productive, and ubiquitous at the Hanford Site. Although a profuse spread of sagebrush accompanied settlement of the West (Hull and Hull 1974), it has dominated large tracts of land in the Intermountain West since the early Pleistocene (Van Devender 1977).

Sagebrush typically benefits from endomycorrhizae infection (Williams and Aldon 1976) and may form symbiotic relationships with microbes to fix atmospheric nitrogen (Wallace and Romney 1972). Sagebrush has been useful for stabilizing disturbed sites throughout the West and often establishes rapidly from both direct seeding and transplanting (McArthur et al. 1979). At the Hanford Site, its establishment appears irregular and dependent on an abnormally cool and moist spring. However, it has encroached into many waste disposal sites within the 200 Areas.

Spiny hopsage (*Grayia spinosa*), a deciduous shrub, is found along the perimeter of the Pasco Basin on fine sandy loam and silt loam soils. It is moderately abundant in the *Artemisia tridentata/Poa secunda* association surrounding the McGee old field. The dense canopy of individual plants traps aeolian fines and, thus, appears largely responsible for the characteristic hummocky microrelief of this area. *Grayia* sprouts readily following fire, and its spiny twig tips protect it against excessive grazing by livestock (Daubenmire 1970).

Rabbitbrush (*Chrysothamnus nauseosus*) is one of the first woody plants to encroach on disturbed sites in the 200 Areas. It grows best on sandy and gravelly soils (McArthur et al. 1979), is excellent for controlling erosion on disturbed sites (USDA 1974), often dominates big sagebrush ranges destroyed by fire or heavy grazing (Evans et al. 1973), yet is not overly competitive with herbaceous species (Plummer et al. 1968).

Bitterbrush (*Purshia tridentata*) thrives on sandy soils in the Columbia Basin, has the ability to resprout following fire, and has been successfully established by direct seeding in the Northwest (Monsen and Davis 1985). Recovery following fire, however, can be slow (30 yr or more) (Nord 1965) and highly variable (Driscoll 1963). Because bitterbrush germination requires 5 to 6 wk of cold, moist stratification (Giunta et al. 1978), fall seeding is advised. Seed dormancy can also be overcome using thiourea or hydrogen peroxide (Everett and Meeuwig 1975). Many ecotypes are not well adapted to other sites (Medin and Ferguson 1980). other sites (Medin and Ferguson 1980). However, the only accession released to date, Lasson, from Lassen County, California, is reported to be well adapted throughout the Intermountain and Pacific Northwest regions (Shaw et al. 1983).

Table 4-2. Plant Species, Accessions, Cultivars, and Seeding Rates for the Vegetation Treatment of the Gravel Admix Field Experiment.

Species	Accession or cultivar	Seeding rate	
		Seeds/m^2	kg/ha
Big sagebrush (*Artemisia tridentata*)	Idaho ssp. *tridentata*	560	1
Rabbitbrush (*Chrysothamnus nauseosus*)	Idaho ssp. *albicaulis*	100	8
Spiny hopsage (*Grayia spinosa*)	Idaho	40	7
Bitterbrush (*Purshia tridentata*)	Lassen	65	20
Siberian wheatgrass (*Agropyron sibericum*)	P-27	540	10
Thickspike wheatgrass (*Agropyron dasystachyum*)	Critana	700	15
Indian ricegrass (*Oryzopsis hymenoides*)	Nezpar	540	10
Sheep fescue (*Festuca ovina*)	Covar	725	5
Canby bluegrass (*Poa canbyi*)	Canbar	500	3

PST87-3337-5

Five grass species will be seeded in the mixture: Siberian wheatgrass, thickspike wheatgrass, Indian ricegrass, Canby bluegrass, and sheep fescue. Many characteristics of P-27 Siberian wheatgrass are similar to the more widely used Fairway and Nordan crested wheatgrass cultivars, particularly ease of establishment and survival. However, P-27 is reportedly more drought tolerant and better adapted to sandier soils (Hanson 1972; Currie and White 1982). The P-27 is the most abundant of the perennial grasses seeded on the waste burial grounds. Found to spread away from seeded areas at the Hanford Site and to competitively limit cheatgrass where seeded, P-27 may have the potential to become a persistent resident of disturbed Hanford Site landscapes. In addition, the exotic Russian wheatgrasses develop a much larger rooting density than native wheatgrasses and, thus, more rapidly extract water from the soil profile (Caldwell et al. 1983).

Thickspike wheatgrass is a rhizomatous native grass of the Pasco Basin and is well-suited for wind erosion control on deep sandy soils (Brown and Wiesner 1984). Although not valued for productivity, thickspike can survive in low (12- to 20-cm) rainfall areas (Assay and Knowles 1985). Noted for excellent seedling vigor, the Critana cultivar, a northern Montana accession, has been successfully established on 200 Areas burial grounds.

Indian ricegrass (*Oryzopsis hymenoides*) has been seeded successfully on sterile, coarse mine spoils throughout the Intermountain West. It can be found along the periphery of active dunes at the Hanford Site and also dominates many older sandy and gravelly disturbed sites in the 200 Areas. Indian ricegrass is perhaps the most resilient native perennial grass in the Pasco Basin. However, it is characterized by extreme embryo dormancy and sporadic germination caused by inhibited embryo gas exchange (McDonald and Kah 1977). Since cool moist stratification improves germination (Young and Evans 1984), fall seeding plus a high seeding rate may help overcome poor establishment. Nezpar, an Idaho accession, is likely closer to the Pasco Basin ecotype than the other available cultivars.

Canby bluegrass (*Poa canbyi*) and sheep fescue (*Festuca ovina*) are short-statured grasses with well-developed root systems. The Canbar cultivar is recommended for erosion control on sites where Sandberg bluegrass (*Poa secunda*) is a major constituent (WSU 1983). Sandberg bluegrass dominates many loam sites at the Hanford Site. Because of its low optimum germination temperature and early summer dormancy (Young et al. 1981), Canbar should be adapted to the Columbia Basin's hot, dry summers. Covar sheep fescue, an accession from the dry mountains of Turkey, is more drought-resistant than other fescues and has been established on loamy soils of the 200 Areas burial grounds.

4.3.2.2 Planting Method. To minimize initial interspecific competition and to provide optimum seedbed ecology, some species will be drill seeded in alternating drill rows and others will be broadcasted. Indian ricegrass will be drill seeded 5 to 8 cm deep (2 to 3 in.). Siberian wheatgrass and thickspike wheatgrass will be drilled 2 to 3 cm (0.8 to 1.2 in.) deep. Seed boxes on the rangeland drill will be partitioned and the depth bands adjusted accordingly. All other species will be broadcasted. Seeding will be completed in late September, the optimum time of the year for most of these species. If seedling establishment is poor the following year, transplantation of containerized sagebrush and rabbitbrush from lower Snake River Valley or Columbia Basin accessions will be considered.

4.3.2.3 Fertilizer. Fertilizer will be applied concurrent with seeding as follows: 100 lb/acre phosphorous pentoxide (P_2O_5) and 40 lb/acre nitrogen.

4.3.2.4 Cultipacking. Following the seeding and fertilizer applications on split plots, the seedbed will be packed and pitted with an implement called a cultipacker. The benefits of this cultural practice include fertilizer incorporation, seedbed water conservation, improved seed-to-soil contact, and variable seed depth placement. Placement of seed at variable depths helps to balance germination of a diverse species mixture.

4.3.3 Irrigation

The historical mean annual precipitation at the Hanford Site is 16.0 cm (6.3 in.) with extremes ranging from 8 to 27 cm (3 to 11 in.) (Stone et al. 1983). Using extreme value statistics, Kinnison (1983) estimated the maximum 100-yr extreme annual precipitation to be 30.1 cm. This value has been used in performance assessment calculations and in all 'wet-year' model simulations of drainage through protective barriers (Fayer et al. 1985). Double the mean annual precipitation, or 32.0 cm, which is a more prudent wet climate estimate than the 100-yr maximum annual precipitation, is one of two water treatment levels. The other level is no supplemental water.

Three of the six whole plots will be irrigated monthly. Water will be added proportional to historical monthly means for a total of 32 cm (combined precipitation and irrigation). Additional irrigation may be applied to sustain seedlings during the first summer. A conventional sprinkler irrigation system has been designed to give a uniform coverage of whole plots (Figure 4-3). The uniformity of water application will be checked with collection cans randomly located on the whole plots. A 9,465-L (2,500-gal) water tank will be moved to McGee Ranch from the 201-W Building and filled as needed from a water truck. An in-line flow meter will be used to precisely measure application rates. For example, 7,734 L (2,043 gal) is equivalent to 2 cm over the three 150-m^2 plots.

4.4 SAMPLING METHODS AND DATA

4.4.1 Soil Moisture and Physical Properties

A neutron probe or hydroprobe will be used to measure volumetric soil water content [American Society of Testing Materials (ASTM) 1986]. Access wells for the neutron moisture probe will be augered at the center of each subplot (36 total) (see Figure 4-2). Field techniques will be used to calibrate the hydroprobe to convert slow neutron counts per unit time to volumetric measure (cubic centimeters of water per cubic centimeter of soil).

Access wells will be excavated to a depth of 300 cm in accordance with ASTM D-1452 (ASTM 1986) using a hand-operated bucket auger with a diameter of 5.08 cm (2 in.). Seamless aluminum tubing (5.08 cm internal diameter) will be inserted into the borehole to serve as well casing. Dry soil sifted into the resulting annulus will provide an adequate seal.

Field calibration of the hydroprobe will be accomplished by measuring the gravimetric water content of soil samples collected during the installation of access wells, multiplying these values by soil bulk density to convert the data to volumetric units, and constructing a calibration curve comparing these values with hydroprobe counts taken immediately following the installation of an access well. Gravimetric water content samples and concurrent hydroprobe readings will be taken in artificially saturated plots adjacent to the test plots, as well as in the relatively dry test plots. The wet-site data will expand the range of observations and thus extend the bounding limits of the calibration function. Gravimetric water content will be determined in accordance with ASTM D-2216-80 (ASTM 1986) for soil samples collected at depths of 30, 45, 80, 125, 175, 225, and 275 cm. Hydroprobe counts will be recorded monthly at these depths for the duration of the experiment. Shielded standard counts will be recorded at the beginning and at the close of each hydroprobe session, in exactly the same manner each time, as a means of checking the validity of the moisture-counting function.

Soil bulk density estimates are needed in the hydroprobe calibration to convert gravimetric water content into volumetric units. Relatively undisturbed soil cores can be recovered by pressing a thin-walled metal tube into a soil profile, removing the soil-filled tube, and sealing the ends to prevent disturbance or moisture loss [ASTM D-1587-83 (ASTM 1986)]. Several cores will be extracted randomly from the buffer areas between whole plots. Bulk density (oven-dry mass/unit volume) will be measured for core sections corresponding to the gravimetric sample depths (30, 45, 80, 125, 175, 225, and 275 cm).

