FINAL PROGRESS REPORT NO. 2
FURTHER EVALUATIONS OF
RADIONUCLIDE PHYTOEXTRACTION
FEASIBILITY USING SOILS FROM
THE U.S. DEPARTMENT OF ENERGY COMPLEX

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DISCLAIMER

EXECUTIVE SUMMARY

Fiscal Year 98 (FY98) radionuclide phytoextraction studies involved resumption of the radiocesium-137 (^{137}Cs) investigations at Brookhaven National Laboratory (BNL) and the total uranium (U_t) investigations at the Fernald Environmental Management Project (FEMP) site. This project was a collaborative effort involving scientists and engineers from MSE Technology Applications, Inc.; the U.S. Department of Agriculture (USDA) Plant Growth Laboratory at Cornell University; Phytotech, Inc.; BNL; and FEMP. In both cases, the essential goal was to improve bioavailability, uptake, and transport of these contaminants from soil to leaf-and-stalk biomass (LSB). In particular, the practical goal was to demonstrate that about half the radionuclide contaminant mass present in near surface [≤30 centimeters (cm) below ground surface (bgs)] soils could be transferred into LSB in approximately 5 years. Based on previous (1996) study results, it would require concentration ratios (CRs) of at 5-to-10 to achieve this goal. In addition, the rate of ^{137}Cs removal must be ≥ 2.3% per year^{-1}[i.e., (0.693/30.2) *100)] to equal or exceed the loss of this radionuclide through natural decay.

This report first presents and discusses the results from greenhouse and field evaluations of ^{137}Cs uptake from rooting zone soils (0-15 cm bgs) located near the Medical/Biological Research Building (No. 490) at BNL. Contamination of this site resulted from the use of near surface soils originating at the former Hazardous Waste Management Facility (HWMF), which served as a source of landscaping materials for erosion control, etc. Project personnel from USDA evaluated various combinations of nonradioactive solutions of cesium chloride (CsCl) and rubidium chloride, ammonium nitrate solution (NH_4NO_3), and humic acid suspensions to enhance and sustain ^{137}Cs levels in soil solution. Of the plants grown in such amended soils, the highest CRs occurred in the golden pigweed (*Amaranthus aureus* L.) with an overall CR of 3.0 (and 275 picoCurie/gram ^{137}Cs in soil). The maximum CR (3.8) was associated with dosing this species with 100 millimole (mM) CsCl solution. However, this treatment was immediately toxic to all the species evaluated. Thus, continued use of ammonium nitrate (NH_4NO_3) (CR=2.9) or humic acid (CR=3.2) and golden pigweed appeared to be the best approach for removing ^{137}Cs from test site soils.

Given the commercial availability of large quantities of redroot pigweed (*A. retroflexus* L.) seed, relative to sources of golden pigweed as well as the favorable results at BNL in FY96, the former species was selected for use at the Demonstration (D) plot. The average CR (2.7) for the first crop (July 1998) was of similar magnitude to the average CR (2.5) observed for the USDA subplot in October 1996. However, the CRs for the second crop (October 1998) had fallen to between 0.06 and 0.7. It is hypothesized that most of the potentially bioavailable fraction of the aged ^{137}Cs was removed by the first crop.

The results from the Experimental (E) plot indicated that cabbage (*Brassica oleracea*) treated with (x) NH_4NO_3 was the preferred remedial option. However, the highest average CR (1.4) for this treatment implies that ^{137}Cs may be less available for uptake in E-plot soils. Finally, the transfer of ^{137}Cs from rooting zone soils to LSB was estimated to be 0.06% per year^{-1} in both the D and E plots.

Phytotech personnel conducted laboratory and greenhouse evaluations of U_t phytoextraction feasibility using soils acquired from FEMP. A soil stockpile located at the former drum baling area (north of former Building No.78) was the source material for this study. Field sampling was performed to produce high contamination soil [i.e., avg. of 955 milligrams/kilogram (mg/kg) acid extractable U_t] at Location 1 and low contamination soil (i.e., avg. of 336 mg/kg acid extractable U_t) at Location 2. Sequential extractions of these materials indicated that approximately 57% and approximately 38% of U_t in Location 1 and 2 soils are potentially plant available (i.e., occurs in the exchangeable and

carbonate fractions). Phytotech personnel applied 20 mM citric acid /kg soil, either alone or in conjunction with either 20 mM sulfuric acid or 25 micromole Triton-X (surfactant), per kg soil. Overall, the greatest accumulation of U_t occurred (across treatments) in redroot pigweed grown in Location 1 soils. Maximum U_t concentration in this species' LSB [1,347 mg/kg (DW)] was associated with combined use of citric and sulfuric acids; such uptake is equivalent to a soil-to-plant U_t mass transfer of approximately 1% per crop or up to 3% per growing season. Furthermore, the only measurable accumulation of U_t in LSB grown in Location 2 soils was associated with this dual-acid treatment; mean U_t levels in LSB in Chinese cabbage (*Brassica chinensis* L.) and redroot pigweed were 84 mg/kg DW and 77 mg/kg DW, respectively.

The ^{137}Cs phytoextraction study results indicate that the species x soil treatment combinations evaluated rapidly depleted the plant available ^{137}Cs in rooting zone soils. Thus, the continuing challenge is to increase the transfer rate of ^{137}Cs into this available fraction. Therefore, laboratory and/or greenhouse studies should be performed prior to resumption of large-scale field trials. Essentially, near-term efforts should focus on sequential (multiple) LSB harvests from large pots (≥10 kg soil) and column studies of enhanced, yet controlled, release of ^{137}Cs into soil solution. Such results would then be used to design drip-type irrigation systems for continuous delivery of the necessary extracting agent(s) to field soils. Similar conclusions and recommendations are made for follow on work regarding phytoextraction of U_t from near surface soils.

ACKNOWLEDGMENTS

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ABBREVIATIONS AND ACRONYMS

AOC	area of concern
bgs	below ground surface
BNL	Brookhaven National Laboratory
Bq	becquerel (SI unit of radioactive decay and equal to one transformation per second)
BRS	Biomass Remediation System
ccpm	corrected counts per minute
CoC	contaminant of concern
CR	concentration ratio
cv.	cultivated variety
D	Demonstration
DOE	U.S. Department of Energy
DW	dry weight (plant or soil materials dried to constant weight at 105 °C)
E	Experimental
EPA	U.S. Environmental Protection Agency
EWTC	Environmental and Waste Technology Center
FDF/TP	Fluor Daniel Fernald
FEMP	Fernald Environmental Management Project
FP	fission product (refers to ^{137}Cs and ^{90}Sr)
FWP	Field Work Proposal
FY	fiscal year
HWMF	Hazardous Waste Management Facility
ICPES	inductively coupled plasma emission spectrometry
LSB	leaf-and-stalk (or stem) biomass
MDL	Method Detection Limit
MSE	MSE Technology Applications, Inc.
NPK	nitrogen, phosphorus, potassium
NPL	National Priorities List
OU	Operable Unit
pCi	picoCurie ($1 * 10^{-12}$ Curie; 27 pCi=1Bq)
PSP	project-specific plan
RMI	Reactive Metals, Inc. Environmental Services
ssp	subspecies of a particular plant species
TP	Technology Programs
USDA	U.S. Department of Agriculture
U_t	total uranium (having naturally occurring ratio of ^{238}U, ^{236}U, ^{235}U, and ^{234}U)
^{90}Sr	radiostrontium - 90 (and associated Y-90)
^{137}Cs	radiocesium- 137 (and associated Ba-137m)

1. INTRODUCTION

1.1 PHYTOEXTRACTION OVERVIEW

1.1.1 Process Description

Soil cleanup using phytoextraction involves a two-step process. First, there must be accelerated transfer of contaminant(s) from rooting zone soils to vascular plant leaf and stalk biomass (LSB). Second, the LSB is harvested and processed (e.g., by ashing) to accomplish further volume reduction and concentration of the contaminant(s) prior to disposal. The first step involves optimizing LSB production (for the most suitable crop species) and contaminant uptake through appropriate (and often site-specific) agronomic practices. As shown in Figure 1-1, the first step must reduce the contaminant mass in soil while lowering its environmental mobility and biological availability over time (Ref. 1).

These goals are accomplished by sequential removal of the contaminant(s) from the various binding sites (e.g., ion-exchange sites on clay particles), contaminant diffusion through soil solution to the root surface, and uptake and transfer of the contaminant from root to aboveground plant tissues. This series of events must be accomplished without causing long term adverse effects on physicochemical or biological processes occurring in bulk soil. Furthermore, process kinetics and thermodynamic conditions in the soil must allow continuous flow of contaminant(s) to the roots and their accumulation into LSB. Finally, the cleanup process must continue until the residual contaminant (mass fraction) is either significantly lowered or immobilized so it no longer poses a threat to human health and the environment.

Phytoextraction effectiveness is controlled by plant productivity [in grams (g) dry weight (DW) of LSB produced/square meter (m^2) * day], the consequent biomass yield [in kilograms (kg) DW/m^2 · season], and contaminant concentration accumulated into each crop's aboveground biomass (Ref. 2).

Although greatly simplified, literature review supports the use of the following exponential relation to estimate the reduction of contaminant-of-concern (CoC) levels in soil over time.

$$C_t = C_o e^{-kt} \quad (1)$$

Where:

C_t = CoC concentration in soil after phytoremediation for a given time period;
C_o = initial CoC concentration [e.g., picoCuries/gram (pCi/g)] in soil at the start of remediation;
k = the product of the plant mass/soil mass ratio and CoC uptake coefficient (i.e., CoC concentration in aboveground oven-dried biomass divided by CoC concentration in oven-dried soils); and
t = time of remediation in years.

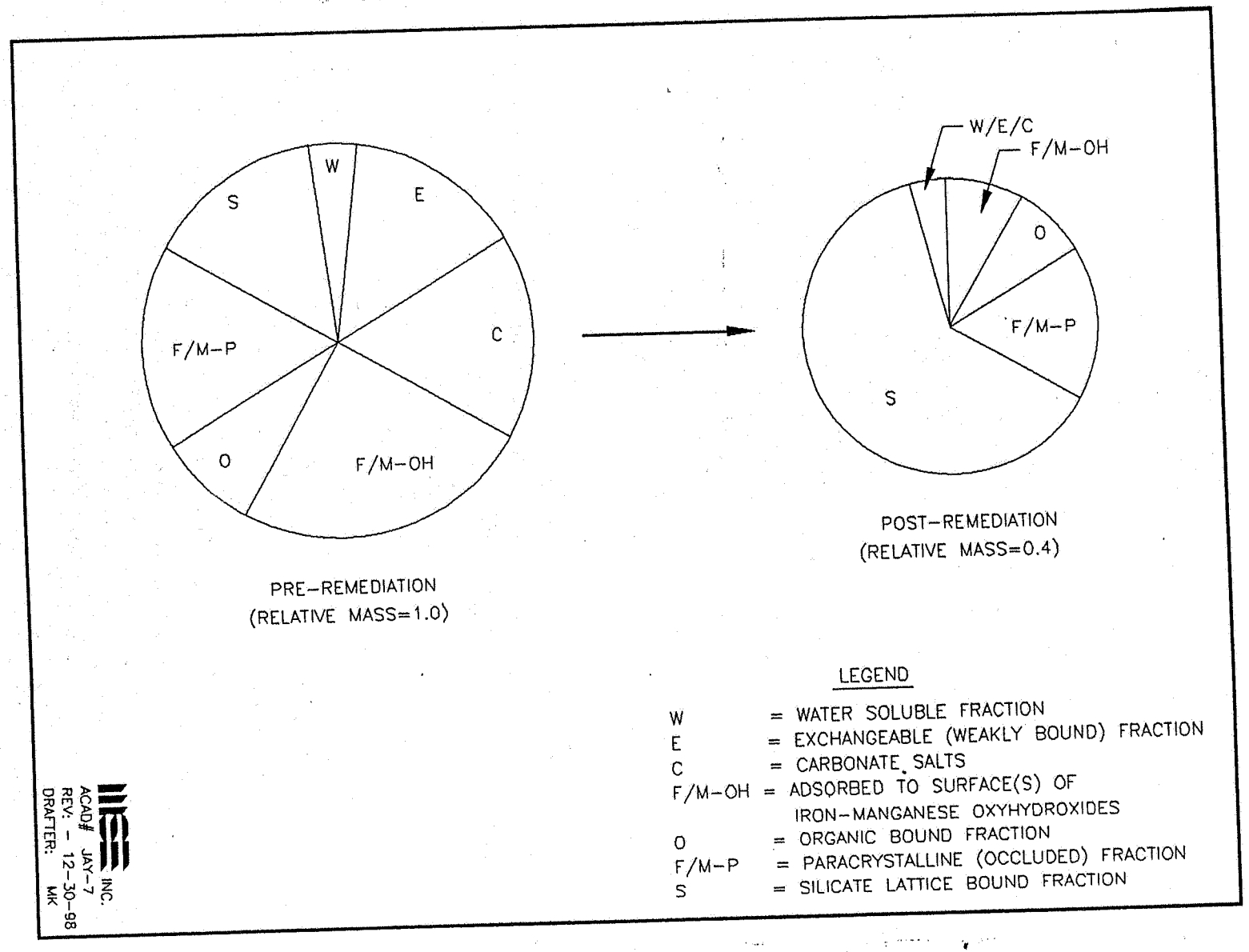


Figure 1-1. Contaminant fractionation in soil (typical case).

Phytoextraction involves the enhanced transfer of heavy metal and/or radionuclide contaminants from the uppermost 50 centimeters (cm) of soils into vascular plant LSB. Literature review supports the hypothesis of two-phase (i.e., rapid then slow) desorption of contaminants from soil particles. The overall effect can be approximated as an exponential decrease in contaminant mass extraction over time (Ref. 3). For purposes of technology evaluation, it is assumed that contaminant removal from soil occurs according to Equation 1. The level of contaminant remaining in the soil at time "t" is determined by the dry biomass production (kg DW/m^2 · season) and concentration ratio (CR); CR is the contaminant level ratio in dry LSB divided by contaminant level in dry, rooting zone soil. Theoretically, approximately 50% of the initial soil contamination could be removed from the upper 50 cm of the soil profile in approximately 5 years if the following conditions are met: CR≥30, LSB production ≥ 3 kg DW/m^2 · year, and 639 kg DW/0.5 cubic meter (m^3) of soil volume. This calculation is shown graphically in Figure 1-2.

1.1.2 Application of Phytoextraction Technology to Radionuclide-Contaminated Soils

Fission products radiocesium—137 (^{137}Cs) and radiostrontium—90 (^{90}Sr) and total uranium (U_t) commonly occur in moderate but environmentally significant levels in near surface (0-50 cm) soils throughout the U.S. Department of Energy (DOE) Complex (Ref. 4). Development of cost-effective, environmentally benign means of in situ remediation of large (≥0.5 hectacre) areas having these contaminants would be an important contribution to solving these concerns. Phytoextraction technology will be particularly useful at a site where the baseline risk/cleanup schedule allows for multiple cropping seasons rather than implementing short duration/more costly ex situ cleanup approaches.

The principal issue regarding use of phytoextraction technology is optimization of LSB production and controlled desorption/uptake of soil contaminants into aboveground biomass. As implied in Figures 1-1 and 1-2, the phytoextraction optimization process will probably need to be adjusted over time, as the less biologically available forms of the contaminant(s) become more prevalent at the given site. Furthermore, two additional issues must be addressed prior to the widespread deployment of this technology. First, the practicality of performing agricultural operations in radioactive environments must be demonstrated. Secondly, the technology vendor must provide acceptable methods for handling harvested biomass as well as any final waste forms (e.g., incinerator ash) generated at the particular site. Progress made in resolving these concerns is presented in the remainder of this report.

1.2 REVIEW OF PREVIOUS ACCOMPLISHMENTS

1.2.1 Radiocesium (^{137}Cs)

Based on the literature review performed in the fall of 1995, a preliminary treatability study regarding the removal of ^{137}Cs from surface soils was proposed to DOE personnel at Brookhaven National Laboratory (BNL) in February 1996. In particular, the vegetated southeastern corner of the original Hazardous Waste Management Facility (HWMF) was the suggested field trial site for the following reasons.

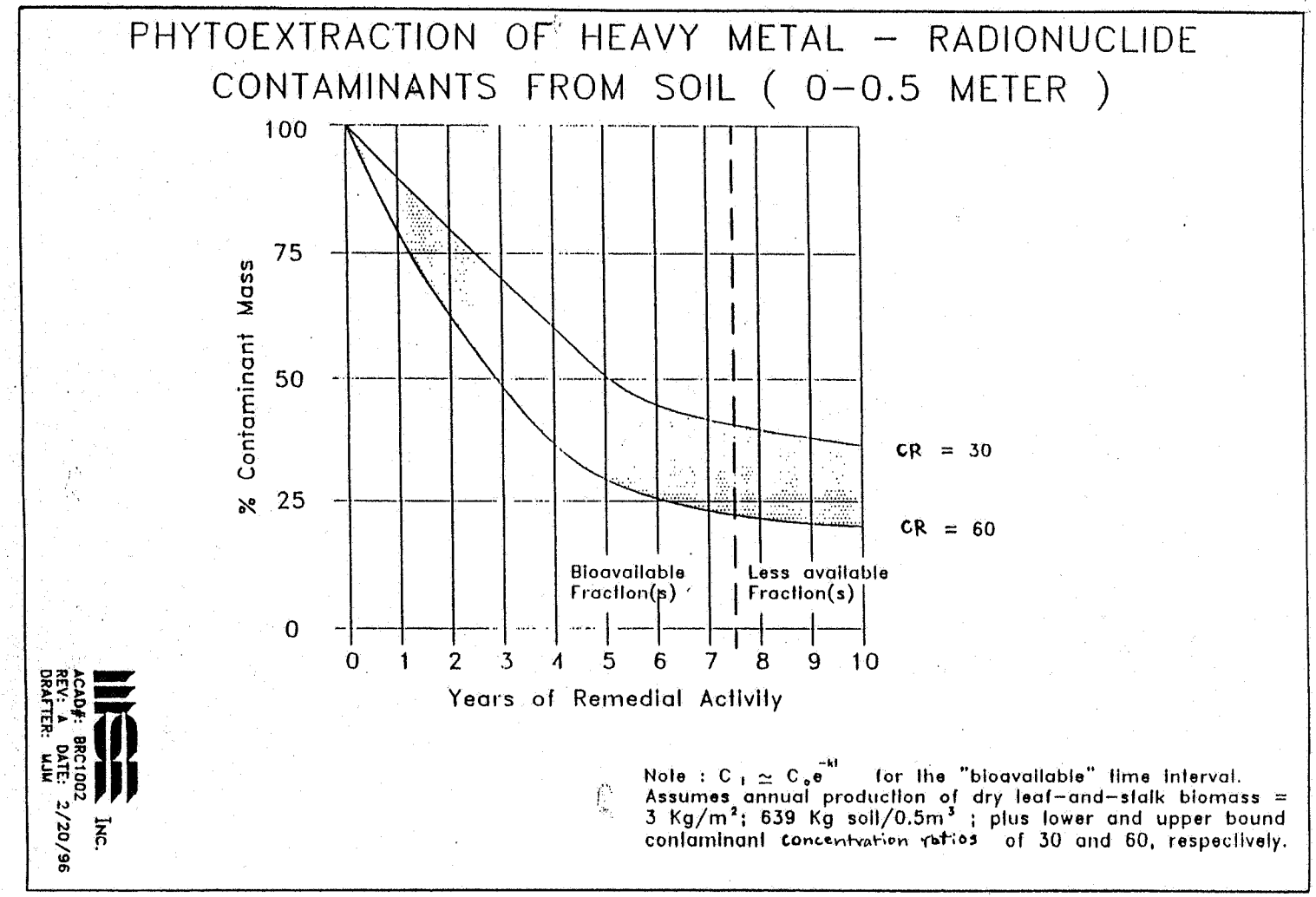


Figure 1-2. Phytoextraction of heavy metal radionuclide contaminants from soil [0 to 0.5 meter (m)].