Subsampling soil moisture within subplots may become necessary if a high variance attributable to soil heterogeneity masks treatment

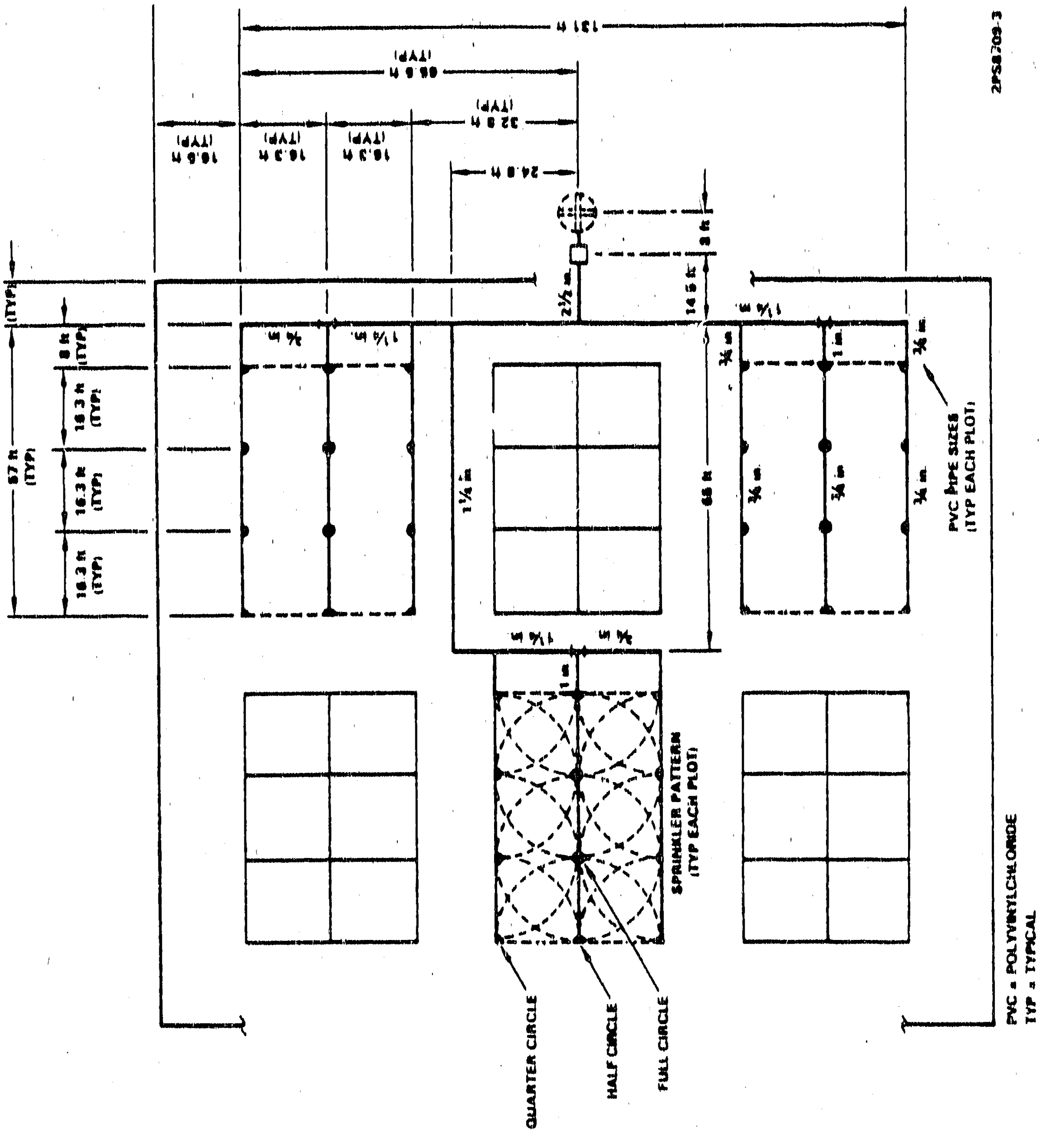

Figure 4-3. Sprinkler Irrigation System for the Gravel Admix Field Experiment.

effects. Additional hydroprobe access wells would be installed to accomplish this and a modified ANOVA model for multiple observations per experimental unit would be adopted for the analysis (see Appendix B). Nonuniformity in soil hydraulic properties with depth in the profile and among treatment subplots will be inferred from particle-size analyses [ASTM D422 (ASTM 1986)] of soil samples excavated during the installation of hydroprobe ports.

4.4.2 Plant Species Composition and Abundance

Plant species composition will be documented for the community surrounding as well as within the experimental plots. Because many plants have senesced and are not identifiable in the summer, and others do not emerge until summer, species composition will be documented periodically throughout the growing season. This will ensure that identifying characteristics are observed and, thus, that all species are accounted for.

Percent cover will be estimated to evaluate vegetation establishment. Cover will be estimated in quadrats randomly located in each small plot. An adequate number of quadrats for 95% confidence and a relative precision (u) of ± 10% will be selected using the following estimator (McDonald and Cochran 1983):

$$n_o = \frac{z^2 s^2}{(u\,\bar{y})^2}$$

where

- n_o = The estimated minimum sample size
- z = 1.960 in the standard normal distribution
- s^2 = The sample variance
- $\bar{y}$ = The sample mean.

This confidence statement suggests that if density were sampled repeatedly, the sample mean would be within 10% of the population mean 95% of the time. These levels of precision and confidence will be used to estimate adequate sample sizes for the other parameters as well. However, in all cases budget may have an influence on how large the sample will be.

Canopy cover is considered a good index of the importance of a species in a community because it permits comparisons of different growth forms (Mueller-Dombois and Ellenberg 1974). The percentage of canopy cover will be estimated using a point-intercept sighting instrument. The ocular point-intercept method provides less biased, more precise, and less time-consuming estimates of percentage of cover in sagebrush-grass vegetation than the line-intercept or the Daubenmire (1959) cover-class method (Floyd and Anderson 1983).

4.4.3 Phenology, Leaf Area, and Evapotranspiration

Phenology, leaf area, and species composition data will be collected in concert. An automated, inclined point frame will be used to measure leaf area nondestructively as an index of plant growth rates and phenology. To ensure the accuracy of the point-frame method, vegetation surrounding the plots will be randomly measured with the point frame, harvested, and measured again with a leaf area meter. These data are needed for correlation estimates to calibrate the point frame and to determine an adequate sampling frequency. For outyear sampling, methods developed under the transpiration subtask of the barrier program's water infiltration control task (Adams and Wing 1987) may be adopted for estimating transpiration flux density.

4.4.4 Environmental Monitoring

A remote meteorological station will be set up at McGee Ranch, fitted with sensors and a data logger, and programmed for continuous recording of precipitation (tipping bucket), air temperature at 1.5 m, relative humidity at 1.5 m, photosynthetically active radiation, and wind speed and direction at 3 m. Only precipitation will be used in the ANOVA tests of hypotheses. The other parameters will be needed for interpretations of differences between McGee Ranch soil water storage data and data sets from the Field Lysimeter Test Facility (Section 5.0).

4.5 SCHEDULE

Construction of the gravel-admix field plots is estimated to take 1 yr [fiscal year (FY) 1986]. Data collection will continue through FY 1991 with a final report prepared in FY 1992 (Figure 4-4).

4.6 COSTS

The total cost of the project through FY 1992 is estimated to be $387,000 (Tables 4-3 and 4-4).

5.0 SMALL-TUBE LYSIMETER EXPERIMENT

5.1 INTRODUCTION

This experiment will use lysimeters to test whether or not a gravel mulch, designed to control erosion of the barrier topsoil, will increase soil water storage enough to cause the barrier to drain. Drainage is a key barrier performance parameter. However, for the ultimate goal of predicting long-term barrier performance, the critical parameter may not be drainage, but ET.

Drainage across the fine- to-coarse-layer interface in the barrier may occur as the threshold response to water storage changes. If so, drainage may be relatively insensitive to variability in the surface environment as long as soil water storage values remain below the threshold. In contrast, ET is highly sensitive to environmental change and, thus, may be a salient measure for barrier performance. Therefore, ET will also be a key parameter in tests of gravel mulch and soil water interactions. This experiment will answer the question: Will plant transpiration offset a gravel-induced increase in infiltration and decrease in evaporation?

The experiment was designed to test the following three hypotheses.

H1 Gravel mulch layer configuration will not affect soil water storage, drainage, or ET.

H2 Vegetation abundance will not affect storage, drainage, or ET.

H3 Increased precipitation will not affect storage, drainage, or ET.

In addition to testing these hypotheses, this experiment was designed to be consistent with model simulations of gravel mulch effects on soil water dynamics (Fayer et al. 1985). The results will provide a check of the UNSAT-H results. Subsequent experiments may include treatments for testing gravel size, gravel amount, multiple levels of enhanced precipitation, and soil type.

An array of combination weighing/drainage lysimeters will comprise the experimental units for this study. This grid of small-tube lysimeters will be constructed adjacent to the large caisson lysimeters at the Field Lysimeter Test Facility (Figure 5-1) on the grounds of the Hanford Meteorological Station.

The unsaturated soil moisture flow code, UNSAT-H, has been developed, in part, to help quantify the potential for water drainage through barriers (Fayer et al. 1986). However, the plant/water relations components of UNSAT-H presently limit its usefulness for predicting the performance of barrier designs that include gravel for erosion control. Plant transpiration may be essential in such designs to offset the higher infiltration and lower soil evaporation caused by gravel. Although model development is beyond the scope of this document, the small-tube lysimeters, when coupled to a gas-exchange control and measurement system, can be used to measure functional relationships between ET and environment-driving variables for use in developing predictive models of water movement in barriers. A gas-exchange system can control determinants of ET such as temperature, vapor pressure, CO_2, and convection. A description of a gas-exchange measurement system and its potential application is provided in Appendix C. Stomatal conductance models and driving variables are discussed in Appendix D. An experimental plan for using the gas-exchange system on the tube lysimeters will be prepared in FY 1988.

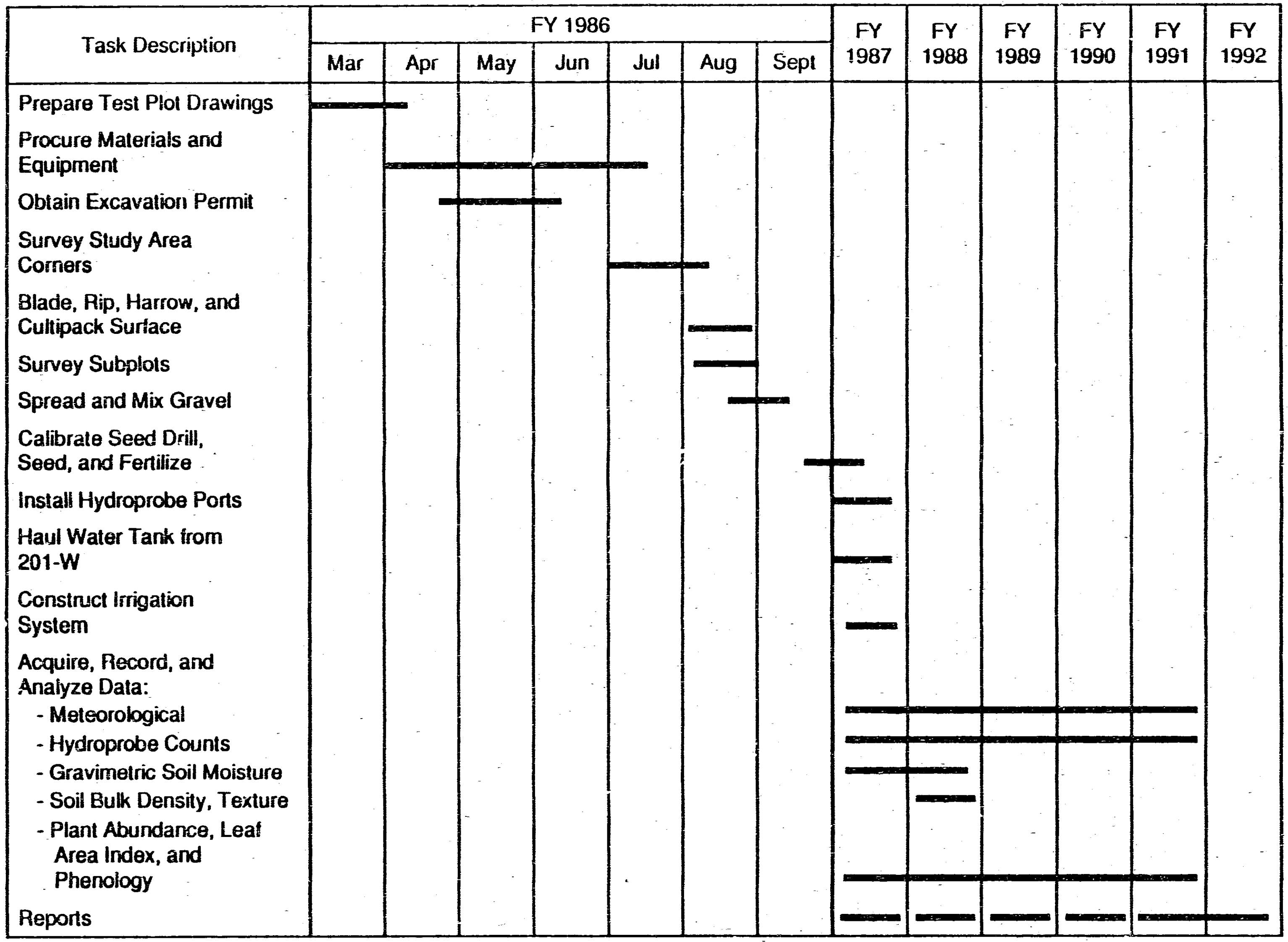

Figure 4-4. Gravel Admix Experiment Task Schedule.

Table 4-3. Gravel Admix Field Experiment Construction Costs.

Category	Materials (dollars x 1,000)	Manpower[a]	
		Dollars x 1,000	Manhours
Lead scientist coordination--fiscal year 1986 (65630)	--	5.4	114.0
Test plot drawings (Kaiser Engineers Hanford Company)	--	4.0	107.0
Materials	--	--	--
23 m^3 (30 yd^3) pea gravel	0.5	--	--
Polyvinylchloride pipe, fittings, and sprinklers	0.3	--	--
8-hp gas-powered pump (80 gal/min at 100 ft head)	0.6	--	--
In-line flow meter	0.3	--	--
Neutron moisture probe	5.0	--	--
Micrometeorology data logger and sensors	4.0	--	--
Telecommunications for meteorology data transfer	4.5	--	--
110 m (360 ft) of 5.08-cm (2 in. inside diameter) aluminum tubing	1.1	--	--
Automated point frame	5.0	--	--
Thin-wall tube sampler for bulk density	0.2	--	--
Seed, fertilizer, and herbicide	0.6	--	--
Statistics software	0.8	--	--
Surface preparation (38530)	--	--	--
Blade, deep rip	--	0.4	16.0
Harrow and cultipack	--	0.2	8.0
Move 2,500 gal water tank from 201-W Building (38530)	--	2.7	110.0
Spread gravel (38530)	--	0.2	8.0
Fertilize, drill seed (38530)	--	1.0	41.0
Cut aluminum tubing (38540)	--	0.2	8.0
Auger hydroprobe wells (65630)	--	3.0	80.0
Totals	22.9	17.1	522.0

[a]Manpower conversions (overhead included): 65630 = \$37.5/h; 38530 = \$24.4/h. PST87-3337-7

Table 4-4. Tasks and Manpower Costs, Fiscal Year 1987 through Fiscal Year 1991.

Task	FY 1987		FY 1988		FY 1989		FY 1990		FY 1991		FY 1992	
	MP[a]	MH[a]	MP	MH	MP	MH	MP	MH	MP	MH	MP	MH
Field data acquisition												
Hydroprobe readings	11.3	300	11.3	300	11.3	300	11.3	300	11.3	300	--	--
Hydroprobe calibration								--				
Cores for soil moisture and texture	3.0	80	3.0	80	--	--	--	--	--	--	--	--
Thin-wall cores for bulk density	2.3	60	2.3	60	--	--	--	--	--	--	--	--
Micrometeorology maintenance	3.0	80	3.0	80	3.0	80	3.0	80	3.0	80	--	--
Plant abundance, LAI, and phenology	4.9	130	4.9	130	4.9	130	4.9	130	4.9	130	--	--
Laboratory tasks												
Hydroprobe calibration	1.2	30	1.2	30	1.2	30	1.2	30	1.2	30	--	--
Gravimetric soil moisture	5.3	140	5.3	140		--	--	--	--	--	--	--
Soil textural analysis	6.5	170	--	--	--	--	--	--	--	--	--	--
Bulk density	4.5	120	4.5	120	--	--	--	--	--	--	--	--
Leaf area measurement	1.5	40	1.5	40		--	--		--	--	--	--
Data logging and checking	13.5	360	13.5	360	13.5	360	13.5	360	13.5	360	--	--
Data analysis (includes VAX computer account)	6.8	180	6.8	180	6.8	180	6.8	180	6.8	180	--	--
Status reports and presentations	6.8	180	36.8	180	6.8	180	6.8	180	6.8	180	--	--
Final report preparation and clearance	--	--	--	--	--	--	--	--	--	--	11.3	300
Technical editing	6.0	160	6.0	160	6.0	160	6.0	160	6.0	160	6.0	160
Manpower	76.6	2,030	70.1	1,860	53.5	1,420	53.5	1,420	58.0	1,540	17.3	460
Travel	1.5	--	1.5	--	1.5	--	1.5	--	1.5	--	1.5	--
Replacement materials	2.0	--	2.0	--	2.0	--	2.0	--	2.0	--	--	--
Yearly totals	79.1	--	73.6	--	57.0	--	37.0	--	61.5	--	--	18.8

PST87-3337-8

FY = Fiscal year.
LAI = Leaf area index.
NOTE: Costs in dollars x 1,000; 65630 manpower conversion (overhead included) = $37.5/h.
[a]Codes: MP = Manpower costs; MH = Manhours.

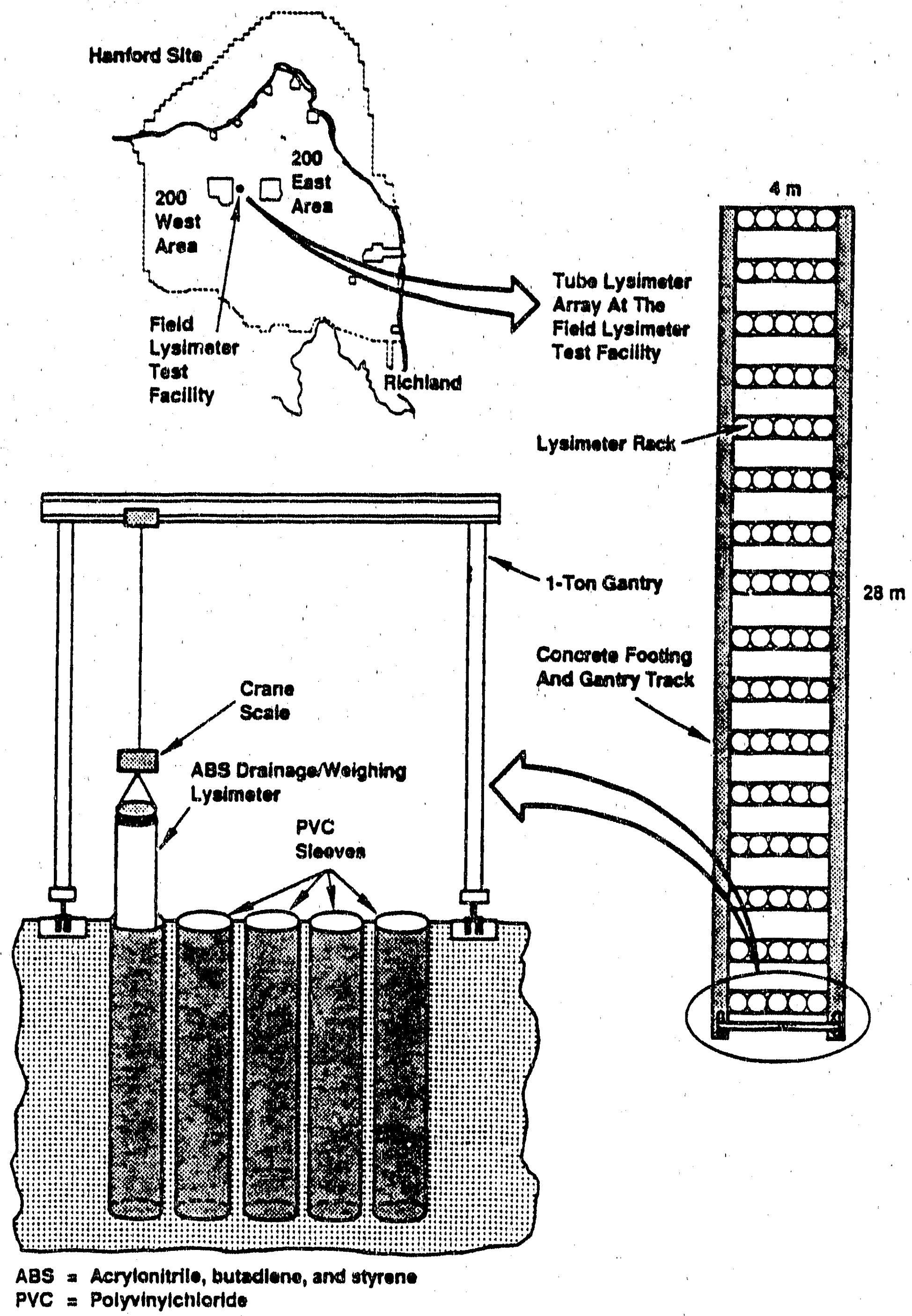

Figure 5-1. Schematic Drawing of the Small-Tube Lysimeter Grid at the Field Lysimeter Test Facility.

5.2 TEST DESCRIPTION

5.2.1 Experimental Design

The treatment structure of the small-tube lysimeter experiment consists of 16 treatment combinations replicated five times (Table 5-1). The treatment combinations will be imposed on 80 experimental units (lysimeters). The 16 treatment combinations are defined by four levels of gravel layer depth, two levels of water, and two levels of vegetation. Each of the 16 treatment combinations will be replicated five times for a total of 80 experimental units. The 80 lysimeters are to be arranged in 16 rows of five lysimeters per row with the treatment combinations assigned to individual lysimeters in a random order. The design structure is a textbook example of a completely randomized four by two by two factorial experiment with five replications.

Each of the three hypotheses in this first experiment can be tested using F-tests from the ANOVA. Discussion of critical F-test values, power of F-tests, the ANOVA model, and other pertinent ANOVA information required for hypothesis testing is provided in Appendix E.

5.2.2 Lysimeter Design

The lysimeters will consist of 175-cm (69-in.) sections of 30.5-cm- (12-in.-) internal diameter acrylonitrile, butadiene, and styrene (ABS) tube sealed at one end with a cap. The tube will serve as a combined drainage and weighing lysimeter. Drainage will be measured directly by collecting water from a drain plug located at the bottom of the cap. Water storage changes will be inferred from a record of weight changes measured by suspending lysimeters from a hoist-mounted load cell. The load cell has a resolution equivalent to approximately 0.058 cm of precipitation or ET. Holes will be augered in the ground and lined with 38-cm- (14-in.-) internal diameter polyvinylchloride (PVC) casing, and the lysimeters will be emplaced at grade with the surrounding soil.

It is important to design a hoist connection that will not perturb the continuity of the lysimeter surface with the surrounding soil. This will be accomplished by constructing the lysimeters with flush-threaded ABS well casing. A long section of ABS well casing with male threads at one end and an internal recessed cap at the other end will constitute the lysimeter itself. The lifting collar will consist of a short ABS section with female threads.

The lysimeter is designed to permit the coupling of an acrylic gas-exchange measurement chamber (Appendix C). The nominal external diameter of the chamber equals the internal diameter of the lysimeter. A threaded collar fitted with an O-ring will be used to seal the gas-exchange chamber to the lysimeter.

5.2.3 Lysimeter Installation

Fabrication and installation of the 80 lysimeter grids will be completed in FY 1988. The lysimeter will be filled with four layers of

Table 5-1. Factorial Treatment Structure for the Initial Small-Tube Lysimeter Experiment.

Factor	Level	Treatment description*
Gravel mulch configuration	3	1. 7.5-cm layer of 15% by weight pea gravel 2. 20-cm layer of 15% by weight pea gravel 3. Surface gravel mulch (volume = level 2) 4. Control--no gravel mulch
Vegetation	2	1. Cheatgrass 2. Control--bare soil (herbicide)
Water	2	1. Double the monthly normal precipitation 2. Control--no additional water

*16 treatment combinations x 5 replications = 80 experimental units. PST87-3337-9 material to create a capillary barrier similar to the design used in the construction of the Field Lysimeter Test Facility lysimeters (Kirkham et al. 1987): 150 cm of Warden silt loam from the McGee Ranch over 5 cm of 20/30 quartz sand over 5 cm of No. 8 quartz sand over a 5- to 7-cm layer of 1- to 2-cm washed pea gravel.

Initial soil bulk density and moisture content will be controlled as the lysimeters are backfilled. Ideally, soil bulk density and moisture content would be consistent with the large lysimeter and field-plot experiments. To approach an acceptable degree of consistency, lysimeters will be backfilled in lifts, tamped, and weighed until the desired density is achieved. The density and moisture content will be as consistent as possible with that achieved in the large lysimeters at the Field Lysimeter Test Facility.

5.2.4 Data Collection Methods

Critical parameters for measuring treatment effects include precipitation, water storage changes, drainage, and ET. The ET is estimated by subtracting the drainage value from the sum of water storage and precipitation change values. Temperature, solar radiation, photosynthetically active radiation, maximum and minimum air temperature, vapor pressure, and wind speed may also be needed for model development and validation. Quality-assured environmental data from the nearby Hanford Meteorological Station, operated by Pacific Northwest Laboratory, will be used whenever possible.