First, the ^{137}Cs levels in the upper 30 cm of soil (i.e., averaging between 200 to 400 pCi/g) appeared to be the appropriate range for phytoextraction treatment. Furthermore, soil properties (e.g., texture, acidity, and clay mineralogy) and site accessibility were favorable. The proposal was accepted by DOE in mid-March 1996. Consequently, MSE Technology Applications, Inc. (MSE) and its subcontractors [U.S. Department of Agriculture (USDA)/Plant, Soil, and Nutrition laboratory and Phytotech, Inc.] began preparing work plans and coordinating activities with on-site personnel.

Laboratory and greenhouse investigations of ^{137}Cs extractability and uptake by plants were performed at USDA, BNL and Phytotech facilities from April through June 1996. The overall results indicated that treatment of HWMF soil with ammonium (NH_4^+) ion at concentrations $\geq$ 0.1 mole (M) and under controlled environmental conditions can desorb up to 20% of the soil's ^{137}Cs burden. Further discussions regarding methodologies used as well as results and interpretation of these studies are provided elsewhere (Ref. 5).

The field trial was initiated in early June 1996 and concluded in early October 1996; two key observations arising from this trial are as follows (Ref 6).

- Although NH_4^+ desorbs ^{137}Cs from HWMF soils under controlled environmental conditions, no such effect on ^{137}Cs desorption was observed at the field site. It was hypothesized that NH_4^+ was leached below the rooting zone before it could effectively solubilize the ^{137}Cs.

- The mean values for ^{137}Cs level in redroot pigweed *(Amaranthus retroflexus L.)* LSB (909 pCi/g) and CR ($\geq$2.1) exceeded their respective performance goals of 300 pCi/g and 1.0 CR. Using the maximum LSB production (i.e., 2.6 kg/m^2) and CR (i.e., 5.4) values, annual removal of ^{137}Cs from the upper 30 cm of soil was estimated at 3% (as calculated below).

  $C_1=300e^{-(5.4*2.6/450)1}=300e^{-0.031}$
  $C_1=(300)(0.97) = 291$ pCi/g
  % transfer = (300-291/300)(100) = 3%/year.

This value is 3 times the commonly cited upper bound estimate for ^{137}Cs mass transfer, namely 1% per year (Ref. 7). Furthermore, the LSB production reported here (for the USDA subplot) was obtained in only 2 months. Given the effective use of soil amendments (e.g., NH_4^+) over a 4-month growing season, it may be possible to transfer 5% - 6% ^{137}Cs per year from soil to LSB.

Thus, evaluation of the enhanced NH_4^+ dosing and extended cropping hypotheses were incorporated into the goals of the Fiscal Year 98 (FY98) phytoremediation program at BNL (Section 1.3.1).

1.2.2 Total Uranium (U_t)

In mid-January 1996, Phytotech, Inc., began laboratory and greenhouse studies of U_t phytoextraction feasibility using soils collected east of Reactive Metals, Inc. Environmental Services (RMI) historic uranium extrusion facility located in Ashtabula, Ohio. A second (~50 kg) bulk sample was sent to the USDA's Plant, Soil and Nutrition Laboratory for evaluation of speciation (e.g., free ion vs. complexed ion) effects on U_t uptake in plants.

A detailed presentation of Phytotech's methods, study results, and interpretation is found in Huang et al. (Ref. 8). The two findings of greatest importance to the Biomass Remediation System (BRS) Project are as follows.

1.3 GOALS AND OBJECTIVES

1.3.1 Goals

Primary goals of the BRS Project in FY98 were: 1) completion of the ^{137}Cs phytoextraction field demonstration at BNL; 2) further evaluation of U_t phytoextraction using soils from Fernald Environmental Management Project (FEMP); and 3) reporting of results from these efforts (Ref. 10). The technology performance (i.e., secondary) goals relevant to BRS include the following:

- demonstrate that phytoextraction can remove fission product (FP) mass from rooting zone soils at rates 5 to 10 times faster than loss occurring through radiological decay;
- validate that surface soils contaminated with moderate (i.e., ≤500 pCi/g) levels of radionuclide contaminants can be cleaned up within an acceptable time period (e.g., ≤10 years) using phytoextraction technology;
- provide preliminary evidence that a 5:1 return on investment is attainable using phytoextraction technology; and
- provide evidence that phytoextraction technology will be ready for full-scale cleanup of a DOE end-user site in FY99.

Assuming successful completion of first-stage of cleanup at the target sites in FY98, the anticipated goal in FY99 was further optimization and full-scale development of phytoextraction technology at one or both of the above sites.

1.3.2 Objectives

The major objectives (or tasks) associated with the BRS Project in FY98 were as follows (Ref. 10):

- gather and assess environmental characterization data for candidate sites at BNL and FEMP, then select the most promising sites for demonstrating the phytoextraction technology;
- acquire bulk soil samples from the selected sites for evaluation of phytoextraction feasibility then optimize contaminant bioavailability and uptake into LSB;
- perform multiple LSB croppings at each site retained from the laboratory/greenhouse screening to assess phytoextraction performance over a complete growing season;
- evaluate various field-scale approaches to handle and dispose of the harvested LSB; and
- assemble, interpret, and report the results of the above activities.

2. RADIOCESIUM-CONTAMINATED SOILS FROM BROOKHAVEN NATIONAL LABORATORY

2.1 METHODOLOGIES

2.1.1 Preliminary Activities

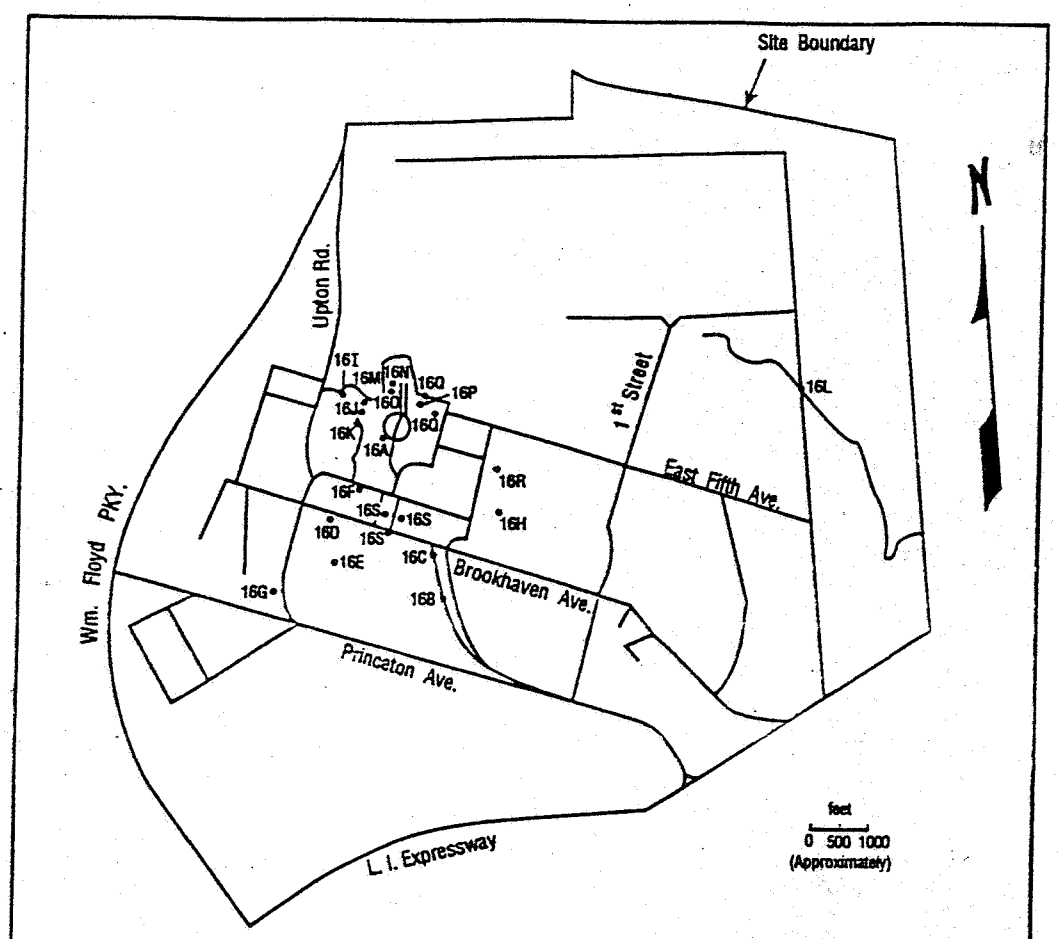
2.1.1.1 Site selection and baseline characterization of ^{137}Cs contamination

As followup to aerial radiation surveys conducted over the BNL site in 1980 and 1983, ^{137}Cs-contaminated soils were identified adjacent to or near a number of buildings on-site. These locations are shown in Figure 2-1 (Ref. 11). The source of these contaminated soils is believed to have been the former HWMF where the soils were subjected to various spills of aged fission products stored at that location (Ref. 6). These soils were mistakenly removed from the HWMF and spread throughout various locations on-site for landscaping purposes. Levels of exposure do not present an immediate health hazard to employees in these areas; however, the ^{137}Cs levels often exceed the risk-based cleanup level of 23 pCi/g for future suburban residential land use (Ref. 12). The contaminated lands are collectively referred to as the Area of Concern (AOC) No. 16 in the *Site-Specific Environmental Restoration and Waste Management Plan* for BNL (Ref. 11). This AOC will be remediated as part of sitewide Operable Unit VII, under Interagency Agreement between the DOE, Environmental Protection Agency (EPA) and State of New York. Actual cleanup will probably begin in the summer of 2000.

Following investigations by Dr. Mark Fuhrmann and Dr. James Brower at BNL, the grassy field located south of Medical/Biological Research Building (No. 490) was selected for phytoextraction technology demonstration in late November 1997. This site, designated as sub-AOC No.16E.1-2, is demarcated in Figure 2-2. Results from the previous surface survey (for gamma activity in counts per minute) for this site are shown in Figure 2-3. The area of greatest ^{137}Cs contamination (Figure 2-3) apparently resulted from backfilling an erosion channel with "landscaping soils" taken from the HWMF. Limited sampling of surface (0-30 cm) soils was performed in this area as part of the Operable Unit VII Remedial Investigation in December 1995. The analytical results for sub-AOC 16E.1 indicated that ^{137}Cs was the only contaminant that exceeded its risk-based cleanup level for residential reuse. Contaminant levels ranged between 24 and 81.4 pCi/g while the arithmetic mean $\pm$ standard deviation was 51 $\pm$ 20 pCi/g (n=7). Although the representativeness of this data is uncertain, the observed activities are well above the background level (i.e., 0.11 pCi/g) for this site. Thus, as the average contaminant level was twice that required for cleanup, sub-AOC 16E.1 appeared to be ideal for remediation by phytoextraction (Figure 1-2).

2.1.1.2 Project Startup

MSE received notice from the DOE on December 3, 1997, stating that the BRS Project would be funded in FY98. Consequently, MSE finalized the Technical Task Plan (Section 1.3) and prepared a draft baseline soils sampling plan in early December. Simultaneously, BNL personnel began preparation of a Field Work Proposal (FWP) to allow BRS funds to be transferred to them for support of this project. The FWP was approved by DOE in mid-March 1998, and funds were officially transferred to BNL in early June.



Subareas of Concern for AOC #16

16A. Alternating Gradient Synchrotron (AGS) Storage Area
16B. Warehouse Near Building 196
16C. Warehouse Area, Space Effects Research Lab Magnets
16D. Accelerator Storage
16E. Field Behind Medical Building
16F. Field Behind Chemistry Building
16G. Field East of Brookhaven Center
16H. Decontamination and Hot Laundry
16I. South End of LINAC, Building 930
16J. CLIP, Building 931A
16K. BLIP, Building 931B
16L. Peconic River Station M, Flow Gate Measurement Device Plus Sedimentation Due to Bend in Stream
16M. AD Beam Components Assembly Facility, Extraction Magnet Repair Facility, Building 914
16N. Trailers North of Building 919A, Cryogenic Target Assembly Bldg., Service Area Adjacent to Gate 3 of Fast Beam Tunnel
16O. Helium Systems Compressor Room, North Conjunction Area Used for Beam Pipe Modification, Building 919
16P. On-Line Data Facility, Experimental Area Operations, Hot Magnet Storage Area, Building 912
16Q. Trailers North and East of Building 912, Storage Area for Surplus Steel Shielding
16R. Nuclear Waste Management Facility, Radioactive Waste Research Program and High Intensity Rad Lab, Building 830
16S. Contaminated Landscaping Soil

Figure 2-1. Sites associated with AOC Number 16 at BNL (Ref. 11).

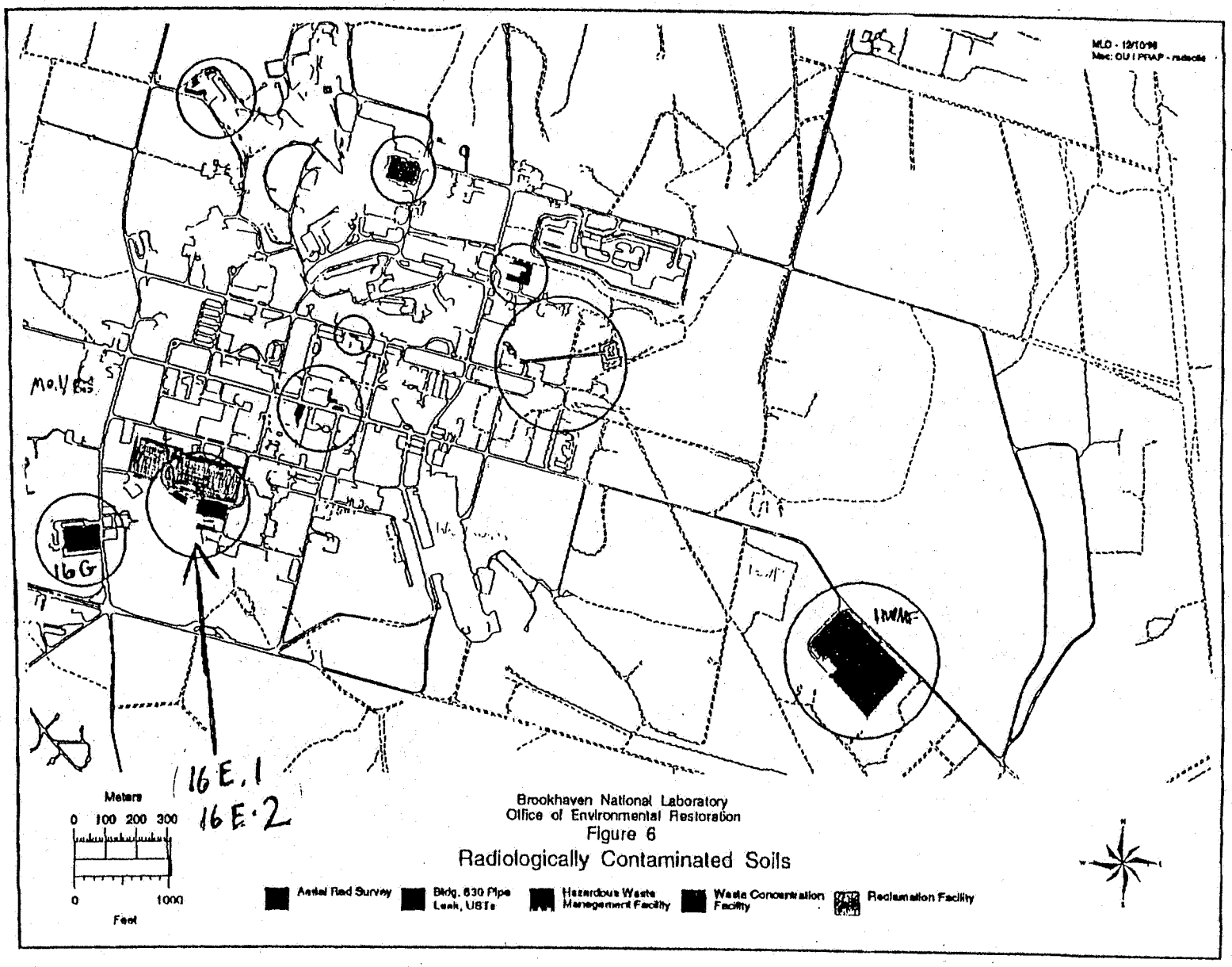


Figure 2-2. Location map for AOC 16E.1-2 and vicinity at BNL (M. Fuhrmann).