Drainage and water storage changes will be measured monthly. Lysimeters will be hoisted fully above grade with a gantry crane. Drain valves at the bottom of the lysimeters will be released to measure drainage (water volume). The difference between the current weight of the drained lysimeter and its drained weight from the previous session will constitute the water storage change measurement. A load cell suspended from the hoist will be used to weigh the lysimeters. Total ET during the interim period will be estimated by subtracting the drainage value from the sum of precipitation and storage change values recorded for the period.

A standard will be weighed with the load cell before, after, and randomly throughout each lysimeter weighing session to yield a measure of the load cell's bias due to time, temperature, and other physical variables. This will provide an estimate of measurement error in lysimeter weights for that session and between sessions. Otherwise, the assumption that the weighing error is constant for all time and environmental conditions must be made.

5.3 SCHEDULE AND COST

The tube lysimeter facility will be constructed in FY 1988. Data collection will continue through FY 1993. The total cost of the tube lysimeter experiment through FY 1993 is estimated to be $337,000 (Table 5-2).

6.0 TREATMENT CONSISTENCY

The level of agreement among results of the gravel admix field experiment (Section 4.0), the small-tube lysimeter experiment (Section 5.0), and the large lysimeter experiment will be an important measure of confidence in all three. For example, high covariance for water change measurements in the large and small lysimeters would support the use of the less costly small lysimeters for tests of future barrier design modifications. All three experiments have the following treatments in common.

Factor	Treatment level
Surface	1. 20-cm-thick layer of 15% by weight admix pea gravel (1.0- to 2.0-cm dia)
	2. No gravel mulch
Water	1. Natural precipitation
	2. 32-cm total precipitation
Vegetation	1. Native and exotic species mix
	2. No vegetation

Table 5-2. Small-Tube Lysimeter Project Costs.

Category	FY 1988[a]			FY 1989			FY 1990			FY 1991			FY 1992			FY 1993		
	MAT	MP	MH	MAT	MP	MH	MAT	MP	MH	MAT	MP	MH	MAT	MP	MH	MAT	MP	MH
Small-tube lysimeter facility materials:																		
80 5.5-ft x 12-in.-ID flush-thread ABS tubes	25.6																	
80 6-ft x 14-in.-ID plain schedule 40 polyvinylchloride pipe	3.2																	
Construction:																		
Emplace lysimeter sleeves	18.0																	
Fill and emplace treatments		6.8	180															
Characterize materials		4.5	120															
Irrigation					6.8	180		6.8	180		6.8	180		6.8	180		6.8	180
Data acquisition																		
Drain and weigh lysimeters					9.0	240		9.0	240		9.0	240		9.0	240		9.0	240
Plant phenology, leaf area index, and biomass					4.5	120		4.5	120		4.5	120		4.5	120		4.5	120
Data logging and checking					6.0	160		6.0	160		6.0	160		6.0	160		6.0	160
Data analysis					3.7	100		3.7	100		3.7	100		3.7	100		3.7	100
Instrument calibration					3.0	80		3.0	80		3.0	80		3.0	80		3.0	80
Reports and presentations					11.3	300		11.3	300		11.3	300		11.3	300		11.3	300
Technical editing					6.0	160		6.0	160		6.0	160		6.0	160		6.0	160
Replacement materials				2.0			2.0			2.0			2.0			2.0		
Travel	2.0			2.0			2.0			2.0			2.0			2.0		
Yearly totals	48.8	11.3	300	4.0	51.3	1,340	4.0	51.3	1,340	4.0	51.3	1,340	4.0	51.3		4.0	51.3	1,340
Project total--181.2[b]																		

PST87-3337-10

ABS = Acrylonitrile, butadiene, and styrene.
ID = Inside diameter.
[a] Codes: FY = Fiscal year, MAT = materials, MP = manpower costs, MH = manhours.
[b] Costs in dollars x 1,000. Manpower conversions (overhead included): Westinghouse Hanford Company = $37.5/h; Pacific Northwest Laboratory = $54/h.

7.0 SAFETY

No unique or unusual safety hazards are anticipated in the construction of these experiments or with subsequent sampling. Standard plant safety procedures pertaining to the operation of heavy equipment will be followed. Hard hats and steel-toed shoes shall be worn by workers lifting lysimeters to obtain drainage and weight measurements. Only workers who have completed a basic training course on radiation safety and the use of nuclear soil gages may operate the hydroprobe.

8.0 QUALITY ASSURANCE

These experiments will be conducted in accordance with a quality assurance program plan for the High-Level Waste Program once that document has been prepared and approved. Work initiated at Westinghouse Hanford Company will be continued at Pacific Northwest Laboratory (PNL) and will be prepared to PNL quality assurance Level III standards.

A hardbound logbook will be maintained for the duration of the experiments. All entries will be signed and dated by the responsible scientist, engineer, or technician, as will field and laboratory data sheets. The transfer of data from field or laboratory records to computer files will be double-checked by individuals identified in the logbook. All analytical tools such as statistical estimators, models, and computer software packages not included in this test plan will be referenced in the logbook and/or in yearly status reports. Instruments will be operated and calibrated according to manufacturers' specifications or applicable ASTM procedures as discussed in the text of this test plan. If the experimental designs, sampling methods, analytical tools, responsible organization listings, cost estimates, or schedules require modification, these changes will also be recorded in the logbook and/or status reports. All documents, correspondence, logbook entries, and data files will be duplicated and archived in accordance with the Protective Barrier Development Program's records management procedures.

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APPENDIX A

REVEGETATION CONCEPTS AND PRACTICES

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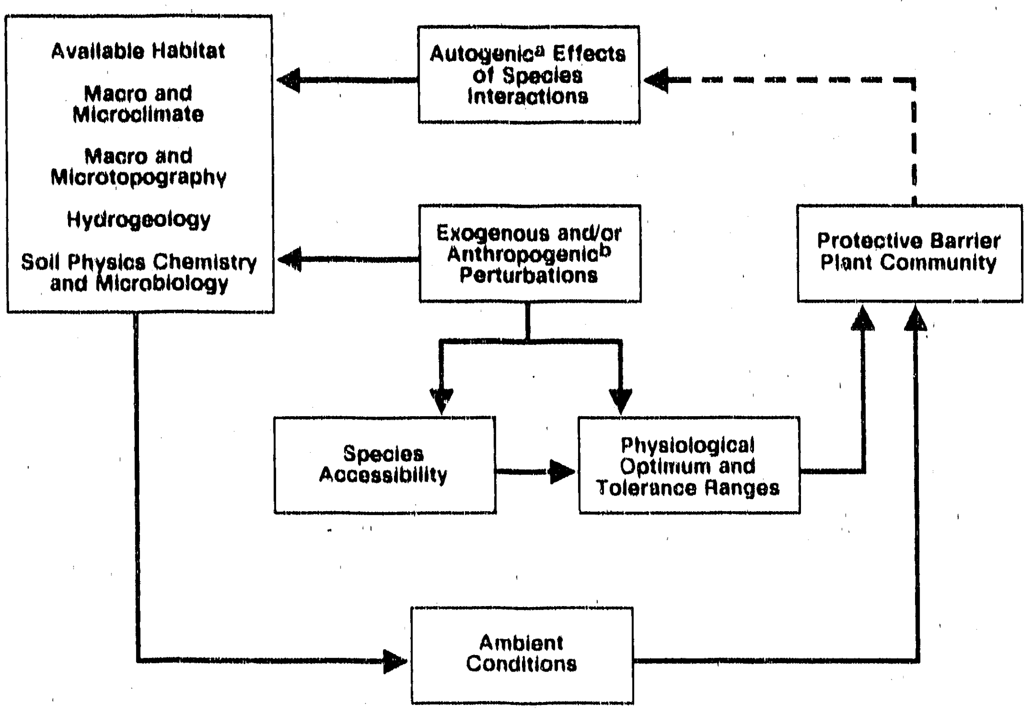
REVEGETATION CONCEPTS AND PRACTICES

Revegetation can be viewed as the manipulation of natural causal factors of plant community development. Figure A-1 is a conceptual model illustrating groups of causal factors arranged so as to depict their interaction. The selection of factors in Figure A-1 generally concurs with the plant community formation function proposed by Mueller-Dombois and Ellenberg (1974). Although not shown in the diagram, time and space are recognized as all-pervading dimensions.

Potentially all of the factors in Figure A-1 could be manipulated in an initial effort to force conformity of a plant community to management goals. Methodologies have been best developed for the reconstruction of ecosystems destroyed by surface mining. However, revegetation of protection barriers for in-place disposal of radioactive waste presents a unique set of problems not encountered in mine land reclamation. A discussion of some causal factor manipulations for accelerating plant succession in a soil mantled with gravel mulch follows.



[a]Changes in the available habitat brought about by resident organisms.
[b]Includes planned manipulations of causal factors--revegetation practices.

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Figure A-1. Basic Causal Factors of Plant Community Development on Protective Barriers.

A.1 MANIPULATION OF SPECIES ACCESSIBILITY

An obvious manipulation of natural plant community development is the introduction of seed form species not otherwise accessible; either exotic species or native species that have slow, sporadic, or inefficient seed dispersal mechanisms. Species growing on the soil that was borrowed to construct a barrier might be seeded, if it could be assumed that succession would eventually lead to that plant community. Sagebrush (*Artemisia tridentata* ssp. *tridentata*) dominates potential topsoil borrow areas. However, because of the introduction of cheatgrass (*Bromus tectorum*), an annual grass of Eurasion origin, sagebrush-dominated communities of the Columbia Basin may not be very resilient following a disturbance. Fairly homogenous swards of cheatgrass invaded agricultural lands abandoned in 1943 on the Arid Lands Ecology (ALE) preserve at the Hanford Site and persist there today (Rickard 1985). These areas once supported, and are presently surrounded by, native sagebrush-bunchgrass communities (Daubenmire 1970; Rickard and Sauer 1982). Therefore, seeding protective barriers with cheatgrass might be advocated as a means for accelerating succession.

Conversely, an assumption that old agricultural field succession on the ALE preserve portends plant community dynamics on disturbed sites in the 200 Areas may not be justified. A progressive succession of species is apparent on the burial grounds. Russian thistle (*Salsola kali*), noted for broad seed dispersion and relatively high germination rates under very negative water potentials (Evans and Young 1982), readily colonizes bare waste sites. Russian thistle may play an autogenic role. It produces chemicals phytotoxic to other weeds but tolerated by perennial grasses (Lodhi 1979). Through shading, it may ameliorate high surface soil temperatures, which also promotes grass establishment. Over the years, the plant community on a protective barrier may begin to resemble that in surrounding areas as cheatgrass abundance increases and rabbitbrush (*Chrysothamnus nauseosus*) and sagebrush encroach. The chronosequence in Table A-1 exemplifies this change.

Sagebrush seedling establishment in the 200 Areas appears to be dependent on spring moisture conditions. Sagebrush seedlings carpeted several disturbed 200 Area sites in 1981 following a wetter than normal spring. A growing dendrochronological record of sagebrush age structure at the Hanford Site indicates that this is a recurring pattern.

Once species have been selected, the plant materials, planting method, and planting time must be considered. Transplanting certain species, either as an alternative to or in conjunction with seeding, may be beneficial if (1) seed dormancy is a problem, (2) moisture is insufficient for germination, and/or (3) early seedling vigor is poor. Drill seeding has been more successful than broadcast seeding wheatgrasses for remedial burial ground stabilization at the Hanford Site. Seeding in September, just before the 'wet' season, has proven more successful than spring seeding. Without supplemental irrigation, seedling emergence and some root development in the fall may be necessary for seedling survival the following dry summer.

A.2 MANIPULATION OF SOIL MICROORGANISMS

Microorganism succession in disturbed arid-land soils parallels higher plant succession. Blue-green algae and lichens, which can form crusts on the soil surface, are photosynthetically active, are able to fix atmospheric nitrogen (Rychert and Skujins 1975), and may help stabilize disturbed soil. Protozoa ingest bacteria and may hasten nutrient cycling (Wallwork 1970). Decomposition of organic residue by molds and symbiotic interactions with the roots of higher plants are the more important roles of soil fungi. Fungi/plant interactions can be antagonistic (pathogenic) as well.

Table A-1. Mean Percent Canopy Cover (and standard error of the mean) by Species for a Chronosequence of Waste Burial Grounds Sampled in 1976 (modified from Rogers and Rickard 1977).

Plant taxa	Waste burial ground and date backfilled			
	216-S-4 1956	218-E-8 1959	216-A-9 1969	216-A-6 1970
Annual grasses				
Bromus tectorum (cheatgrass)	63.8 (2.6)	66.9 (12.6)	49.1 (15.4)	0.05 (0.05)
Festuca octaflora (six-weeks fescue)			0.08 (0.08)	
Perennial grasses				
Poa sandbergii (Sandberg's bluegrass)	2.9 (0.5)	2.0 (1.3)	1.0 (0.9)	
Forbs				
Salsola kali (Russian thistle)	0.06 (0.06)	1.8 (1.1)	24.2 (1.3)	44.6 (0.3)
Sisymbrium altissimum (Jim Hill mustard)	0.05 (0.05)	8.2 (1.9)	1.0 (0.9)	0.03 (0.03)
Descurainia pinnata (tansymustard)		0.2 (0.2)		
Cryptantha sp. (white forget-me-not)		0.03 (0.03)		
Machaeranthera canescens (hoary aster)			2.7 (1.7)	
Lactuca serriola (prickly lettuce)			0.03 (0.03)	
Epilobium sp. (willow-herb)			0.03 (0.03)	
Shrubs				
Chrysothamnus nauseosus (gray rabbitbrush)	33.2 (6.7)			
Total[a]	71.5 (4.9)	51.7 (7.3)	54.4 (12.2)	44.6 (0.3)

[a]Estimated as a total and not the sum of species cover.

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Mycorrhizal fungi (which form a mutualistic symbiosis with plant roots) aid in water and nutrient uptake by plants, particularly in phosphorus uptake. These fungi may play a major, deterministic role in plant community development on disturbed land (Loree and Williams 1984). Symbiotic fungi may accelerate the establishment of perennial grasses on disturbed soils initially colonized by Russian thistle (Allen 1984). Reeves et al. (1979) found that 99% of the plant cover on an undisturbed sagebrush-grass site consisted of mycorrhizae hosts while only 1% of the plant cover on an adjacent disturbed area was mycorrhizal.

Species dependent on vesicular-arbuscular (VA) mycorrhizae for uptake of phosphorus and other nutrients may be poor competitors with nonmycorrhizal species when seeded concurrently on soils depleted of inoculum (Loree and Williams 1984). Succession to a mycotrophic perennial wheatgrass association may be retarded on disturbed areas by the combination of low mycorrhizal inoculum and high densities on nonmycorrhizal annuals such as Russian thistle (Allen 1984). Application of VA mycorrhizae to accelerate succession is yet at an experimental scale. Technical problems associated with high production of superior strains and an uncertain market has delayed commercial development (Wood 1984).

Comparatively insignificant in number, autotrophic bacteria are immensely important in nitrogen fixation, nitrification and sulfur oxidation. The symbiosis of legumes and nitrogen-fixing bacteria of the genus *Rhizobium* is well recorded in the agronomy literature. *Lupinus* and *Astragalus* species, which recover fairly rapidly following fire at the Hanford Site, may accrue some of their resiliency from symbiotic, nitrogen-fixing bacteria. The presence of free-living, heterotrophic nitrogen-fixing and nitrifying bacteria, *Azobactor* and *Nitrobactor*, respectively, could also augment soil development and thus plant growth on disturbed sites.

Inoculation of protective barrier topsoil with nitrogen-fixing bacteria and infectious soil fungi may help accelerate plant succession. Cundell (1977) suggested inoculating mine spoil with free-living heterotrophic nitrogen-fixing bacteria to stimulate perennial grass establishment. If soil water is limiting, however, an organic amendment may be more critical than topsoil inoculant to stimulate the growth of nitrogen-fixing and nitrifying bacteria populations (Fresquez and Lindemann 1982).

A.3 FERTILIZER APPLICATIONS

Fertilizers are commonly used in revegetation to supplement nutrient-deficient soils. Other than poor soil moisture retention, limited available nitrogen, low organic matter content, and near-neutral pH are perhaps the most important edaphic characteristics of 200 Area soils (Rogers and Rickard 1977). Although calcium carbonate illuviation is apparent in some soils, sodium and other salts occur in minor concentrations. Analyses of 200 Area soil fertility provided the following mean values (Fuchs and Cox 1983): 0.43% organic matter, 6.7 kg/ha nitrate, 8 p/m available phosphorus, 213 p/m exchangeable potassium, 8.6 meq/100 g exchangeable calcium, 1.2 meq/100 g exchangeable magnesium, 0.07 meq/100 g exchangeable sodium, 0.23 mmho/cm soluble salts, and a pH of 7.7.

Nitrogen is the most limiting nutrient in 200 Area burial ground backfill. For remedial stabilization of Hanford Site burial grounds, wheatgrass cover was considerably greater with 40 lb/acre nitrogen application than with no nitrogen supplement. Initial nitrogen fertilization may not be advisable for the establishment of a shrub-grass mixture because of high variability among species in nitrogen response. Supplemental nitrogen may reduce species diversity in an emerging stand. In general, weedy annuals and perennial grasses respond vigorously while woody species are little affected (Berg 1980).

Levels of phosphorus, a relatively immobile soil nutrient that is particularly important for seedling establishment (USDA 1979), are considered adequate in soil borrowed for burial ground stabilization when compared to soil fertility standards. In addition, phosphorus fertilization may retard VA mycorrhizae infection. Conversely, a soluble form of phosphorus may enhance seedling establishment for all species in a mixture.

A.4 IRRIGATION

Supplying additional water by irrigation is often necessary for adequate establishment of perennial species in areas where precipitation is irregular or rarely sufficient. Moderate irrigation rates can stimulate cool-season perennial grasses and thus inhibit the productivity of annual weeds such as Russian thistle (DePuit et al. 1982). The amount, frequency, and duration of irrigation depends on soil water retention, the water requirements of the species planted, and the amount, frequency, and duration of precipitation. Variable success of wheatgrass establishment on waste burial grounds is attributable, in part, to insufficient precipitation and poor moisture retention in the sandy backfill.

If not controlled, irrigation can prove disadvantageous. The conceptual protective barrier is designed to retain the 100-yr maximum annual precipitation (30.1 cm). Excessive irrigation would saturate the topsoil layer and promote leaching into the underlying sediments. Over-irrigation can also result in initial plant production levels beyond the natural capacity of the site. Consequently, when irrigation is curtailed, plants may become overly stressed. Root biomass may be concentrated near the soil surface, causing inefficient utilization of deeper moisture following cessation of irrigation. Sustained (second year) irrigation may lead to a less diverse community due to varying responses of species to the supplemental moisture (DePuit et al. 1982).

The mean annual precipitation at the Hanford Site is 15.9 cm (Stone et al. 1983). Much of this precipitation comes as snow, some of which is lost by sublimation. Less than 12% of the annual precipitation comes during July through September, creating an extended growing season drought. Supplemental irrigation, not to exceed the protective barrier performance criteria for soil moisture retention, may greatly enhance germination and seedling establishment.

A.5 SURFACE MANIPULATIONS

Many types of surface manipulations common in mine land reclamation do not apply to protective barrier stabilization, particularly gross recontouring of landscape topography. However, microtopographical modifications, such as furrowing, pitting, plowing, and soil imprinting, are intended to improve the microclimate for seedling establishment (Wight 1976; Dixon 1983), and could be advantageous on barriers.

Much of the effect of soil depressions on plant microclimate is related to energy balance; the balance of incoming and outgoing energy of a plant. The temperature of a plant is a function of solar irradiation, infrared radiation from surrounding objects, and loss by convection, latent heat of transpiration, and infrared emission. Plant metabolic heat is insignificant. A soil depression offsets the balance of these factors, causing the microclimate to be cooler and wetter in the summer and warmer in the winter than it would be otherwise.

The effects of soil microdepressions on energy balance and water balance, since the two are tightly coupled, are sometimes overlooked because of more obvious, larger scale physical attributes: snowmelt and rainwater retention, soil deposition, litter accumulation, and increased infiltration. The potential disadvantages of these practices--increased water infiltration, deep percolation, and, thus, an effective decrease in topsoil layer thickness--may outweigh the advantages. However, gravel mulch may impart somewhat analogous energy balance improvements. Ambient boundary layer conditions in interstitial spaces at the soil/air interface of a mulch may enhance seedling establishment.

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APPENDIX B

FIELD-PLOT EXPERIMENTAL DESIGN

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Split-split plot (SSP) and split-plot (SP) designs will be used to test the following four hypotheses as part of the gravel mulch field experiment.

H1 - Gravel volume will not affect soil water storage below the root zone (SSP design).

H2 - Doubling of the mean annual precipitation will not increase soil water storage below the root zone (SSP design).

H3 - Gravel volume will not alter plant abundance (SP design).

H4 - Gravel volume will not alter evapotranspiration (ET) (SSP design).

Often SP or SSP designs are used when physical conditions make it impossible to completely randomize a factorial experimental design. Logistic problems associated with the application of irrigation and vegetation treatments to the field plots necessitates this special design. An SP or SSP design is also used when the experimenter is more interested in one factor than in the others. In this case, the effects of gravel mulch can be estimated more accurately than the effects of vegetation or precipitation. Using the SSP design, hypotheses H1 and H3 can be tested with more accuracy than hypothesis H2 (H4 requires an SSP design).

To test these hypotheses, soil water and plant species composition and abundance will be measured from the beginning of the experiment. The ET indices will be measured as instrumentation becomes available and will be adapted to the conditions of this experiment. Each hypothesis will be tested using an F-test from the appropriate analysis of variance (ANOVA). Soil water storage and ET data will be analyzed using the SSP ANOVA. All three factors in the treatment structure (precipitation, vegetation, and gravel) will be compared. The SP ANOVA will be used to analyze plant abundance data because vegetation has been eliminated as a treatment. Only precipitation and gravel mulch effects on plant abundance will be compared.

The ANOVA model for SSP and SP designs may be specified in two ways. The data can be fitted either to a full model, in which all possible treatment interactions are included, or to a reduced model, in which treatment-replication interaction effects are not included. The full ANOVA model approach gives exact F-tests with a small number of degrees of freedom associated with the denominator. The reduced model approach gives approximate F-tests with many more degrees of freedom associated with the denominator. The most desirable test would produce exact F-tests with many degrees of freedom for the denominator. Because this is not possible, both models will be computed. Full and reduced models and related ANOVA information for the SSP and SP designs are included in Tables B-1 through B-4.

Subsampling within the 5-m by 5-m plots to obtain estimates of plant abundance, ET, and possibly soil water, will require applying an expanded SSP full model (Table B-5). If equal numbers of subsamples per plot are used, the tests of hypotheses will remain the same. Equal-sized subsamples ensures 'simple' statistical analysis and interpretation of data.

Table B-1. Full Analysis of Variance Model and Table for the Split-Split-Plot Gravel Mulch Field Experiment.

$$Y_{ijkm} = \mu + R_i + P_j + (RP)_{ij} + V_k + (RV)_{ik} + (PV)_{jk} + (RPV)_{ijk} + G_m + (RG)_{im} + (PG)_{jm} + (RPG)_{ijm} + (VG)_{km} + (RVG)_{ikm} + (PVG)_{jkm} + (RPVG)_{ijkm} + e_{(ijkm)}$$

where

Y_{ijkm} = Water storage or plant measurement taken on a plot that has assigned to it replication $_i$, irrigation method $_j$, revegetation method $_k$, and gravel volume $_m$.
μ = Overall mean
R_i = Replication effect for level $_i$, where $_i$ = 1,2,3
P_j = Irrigation effect for method $_j$, where $_j$ = 1,2
V_k = Revegetation effect for method $_k$, where $_k$ = 1,2
G_m = Gravel effect for volume $_m$, where $_m$ = 1,2,3
$(PV)_{jk}$ = Interaction effect of irrigation method $_j$ and vegetation method $_k$
$(PG)_{jm}$ = etc.
$e_{(ijkm)}$ = Error for split-split-plot effects.

<u>Notation Used for Expected Mean Square</u>

σ_{RP} = Random error due to RxP interaction
ϕ_P = Component of expected mean square (EMS) due to fixed effects of irrigation, P.

In general,

σ_{factor} = Random error due to 'factor'
ϕ_{factor} = Component of EMS due to fixed effects of 'factor'.