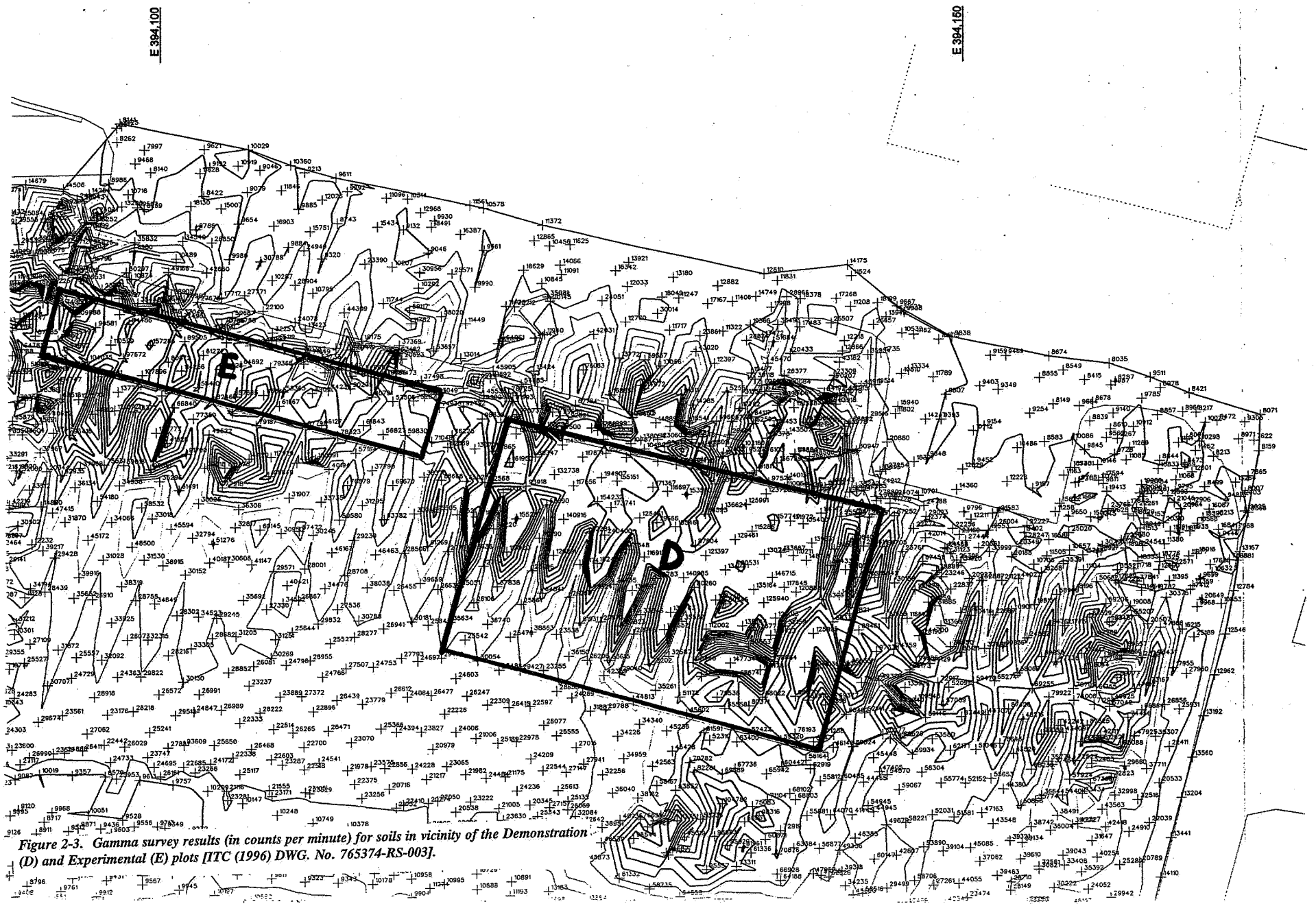


Figure 2-3. Gamma survey results (in counts per minute) for soils in vicinity of the Demonstration (D) and Experimental (E) plots [ITC (1996) DWG. No. 765374-RS-003].

The draft Work Plan, including the December 1997 soil sampling results, was submitted to the DOE on April 16, 1998 (Ref. 13). Teleconference calls involving MSE, BNL, and USDA personnel were held weekly between April 27 and May 26, 1998 to refine the plan; detailed notes taken during these calls are found in BRS project files at MSE. During the latter half of April, the following tasks were accomplished:

- acquisition of radiation work and subsurface excavation permits, approval of the Environmental Safety and Health Plan, and project notifications sent to Building 490 Managers; and
- procurement of field materials (e.g., irrigation supplies) and mobilization of equipment (e.g., tractor with a rotary plow)/personnel for installation of the field plots.

Additional details pertaining to the methods used in completing the ^{137}Cs phytoextraction investigation are presented in the remainder of Section 2.1.

2.1.2 ^{137}Cs Plant Uptake (Greenhouse) Investigation at USDA

BNL personnel collected approximately 20 kg of composite soil samples [0-20 cm below ground surface (bgs)] from each 5-m by 5-m subcell of the 10-m by15-m experimental plot in mid-May 1998. The locations of these samples, designated A through F, are shown in Figure 2-4. The results of ^{137}Cs analyses performed by USDA on homogenized grab samples taken from each subcell are shown in Table 2-1.

Table 2-1. ^{137}Cs levels in E Plot soils.

Subcell Designation	^{137}Cs Level, pCi/g
A	8.5
B	7.4
C	8.3
D	123
E	160
F	366

The levels of ^{137}Cs in subcells A-C are below regulatory concern, and soils from these areas were not used in greenhouse studies. Fortunately, sufficient quantities of soils from subcells D and F were available for plant uptake/soil amendment experiments. Thus, soils from these two subcells were mixed to obtain a homogeneous bulk mixture containing 275 pCi of ^{137}Cs/g dry soil. The experimental design included six treatments in which each treatment was replicated three times (i.e., for a total of 18 2-L capacity pots filled with the soil mixture). Beginning on July 15, 1998, several seedlings of the following species were grown in each pot: cabbage (*Brassica oleracea*, "Storage 1"), Indian mustard (*B. juncea*, from Phytotech, Inc.), golden pigweed (*Amaranthus aureus*), and redroot pigweed (*A. retroflexus*).

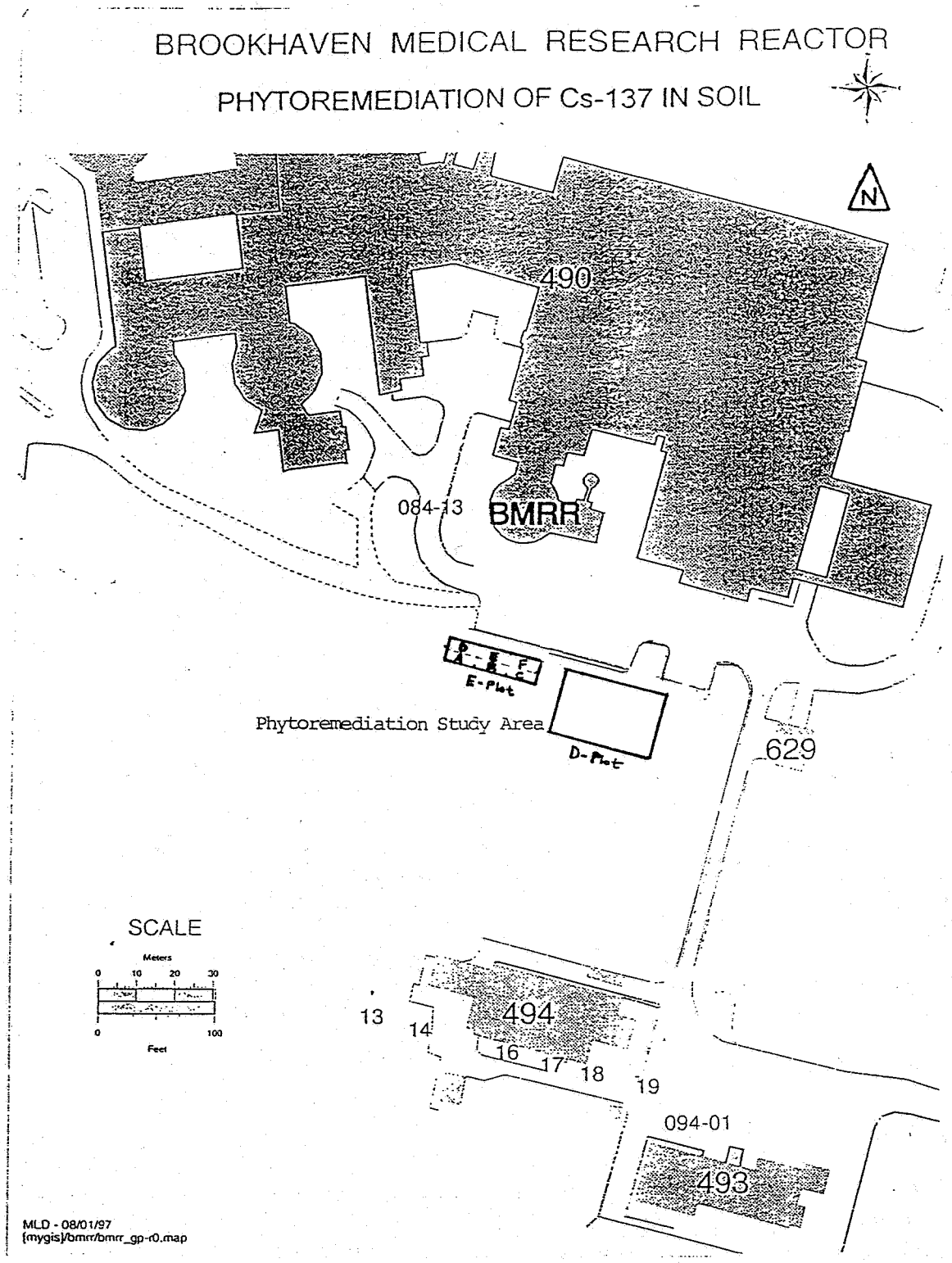


Figure 2-4. General layout of the Demonstration (D) and Experimental (E) phytoextraction field plots at BNL AOC 16E.1.

The composition, volume, and date for each treatment implemented are shown in Table 2-2. With the exception of the cesium chloride (CsCl) treatment, LSB was harvested from the other (15) pots on September 2, 1998. The fresh weight of biomass produced by each species (within treatments) was recorded prior to drying these materials for 5 days at 65 °C. The oven-dried samples were then used for ^{137}Cs analyses through gamma spectroscopy. Analytical results are summarized in Section 2.2.2 of the report.

Table 2-2. Summary of USDA's soil treatment regimen.[a]

TREATMENT DATE/TYPE			
Treatment No.	**August 13, 1998**	**August 18, 1998**	**August 28 and September 1, 1998**
1	100 mL deionized water	100 mL deionized water	100 mL deionized water
2	100 mL of 80 mM RbCl solution	100 mL of 80 mM RbC1 solution	100 mL of 200 mM NH_4NO_3 solution
3	75 mL of 200 mM NH_4NO_3 solution	75 mL of 200 mM NH_4NO_3 solution	100 mL of 200 mM NH_4NO_3 solution
4	75 mL of 100 mM CsC1 solution	CsCl very toxic- plants were harvested	—
5	75 mL of humic acid suspension (5g acid in 100 mL water)	same as for 8/13/98	100 mL of 200 mM NH_4NO_3 solution
6	75 mL of solution containing 70 mM NH_4NO_3 + 35mM CsC1 + 2.5g humic acid/150 mL water	100 mL of solution containing 100 mM NH_4NO_3 + 40 mM RbC1	100 mL of 200 mM NH_4NO_3 solution

Note: [a] Using a soils mixture from subcells D and F within the E Plot at BNL's AOC 16E.1 (see Figure 2-3).

In early May 1998, MSE was informed that the independent contractor laboratory could not perform agricultural-related analyses on soils containing greater than background levels of radionuclides. Since MSE's laboratory had considerable experience with agricultural-related analyses of "cold" samples, they could complete this task on soils having ≤4 pCi ^{137}Cs /g soil. Consequently, BNL collected a 5-kg composite sample (0 to 15 cm bgs) from an area approximately 10 m south of the E plot (Figure 2-3) in late June 1998. Based upon inspection of the USDA's soil survey for BNL, the ^{137}Cs-contaminated "landscaping" soils and adjacent "native" soils both belong to the Riverhead sandy loam series, 0%-3 % slope phase (Ref. 14). The soil sample (containing 0.4 pCi ^{137}Cs/g soil) was received at MSE on July 8, 1998 and was split into two subsamples prior to analysis. The resulting data, also presented in Section 2.2.2, was used to interpret the greenhouse study results and to complete the E plot design.

2.1.3 FY98 Demonstration Plot

The 15-m by 25-m D plot was tilled on May 2, 1998, using a small tractor and rotary plow. The sod layer was completely broken up after four passes with this equipment. Some concrete and rebar were encountered, but such debris caused only minor problems with tillage efforts. Collocated soil-grass samples were collected along the edge of the plot to establish a baseline ^{137}Cs concentration ratio at the AOC; results of these analyses are found in Section 2.2.3. Given that 1:1 soil:water pastes had pH values ≥ 5.5, team personnel decided to postpone application of 100-200g/m^2 of crushed (-50 mesh) limestone. Steel fence posts and galvanized turkey wire (approximately 1.8 m high) fencing were

installed during lulls in the rainy weather within a week of rotoplowing.

Upon suitable drying of rooting zone soils, the plot was broadcast-fertilized and then seeded on May 22, 1998 using an all-in-one hand-operated device (Lambert Manufacturing, Model GSF31M, Ansonia, Ohio). The seeder/fertilizer unit was calibrated (in the laboratory at BNL) to deliver approximately 0.7 g of redroot pigweed (*Amaranthus retroflexus*) and approximately 50.0 g of trace element-fortified 8-12-8 [nitrogen, phosphorus, potassium (NPK)] garden-type fertilizer per m^2 of plot area. The seed was placed in rows spread approximately 15 cm apart. The envisioned result from this seeding rate was 40 mature plants/m^2 after incorporation of seed viability and seedling survival effects. Such a plant density should result in optimal growth rate, LSB production, and ^{137}Cs uptake over the growing season.

By late June 1998 the pigweed was growing rather densely in the rows. However, plant growth was not uniform; plant height varied from approximately 10 cm in some areas to only a few cm elsewhere. Furthermore, iron chlorosis (deficiency) appeared at high clay and poorly drained soil spots within the plot. Based on the analytical results from soil samples taken in early July and field observations made in mid-July, it was decided that the crop was suffering from nutrient deficiency. Consequently, the following actions were taken. First, overly dense patches of pigweed were thinned while undesired plant growth elsewhere in the plot was removed prior to reseeding. Second, approximately 4 kg of water-soluble Miracle Gro® fertilizer was manually sprayed throughout the plot. Although fertilizer application improved plant health and growth, many of the plants were flowering by late July. Based on literature review and past experience, it was judged that ^{137}Cs uptake was beginning to decline at this stage of plant development. Thus, the entire crop was harvested on July 28, 1998. Grab samples of LSB contained 44 to 194 pCi ^{137}Cs/g of dry plant material. The LSB was collected in approximately 23-kg capacity "onion bags" and dried at 60 °C for 10 days. A Canberra Bag Monitor calibrated with a 1 μCi ^{137}Cs point source was used to determine ^{137}Cs content in each bag. This approach allowed quantification of total ^{137}Cs uptake by this crop of LSB. The results are tabulated in Section 2.2.3.

On July 30, 1998 approximately 2.6 g/m^2 of commercial herbicide (Roundup-Pro®) was sprayed throughout the D plot. The plot was rototilled again on August 7, 1998; approximately 20.4 kg of 10-10-10 NPK fertilizer was tilled into the soil during plowing while another 9.1 kg was broadcast after plowing. Pigweed seed was applied using a hand-held spreader at a rate of approximately 0.6 g/m^2 on August 11, 1998. The seed was purchased from Valley Seed Service in Fresno, California. This company provided the seed used in the FY96 field study (Ref. 6). Seed from this source produced more robust plants prior to flowering. The crop was well established by the end of August. However, plant germination rate and growth appeared to be very heterogeneous. Some plants were approximately 25 cm in height while others were only several cm tall. It is not clear whether there are two (separate) populations of plant growth types as appeared to be the case in the first crop. The second crop was harvested on October 20, 1998, and LSB handling and analyses were performed as described above. The analytical results for ^{137}Cs uptake by this crop are also presented in Section 2.2.3.

2.1.4 FY 98 Experimental Plot

Based on previous phytoremediation studies, the use of seedlings generally results in superior plant coverage and LSB production relative to initial seeding of the particular site. Thus, the following seedlings were grown on greenhouse-nursery flats at USDA: 1) redroot pigweed (*Amaranthus retroflexus*), golden pigweed (*A. aureus*) and hybrid pigweed (*A. cruteus* x *A. powelii*) beginning on July 16; and 2) cabbage (*Brassica oleracea* cv. "Storage 1") and a cv. of Indian mustard (*B. juncea*)

obtained from Phytotech, Inc., beginning on July 24, 1998.

Brookhaven National Laboratory plant engineering personnel rototilled the E plot on August 7, 1998. The original (10-m by 15-m) plot design was extended westerly (to 10-m by 22- m) to include more ^{137}Cs-contaminated soils in that direction. The experimental design is summarized in Figure 2-5. In mid-August, fertilizer was added to all 50-cm by 50-cm cells. An organic amendment was added to certain cells (Figure 2-4) at this same time. This composite manure/organic humus material was purchased from Agway Company in 18.2-kg bags. The seedlings were transplanted to the four blocks (replications) on August 20, 1998, in accordance with the plan shown in Figure 2-5. Excess seedlings were planted in eight additional cells that had received only fertilizer. A light cover (approximately ≤ 1 cm) of straw was added to the surface of each cell for reduction of soil temperature and moisture losses during establishment of the seedlings within the plot.

Some cells received 2-L aliquots of 100 mM NH_4^+ ion twice a week for a total of 3 weeks. Given limited space for drying the LSB, the first half of the E plot was harvested on October 13, 1998, while the second half was harvested on October 19, 1998.

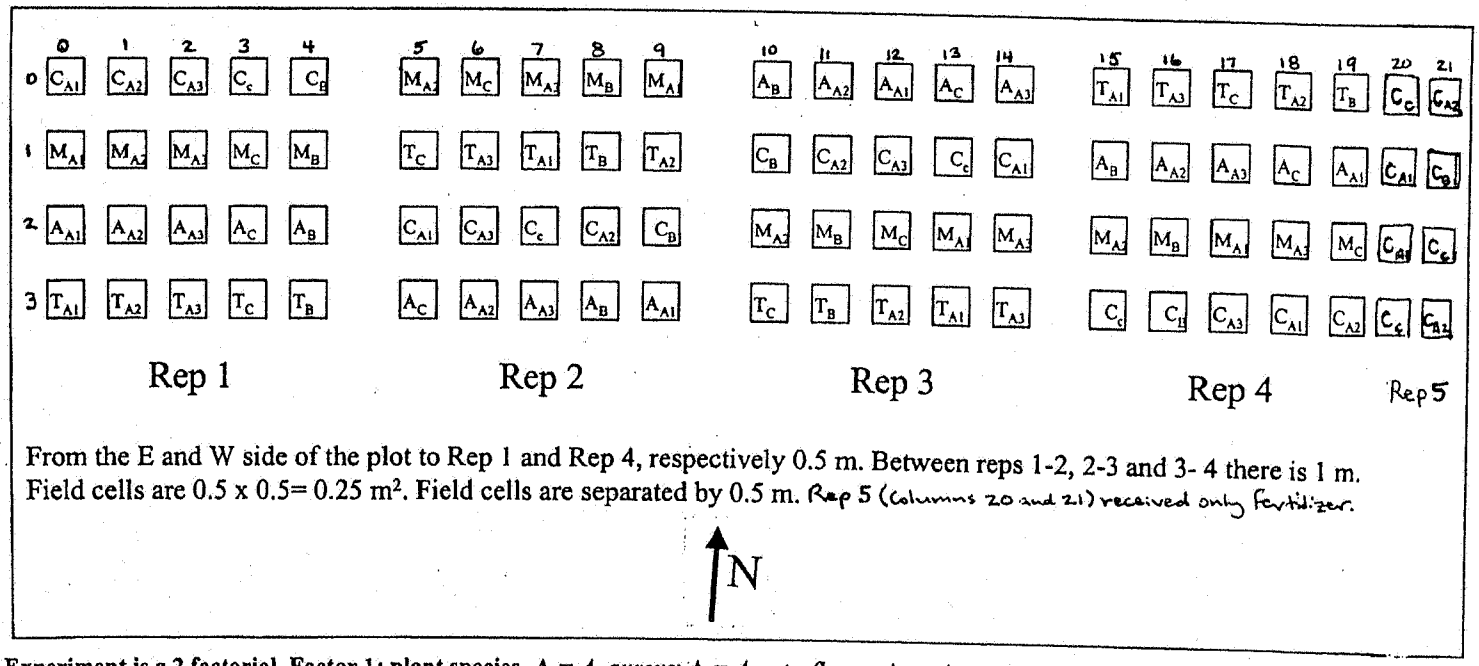
Plants harvested from the E plot were placed in labeled paper grocery bags, weighed, dried at 60 °C for several days, and reweighed. Tare weights for the bags were taken as an average of several bags. An activity survey in each sample was made by placing the bag over an intrinsic germanium gamma-ray detector for 2 minutes. Analysis for ^{137}Cs was done using the 661-kiloelectrovolt gamma line. High activity plants were then analyzed in the same Canberra Bag Monitor used for the large bags of harvested plants from D plot. Lower activity samples were analyzed on one of two germanium detectors. These samples were formed into a standard geometry by pressing them [at 1,000 pounds maximum] into large plastic containers using a compression testing machine. All three detectors were intercalibrated by counting a set of samples on each. A vegetation standard (VEBN from the DOE's Environmental Measurement Laboratory), containing a known level of ^{137}Cs, was also used as a secondary laboratory control standard. Appendix Figure A-1 shows the results of the intercalibration of these detectors. Samples were counted on the germanium gamma detectors for periods of time ranging from 30 to 1,000 minutes depending on the sample's activity. Each sample was counted twice. Once in the container as it had been pressed, and the second time as the sample was removed from the container, turned upside down, pressed back into the container, and recounted. This was necessary because of the different thicknesses of the samples after being pressed. The average of the two measurements was used. Activity in pCi/g (DW) was then calculated.

The analytical results for the LSB and soil samples are presented in Section 2.2.4.

2.2 RESULTS AND INTERPRETATIONS

2.2.1 Baseline Soils Characterization

Results for agronomic analyses performed by MSE on a split sample collected adjacent to the E plot are shown in Table 2-3. Raw data is provided in Appendix A.1. Given this data, the site's soils can be generally characterized as being moderately acidic, infertile/nonsaline, and well-drained and exhibit low to moderate levels of dissolved metals.



Experiment is a 2 factorial. Factor 1: plant species- A_1= *A. aureus*; A_2= *A. retroflexus*; A_3= *A. cruteus* x *A. powelii*; B= *B. juncea* (Phytotech); C= cabbage. Factor 2: soil treatment- C= control; M= manure (1 lb/field cell, apply before transplanting); A= NH_4NO_3 (apply twice a week: 2 L of a 0.1 M solution. Start application when plants are established- 2-3 weeks after transplant ?; T= Manure + NH_4NO_3 (applied as M and A treatments).

Number of plants to be transplanted: A_1=20 plants (11 flat cells)/field cell; A_2=20 plants (10 flat cells)/field cell; A_3= 3 plants/field cell; C= 15 plants (8 flat cells)/field cell; B= 16 plants (10 flat cells)/field cell

Fertilizer: 20 g of 10-10-10/field cell to be applied before planting.
Soil to be sampled before planting.

Figure 2-5. Study design for the E plot at BNL AOC 16.E.

Table 2-3. Summary of agronomic data for the D and E test plots at BNL.[a]

Part A. General Parameters Universe		
Parameter	**Mean Value (n=2)**	**Unit of Measurement**
Alkalinity	31.1 ± 1.6	mg/L
Cation exchange capacity	13.6 ± 2.9	meq/100g
Chloride ion	15.0 ± 2.3	mg/L
Electrical conductivity (EC)	0.203 ± 0.025	mmhos/cm
Nitrate/Nitrite - N	4.4 ± 0.8	mg/L
pH (1:1 soil:water)	5.86 ± 0.08	standard units
Phosphate (as ortho-P)	1.1 ± 0.4	mg/L
Redox potential (E_h)	318 ± 43	mv
Soils separates		
• sand	76.0 ± 0	% by volume
• silt	22.0 ± 0	% by volume
• clay	2.0 ± 0	% by volume
• texture	Loamy sand	—
Sulfate ion	54 ± 2	mg/L
Total organic carbon	1.61 ± 0.01	% by weight
Part B. Dissolved Metals		
Parameter	**Mean Value (n=2)**	**Unit of Measurement**
Aluminum	5.68 ± 0.28	mg/L
Calcium	24.15 ± 1.48	mg/L
Iron	1.88 ± 0.04	mg/L
Magnesium	5.22 ± 0.28	mg/L
Manganese	0.42 ± 0.001	mg/L
Potassium	3.46 ± 0	mg/L
Sodium	4.52 ±0.13	mg/L
Note: [a] results reported in mg/L are for an 0.45-μ-filtered extract from a 1:1 soil to water paste; EC and E_H were also determined in the paste before filtering.		

Grab and soil core samples (all 0- to 15-cm bgs) were collected within and along the perimeter of the D plot before the first crop of redroot pigweed was planted. The results of the ^{137}Cs analyses performed at BNL are summarized in Table 2-4 (raw data is provided in Appendix A.3), and presented graphically in Figure 2-6.

Table 2-4. Summary of ^{137}Cs analyses for baseline D plot soils.

Location of Samples	^{137}Cs Levels, x ± sd (n), in pCi/g
Perimeter of plot	94.2 ± 77.9 (4)
Within plot (grabs)	53.2 ± 59.5 (12)
Within plot (cores)	81.3 ± 57.4 (5)

The average level of ^{137}Cs in these 21 samples is 71.5 ± 61.3 pCi/g of soil. This central tendency value was used in assessing the calculated CRs for LSB (Section 2.2.3).

An additional 12 grab samples (0- to 15-cm bgs) were collected from the E plot before planting the (0.5- by 0.5-m) cells. Data for the respective cells sampled is shown in Appendix A-1 and are summarized graphically using Surfer® software in Figure 2-7. As the mean ^{137}Cs level is 101.5 ± 75.4 pCi/g, this plot appears to be slightly more contaminated overall than the D plot.

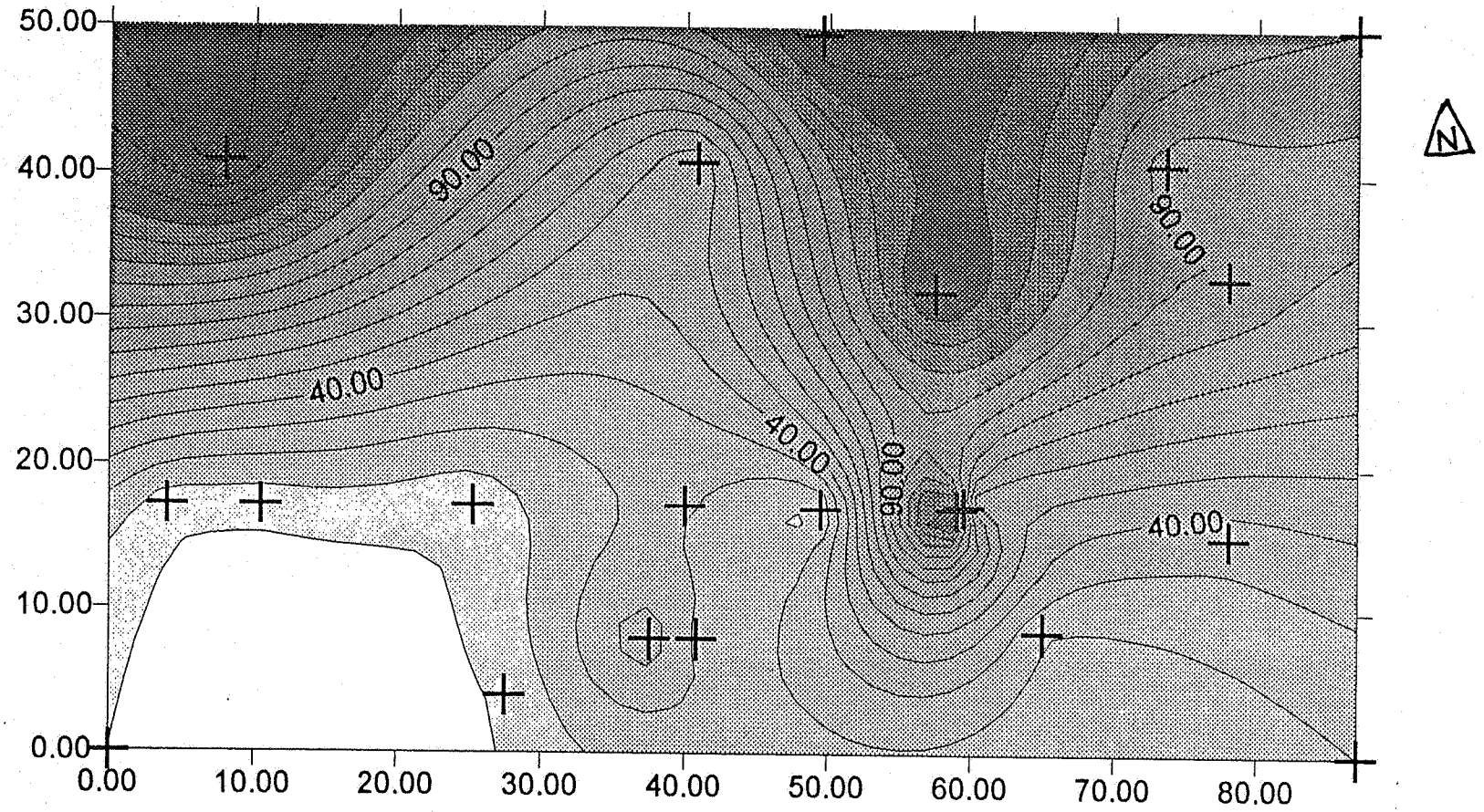


Figure 2-6. Surfer®- based plot of ^{137}Cs (pCi/g) levels in rooting zone soils (0- to 15-cm bgs) at the D plot.

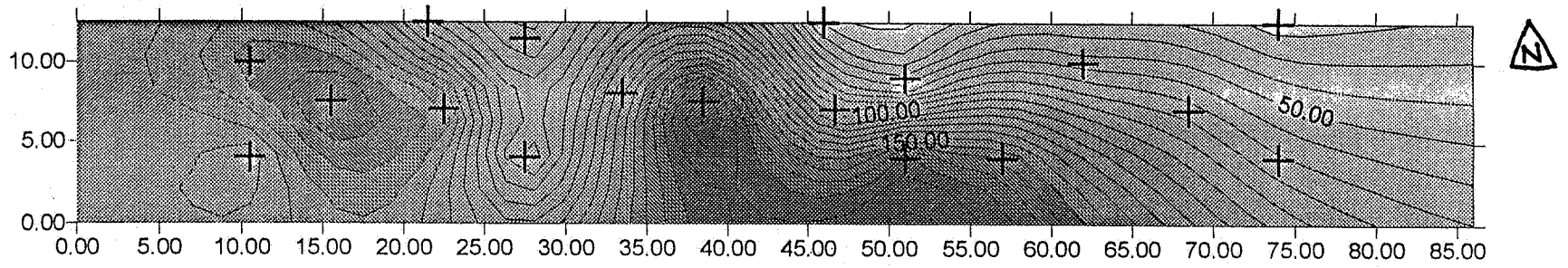


Figure 2-7. Surfer® -based plot of ^{137}Cs (pCi/g) levels in rooting zone soils (0- to 15-cm bgs) at the E plot.

Finally, five collocated plant-soil (0- to 15-cm bgs) samples were collected along the edge of the parking lot at Building No. 490 on May 2, 1998. The intent of this sampling was establishment of a baseline for assessing the effectiveness of phytoextraction technology relative to natural uptake of ^{137}Cs plants. This baseline data is presented in Table 2-5 below.

Table 2-5. Baseline plant soil data summary.

Location No.	Plant Type	^{137}Cs in LSB (pCi/g)	^{137}Cs in Soil (pCi/g)	CR (unitless)
1	coarse-leaved grass	5.50	123.94	0.04
2	coarse-leaved grass	5.98	244.91	0.02
3	fine-leaved grass	8.42	66.87	0.13
4	coarse-leaved grass	1.72	83.14	0.02
5	low broadleaf plant	7.02	163.40	0.04

It is suggested that the higher average level of ^{137}Cs (136.4 $\pm$ 71.3 pCi/g) in these soils relative to those observed in the test plots is due to accumulation of finer grained (and more contaminated) sediment transported downgradient of the test site through water erosion. Nevertheless, CR values for plants growing in these soils are in the range typically observed in LSB (Ref. 6).

2.2.2 Greenhouse Investigations at USDA

Results of the treatment-specific uptake of ^{137}Cs by the various test species are summarized in Table 2-6. Raw data is provided in Appendix A.2. Inspection of these results allows three general observations to be made. First, the degree of ^{137}Cs uptake by the tested species (across all soil treatments) can be ranked as follows: golden pigweed (*Amaranthus aureus*) > redroot pigweed (A. *retroflexus*) > Indian mustard (*Brassica juncea*) > cabbage (*B. oleracea*). Secondly, only cabbage failed to consistently meet the minimally required CR of >1.0 (see Section 1.2.1). However, none of the above species met the CR goal of 5 to 10 as stated in Section 1.3.1 of this report. Third, the general effectiveness of the soil treatments can be ranked as follows: mixture (of CsCl or RbCl, NH_4NO_3 and humic acid) $\geq$ CsCl (alone) > humic acid > NH_4NO_3 > control (deionized water) > RbCl. However, it was noted in Section 2.1.2 that the 100-mM of CsCl addition to soil was almost immediately toxic to all of the test species. The mixture included 35-mM CsCl or 40-mM RbCl (Table 2-2). Such treatment appears to stimulate production of Indian mustard LSB relative to individually applied components (i.e., NH_4NO_3 or humic acid alone—see Appendix A.2).

Table 2-6. Summary of USDA's greenhouse investigations.[a, b]

Treatment	Plant Type								Treatment Summary x ± sd	
	Indian Mustard		Cabbage		Redroot pigweed		Golden pigweed			
	pCi/g	CR	pCi/g	CR	pCi/g	CR	pCi/g	CR	pCi/g	CR
Control	350	1.3	300	1.1	387	1.4	713	2.6	438 ± 173	1.6 ± 0.6
RbCl	281	1.0	299	0.8	442	1.5	458	1.7	348 ± 103	1.3 ± 0.4
NH_4NO_3	411	1.5	376	1.4	440	1.6	793	2.9	517 ± 190	1.9 ± 0.7
CsCl	622	2.4	440	1.6	616	2.2	1038	3.8	689 ± 255	2.5 ± 0.9
Humic Acid	334	1.2	176	0.6	704	2.6	880	3.2	524 ± 331	1.9 ± 1.2
Mixture	633	2.3	317	1.2	739	2.7	1020	3.7	677 ± 315	2.5 ± 1.1
Species-Specific Summary (x ± sd)	445 ± 171	1.6 ± 0.6	302 ± 121	1.1 ± 0.4	551 ± 180	2.0 ± 0.6	817 ± 255	3.0 ± 0.9	———	———

Note: [a]Study methods for plant uptake of ^{137}Cs are provided in Section 2.1.2. Raw data is presented in Appendix A.2.
[b]CR = ^{137}Cs in plant LSB ÷ ^{137}Cs in soil (all data in pCi/g); average ^{137}Cs in soil = 275 pCi/g

2.2.3 FY98 Demonstration Plot

Results for the first (July 1998) and second (October 1998) harvests of redroot pigweed are summarized in Table 2-7. Raw data is presented in Appendix A.3. Several important observations can be made regarding the July 1998 results. First, the average CR [2.7 ± 1.5 (n=12)] for pigweed is very similar to that observed at the USDA subplot in October 1996 [CR=2.5 ± 1.3 (n=13); Ref. 6]. In addition, the respective maximum CR values are also similar (i.e., 828/152 = 5.4 in 1996 vs. 29.9/4.2 = 7.1 in 1998) between the two studies. Second, the uptake of ^{137}Cs into pigweed LSB appears to be fairly linear over the range of contamination present in D Plot soils (see Figure 2-8), thus, extending the linearity reported in the previous results (Ref. 6). Thirdly, the maximum CR (90.2/34.7 = 2.6) for non-Amaranth sp. was associated with a presently unknown broadleaf plant; a "cold" specimen was submitted to the local USDA/Extension Service for taxonomic identification. The lowest CR (10.7/57.1= 0.2) was associated with an unidentified grass species growing within the plot.