Effects	Source	Degrees of freedom	ID code	EMS	F-test	(df_1, df_2)	F-statistic 0.05 level
Whole plot	R_i	2	A	$\sigma_e + 12\,\sigma_R$	A/E	(2,0)*	--
	P_j	1	P	$\sigma_e + 6\,\sigma_{RP} + 18\,\phi_P$	P/E1	(1,2)	18.5
	$(RP)_{ij}$	2	E1	$\sigma_e + 6\,\sigma_{RP}$	E1/E	(2,0)*	--
Split-plot	V_k	1	V	$\sigma_e + 6\,\sigma_{RV} + 18\,\phi_V$	V/RV	(1,2)	18.5
	$(RV)_{ik}$	2	RV	$\sigma_e + 6\,\sigma_{RV}$	RV/E	(2,0)*	--
	$(PV)_{jk}$	1	PV	$\sigma_e + 3\,\sigma_{RPV} + 9\,\phi_{PV}$	PV/E2	(1,2)	18.5
	$(RPV)_{ijk}$	2	E2	$\sigma_e + 3\,\sigma_{RPV}$	E2/E	(2,0)*	--
Split-split plot	G_m	2	G	$\sigma_e + 4\,\sigma_{RG} + 12\,\phi_G$	G/RG	(2,4)	6.94
	$(RG)_{im}$	4	RG	$\sigma_e + 4\,\sigma_{RG}$	RG/E	(4,0)*	--
	$(PG)_{jm}$	2	PG	$\sigma_e + 2\,\sigma_{RPG} + 6\,\phi_{PV}$	PG/RPG	(2,4)	6.94
	$(RPG)_{ijm}$	4	RPG	$\sigma_e + 2\,\sigma_{RPG}$	RPG/E	(4,0)*	--
	$(VG)_{km}$	2	VG	$\sigma_e + 2\,\sigma_{RVG} + 6\,\phi_{VG}$	VG/RVG	(2,4)	6.94
	$(RVG)_{ikm}$	4	RVG	$\sigma_e + 2\,\sigma_{RVG}$	RVG/E	(4,0)*	--
	$(PVG)_{jkm}$	2	PVG	$\sigma_e + 2\,\sigma_{RPVG} + 3\,\phi_{PVG}$	PVG/RPVG	(2,4)	6.94
	$(PVG)_{ijkm}$	4	RPVG	$\sigma_e + 2\,\sigma_{RPVG}$	RPVG/E	(4,0)*	--
	$e_{(ijkm)}$	0	E	σ_e (not retrievable)	--	--	--

*Test cannot be computed

PST88-3179-B-1

Table B-2. Reduced Analysis of Variance Model and Table for the Split-Split-Plot Gravel Mulch Field Experiment.

$$Y_{ijkm} = \mu + R_i + P_j + e_{(ij)} + V_k + (PV)_{jk} + e_{(ijk)} + G_m + (PG)_{jm} + (VG)_{km} + (PVG)_{jkm} + e_{(ijkm)}$$

where

$e_{(ij)}$ = Error for whole plot effects
$e_{(ijk)}$ = Error for split-plot effects
$e_{(ijkm)}$ = Error for split-split-plot effects.

All other notation was previously defined in Table B-1.

Effects	Source	Degrees of freedom	ID code	EMS	F-test	(df_1, df_2)	F-statistic 0.05 level
Whole plot	R_i	2	A	$\sigma_e + 3\sigma_g + 6\sigma_1 + 12\sigma_R$	A/W	(2,2)	19.0
	P_j	1	P	$\sigma_e + 3\sigma_g + 6\sigma_1 + 18\phi_P$	P/W1	(1,2)	18.5
	$e_{(ij)}$	2	W1	$\sigma_e + 3\sigma_g + 6\sigma_1$	W1/W	(2,4)	6.94
Split-plot	V_k	1	V	$\sigma_e + 3\sigma_g + 18\phi_V$	V/W2	(1,4)	7.71
	$(PV)_{jk}$	1	PV	$\sigma_e + 3\sigma_g + 9\phi_{PV}$	PV/W2	(1,4)	7.71
	$e_{(ijk)}$	4	W2	$\sigma_e + 3\sigma_g$	V2/W	(4,16)	3.01
Split-split plot	G_m	2	G	$\sigma_e + 12\phi_G$	G/W	(2,16)	3.63
	$(PG)_{jm}$	2	PG	$\sigma_e + 6\phi_{PG}$	PG/W	(2,16)	3.63
	$(VG)_{km}$	2	VG	$\sigma_e + 6\phi_{VG}$	VG/W	(2,16)	3.63
	$(PPG)_{jkm}$	2	PVG	$\sigma_e + 3\phi_{PVG}$	PVG/W	(2,16)	3.63
	$e_{(ijkm)}$	16	W	σ_e	--	--	--

PST88-3179-B-2

Table B-3. Full Analysis of Variance Model and Table for Testing Split-Plot Effects of Precipitation and Gravel Mulch on Plant Abundance.

$$Y_{ijm} = \mu + R_i + P_j + (RP)_{ij} + G_m + (RG)_{im} + (PG)_{jm} + (RPG)_{ijm} + e_{(ijm)}.$$

Effects	Source	Degrees of freedom	ID code	EMS	F-test	(df_1, df_2)	F-statistic 0.05 level
Whole plot	R_i	2	A	$\sigma_e + 6\,\sigma_R$	A/E	(2,0)[a]	--
	P_j	1	P	$\sigma_e + 3\,\sigma_{RP} + 9\,\phi_P$	P/E1	(1,2)	18.5
	$(RP)_{ij}$	2	E1	$\sigma_e + 3\,\sigma_{RP}$	E1/E	(2,0)[a]	--
Split-plot	G_m	2	G	$\sigma_e + 3\,\sigma_{RG} + 6\,\phi_G$	G/RG	(2,4)	6.94
	$(RG)_{im}$	4	RG	$\sigma_e + 2\,\sigma_{RG}$	RG/E	(4,0)[a]	--
	$(PG)_{jm}$	2	PG	$\sigma_e + 1\,\sigma_{RPG} + 3\,\phi_{PG}$	PG/RPG	(2,4)	6.94
	$(RPG)_{ijm}$	4	RPG	$\sigma_e + 1\,\sigma_{RPG}$	RPG/E	(4,0)[a]	--
	$e_{(ijm)}$	0	E	σ_e (not retrievable)	--	--	--

[a]Test cannot be completed.

PST88-3179-B-3

Table B-4. Reduced Split-Plot Analysis of Variance Model and Table for Testing Precipitation and Gravel Mulch on Plant Abundance.

$$Y_{ijm} = \mu + R_i + P_j + e_{(ij)} + G_m + (PG)_{jm} + e_{(ijm)}$$

where

$e_{(ij)}$ = Error for whole plot effects
$e_{(ijm)}$ = Error for split plot effects.

All other notation was previously defined in Table B-1.

Effects	Source	Degrees of freedom	ID code	EMS	F-test	(df_1, df_2)	F-statistic 0.05 level
Whole plot	R_i	2	A	$\sigma_e + 3\,\sigma_1 + 6\,\sigma_R$	A/W	(2,2)	19.0
	P_j	1	P	$\sigma_e + 3\,\sigma_1 + 9\,\phi_P$	P/W1	(1,2)	18.5
	e_{ij}	2	W1	$\sigma_e + 3\,\sigma_1$	W1/W	(2,4)	6.94
Split-plot	G_m	2	G	$\sigma_e + 6\,\phi_G$	G/W	(2,8)	4.46
	$(PG)_{jm}$	2	PG	$\sigma_e + 3\,\phi_{PG}$	PG/W	(2,8)	4.46
	$e_{(ijm)}$	8	W	σ_e	--	--	--

PST88-3179-B-4

Table B-5. Expanded Split-Split-Plot Full Model and Table for Plant Abundance and Soil Water Subsampling Within the 5-m x 5-m Subplots.

$$Y_{ijkm} = \mu + R_i + P_j + (RP)_{ij} + V_k + (RV)_{ik} + (PV)_{jk} + (RPV)_{ijk} + G_m + (RG)_{im} + (PG)_{jm} + (RPG)_{ijm} + (VG)_{km} + (RVG)_{ikm} + (PVG)_{jkm} + (RPVG)_{ijkm} + e_{(ijkm)} + e_{q(ijkm)}$$

where

Y_{ijkm} = Water storage or plant measurement $_q$ taken on a plot that has assigned to it replication $_i$, irrigation method $_j$, revegetation method $_k$, and gravel volume $_m$.

$e_{(ijkm)}$ = Experimental error (not retrievable)

$e_{q(ijkm)}$ = Observational error

$e_{(ijkmq)}$ = $e_{ijkm} + e_{q(ijkm)}$ (the combined errors are notationally simpler to use)

Effects	Source	Degrees of freedom	ID code	EMS	F-test	(df_1, df_2)	F-statistic 0.05 level
Whole plot	R_i	2	A	$\sigma_e + 12\,\sigma_R$	A/E	(2,D)	--
	P_j	1	P	$\sigma_e + 6\,\sigma_{RP} + 18\,\phi_P$	P/E1	(1,2)	18.5
	$(RP)_{ij}$	2	E1	$\sigma_e + 6\,\sigma_{RP}$	E1/E	(2,D)	--
Split-plot	V_k	1	V	$\sigma_e + 6\,\sigma_{RV} + 18\,\phi_V$	V/RV	(1,2)	18.5
	$(RV)_{ik}$	2	RV	$\sigma_e + 6\,\sigma_{RV}$	RV/E	(2,D)	--
	$(PV)_{jk}$	1	PV	$\sigma_e + 3\,\sigma_{RPV} + 9\,\phi_{PV}$	PV/E2	(1,2)	18.5
	$(RPV)_{ijk}$	2	E2	$\sigma_e + 3\,\sigma_{RPV}$	E2/E	(2,D)	--
Split-split plot	G_m	2	G	$\sigma_e + 4\,\sigma_{RG} + 12\,\phi_G$	G/RG	(2,4)	6.94
	$(RG)_{mm}$	4	RG	$\sigma_e + 4\,\sigma_{RG}$	RG/E	(4,D)	--
	$(PG)_{jm}$	2	PG	$\sigma_e + 2\,\sigma_{RPG} + 6\,\phi_{PG}$	PG/RPG	(2,4)	6.94
	$(RPG)_{ijm}$	4	RPG	$\sigma_e + 2\,\sigma_{RPG}$	RPG/E	(4,D)	--
	$(VG)_{km}$	2	VG	$\sigma_e + 2\,\sigma_{RVG} + 6\,\phi_{VG}$	VG/RVG	(2,4)	6.94
	$(RVG)_{ikm}$	4	RVG	$\sigma_e + 2\,\sigma_{RVG}$	RVG/E	(4,D)	--
	$(PVG)_{jkm}$	2	PVG	$\sigma_e + 2\,\sigma_{RPVG} + 3\,\phi_{PVG}$	PVG/RPVG	(2,4)	6.94
	$(RPVG)_{ijkm}$	4	RPVG	$\sigma_e + 2\,\sigma_{RPVG}$	RPVG/E	(4,D)	--
	$e_{(ijkmq)}$	D=36(q-1)	E	σ_e	--	--	--

PST88-3179-B-5

APPENDIX C

THE USE OF GAS EXCHANGE TO MEASURE AND MODEL EVAPOTRANSPIRATION

APPENDIX C

THE USE OF GAS EXCHANGE TO MEASURE AND MODEL EVAPOTRANSPIRATION

C.1 INTRODUCTION

The small-tube lysimeters (Section 5.0) were designed to be connected to a gas-exchange measurement system for the purpose of conducting experiments on variables that control evapotranspiration (ET). Evapotranspiration is the loss of water from an ecosystem to the atmosphere. It is the major source of water loss from arid ecosystems (Campbell and Harris 1977) and the most difficult to predict because of the many factors influencing plant transpiration. Predictive models of ET may be critical to the success of the Protective Barrier Development Program (Section 5.0). Gas-exchange technology provides the capability to directly measure ET. Perhaps of greater importance for the Protective Barrier Development Program, the combined lysimeter/gas-exchange measurement system can be used to control environmental driving variables of ET and thus aid in developing functional relationships for modeling purposes.

Early gas-exchange systems concentrated on controlling CO_2 and temperature within chambers over crops (Louwerse and Eikhoudt 1975; Brown and Trlica 1977; Redmann 1978). These systems were not able to control ET and could not measure it accurately because of inaccurate sensors. Recent improvements allow for the concurrent measurement and control of temperature, wind speed, CO_2, and H_2O (Caldwell et al. 1983), which makes it possible to develop functional relationships between ET and its environmental driving variables.

Gas-exchange work would proceed in three phases. The first would be to test the seal connecting gas-exchange chambers to lysimeters. The second would be to check gas-exchange measurements against lysimeter weight change estimates of ET. The third would be to design experiments, in cooperation with contributors to the development of barrier performance models, such as UNSAT-H (Fayer et al. 1986), for the purpose of parameterizing predictive models of ET. An experimental plan will be prepared during fiscal year (FY) 1988 that describes this work in greater detail.

C.2 GAS-EXCHANGE SYSTEM DESCRIPTION AND TESTING

Gas exchange will be monitored by placing a chamber over the entire lysimeter surface. Computers will be used to control the chamber environment, serially sample gas, and log data. Ambient air will be drawn from a height of 3 m by oilless compressors and passed through heatless dryers and into a large pressurized mixing tank. The dryers remove a substantial portion of the CO_2 and water vapor. To compensate for this, as well as for CO_2 uptake by plants, pure CO_2 will be metered into the incoming air to supply 350 p/m. All air-line components will be constructed of stainless-steel piping or Teflon* to prevent adsorption of CO_2 and H_2 (Bloom et al. 1980). Flow rates will be measured and controlled with computers.

Chamber walls will be constructed of acrylic plastic coated with a clear Teflon film, which reduces photosynthethically active radiation by only 5%. Nonstainless steel components within the chambers will be nickel plated to reduce gas adsorption (Bloom et al. 1980). Chamber air samples will be

*Teflon is a trademark of E.I. duPont de Nemours & Company.

pumped to an infrared gas analyzer (IRGA) for CO_2 measurement and into a dewpoint hygrometer for H_2O measurement. Computer-driven, water-cooled heat exchangers either will control chamber temperature to a set point or will track ambient air temperature. Thin-wire thermocouples will be randomly placed to measure chamber air temperature, canopy leaf mesophyll temperature, and outside air temperature at canopy height.

Relative humidity of the ambient canopy air and air entering and returning from the chamber will be measured with a thin-film capacitance sensor and a dewpoint hygrometer, respectively. The capacitance sensor provides the signal for controlling chamber humidity when tracking ambient conditions. Chamber humidity will be controlled by varying the flow rate of incoming dry air. Air lines will be insulated and/or heated to prevent water vapor condensation. Photosynthetically active radiation will be measured at a height of 1.5 m.

Analog signals will be digitized with a digital data logging system. Data will be acquired every 10 s, averaged over a 5-min period, and stored on a floppy disk with a microcomputer. The program controls solenoids for the serial interrogation of chambers and for periodic automatic recalibration of the IRGA. Chamber temperature, relative humidity, and flow rates will be controlled by the CR7X.

The first of four gas-exchange chamber tests will be to seal the chamber over a nonevaporative, inert surface and operate the system to determine if zero H_2O and CO_2 exchange can be maintained. The seals connecting the gas-exchange chamber to lysimeter prototypes will be tested second. It must be established that measurements of ET in the chamber are attributable to the lysimeter column and not to leaks.

The sensitivity of the system to known water loss rates will be tested. Evaporation loss from a surface will be monitored concurrently by the gas-exchange system and a porometer placed inside the chamber. The amount of water monitored by the gas-exchange system integrated over the observation period should correspond to that observed with the porometer (Tranquillini and Caldwell 1972). Carbon dioxide exchange will be verified in the fourth test by metering it into a chamber at a known concentration and flow rate. The amount of CO_2 measured with the gas-exchange systems should correspond with the metered source.

C.3 COMPARISON OF GAS-EXCHANGE AND WEIGHT-CHANGE ESTIMATES OF EVAPOTRANSPIRATION

The accuracy of ET measurements using the gas-exchange system will be checked by comparison with lysimeter weight changes. This will be done by weighing lysimeters immediately before and immediately after a session of monitoring ET with the gas-exchange system. The environmental control mechanism of the system will be similarly tested by comparing weight changes for lysimeters with and without the gas-exchange chambers attached. Observations will consist of steady-state measurements of ET rates under conditions imposed by the control mechanism of the gas-exchange system.

By imposing standard environmental conditions on lysimeters with the control mechanism, the gas-exchange system can also be used to measure gravel mulch treatment effects on ET. Standard conditions will consist of constant wind speed, vapor pressure, humidity, and high light. All 80 lysimeters could be monitored by moving the chamber from lysimeter to lysimeter. The monitoring would be reduced substantially with a multiple chamber system. Because treatments will be randomly assigned to lysimeters in the field, the effect of time will also be randomized.

C.4 EVAPOTRANSPIRATION MODEL DEVELOPMENT

The unsaturated soil moisture flow code, UNSAT-H, has been developed to help quantify the potential for water drainage through barriers (Fayer et al. 1986). The plant/water relations component of UNSAT-H, which was based on data from 2 mo of cheatgrass growth, limits the usefulness of the code for predicting long-term drainage. The purpose of this phase of the study would be to measure functional relationships between ET and environmental driving variables for use in predictive models of water movement through barriers.

Predictive ET models for barrier development must account for a broad range of plant community and climatic possibilities. With adequate computer resources, the model should be able to predict ET on a time step small enough to incorporate diurnal variation in plant activity. Diurnal prediction can be integrated numerically to yield daily and then seasonal ET, and so on, to any point in the future relevant to drainage processes. The model should also predict ET for conceivable climate and ecosystem changes by changing environmental input parameters as the simulation progresses.

Evapotranspiration can be quantified in two ways; each provides only part of the answer. Evapotranspiration can be measured either at the community level or holistically or can be considered the sum of soil evaporation and plant transpiration. Community-level data integrate plant and soil losses but do not lend themselves well to the parameterization of mechanistic relationships. Separate soil and plant data allow for mechanistic parameterization, but fail to account for community-level synergism. Because UNSAT-H requires mechanistic descriptions of the ET, soil and plant model development may need to be done separately, while model validation should include correlations of model predictions with holistic measurements. Soil and plant components can be measured separately with a combination of lysimetry and gas-exchange techniques. Estimates of community-level ET may be possible with lysimetry (water balance), micrometeorology (energy balance), light detection and ranging, and/or short- and long-range multispectral remote sensing.

C.4.1 Mechanistic and Empirical Models

The problem in writing differential equations describing the separate responses of plants and soil to the environment is determining the functional form and parameter values for the equations. While mechanistic formulations will be used, their parameterization will be based on empirical data. In a strict sense, mechanistic models break system processes down into individual physical and chemical components and then try to explain the behavior of the system from component interactions. At present, formulating a mechanistic, ecosystem-level model by this strict definition is not possible. However, combining the best effort at a mechanistic model with empirical information is possible.

In practice, model components are chosen to conform to the capabilities of current technology. As such, most model components will combine underlying physical and chemical processes. Functional relationships are only empirically known and parameter values for them are not constants as in a fundamental physical law. For this reason, parameters for model equations must be determined by controlled experimentation.

C.4.2 Factors Controlling Evapotranspiration

Evaporation from the soil surface depends on several soil properties, soil water content, surface litter, cryptogam cover, shading by vascular plants, solar radiation, temperature, atmospheric vapor pressure, wind speed, and animal activity. Transpiration is controlled by the supply of water to the roots, plant liquid water conductance, stomatal conductance, and leaf area. If a plant can acquire adequate water by root exploration, it will transpire at rates controlled by plant liquid water conductance, stomatal conductance, and leaf area. Transpiration will decrease as the water supply is reduced.

Plant liquid water conductance is mainly a function of root temperature, the depth of usable water, and species. Root growth is controlled mainly by soil temperature, nutrient status, soil water content, carbon gain, and genetically determined species-specific phenology. Stomatal conductance is mainly a function of light, temperature, vapor pressure deficit, leaf water potential, leaf age, wind speed, nutrient status, acclimation to current environmental conditions, and species effects. Leaf area is mainly a function of carbon gain, nutrient status, water stress, and genetically determined species-specific phenology. Carbon gain is a function of several of the above factors and is closely related to the water status of the plant. Stomatal closure because of water stress necessarily restricts the supply of CO_2 to the plant. (A literature review of stomatal models and the biotic and abiotic factors controlling stomatal conductance are provided in Appendix D.)

C.5 EXPERIMENTAL APPROACH

Controlled experiments with lysimeters and gas-exchange methods will be used to establish parameters for models of evaporation and transpiration. In the field, some determinants of transpiration change slowly through the season, while others change rapidly on a diurnal basis. The basic strategy for establishing parameters for transpiration will be to construct multidimensional response surfaces at points through the growing season and to consider such parameters as a function of slowly changing determinants. Some of those determinants will be found to contribute little to the explanation of variation in transpiration and can be ignored. The methods that will be used for measuring stomatal conductance and its important determinants are described below. Development of treatment structures for these model parameter-establishing experiments would be premature at present. The design of these experiments must be done in concert with the UNSAT-H refinement tasks and community-scale ET experiments (Adams and Wing 1987).

The experimental units for the model parameter-establishing experiments will consist of multiple gas-exchange chambers affixed to the small-tube lysimeters. The gas-exchange system can control factors such as convective loss, chamber humidity and chamber air temperature. Carbon dioxide concentrations can also be controlled if expanding the model to predict plant responses to increased atmospheric CO_2 (greenhouse effect) is desired. Lysimeter weight differences will be used to estimate water storage changes. Lysimeters with and without vegetation will be compared to measure the net effect of plants. Root growth and wetting fronts will be monitored with fiber-optic periscopes. Root distribution will also be measured with the lysimeters and excavated at the end of an experiment. Cross-hole, high-frequency tomography will be investigated as an alternate method for root structure measurements. Root zone temperature can be monitored with thermistors. Nutrient status will be monitored with standard agricultural practices. Leaf area will be measured nondestructively with an automated inclined point frame.

C.6 COST

Category	FY 1988[a]			FY 1989		
	MAT	MP	MH	MAT	MP	MH
Multiple gas-exchange system materials						
Chamber materials	2.0					
Air conditioning	12.0					
Flow controls	6.0					
Infrared gas analyzer	14.0					
Air compressor	4.0					
Hoses and sensors	5.0					
System construction and testing		27.0	500			
Data acquisition and model development					54.0	1,000
Reports and presentations		21.6	400		21.6	400
Technical editing		8.6	160		8.6	160
Yearly totals	42.0	57.2	1,060		83.2	1,560
Project total	182.4[b]					

[a]Codes: MAT = materials, MP = manpower, HRS = manhours.
[b]Costs in dollars x 1,000. PNL manpower conversions = $54/h.

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APPENDIX D

REVIEW OF STOMATAL MODELS AND FACTORS CONTROLLING STOMATAL CONDUCTANCE

APPENDIX D

REVIEW OF STOMATAL MODELS AND FACTORS CONTROLLING STOMATAL CONDUCTANCE

D.1 STOMATAL MODELS

Most models that focus on stomatal conductance usually consider only one influencing factor. Multivariate models of stomatal conductance are fewer. The model of Avissar et al. (1985) describes the response of stomatal conductance to abiotic factors, while that of Kuppers and Schulze (1985) couples the responses of CO_2 assimilation and stomatal conductance to abiotic factors.

D.1.1 Model of Kuppers and Schulze (1985)

The model of Kuppers and Schulze (1985) is a recent model that couples CO_2 assimilation and stomatal conductance to environmental factors. It predicts diurnal assimilation and conductance for *Pinus silvestris* L. It consists of two submodels, one describing the response of CO_2 uptake to light and temperature, the other describing the response of leaf conductance to temperature and humidity. The submodels are joined via the linear relationship between CO_2 uptake and leaf conductance at short-term variations of light. From the humidity response of leaf conductance and the demand function (Raschke 1979) of CO_2 in the mesophyll, the effect of stomata on the diffusion of CO_2 between leaf and air is determined. The end point of the analysis of this model will be to provide an estimate of internal CO_2 concentration as a function of light, temperature, and humidity. Because the diffusivity of CO_2 can be correlated with that of some gaseous air pollutants, this model should also provide predictions of air pollutant internal concentrations. Carbon dioxide assimilation was related to light and temperature as follows:

$$A_{(I,T)} = A_{max(T)} \left\{ 1 - e^{-a_1 \left[I - I_{c(T)} \right]} \right\} \tag{1}$$

where

$A_{(I,T)}$ = Light response of CO_2 assimilation at a given leaf temperature
T = Leaf temperature
I = Light
$A_{max(T)}$ = The light-saturated response of CO_2 assimilation to temperature
$I_{c(T)}$ = Light compensation point at T.