Table 2-7. Summary of ^{137}Cs uptake by plants in the D plot.

Part A. First Harvest (July 1998) Results (pCi/g)					
Soil	Redroot Pigweed	CR	Soil	Other Species	CR
51.1 ± 60.4	113.2 ± 126.7 (12), LSB	2.7 ± 1.5	86.8 ± 69.6	110.3 ± 161.9	1.2 ± 1.2
76.0 ± 96.1	341.1 ± 447.0 (2), seed heads	------	------	------	------
Part B. Second Harvest (October 1998) Results (pCi/g)					
Soils		Redroot Pigweed		CR	
102.9 + 96.5		12.5 + 10.6		0.2 + 0.2	

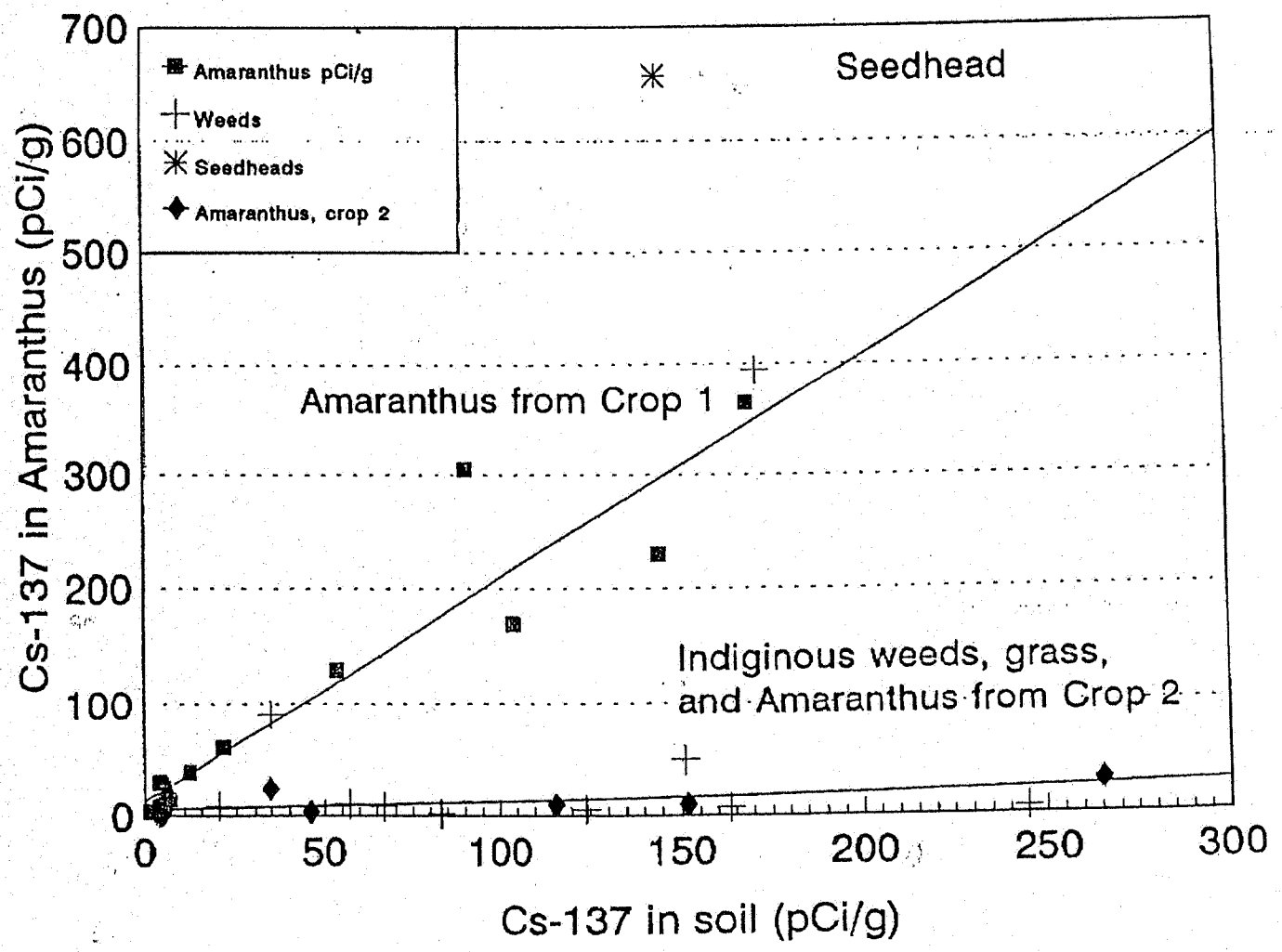


Figure 2-8. Partitioning of ^{137}Cs between Amaranthus and soil.

The most disconcerting observation is the large decrease in ^{137}Cs uptake by pigweed during the second harvest, as shown in Figure 2-8. Here, the CRs ranged from approximately 0.06 (i.e., 9.8/151.8) and 0.7 (23.8/34.6). As noted in Reference 6, this variance is essentially the same as reported in the global literature for historically contaminated ("aged") soils. It is suggested that most of the potentially bioavailable ^{137}Cs was removed by the first crop. If this hypothesis is true, the above results cast doubt on the universal validity of the exponential-type contaminant uptake model shown in Figure 1-2. Rather, a "hockey stick" model may be more appropriate for ^{137}Cs phytoextraction from aged soils. Nevertheless, it is reasonably clear that use of redroot pigweed did not meet the project goals set out in Section 1.3.1 of this report.

As noted in Section 2.1.3, the total uptake of ^{137}Cs in each crop's LSB was determined using a Canberra® bulk gamma monitor (bag counter). The total dry weights for the July and October harvests are approximately 19.5 kg and 20.5 kg, respectively. The latter value may reflect the more robust nature of the plants arising from the California seed source vs. the USDA-source plants associated with the first harvest, which also contained some grass biomass. Total (and average/g) uptake of ^{137}Cs into LSB was calculated to be approximately 2,400 nanoCuries (nCi) (123 pCi/g) and 561.4 nCi (27.3 pCi/g) in the July and October harvests, respectively. Using Surfer® software and assuming a loose bulk density of 1.2 g/cm^3 within the upper 15 cm of soil, the total ^{137}Cs loading was estimated. The result is approximately 4.5 milliCurie (mCi), equivalent to 4.5 x 10^6 nCi. Therefore, the transfers of ^{137}Cs from these soils to redroot pigweed LSB are approximately 0.05 and 0.01%, respectively, for the July and October 1998 harvests. These rates are smaller than the approximately 2.3% year^{-1} natural rate of decay [i.e., (0.693/30.17) * 100] for this isotope.

2.2.4 FY98 Experimental Plot

Uptake of ^{137}Cs by the various combinations of test species x soil treatments is summarized in Table 2-8. Raw data is found in Appendix A.4. Inspection of this data allows two general observations to be made. First, ^{137}Cs accumulation in LSB can be ranked as follows: golden pigweed > cabbage > hybrid Amaranth > redroot pigweed > Indian mustard. Second, the relative effectiveness of the soil amendments appears to be ranked as follows: ammonium nitrate > control (water only) > manure > combined NH_4NO_3 and manure. The selection of golden pigweed x NH_4NO_3 as the best option is generally supported by the USDA's greenhouse results.

However, the following two examples indicate that caution must be applied when extrapolating greenhouse results to a field setting. First, note that the rank ordering of cabbage and redroot pigweed are essentially reversed when going from pot to field studies (compare Tables 2-6 and 2-8). Secondly, addition of relatively concentrated humic acid suspensions to potted plants appears to have greater effect on ^{137}Cs uptake than does tilling composted manure (having less bioavailable humic acids?) into field soils. Furthermore, it appears as though combined use of NH_4NO_3 and manure decreases plant uptake of ^{137}Cs (Table 2-8). This potentially adverse interaction was probably masked by CsCl addition to the mixture used in the greenhouse study (Table 2-6). Field related results may contradict the hypothesis that humic acid addition would enhance the bioavailability of ^{137}Cs. However, composted manure probably contained lower concentrations of soluble humic acids than was present in the humic acid suspension used in the greenhouse study. Thus, the manure may have had less capacity to maintain dissolved ^{137}Cs in soil solution (i.e., as Cs-humic complexes), relative to that observed for humic acid suspensions.

Table 2-8. Summary of ^{137}Cs levels in LSB from test species grown in the E plot at BNL [a].

Test Plant	Treatment Type				
	Control	Ammonium Nitrate (NH_4NO_3)	Manure	NH_4NO_3 + Manure	Species Specific Summary [b]
Golden pigweed (*A. aureus*)	100.2 ± 25.8 (6)	81.9 ± 93.5 (4)	63.1 ± 43.2 (4)	35.0 ± 31.8 (4)	73.4 ± 53.8 (18)
Redroot pigweed *A. retroflexus*	82.8 ± 34.2 (5)	80.8 ± 92.4 (4)	39.8 ± 36.5 (2)	24.6 ± 14.5 (3)	62.4 ± 55.1 (15)
Hybrid Amaranth (*A. cruteus x A. powelii)*	102.5 ± 35.1 (4)	69.4 ± 83.4 (4)	63.3 ± 48.1 (6)	28.6 ± 25.1 (5)	63.7 ± 53.2 (19)
Indian mustard (*B. juncea*)	39.8 ± 21.1 (5)	32.4 ± 31.2 (4)	23.9 ±16.9 (4)	18.8 ± 15.0 (3)	30.0 ± 21.7 (16)
Cabbage (*B. oleracea)*	56.0 ±22.3 (7)	112.1 ± 97.0 (4)	74.7 ± 35.5 (4)	40.8 ± 34.9 (4)	68.6 ± 53.0 (19)
Treatment Summary [b]	74.7 ± 35.3 (27)	75.3 ±78.5 (20)	54.5 ± 40.5 (20)	30.3 ± 24.8 (19)	----------

Note: [a]Arithmetic mean ± standard deviation for a particular number (n) of replicates in pCi/g DW. Raw data is found in Appendix A.4.
[b]Mean + standard deviation of the species-specific or treatment-specific data sets.

Soil ^{137}Cs levels were determined by instrumental analysis at 18 of the total 80 total cells in the E plot (Figure 2-6). The mean ± standard direction of ^{137}Cs in these 18 samples was calculated to be approximately 106.5 ± 68.0 pCi/g of soil (Section 2.2.1). In addition, Surfer® output (Figure 2-7) was used to generate estimates of ^{137}Cs in levels within each of the 80 (0.5-m by 0.5- m) test cells. For a given cell, the contoured estimated levels at Surfer® nodes situated nearest the cell were used; linear interpolation between nodes was used in those cases wherein ^{137}Cs levels changed rapidly over relatively short distances. The results of these estimates are tabulated in Appendix A.4.

The soils and plant ^{137}Cs data was used to calculate concentration ratios for each of the plant species x treatment combinations evaluated at the E plot. The resulting CRs are summarized in Table 2-9. Inspection of this table indicates the highest average CR (1.4) is associated with the cabbage x NH_4NO_3 treatment.

Table 2-9. Summary of ^{137}Cs concentration ratios for the E plot at BNL.

Test Plant	Control	Treatment Type			
		Ammonium Nitrate NH_4NO_3	Manure	NH_4NO_3 + Manure	Species-Specific Summary
Golden pigweed (*A. aureus*)	1.0 ± 0.4 (6)	0.8 ± 0.4 (4)	0.6 ± 0.2 (3)	0.4 ± 0.2 (4)	0.8 ± 0.4 (17)
Redroot pigweed (*A. retroflexus*)	0.6 ± 0.3 (5)	0.7 ± 0.4 (4)	0.4 ± 0.3 (2)	0.3 ± 0.1 (3)	0.5 ± 0.3 (14)
Hybrid Amaranth (*A. cruteus x A. powelii*)	1.0 ± 0.3 (4)	1.0 ± 0.5 (4)	0.8 ± 1.0 (6)	0.3 ± 0.1 (5)	0.8 ± 0.7 (19)
Indian mustard (*B. juncea*)	0.4 ± 0.1 (4)	0.3 ± 0.1 (4)	0.2 ± 0.1 (4)	0.3 ± 0.1 (3)	0.3 ± 0.1 (15)
Cabbage (*B. oleracea*)	0.6 ± 0.3 (7)	1.4 ± 0.5 (4)	0.5 ± 0.1 (4)	0.4 ± 0.3 (4)	0.7 ± 0.5 (19)
Treatment Summary	0.7 + 0.4 (26)	0.9 + 0.5 (20)	0.5 + 0.6 (19)	0.3 + 0.2 (19)	----------

The reason for redroot pigweed's lower CRs (≤0.7) in the E plot, relative to CRs in the D plot (approximately 2.7; Table 2-5), is not immediately obvious. It may be that ^{137}Cs is generally more plant available in soils at the D plot. Nevertheless, the results from the E plot also failed to meet the goals stated in Section 1.3.1.

Finally, a crude estimate of overall phytoextraction efficiency can be made by dividing total ^{137}Cs in LSB (1,185 nCi) by total ^{137}Cs in rooting zone soils (approximately 1.89 mCi). The resulting value of 0.06 % indicates greater removal of ^{137}Cs via natural decay than from uptake into aboveground plant biomass.

3. URANIUM-CONTAMINATED SOILS FROM FERNALD ENVIRONMENTAL MANAGEMENT PROJECT

3.1 METHODOLOGIES

3.1.1 Preliminary Activities

3.1.1.1 Site Selection and Baseline Characterization of U_t Contamination

On November 5, 1997, personnel from Fluor Daniel Fernald's (FDF) Technology Programs (TP) contacted MSE regarding the feasibility of phytoextraction of U_t from soils at the FEMP site. This former uranium processing facility is located approximately 29 km northwest of Cincinnati, Ohio. After transfer of the requested information on November 6, communication was maintained intermittently between FDF and MSE over the next 3 months via electronic mail. On February 4, 1998, MSE received a letter stating that:

- remedial technologies as well as the cleanup levels and schedules have been firmly established by the federal and state regulatory agencies; and
- although application of innovative technologies to improve remediation and cost effectiveness was recognized by these agencies, FDF/TP personnel did not see how phytoextraction could be readily included in site cleanup efforts (Ref. 15).

A teleconference call followed on March 3, 1998, between FDF/TP and MSE/BRS personnel to discuss these issues further. The outcome of the call is stated below.

- Relatively small areas of moderately contaminated soils exist in the northeastern corner of the former production area at FEMP and are not scheduled for excavation and removal for at least 1 to 2 years from now.

- FDP cannot can not promise the use of phytoremediation, even if proven technically feasible, given the likelihood of better economics associated with the baseline technology (i.e., on-site excavation and landfilling). However, FDF personnel expressed interest in performing such a study as long as it was funded by someone else.

- FDF agreed to transmit readily available data tables and maps regarding U_t levels in soils for candidate sites within the northeastern corner of the historic production area. Once a suitable site was identified, a bulk soil sample will be provided to the BRS project team for performing laboratory/greenhouse treatability studies. If these initial tests produce encouraging results, an on-site field trial/technology demonstration would be considered by FDF and the regulators.

On April 2, 1998, MSE received an information package for the one (and only) potential location for a U_t phytoextraction study. As shown in Figure 3-1, this approximately 930 m^2 site lies in the northeast corner of the former production area. This tract is situated south of the new railroad staging area and north of the haul road to the onsite disposal facility (landfills). Total uranium levels within the upper 0.45 m of soil were predicted to range between 10 and 100 mg/kg, based on inspection of area-wide contaminant distribution maps (Ref. 16). MSE evaluated these materials and promptly identified an

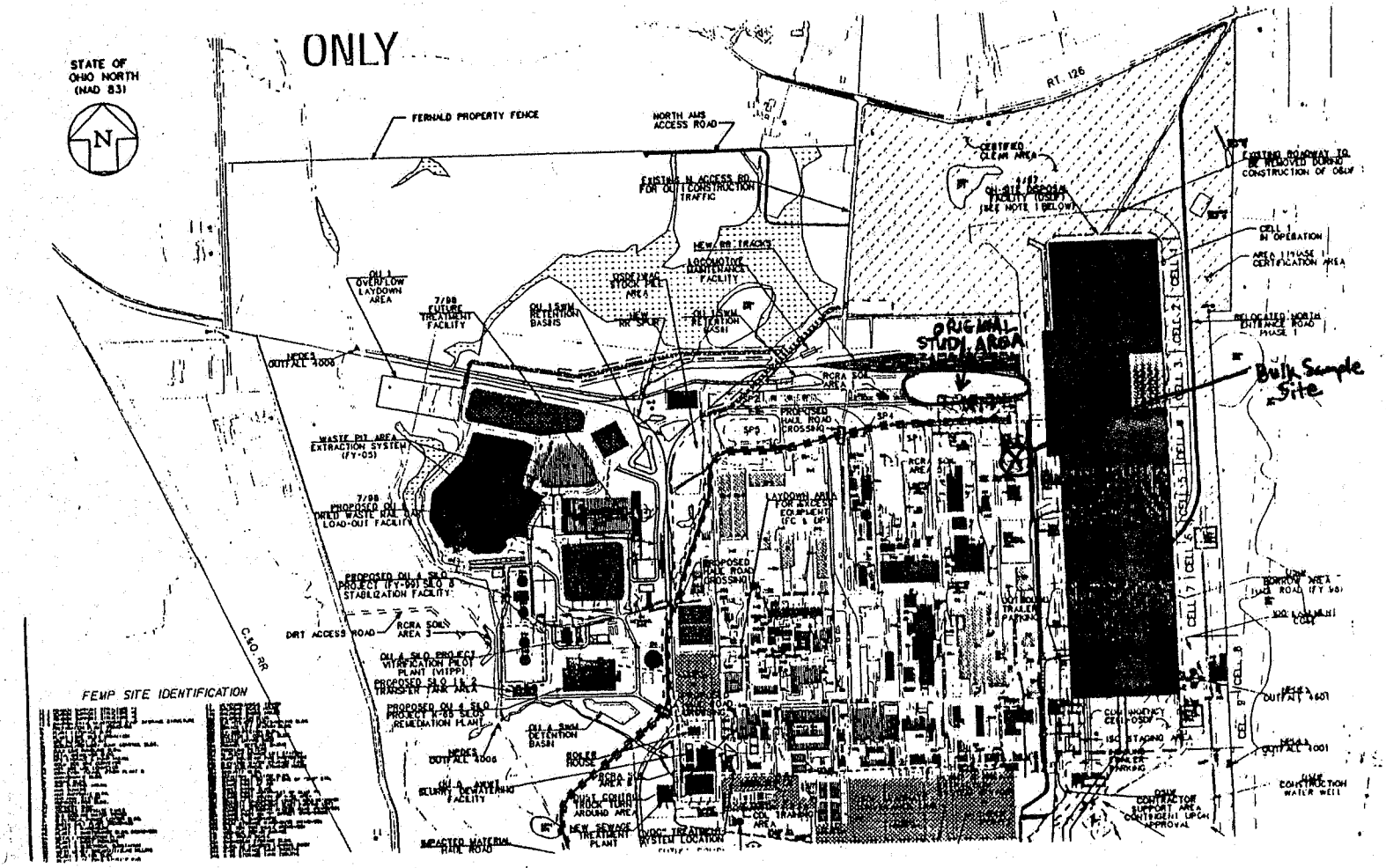


Figure 3-1. General location map for the U_t phytoextraction study at FEMP.

approximately 30-m by 15-m plot for the phytoextraction study. The proposed site location was conveyed to FDF on April 2, 1998 (Ref. 17). In this letter, MSE requested receipt of boring logs and/or analytical data relevant to the proposed site. Such information could be used to ensure that U_t levels were >20 mg/kg (i.e., the on-site cleanup level) in rooting zone soils and these soils could be tilled effectively. A suggested approach to acquisition of the bulk sample for off-site investigations by Phytotech, Inc. was also included in this correspondence. Other major accomplishments in April 1998 included preparation and submittal of the draft FWP (Ref. 18) and conceptual Work Plan (Ref. 19) to FDF/TP personnel.

Through a series of electronic mail and phone conversations occurring between mid-to-late April 1998, the Phase 1 Project-Specific Plan (PSP) was completed on May 1, 1998. In essence, the intent was the collection of three 0-cm to 15-cm soil cores from each of the three transects set within the 30-m by 15-m candidate plot. The nine (total) samples would be analyzed on site for ^{238}U levels via gamma spectroscopy [Method Detection Limit (MDL) approximately 5 mg/kg]; if all (or most) results are >20 mg/kg, the efforts would proceed to Phase 2. The Phase 2 PSP was completed on May 11, 1998. This plan envisioned a collection of three approximately 36.4-kg soil samples (0- to15-cm bgs) from each of the three previously established transects. Personnel from FEMP's Sample Management Group would then ship these materials to Phytotech, Inc. (Monmouth Junction, New Jersey). Once received, these soils would be used for completion of the laboratory and greenhouse U_t phytoextraction treatability studies. In mid-May 1998, it appeared as though the on-site sampling crew would be available to complete the Phase 1 work by early June.

The completed FWP (for provision of on-site support by FDF) was received at MSE on June 5, 1998. This document was passed along to DOE /Western Environmental Technology Office personnel for review and approval on June 9, 1998 (Ref. 20). After several additional postponements, the soil sampling crew from FEMP preformed a walkdown of the candidate plot (but outside of the radiation control fence) on June 29, 1998. However, MSE was informed by phone on July 2, 1998, that Phase I sampling would be delayed until mid-July and analytical results would not be available for a week or two thereafter. On July 15, 1998, MSE learned that the crew had attempted sampling the plot the day before. Given the weedy vegetation covering the site, it had not been evident that the upper 30 cm of the site and vicinity was composed almost entirely of coarse gravel. However, teleconference calls held on July 21 and 22, 1998, between FDF and MSE resulted in the identification of stockpiled soils that could be used for the off-site treatability studies at Phytotech. Details regarding the acquisition of the bulk sample are presented below.

3.1.1.2 Project Startup

The revised PSP (Ref. 21) was approved by FDF/Environmental Monitoring personnel on August 4, 1998 and implemented the next day by the sampling crew (Mr. John DeHo et. al). Approximately 103 kg (total) of stockpiled soils were collected in six 5-gallon pails at the site within Area 3, near the center of the former drum baling area and north of former Building No. 78 (see Figure 3-1). A shovel and 1.25-cm screen were used to collect soils from the upper 15 cm of the two piles. Buckets 1 and 2 were obtained from the sites located northeast of the high contamination area. Field beta/gamma surveys of these buckets indicated an average of 800 corrected counts per minute (ccpm) of fixed plus removable radioactivity. Buckets 3 through 6 were collected from an area situated approximately 23 m northwest of the first two buckets. The beta-gamma activity in these buckets averaged approximately 200 ccpm. A seventh soil sample was collected from Area 1 in a 120-mL glass bottle for on-site alpha/beta radionuclide screening.

The six containers were shipped from FEMP to Phytotech, Inc. on August 10, 1998, and arrived the next day. A small (approximately 14-kg) subsample of the homogenized materials from buckets nos. 3 through 6 was sent to USDA/Plant, Soil, and Nutrition Laboratory on August 28, 1998. Dr. Stephen Ebbs is using this soil for further investigation of acidification and chelating effects on uranium solubilization/plant uptake from contaminated soils (Ref. 22). This investigation will supplement the efforts found in Phytotech's contracted Scope of Work with MSE (Ref. 23).

The soil mixture from buckets 1 and 2 was sieved to -2 mm and stored in sealed containers until used for analysis. The soil mixture prepared from buckets 3 through 6 was prepared and stored in the same manner as above. Baseline analyses included pH and EC on 1:1 soil to water paste. Results of these analyses are presented and discussed in Section 3.2.1 and Appendix B.

3.1.2 Laboratory (U_t Extractability) Studies

The soil mixture from buckets 1 and 2 was sieved to -2 mm and stored in sealed containers prior to the analysis. Laboratory determinations included water extractable and acid extractable U_t levels (via Inductively Coupled Plasma Emission Spectrometry) as well as sequential extraction of U_t. The latter-most analysis was performed to assess chemical speciation and plant availability of U_t. Results of these analyses are presented and discussed in Section 3.2.1.

3.1.3 Greenhouse (Plant Uptake) Studies

Indian mustard [*Brassica juncea* (L.) Czern.], Chinese cabbage (*B. chinensis* L.) and redroot pigweed (A. *retroflexus L.*) plants were grown in the sieved/fertilized bulk composite soils (from FEMP) under controlled environmental conditions at Phytotech. Over a period of 4 weeks, plant growth was thinned from 10 plants down to 2 plants of equal size (and located on opposite sides) in each of the 9-cm diameter pots. At that time, the treatment regimen shown in Table 3-1 was implemented with three replications for each species times treatment combination.

Table 3-1. Soil amendments used in the greenhouse experiments with the representative FEMP site soil samples.

Treatment	Soil Amendments
Control	No soil amendments
Treatment 1	10 mM citric acid kg^{-1} soil
Treatment 2	20 mM citric acid kg^{-1} soil in combination with 20 mM sulfuric acid kg^{-1} soil
Treatment 3	20 mM citric acid kg^{-1} soil in combination with 25 μM Triton-X-kg^{-1} soil

Treatments 1 through 3 resulted in foaming at soil surface, probably due to reactions between the acidic amendments and carbonate minerals present in the soil. One week after application of the amendments, the plants were harvested, dried, and analyzed for their respective U_t contents. The analytical results are presented and discussed in Section 3.2.3 and Appendix B.

3.2 RESULTS AND INTERPRETATIONS

3.2.1 Baseline Soils Characterization

The pH values for 1:1 soil to water pastes from Location 1 (high contamination area) and Location 2 (low contamination area) were 7.1 and 7.0, respectively. Both of these soils had an EC of 0.5 dS m^{-1} (i.e., 0.5 mmho/cm) and are interpreted to be nonsaline in nature.

Average U_t concentration was higher at Location 1 (955 $\pm$ 91 mg/kg) compared to U_t at Location 2 (336 $\pm$ 1 mg/kg). Water extractable U_t levels in representative soil samples were 20 mg/kg and 2 mg/kg for Locations 1 and 2.

3.2.2 Evaluation of Phytoextractable Uranium

Plant availability of U_t in Locations 1 and 2 soils was evaluated using a five step sequential extraction procedure (Ref. 24). The average results for two replicates from each site are shown in Table 3-2 below.

Table 3-2. U_t fractionation in FEMP soils Locations 1 and 2 (in mg/kg).

Fraction	FEMP Soil, Location 1	FEMP Soil, Location 2
Exchangeable	0	0
Carbonate	396	115
Oxide	137	0
Organic	88	10
Residual	425	76
Total	1046	201

As expected for these carbonate-rich soils, the predominant forms of U_t are the carbonate and residual fractions. Addition of 20-mM citric acid/kg soil resulted in solubilization of 186 mg/kg U_t in Location 1 soil and 82 mg/kg U_t in Location 2 soil. These levels represent approximately 50 % and 75 % of the U_t associated with the exchangeable and carbonate fractions in soils 1 and 2.

3.2.3 Greenhouse Studies at Phytotech, Inc.

3.2.3.1 Plant Growth

Seed germination was 100 % for all three species, and the plants developed normally. Inspection of Figures 3 through 6 in Phytotech's report in Appendix B allows several observations to be made. First, the average production of dry biomass across all treatments was similar for Indian mustard (approximately 3.5 $\pm$ 0.4 g/pot) and Chinese cabbage (approximately 3.8 $\pm$ 0.8 g/pot); the slower growing pigweed averaged approximately 1.0 $\pm$ 0.7 g/pot. Second, the overall LSB production for the two Brassica species does not appear to be significantly affected by the type of soil treatment relative to the control results. However, the considerable difference in pigweed biomass production between soil Locations 1 and 2 may imply that the former is phytotoxic to this species (see Phytotech report, Figure 5 in Appendix B).

3.2.3.2 U_t Uptake by Plants

The species x treatment results for U_t uptake are summarized in Table 3-3. Raw data is found in the Phytotech report (Appendix B). Two observations can be made from this data. First, the pigweed generally accumulates the greatest amount of U_t into aboveground biomass, especially when grown in the more contaminated (Location 1) soils. Secondly, plant-available U_t is increased through soil acidification with H_2SO_4. The addition of this strong acid probably converts the uranyl-carbonate forms to the more bioavailable cation (UO_2^{+2}) as shown in previous work by the USDA (Ref. 9).

Table 3-3. Average uranium concentrations in LSB from plants grown in the FEMP site soil samples. [a]

Species	Treatment	Uranium Concentration in Plants (mg/kg) [b]	
		Location 1	Location 2
Indian mustard	Control	<MDL	<MDL
	Treatment 1	<MDL	<MDL
	Treatment 2	77 ± 16	<MDL
	Treatment 3	<MDL	<MDL
Chinese cabbage	Control	<MDL	<MDL
	Treatment 1	<MDL	<MDL
	Treatment 2	144 ± 35	84 ± 44
	Treatment 3	76 ± 45	<MDL
Amaranth (Redroot pigweed)	Control	<MDL	<MDL
	Treatment 1	429 ±122	<MDL
	Treatment 2	941 ± 496	77 ± 39
	Treatment 3	899 ± 168	<MDL

Note: [a] **See Table 3-1 for description of the treatment regimens.**
[b] **MDL = 50 mg/kg.**

4. CONCLUSIONS AND RECOMMENDATIONS

4.1 RADIOCESIUM (^{137}Cs)

4.1.1 Conclusions

In estimating the time required for exponential removal of soil contaminants (Equation 1, p.1), a constant rate of mass transfer from soil to LSB is assumed. Such a rate requires sustained contaminant bioavailability over an acceptable time interval (e.g., 5-7 years; Figure 1-2) for effective soil phytoremediation. This principal issue regarding use of phytoextraction technology is discussed further in Section 1.1.2.

Average CR (2.7) for the first (July 1998) crop of redroot pigweed (*Amaranthus retroflexus* L.) from the D plot was of similar magnitude to the average CR (2.5) observed for the USDA subplot at the HWMF in October 1996. As both soil sources originated at the former HWMF, the reproducibility of these results is satisfying. However, the CRs for the second (October 1998) crop had fallen to between 0.06 and 0.7. This range in CRs for ^{137}Cs is typical of values observed for "aged" soils throughout the world (Ref. 6). It is suggested that the reservoir of plant-available ^{137}Cs was quickly depleted by the first crop of biomass. This hypothesis is supported by the observed removal of approximately 2,400 nCi of ^{137}Cs in 19.5 kg of dry LSB in the first crop vs. 561 nCi of ^{137}Cs in 20.5 kg of dry LSB in the second crop. Therefore, application of the "exponential model" for ^{137}Cs phytoextraction cannot be applied to the present study results. The more correct view appears to be a "hockey stick" model for this particular radionuclide.

Transfer of ^{137}Cs from D-plot soils (approximately 4.5 by 10^6 nCi) to LSB represents approximately 0.06 % of the radionuclide loading present in the rooting zone soil volume. A very similar result was observed for the E plot. Total dry LSB accumulated approximately 1.2×10^{-3} mCi of ^{137}Cs from approximately 1.9 mCi of ^{137}Cs in rooting zone soils. In both plots, the removal of this contaminant by plants is only a small fraction of that lost through radioactive decay (i.e., 2.3 % $year^{-1}$).

The overall conclusion is that the performance goals (Section 1.3.1) for demonstrating commercial viability of ^{137}Cs phytoextraction were not met by this study.

4.1.2 Recommendations

Given that phytoextraction of even 25 % of ^{137}Cs from "aged" soils appears to be a lofty goal, near-term use of this technology should be confined to rooting zone soils having less than 125 % of the risk-based cleanup level (e.g., 23 pCi/g soil for residential reuse). Selection of target sites could be screened further using various extraction schemes for estimating overall bioavailability of ^{137}Cs in the particular soil (Refs. 25 and 26). Furthermore, site-specific multicrop treatability studies should include large diameter pots ($\geq$10 kg soil capacity) and field plots, as the results from greenhouse studies are not necessarily transferable to a field setting (e.g., Section 2.2.4). Finally, other combinations of species x treatments may prove more useful than those evaluated here. For example, Summer Cypress [Kochia scoparia (L.) Schrad.] x 0.25M NH_4NO_3 resulted in ^{137}Cs transfer rates of 0.88 % in LSB and 1.5 % in whole plants when grown in soils (9.9 pCi/g average ^{137}Cs) collected at Argonne National Laboratory-West (Ref. 25).

4.2. Total Uranium (U_t)

4.2.1 Conclusions

Phytotech, Inc. performed U_t phytoextraction feasibility studies on two soil sources collected at the FEMP site between early August and late October 1998. Location 1 (high contamination) soils contained approximately 955 mg/kg of acid extractable U_t, and Location 2 (low contamination) soils contained approximately 336 mg/kg of acid extractable U_t. Sequential extraction of these soils indicted that approximately 50 and 25 %, respectively, of the U_t in Locations 1 and 2 soils occurred in potentially plant available forms of this element. Combined use of 20-mM citric acid and 20 mM sulfuric acid/kg of Location 1 soil resulted in accumulation of up to 1,347 mg/kg in dry LSB of redroot pigweed (*A. retroflexus* L).

Results from the present study indicate a relatively low rate of U_t mass transfer from potting soil to plant LSB as viewed from a technology commercialization perspective. For example, each pot of soil from Location 1 contains 0.330 kg soil (Appendix B, p. 17) times 955 mg U_t /kg soil (Appendix B, p.13). The resulting U_t content is thus approximately 315 mg/pot. Regarding plant uptake of U_t, the best result is calculated by multiplying 2.9 g DW/pot (Appendix B, p. 20) times 1,347 mg U_t /kg dry LSB (Appendix B, p. 23). The resulting U_t content is thus approximately 3.9 mg/pot. Therefore, the U_t transferred per "crop" is calculated to be [(3.9 / 315) * 100] or approximately1.2 %.

The key to effective phytoextraction of U_t is a continuous reservoir of bioavailable (i.e., exchangeable and carbonate-bound) forms of this element in rooting zone soils. Although the maximum CR (1.4) is not particularly large, it is at least one order of magnitude greater than that commonly observed in nature. Furthermore, the high proportion of carbonate forms in FEMP soils are probably amenable to controlled U_t dissolution by acidic amendments for subsequent uptake by plants. It is suggested that long-term conversion of uranyl-carbonates (UO_2^{+2}) to free or complexed (citrate-U) ions could contribute to cleanup of marginally contaminated soils (i.e., where U_t levels are $\leq$125 % of the risk-based cleanup level). However, it may still require three crops per year, grown over 7 years, to remediate even these types of sites.

4.2.2 Recommendations

Given the potential for commercial deployment of U_t phytoextraction in the near term (1 to 3 years), further optimization of soil amendment formulations x species combinations seems reasonable. Given the large areas of U_t-contaminated soils throughout the world, much of which is slightly above regulatory cleanup levels, such work as performed on FEMP soils should continue to be supported in the future.

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CLIENT: RADIOCESIUM (JAY CORNISH)
FIELD ID: BNL-1
LAB ID: S009056
DATE/TIME SAMPLED: 06/22/98/N/A
DATE RECEIVED: 07/13/98
BIF: 004445

Alkalinity	30.0	mg/L
Chloride	16.6	mg/L
EC	221	µmhos
Eh	288	mV
Nitrate/Nitrite-N	3.9	mg/L
pH	5.80	SU
Phosphate Ortho	0.85	mg/L
Sulfate	53	mg/L
Total Organic Carbon (TOC)	1.62	%

Results were from a 1:1 extract.

MS
Review

CLIENT: RADIOCESIUM (JAY CORNISH)
FIELD ID: BNL-2
LAB ID: S009057
DATE/TIME SAMPLED: 06/22/98/N/A
DATE RECEIVED: 07/13/98
BIF: 004445

Alkalinity	32.2	mg/L
Chloride	13.3	mg/L
EC	185	µmhos
Eh	349	mV
Nitrate/Nitrite-N	5.0	mg/L
pH	5.92	SU
Phosphate Ortho	1.36	mg/L
Sulfate	56	mg/L
Total Organic Carbon (TOC)	1.60	%

Results were from a 1:1 extract.