The parameter, a_1, determines the curvature of the light relationship and was found to be independent of temperature.

The light-saturated response of CO_2 assimilation to temperature ($A_{max(T)}$) was described with the following polynomial regression:

$$A_{max(T)} = a_2 T^3 + a_3 T^2 + a_4 T + a_5 \tag{2}$$

and the temperature dependence of the light compensation point given as

$$I_{c(T)} = e^{(a_6 T + a_7)}. \tag{3}$$

With these three equations, describing the response surface of CO_2 uptake to light and temperature is possible.

Independent of the above submodel, the temperature response of dark respiration was determined as

$$A_{(T,I = 0)} = -a_8 T^{a_9}. \tag{4}$$

In the second submodel the response of leaf conductance to temperature and humidity is determined. The response of leaf temperature at low leaf-air vapor concentration differences (*dw*) was described as

$$g_{max(T)} = e^{\left(b_1 T + b_2\right)} \tag{5}$$

where

$g_{max(T)}$ = Response of leaf conductance when it is maximal because of low *dw* (d = delta) to leaf temperature.

The relationship between leaf conductance and *dw* was described as a 'feedforward' response as follows:

$$g_{(dw)} = [g_o - (g^*/dw^*)dw]/[1 - (2 - g_o/g^*)dw/dw^*] \tag{6}$$

where

dw^* = Leaf-air water vapor concentration difference at which transpiration is maximal
g^* = Corresponding leaf conductance.

For the determination of w^*, a regression of the type

$$g_{(dw)} - 1 = e^{(b_3 dw + b_4)} \tag{7}$$

was determined. Extrapolation to $dw = 0$ yielded g_o. The position of maximal transpiration is given by $w^* = b_3{}^{-1}$. Thus g^* can be determined and with it Equation 6 can be solved.

The two submodels can be linked at any given combination of light and temperature as follows:

$$g_{(I,T)} = \left\{ \left| g_{max(T)} - g_{(A=0,T)} \right| A_{(I,T)}/A_{max(T)} \right\} + g_{(A=0,T)} \tag{8}$$

where

$g_{(A=0,T)}$ = Leaf conductance at light compensation for CO_2 uptake.

It was found that $g_{(A=0,T)}$ was linearly related to $g_{max(T)}$ and could be parameterized as

$$g_{(A=0,T)} = p\, g_{max(T)}. \tag{9}$$

The relationship between assimilation and conductance is given by

$$A = (C_a - C_i)\, g_{dw}/1{,}600 \tag{10}$$

where

C_a = Ambient CO_2
C_i = Internal CO_2 concentrations.

The factor 1,600 accounts for the difference of diffusivities of H_2O and CO_2.

For different leaf temperatures and light levels it was assumed that the relative response of stomata to humidity did not vary. Likewise, a similar limitation of CO_2 assimilation because of stomata was assumed for the same *dw*, but different temperatures and light levels. The prediction of transpiration (E) is dependent on the vapor pressure gradient (vpg) and stomatal conductance and is given by:

$$E = vpg\left(g_{dw} \right) \tag{11}$$

D.1.2 Model of Avissar et al. (1985)

The previously described model of Kuppers and Schulze (1985) is very accurate, but is perhaps somewhat involved. It also does not include the effect of water potential on stomatal conductance. The model of Avissar et al. (1985) includes a relationship between soil water potential and stomatal conductance in addition to the effects of vapor pressure deficit, temperature, and light. It is simpler and does not consider assimilation. It also is not quite as accurate, but may be acceptable. This model relates stomatal conductance to solar global radiation, leaf temperature, vapor pressure gradient, ambient CO_2, and soil water potential for *Nicotania tabaccum*.

The general equation used to predict relative stomatal conductance is as follows:

$$d_{rs} = \left| d_{sm} + (d_{sM} - d_{sm}) f_R f_T f_V f_C f_P \right| / d_{sM} \tag{12}$$

where

d_{rs} = Relative stomatal conductance (ms^{-1}/ms^{-1})
d_{sm} = Minimal conductance that occurs through the leaf cuticle when the stomata are closed
d_{sM} = Maximal stomatal conductance obtained when stomata are completely opened.

Each of the f_i functions refers to the influence of a specific environmental factor on the conductance (R for solar global radiation, T for leaf temperature, V for vapor pressure deficit (vpd), C for air CO_2 concentration, and P for soil water potential).

The mathematical expression used to for each of the f_i functions is as follows:

$$f_i = 1 / \left| 1 + e^{[-S(X_i - b)]} \right| \tag{13}$$

where

i = Environmental factor
b = Abscissa at f_i - 1/2
S = The slope of the curve at this point
X_i = Intensity of the factor i.

To use this model $d_{sm\cdot l}$, d_{sM}, b, and S must be determined. In their experiment d_{sm} = 0.05 cm•s and d_{sM} = 0.93 cm•s^{-1}. Values for b and S are found in Table 2.

To predict transpiration, drs must be converted back to absolute values (ds). The equation for transpiration is then

$$E = vpd\, d_s. \tag{14}$$

D.2 ABIOTIC AND BIOTIC FACTORS CONTROLLING STOMATAL CONDUCTANCE

Most models of stomatal conductance consider, at most, only a few of the environmental or biological factors that control stomatal aperture. Most models are specific for the conditions of the experiment, such as the time of year or growing conditions, and are not easily extended to other conditions. Models that can predict stomatal conductance taking into account all the important controlling factors have not been found. Such a model would be able to predict stomatal conductance through the life span or a whole growing season for various abiotic and biotic conditions.

The most important environmental factors controlling stomatal conductance are light intensity, light quality, CO_2 concentration, temperature, humidity, wind speed, soil nutrient status, and leaf water potential.

The response of stomatal conductance to the intensity of white light is a saturation type where conductance increases rapidly with initial increments of light and levels off at higher light intensities. The exact form of the relationship is dependent on the species and other factors that control conductance (Hsiao 1975). Stomatal opening responses are most responsive to light in the blue portion of the spectrum with a peak of action extending from 420 and 460 nm and no action >560 nm. Stomata will respond to this light at low intensities (Raschke 1975). Light in the green portion of the spectrum elicits an opening response only at high intensities (Farquhar and Sharkey 1982).

Stomata tend to maintain a constant internal CO_2 (Raschke 1975), opening as internal concentrations drop and closing as concentrations increase (Sheriff 1979). Stomata also close at high external CO_2 concentrations (Hsiao 1975). Closure at high CO_2 concentrations is mentioned because it can be unintentionally introduced in experimentation by breathing (Heath and Mansfield 1962). Experiments to define stomatal conductance relationships under natural conditions do not require the experimental variation of external CO_2 concentrations, and care must be taken to maintain CO_2 at ambient levels during experimentation. Monitoring CO_2 levels is done by infrared gas analysis.

The most common form of relationship between temperature and stomatal conductance is one with conductance increasing to a broad optimum and then declining with increasing temperature (Hsiao 1975; Avissar et al. 1985). Other relationships have been observed: decreasing, increasing, or no relationship with temperature (Sheriff 1979).

A direct relationship between the vapor pressure gradient and stomatal conductance was conclusively demonstrated and terms a 'feedforward' stomatal response (Cowan 1977). The general form of the relationship is a linearly (Warrit et al. 1980), exponentially (Roessler and Monson 1985), or 'threshold type' (Avissar et al. 1985) decreasing function with increasing vapor pressure deficit depending on species and conditions.

Stomatal closure is induced by bulk leaf water stress in a 'feedback' response (Cowan 1977) and the form of the relationship is generally found to be a 'threshold-type' response (Avissar et al. 1985) with decreasing leaf water potential.

Wind speed influences stomatal conductance. Some species respond to increasing wind speed with stomatal closure and some with stomatal opening (Caldwell 1970; Kramer 1983). These responses are attributed to changes in humidity near the leaf because of changes in the boundary layer (Sheriff 1979) or changes in the internal CO_2 concentrations.

Reductions in stomatal conductance have been observed with deficiencies in a wide variety of soil nutrients: nitrogen, phosphorus, and potassium in particular (Sheriff 1979). Plants also respond to stressful conditions of temperature and water status by 'hardening' to the conditions. Adjustments in stomatal conductance is one manifestation of hardening in response to stress (Tazaki et al. 1980).

The major biotic factors controlling stomatal conductance are physiological leaf age and hormones. The responsiveness of stomates depends on the physiological age of the leaf. Stomata of older leaves of some species do not open as rapidly or as widely as those of younger leaves (Hsiao 1975; Kramer 1983). Tazaki et al. (1980) found that the stomata of older mulberry leaves would not close. The hormone, abscisic acid, has been found to induce stomatal closure, usually in association with water stress (Kramer 1983). In some plants, stomatal closure is not correlated with abscisic acid levels (Ackerson 1980) but may be related to other substances such as phaseic acid

(Sharkey and Raschke 1980). Cytokinins cause stomatal opening and also retard senescence (Farquhar and Sharkey 1982). This may be related to the observed effect of leaf age on stomatal conductance.

D.3 REFERENCES

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APPENDIX E

TUBE-LYSIMETER EXPERIMENTAL DESIGN

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TUBE-LYSIMETER EXPERIMENTAL DESIGN

The first lysimeter experiment (Section 5.0) was designed to test three major hypotheses:

H1 - Admix gravel layer configuration will not affect soil water storage, drainage, or evapotranspiration (ET) rates

H2 - Vegetation will not affect storage, drainage, or ET rates

H3 - Increased precipitation will not affect storage, drainage, or ET.

Table E-1 contains the analysis of variance (ANOVA) model and the ANOVA table for the experiment, including sources of variation, degrees of freedom, expected mean squares, critical values for the F-tests (level 0.05), and associated hypotheses. The magnitudes of the critical F-values are relatively small because of the five replications of each treatment combination. When critical F-values are large, such as for experiments with too few treatment replications, important treatment differences may not appear statistically significant.

Table E-1. Analysis of Variance Model and Table for the 4-by-2-by-2 Factorial Small-Tube Lysimeter Experiments.

$$Y_{jkmq} = \mu + P_j + V_k + G_m + (PV)_{jk} + (VG)_{km} + (PVG)_{jkm} + e_{q(jkm)}$$

where

Y_{jkmq} = Water storage or drainage measurement taken on the qth lysimeter that has precipitation level $_j$, vegetation level $_k$, and gravel layer depth $_m$.

μ = Overall mean

P_j = Precipitation effect for level $_j$, where $_j$ = 1,2

V_k = Vegetation effect for level $_k$, where $_k$ = 1,2

G_m = Gravel layer depth effect for level $_m$, where $_m$ = 1,2,3,4

$(PV)_{jk}$ = Interaction effect of precipitation level $_j$ and vegetation level $_k$

$(PG)_{jm}$ = etc.

$e_{q(jkm)}$ = Randon error--error within treatment combination $_{jkm}$.

<u>Notation Used for Expected Mean Square</u>

σ_ϕ = Random error

ϕp = Component of expected mean square (EMS) due to precipitation levels, p.

In general,

ϕ_{factor} = Component of EMS due to fixed effects of 'factor'.

Source	Degrees of freedom	ID code	EMS	F-test	(df_1, df_2)	F-statistic 0.05 level	Hypotheses
P_j	1	P	$\sigma_0 + 40\,\phi_p$	P/E	(1,64)	3.9910	H3: $\phi_p = 0$
V_k	1	V	$\sigma_0 + 40\,\phi_V$	V/E	(1,64)	3.9910	H3: $\phi_p = 0$
G_m	3	G	$\sigma_0 + 40\,\phi_G$	G/E	(3,64)	2.7322	H3: $\phi_p = 0$
$(PV)_{jk}$	1	PV	$\sigma_0 + 40\,\phi_{PV}$	PV/E	(3,64)	3.9910	--
$(PG)_{jm}$	3	PG	$\sigma_0 + 40\,\phi_{PG}$	PG/E	(1,64)	2.7322	--
$(VG)_{km}$	3	VG	$\sigma_0 + 40\,\phi_{VG}$	VG/E	(3,64)	2.7322	--
$(PVG)_{jkm}$	3	PVG	$\sigma_0 + 40\,\phi_{PVG}$	PVG/E	(3,64)	2.7322	--
$e_{q(jkm)}$	64	E	σ_0	--	--	--	--

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