IMS
Review

Radiocesium J. Cornish
Cation Exchange Capacity (CEC)
MSE Batch: 3064
Results in meq./100 g (as-received basis)
BIF: 4445

SAMPLE ID	FIELD ID	meq./100 g
IDL		0.001
S009056	BNL-1	15.60
S009057	BNL-2	11.54

CAM
Review

RADIOCESIUM J. CORNISH
(1:1) Dissolved Metals
MSE Batch No.: 3063
Results in ug/L

SAMPLE ID	FIELD ID	Al	Ca	Fe	Mg	Mn	K	Na
IDL		16.6	10.3	10.9	9.4	2.3	16.7	7.3
S009056	BNL-1	5870	23100	1910	5020	417	3460 B	4430 B
S009057	BNL-2	5480	25200	1850	5410	419	3460 B	4610 B

CAM
Review

P-4

RADIOCESIUM J. CORNISH
QA/QC SUMMARY
MSE Batch No.: 3063
Results in ug/L

SAMPLE ID	FIELD ID	Al	Ca	Fe	Mg	Mn	K	Na
IDL		16.6	10.3	10.9	9.4	2.3	16.7	7.3
LRB1 #3063		16.6 U	10.3 U	10.9 U	9.4 U	2.3 U	16.7 U	7.3 U
QCS1 #3063		1056.00	1116.00 B	539.00	1040.00 B	520.00	932.00 B	970.00 B
% RECOVERY		105.6	111.6	107.8	104.0	104.0	93.2	97.0
S009056	BNL-1	5872.00	23101.00	1914.00	5018.00	417.00	3462.00 B	4433.00 B
S009056R	BNL-1R	5818.00	22831.00	1892.00	4991.00 B	409.00	3460.00 B	4412.00 B
RPD		0.9	1.2	1.2	0.5	1.9	0.1	0.5
S009056	BNL-1	5872.00	23101.00	1914.00	5018.00	417.00	3462.00 B	4433.00 B
S009056A	BNL-1A	7763.00	24223.00	2833.00	7019.00	1410.00	5736.00	6654.00
% RECOVERY		94.6	N/A	91.9	100.1	99.3	113.7	111.1

CAM
Review

CLIENT: RADIOCESIUM (JAY CORNISH)
FIELD ID: BNL-1
LAB ID: S009056
DATE/TIME SAMPLED: 06/22/98/N/A
DATE RECEIVED: 07/13/98
BIF: 004445

TEXTURE

Sand	76.0	%
Silt	22.0	%
Clay	2.0	%
Texture	Loamy Sand	

Review

CLIENT: RADIOCESIUM (JAY CORNISH)
FIELD ID: BNL-2
LAB ID: S009057
DATE/TIME SAMPLED: 06/22/98/N/A
DATE RECEIVED: 07/13/98
BIF: 004445

TEXTURE

Sand	76.0	%
Silt	22.0	%
Clay	2.0	%
Texture	Loamy Sand	

Review

Results

	B. juncea pCi/g	R[1]	cabbage pCi/g	R	*A. retroflexus* pCi/g	R	*A. aureus* pCi/g	R	observations
Control	350	1.3	300	1.1	387	1.4	713	2.6	*Amaranthus* N-deffient ?
RbCl	281	1.0	229	0.8	422	1.5	458	1.7	*Amaranthus* N-deffient ?
NH_4NO_3	411	1.5	376	1.4	440	1.6	793	2.9	
CsCl	662	2.4	440	1.6	616	2.2	1038	3.8	very toxic
Humic acid	334	1.2	176	0.6	704	2.6	880	3.2	
Mix	633	2.3	317	1.2	739	2.7	1020	3.7	
$\bar{x}$	445	1.6	306	1.1	551	2.0	817	3.0	
± sd	162	0.6	96	0.4	154	0.6	216	0.8	

Mitch will send us data (soil, & harvest) each of 18 pots early next week 10/91

	^{137}Cs	R
Control	438 ± 187	1.6 ± 0.7
RbCl	348 ± 110	1.2 ± 0.4
NH_4NO_3	505 ± 194	1.8 ± 0.7
CsCl	689 ± 252	2.5 ± 0.9
Humic acid	524 ± 325	1.9 ± 1.2
Mix	677 ± 290	2.5 ± 1.0

[1] Biotransfer ratio

FAX TRANSMITTAL # of pages ▸ 1

To	From
JAY CORNISH	MITCH LASAT
Dept./Agency MSE	Phone # 661-235-2133
Fax # 406-494-7230	Fax # 661-235-1132

NSN 7540-01-317-7368 5099-101 GENERAL SERVICES ADMINISTRATION

Jay,
As promised, here is the rest of the data.

	B. juncea		cabbage		*A. retroflexus*		*A. aureus*	
	DW (g)	pCi/g	DW (g)	pCi/g	DW (g)	pCi/g	DW (g)	pCi/g
Control								
Rep 1	27.8	380	23.3	275	1.9	360	11.5	755
Rep 2	35.6	315	17.7	270	6.4	370	8.6	710
Rep 3	28.3	355	28.3	355	5.2	430	7.1	675
RbCl								
Rep 1	32.4	265	16.4	236	6.9	387	5.1	447
Rep 2	30.2	328	10.5	214	6.9	438	11.4	495
Rep 3	24.3	250	9.8	237	8.1	441	7.7	432
NH_4NO_3								
Rep 1	30.8	448	26.4	412	15.5	377	11.5	766
Rep 2	51.6	422	-	-	9.0	461	11.5	922
Rep 3	43.0	363	18.9	340	17.2	482	7.0	691
CsCl								
Rep 1	7.0	592	9.4	512	2.7	614	3.2	1248
Rep 2	3.4	812	3.5	505	1.0	713	4.8	954
Rep 3	5.1	582	10.8	303	1.7	521	4.0	912
Humic acid								
Rep 1	40.8	287	26.5	144	2.5	912	12.6	793
Rep 2	47.2	252	31.2	236	3.5	701	7.4	1176
Rep 3	56.3	463	24.3	148	7.0	499	12.6	671
Mix								
Rep 1	57.7	514	10.6	502	2.9	948	11.3	759
Rep 2	49.2	767	13.2	290	10.6	552	9.8	980
Rep 3	42.1	618	9.3	160	2.7	717	6.1	1321

Grass and weed and soil samples taken along edge of Parking lot at 490 on 5/2/98									
For locations see Phyto notebook.									
Sample Name	Sample date	Type	Count weight	Cs-137 cnts	Detector	time (min)	CPM/g	pCi/g	Factor
Spot 1	"5/2/98	Coarse grass	2.77	46	3	100	0.17	5.50	0.04
Spot 2	"5/2/98	Coarse grass	3.27	591	3	1000	0.18	5.98	0.02
Spot 3	"5/2/98	Fine grass	2.06	524	3	1000	0.25	8.42	0.13
Spot 4	"5/2/98	Coarse grass	2.86	149	3	1000	0.05	1.72	0.02
Spot 5	"5/2/98	low broadleaf	2.24	114	3	240	0.21	7.02	0.04
Spot 1	"5/2/98	soil	11.43	1284	3	30	3.74	123.94	
Spot 2	"5/2/98	soil	8.92	1980	3	30	7.40	244.91	
Spot 3	"5/2/98	soil	11.83	717	3	30	2.02	66.87	
Spot 4	"5/2/98	soil	8.52	642	3	30	2.51	83.14	
Spot 5	"5/2/98	soil	13.68	2026	3	30	4.94	163.40	

typical CRS"

A-10

red soybean

plants

Plants and matching soil from the first crop of Amaranthus and weeds.
Multiply MCA-3 by 1.44 to equate it with MCA-1

Efficiency correction of MCA #1 = factor of 22.3, for MCA #3 = 32

Sample Name	Sample date	Type	Description	Location	weight	Cs-137 cnts	Detector	time (min)	CPM/g	pCi/g	Uptake Factor
Phyto plant 1	7/20/98	Amaranth	1 plant 14"	2, 0.5	4.02	1295	1	240	1.34	29.93	7.04042
soil 1					18.32	221	1	60	0.19	4.25	
Phyto plant 2	7/20/98	Amaranth	10 plants yellowed	2,1.3	2.57	116	1	120	0.38	8.39	1.929648
soil 2					19.11	447	1	120	0.19	4.35	
Phyto plant 3	7/20/98	Amaranth	21 plants 1-3"	2, 2.6	1.74	335	1	1000	0.19	4.29	1.691983
soil 3					19.7	269	1	120	0.11	2.54	
Phyto plant 4	7/20/98	Amaranth	20 plants green small	2, 4	2.46	396	1	60	2.68	59.83	2.823946
soil 4					18.49	1054	1	60	0.95	21.19	
Phyto plant 5	7/20/98	Amaranth	20 plants max= 6"	2, 6	2.56	975	1	85	5.86	130.66	2.436935
soil 5					17.26	2490	1	60	2.40	53.62	
Phyto plant 6	7/23/98	Amaranth	2 plants, 12" about to flower	2.5, 1.5	3.44	3368	1	60	16.32	363.89	2.159906
soil 6					16.4	1239	1	10	7.55	168.47	
Phyto plant 7	7/23/98	Amaranth	13 poor plants, base of #8	4.2, 8	2.69	1233	1	60	7.64	170.36	1.642558
soil 7					12.7	3544	1	60	4.65	103.72	
Phyto plant 8	7/23/98	Amaranth	Big 36" flowering	4.2, 8	3.36	2756	1	60	13.67	304.86	3.389315
soil 8					19.83	4799	1	60	4.03	89.95	
Phyto plant 9	7/23/98	Amaranth	good, 14" in grass	1, 3.7	1.5	108	3	60	1.20	38.53	3.42383
soil 9					22.35	1128	1	100	0.50	11.25	
Phyto plant 10	7/23/98	Amaranth	21 plants yellow, crowded	0.5, 2.7	2.21	25	1	60	0.19	4.20	2.335326
soil 10					15.38	149	1	120	0.08	1.80	
Phyto plant 11	7/29/98	Amaranth	4 plants, poor roots	4, 5.7	8.39	1499	3	25	7.15	229.49	1.583625
soil 11					15.57	3016	1	30	6.46	143.99	
plant 11 seedhead					0.7	3438	3	240	20.46	657.15	
Phyto plant 12	7/29/98	Amaranth	2 plants, seed	2, 0.5	7.26	1145	1	240	0.66	14.65	2.431317
soil 12					16.23	1316	1	300	0.27	6.03	
Plant 12 seedhead					2.04	2292	1	1000	1.12	25.05	
										0.00	
weed 1	7/20/98		large, lavender flowers	1, 6.5	15.1	703	1	120	0.39	8.65	0.435025
soil weed 1					15.1	808	1	60	0.89	19.89	
weed 2	7/23/98		big, 10% taken,	1.5, 8	3.25	548	3	60	2.81	90.24	2.601865
soil weed 2					14.28	2221	1	100	1.56	34.68	
weed 3	7/23/98		big, 34" not much mass	3, 8	1.54	1133	3	60	12.26	393.75	2.297593
soil weed 3					14.86	1713	1	15	7.69	171.36	
weed 4	7/23/98		grass	6, 5	3.96	512	1	60	2.15	48.05	0.318297
soil weed 4					17.01	27638	1	240	6.77	150.97	
weed 5				6, 5	3.57	1194	3	1000	0.33	10.74	0.188185
soil weed 5					17.27	1127	1	25.5	2.56	57.07	
Standard #1 VEBN			EML vegetation secondary		6.59	7547	1	1000	1.15	25.54	
Standard #2 VEBN			EML vegetation secondary		9.85	7293	3	1000	0.73	23.54	
Standard #1 VEBN			EML vegetation secondary		6.59	5287	3	1000	0.80	25.76	
Standard #2 VEBN			EML vegetation secondary		9.95	9600	1	1000	0.98	21.96	

regression of 12 Amaranthus Data $r^2 = 0.881$
intercept = 13.3 Slope = 1.96

type	sample	pole coord	Northing	Easting	Cs-137 pCi/g
Amar soil	1	2, 0.5	17.2	4	4.25
	2	2,1.3	17.2	10.5	4.35
	3	2, 2.6	17.2	25.3	2.54
	4	2, 4	17.2	40	21.2
	5	2, 6	17.2	59.5	53.6
	6	2.5, 1.5	49.5	49.5	168.5
	7	4.2, 8	33	78	103.7
	8	4.2, 8	33	78	90
	9	1, 3.7	8	37.5	38.5
	10	0.5, 2.7	4	27.5	1.8
	11	4, 5.7	32	57.5	144
	12	2, 0.5	17	49.5	6
weed soil	w1	1, 6.5	8.5	65	19.9
	w2	1.5, 8	15	78	34.7
	w3	3, 6	17	59	171
	w4	6, 5	49.5	49.5	151
core 3			8	40.8	16.4
core 11			40.8	73.6	84.3
core 13			40.8	40.8	41
core 15			40.8	8	165
Core 7			50	87	100
			0	87	20
			0	0	0

A-12

Samples of soil from E-plot taken before planting in cells								
	Soil + cup		dry soil	drysoil	Cs-137	Time		Cs-137
Sample	Wet Wt	Cup Wt	& cup	weight g	counts	minutes	detector	pCi/g
9,3	40.45	18.4	38.77	20.37	827	60	1	15.09
5,0	38.12	18.03	35.26	17.23	2698	30	3	172.77
19,2	38.54	17.41	36.32	18.91	2130	15	1	167.46
10,1	39.85	18.5	36.81	18.31	2897	15	1	235.22
17,2	38.88	18.29	35.95	17.66	8933	60	1	188.00
15,3	42.42	17.65	39.93	22.28	2036	26	1	78.38
12,1	37.07	18.32	34.43	16.11	1997	20	1	138.22
7,2	37.92	18.37	36.48	18.11	3197	120	1	32.81
0,3	35.73	18.16	33.68	15.52	828	120	3	14.72
14,2	41.46	18.26	39.25	20.99	1686	60	3	44.31
2,1	38.8	18.25	36.24	17.99	3721	60	1	76.87
4,2	38.99	18.33	36.75	18.42	900	30	3	53.91
9,1	23.11	11.73	21.64	9.91	776	30	3	86.40
0,0	23.73	11.86	21.81	9.95	650	30	3	72.08
14,0	24.98	11.93	23.46	11.53	609	30	3	58.26
19,0	22.74	11.82	21.68	9.86	1085	30	3	121.41
7,0	22.22	11.75	20.79	9.04	1623	30	3	198.09
15,1	24.07	11.95	22.71	10.76	1592	30	3	163.24
						for location the 0 x 0 pole is the n		

Post-it® Fax Note 7671 | Date | # of pages ▶
To [illegible] Jay Gepnish | From Fuhrmann
Co./Dept. | Co.
Phone # | Phone #
Fax # | Fax #

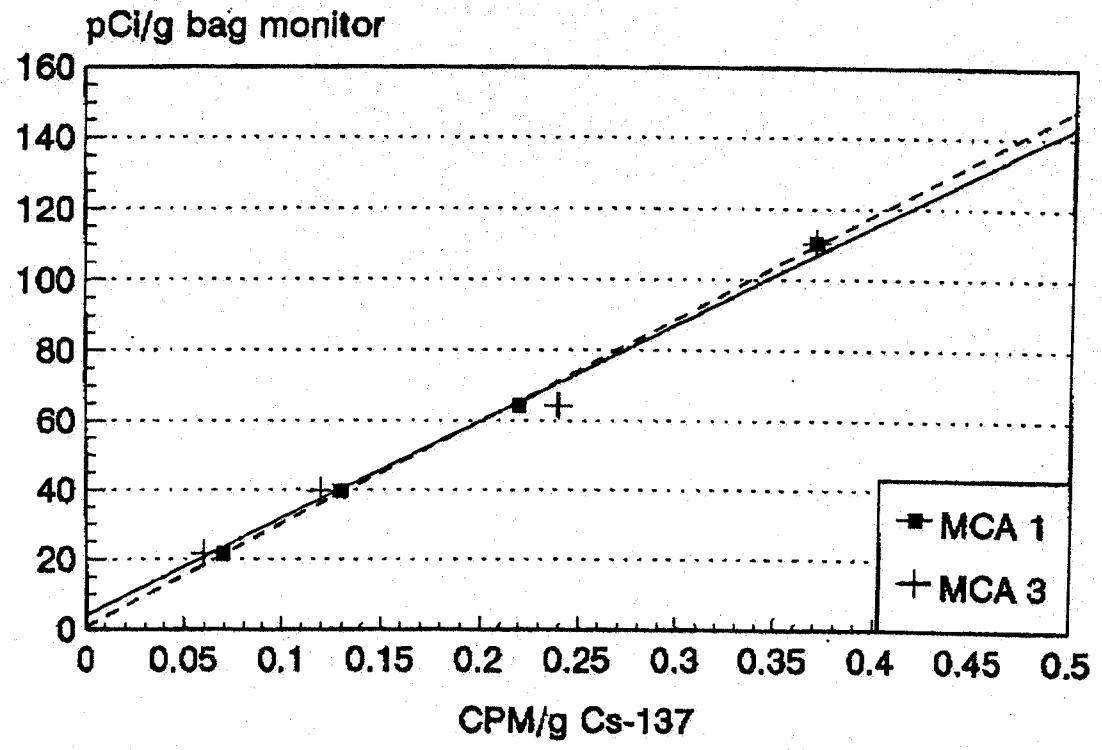
This is counting data from gamma detectors for lower level plants from the E-plot											
Samples were pressed to 1000 pounds in a mold and counted, then turned upside down in the container and recounted										J and K are wrong	
								average			
Location	Description	WT	dry Wt	counts A	counts B	MCA	Time (min)	cpm/g	pCi/g	total nCi	
		Gross	plants	Cs-137	Cs-137			Cs-137	Cs-137	Cs-137	
7,1	T A1	131.18	82.9	780	742	1	60	0.15	45.8	3.8	
19,2	M C	248	165	1789	1376	1	30	0.32	95.0	15.7	
13,0 cal	AC	252.9	170	1141	1350	1	30	0.24	72.7	12.4	
9,2	C B	201.4	153.1	124	828	1	300	0.01	3.8	0.6	
13,1	C C	234.9	151.9	1109	924	1	30	0.22	66.5	10.1	
3,1 cal	M C	337.8	289.5	1256	994	1	30	0.13	38.9	11.3	
4,2	A B	137.7	89.4	534	428	1	120	0.04	14.0	1.2	
6,2	C A3	111.6	63.3	1573	1036	1	120	0.17	51.4	3.3	
18,1	A C		170	9407	8336	1	60	0.87	257.0	43.7	
7,3	A A3	129.3	81	1217	1643	1	400	0.04	13.8	1.1	
0,3	T A1	374.7	326.4	327	344	1	120	0.01	3.3	1.1	
12,1 cal	A A3 cal		159.6	6595	7676	1	120	0.37	110.5	17.6	
5,3	A C		67.7	774	653	1	60	0.18	52.5	3.6	
6,3	A A2		86.5	2715	2471	1	500	0.06	18.4	1.6	
12,3	T A3	274.2	209	800	643	1	120	0.03	9.2	1.9	
11,2 cal			304	1300	1187	1	60	0.07	20.9	6.3	
10,3	T C	235.6	152.6	896	746	1	120	0.04	14.0	2.1	
2,0	C A2	157.4	109.1	520	339	3	50	0.08	25.9	2.8	
5,0	M A3	182.6	134.3	1031	806	3	60	0.11	35.7	4.8	
14,2	M A3	184.5	119.5	2295	715	3	30	0.42	120.8	14.4	
3,4	T B		83.75	1196		3	300	0.02	10.6	0.9	
8,3	A B	152.2	103.9	37	30	3	100	0.00	4.9	0.5	
2,3	T A3	213.4	165.1	509	472	3	100	0.03	12.2	2.0	
13,0 cal	A C		170	1016	1179	3	30	0.22	63.9	10.9	
1,3	T A2	264.5	216.2	294	319	3	100	0.01	7.9	1.7	
3,1 cal	M C		289.5	1007	1118	3	30	0.12	38.0	11.0	
8,0	M B	221.7	173.4	679	951	3	120	0.04	14.9	2.6	
17,0	T C		199.7	4070	3099	3	90	0.20	59.5	11.9	
8,1	T B	162.9	114.6	856	558	3	300	0.02	9.7	1.1	
2,2	A A3		203.7	3265	2685	3	300	0.05	17.5	3.6	
12,1 cal	A A3 cal		159.6	4106	2929	3	60	0.37	106.2	17.0	
4,1	M B	187.5	139.2	432	408	3	120	0.03	11.0	1.5	
14,3	T A3		150	1524	1647	3	400	0.03	11.3	1.7	
1,2	A A2	253.1	204.8	448	669	3	120	0.02	10.3	2.1	
9,3	A A1		79.6	365	228	3	120	0.03	12.6	1.0	
13,3	T A1	300.1	235.1	1242	1252	3	120	0.04	16.3	3.8	
11,2 cal			304	1164	1070	3	60	0.06	21.0	6.4	

Counting data from the Bag Monitor in Building 208					Tare for type bag #2 = 65 g	
Data for the Experimental plot 10/98					Tare for type bag # 3 = 83 g	
			plant	type	Cs-137	Cs-137 nCi
Location	Description	gross dry Wt	Dry Wt	bag	nCi raw	corrected
0,0	C A1	302.5	254.2	1	24.7	23.9
0,1	C A2	369.3	321	1	26.9	26.1
0,2	A A1	370.4	322.1	1	6.4	5.6
1,1	M A2	508.7	460.4	1	7.3	6.5
2,1	M A3	267.2	218.9	1	7.7	6.9
3,0	C C	410	361.7	1	29.8	29.0
3,2	A C	138.2	89.9	1	7.3	6.5
3,3	T C	286.4	238.1	1	3.04	2.2
4,0	C b	248.7	200.4	1	9.7	8.9
10,0	A B	343.2	278.2	2	21.7	20.9
10,1	C B	329.9	264.9	2	11.8	11.0
10,2	M A3	227.9	162.9	2	7.6	6.8
11,0	A A2	305.9	240.9	2	51.5	50.7
11,1	C A2	264.3	199.3	2	17	16.2
11,2	M B	369	304	2	7.4	6.6
11,3	T B	383.1	318.1	2	0.3	-0.5
12,0	A A1	424.4	359.4	2	31.2	30.4
12,1	C A3 cal	224.6	159.6	2	18.4	17.6
13,2	M A1	267.9	202.9	2	12.5	11.7
14,0	A A3	226.4	161.4	2	9.7	8.9
14,1	C A1	300.5	235.5	2	28	27.2
15,0	T A1	396.2	331.2	2	25.5	24.7
15,1	A B	238.1	173.1	2	7	6.2
15,2	M A2	291.5	226.5	2	15.7	14.9
16,0	T A3	451.2	386.2	2	25.7	24.9
16,1	A A2	291.5	226.5	2	19.9	19.1
16,2	M B	305.7	240.7	2	12.5	11.7
16,3	C B	301.9	236.9	2	13.9	13.1
17,1	A A3	149.5	84.5	2	17	16.2
17,2	M A1	280.7	215.7	2	27.3	26.5
17,3	C A3	240	175	2	23.5	22.7
18,0	T A2	310.8	245.8	2	8.6	7.8
18,2	M A3	245	180	2	24	23.2
18,3	C A1	304.1	239.1	2	32.7	31.9
19,0	T B	380.3	315.3	2	12.2	11.4
19,1	A A1	286.2	221.2	2	48	47.2
19,3	C A2	273.1	208.1	2	11.2	10.4
2,0	C A3	231.9	166.9	2	20.9	20.1
20,1	C A1	307	242	2	28.5	27.7
20,2	C A1	310.1	245.1	2	21.1	20.3
21,0	C A2	424.4	359.4	2	50.9	50.1
21,1	C B	415.1	350.1	2	20	19.2
21,3	C A2	332.4	267.4	2	17.6	16.8
9,0	M A1	328.1	263.1	2	14.8	14.0
9,1	T A2	315	250	2	9.4	8.6
12,2	M C	348.1	265.1	3	14.4	13.6
15,3	C C	252	169	3	15.3	14.5
20,0	C C	351.6	268.6	3	15.1	14.3

20,3	C C	470.3	387.3	3	13.8	13.0
21,2	C C	376.1	293.1	3	14.4	13.6
5,1	T C	196.5	113.5	3	10	9.2
7,2	C C	169	86	3	3.2	2.4
6,0	M C	254	171	3	20.3	19.5
13,0	A C intercal	252.9	169.9	p	11.76	10.9
3,1	M C intercal	337.8	289.5	p	12.3	11.5
1,0	M A1	382.6	334.3		7.26	6.4
Blank 1					0	
blank 2					1.08	
blank 3					1.51	
blank 5					0.93	
blank 6					1.19	
blank 7					1.03	
blank 8					0.44	
blank 9					0.66	
blank4					0.73	
					average = 0.84	

Detector Intercalibration for Large Geometry Plant Samples

11/17/98



MCA 1; slope = 294.6; y-int = 0.77; R^2 = 0.999
MCA 2; slope = 278.4; y-int = 3.97; R^2 = 0.987

HG file = MCABAG

Figure A-1. Detector Intercalibration Plot for Large Geometry Plant Samples

APPENDIX B

FEMP-RELATED
Phytotech, Inc. Final Report

Phytotech

FINAL

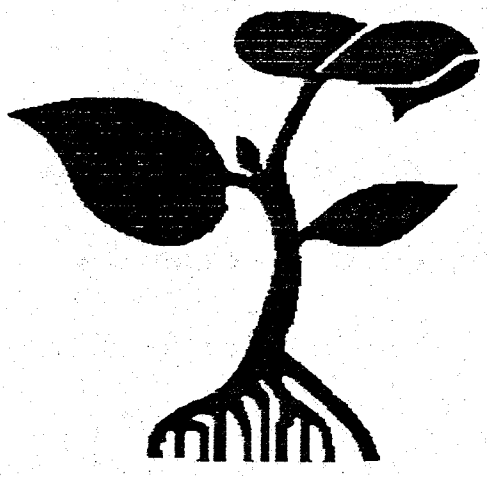
Phytoremediation of Uranium Contaminated Soils at the Fernald Environmental Management Project Site

RFP: No. A69140

Project No: 98019

Prepared by:
Phytotech, Inc.
1 Deer Park Drive, Suite I
Monmouth Junction, NJ 08852

Prepared for:
MSE Technology Applications, Inc.
P.O. Box 4078
Butte MT 59702



NOVEMBER 1998

Phytotech

FINAL

Phytoremediation of Uranium Contaminated Soils at the Fernald Environmental Management Project Site

RFP: No. A69140

Project No: 98019

Principal Investigator: Slavik Dushenkov, Ph.D.

Co-investigator: Mark Elless, Ph.D.

Greenhouse Project Manager: Christopher Gussman

Field Project Manager: Buck Rogers

Technician: Michael Lifton

Research Director: Cindy Orser, Ph.D.

Clerical: Kathy Makowski

NOVEMBER 1998

EXECUTIVE SUMMARY

The scope of the Fernald Environmental Management Project (FEMP) is the implementation of full-scale environmental remediation and waste management activities at an inactive uranium processing facility located near the village of Fernald in Southwestern Ohio. Phytoextraction is used to reduce the concentration of contaminants in the soil to below regulatory standards. The main idea of phytoextraction is to exploit a plant's natural ability to accumulate elements of interest, e. g. remove them from the soil and concentrate in plant tissues.

Soil characterization and greenhouse experiments were performed on two representative bulk soil samples obtained from the FEMP site. The representative soil samples had near neutral pH and an EC at 0.50 dS m^{-1}. Average U concentrations were 955 mg kg^{-1} (20 mg kg^{-1} water soluble) and 336 mg kg^{-1} (2 mg kg^{-1} water soluble) for Location 1 (high contamination area) and Location 2 (low contamination area) soil, respectively.

The majority of U was associated potentially with the plant available soil chemical fractions. However, no exchangeable U was detected and the acid-extractable residual fraction (i.e. that which can not be targeted by phytoremediation) constitutes 41% in the Location 1 representative soil sample and 38% in the Location 2 representative soil sample. Citric acid-extractable U in Location 1 representative soil sample averaged 186 mg U kg^{-1} soil, which represents approximately 20% of the total U content and approximately 50% of the uranium associated with the exchangeable and carbonate fractions, the two fractions considered the most labile and available fractions for plant uptake. Citric acid-extractable U in the Location 2 representative soil sample

averaged 82 mg U kg^{-1} soil, which represents approximately 25% of the total U content and approximately 75% of the uranium associated with the exchangeable and carbonate fractions.

The composite representative FEMP site soil samples from both locations were capable of supporting good plant growth under agricultural practices developed by Phytotech.

Application of soil amendments resulted in U hyperaccumulation, bringing U concentration in shoots of Amaranth up to 1347 mg U kg^{-1} plants, at least two orders of magnitude above the control plant levels. However, the effectiveness of the soil amendments was significantly limited by the high soil pH and buffer capacity of these carbonate-rich soils from the FEMP site. Further optimization of the amendment formulation is required for optimal phytoextraction of U from such carbonate-rich soils.

Uranium concentration in plants achieved in this study (1347 mg U kg^{-1} plant) exceeded the U concentration in plants during the 1997 field trial east of RMI's historical uranium extrusion facility located in Ashtabula, Ohio. During the field trial, significant reduction of U concentration in the top 0.45 m of soil was achieved. It is reasonable to expect significant reduction in soil U concentration at the FEMP site, provided good plant growth and optimization of the soil amendment application can be achieved.

Phytotech

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Abbreviations and Acronyms

DOE	Department of Energy
DW	Dry weight
FEMP	Fernald Environmental Management Project
FDF	Fluor Daniel Fernald, Inc.
kg	Kilogram
km	Kilometer
m	Meter
meq	Milliequivalent
mi	Mile
mm	Millimeter
USDA-ARS	United States Department of Agriculture, Agricultural Research Service

Phytotech

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1. INTRODUCTION

1.1. Site Description and History[1]

1.1.1. Site History

The scope of the Fernald Environmental Management Project (FEMP) is the implementation of full-scale environmental remediation and waste management activities at an inactive uranium processing facility located near the village of Fernald in Southwestern Ohio. The facility was built by the Atomic Energy Commission (a predecessor to the DOE) and was originally used to produce "feed" materials in the form of purified uranium metal for use by other DOE sites (Fernald, 1998).

The FEMP site consists of a 425-hectare (1,050-acre) facility located just north of Fernald, Ohio, on the boundary between Hamilton and Butler Counties. Of the total site area, 345 hectares (850 acres) are in Crosby Township of Hamilton County, and 80 hectares (200 acres) are in Ross and Morgan Townships of Butler County. Other nearby communities include Shandon, New Baltimore, Ross, and Harrison, Ohio.

Production operations began in 1952 and ended in 1989. During that time, in excess of 227 million kg of uranium metal products were delivered from the FEMP site to other DOE sites in support of national security initiatives. As a consequence of this large-scale production operation, an estimated 180,000 to 450,000 kg of uranium were released in to the environment. This environmental release resulted in widespread contamination of surface soil, surface water, sediments, and groundwater.

[1] Based on the 1997 Integrated Site Environmental report(Fernald, 1998) and materials available on the Fernald Web Page (FEMP, 1998).

1.1.2. Site Geology

The FEMP site is located within a 3-5 km (2-3 mi) wide subterranean valley known as the New Haven Trough. The trough cuts deep into Middle and Late Ordovician shale and limestone bedrock to a depth of 61 m (200 ft) and was carved 300,000-400,000 years ago by the ancestral Ohio River and its confluence with the Great Miami River. Blocking of the rivers' confluence by the Illinoisan ice sheet catastrophically diverted the Ohio River to its present day channel. This trough was filled in by glacial outwash deposited by the lower flow of the Great Miami River to now define the area's underlying aquifer.

FEMP's storm sewer system originates east of the production area and flows southwesterly and enters Paddy's Run in the southwest corner of the site. Storm water retention basins were constructed in 1986 and 1989 to intercept and hold, for settling of solids, the contaminated surface water run-off from the site's production area. Its volume is sized to accommodate a 10 year, 24 hour probabilistic rainfall event (the largest 24 hour duration rainfall that will re-occur at least every 10 years). Overflows from larger storms will be directed to Paddy's Run.

FEMP's surface water eventually drain to the Paddy's Run watershed. The stream is 14.1 km (8.8 mi) long and drains approximately 40.9 km (15.8 mi). Paddy's Run functions as the site's stormwater outfall ditch and flows southward along the western boundary of the site and exits in the site's southwest corner. The Run has cut 1.8 m (6 ft) or more into the geological deposits which directly connects surface drainage to the aquifer. This is the probable path of the uranium contaminant plume in the aquifer.

1.1.3. Site Endangered and Threatened Plant and Animal Species

Federally Listed Plant Species: None identified

Federally Listed Animal Species: One species of mammal, the Indiana bat (*Myotis sodalis*), is listed as federally endangered and occurs in Butler and Hamilton counties.

Surveys were conducted as part of the Remedial Investigation/Feasibility Study process for the various Operable Units at the site to determine the distribution and presence of the Indiana bat and to identify potential habitats on the Site and in the immediate vicinity. The Indiana bat was not found within site boundaries, but a breeding population was found on Banklick Creek, a tributary to the Great Miami River, near Ross, Ohio.

State Listed Plant Species: None identified

State Listed Animal Species: Ohio populations of the cave salamander (*Eurycea lucifuga*), an amphibian species recognized as state endangered, are limited to Butler, Hamilton, and Adams counties. Reported locations of the cave salamander in the site vicinity include the Mount Airy Forest, Groesbeck, 1.6 km (1 mi) northeast of New Baltimore, and Sheits Road near Blue Rock Road. Surveys were conducted to determine the distribution of the cave salamander and to identify potential habitat on the site and in the immediate vicinity. The cave salamander was not found within site boundaries, but individuals were found near New London Road north of the site and within the boundaries of the Camp Ross Trails northeast of the site.

The Cincinnati crayfish (*Orconectes sloanii*) is not listed as a state or federal threatened or endangered species, but has been considered threatened following field studies in Paddy's Run to determine species distribution. Historically, this crayfish has been collected primarily in tributaries of the Great Miami River system south of the confluence of Greenville Creek.

The Cobblestone Tiger beetle (*Cicendela margipennis*), which is under review by the U.S. Fish and Wildlife Service for possible inclusion in threatened or endangered species list, was found during the Indiana bat survey on a gravel bar in the Great Miami River 3.2 km (2 mi) west southwest of the bridge at New Baltimore, Ohio.

Three raptors, the Red-shouldered hawk (*Buteo lineatus*), Cooper's hawk (*Accipiter cooperii*), and northern harrier (*Cirus cyaneus*), are listed as "Rare species of

the Native Ohio Wild Animals" and have been observed on the site. The Cooper's hawk is considered an uncommon but regular breeding species in the Cincinnati vicinity and a threatened breeding species in Ohio. This species was frequently observed during the summer over the pine plantations and pastures throughout the Site. The Northern harrier is listed as State endangered.

1.2. Phytoextraction Overview

1.2.1. Phytoremediation Paradigm

Recently, significant attention has been drawn to phytoremediation, an emerging technology using plants to remove pollutants from the environment. Phytoremediation provides an affordable way to restore the economical value of contaminated land. This technology employs a plant's natural ability to concentrate essential and nonessential elements in their tissues. Plants are not capable of distinguishing isotopes of the same element. Radioactive isotopes like ^{14}C, ^{18}O, ^{32}P, ^{35}S, ^{64}Cu, and ^{59}Fe are widely used as a tracers in plant physiology and biochemistry. In some cases, plants react analogously to ions with similar physico-chemical properties. It is known that Sr is an analog of Ca in living organisms (Kabata-Pendias and Pendias, 1989) and the effect of K on ^{137}Cs accumulation in plants is well documented (Seel, et al., 1995).

The ability of plants to tolerate elevated levels of heavy metals, and to accumulate them to unusually high levels has been shown in a number of different plant species (Baker and Brooks, 1989; Ernst, et al., 1992). However, the value of metal-accumulating

plants for environmental remediation has been fully realized only recently (Cunningham and Ow, 1996; Huang, et al., 1998; Raskin, et al., 1994; Raskin, et al., 1997).

Several subsets of phytoremediation technology are being developed (Salt, et al., 1995). The most advanced are: (a) phytoextraction (Dushenkov, et al., 1997; Kumar, et al., 1995) - the use of metal-accumulating plants, which can transport and concentrate metals from the soil in the roots and above ground shoots, (b) rhizofiltration (Dushenkov, et al., 1995) - the use of plant roots to absorb, concentrate and precipitate toxic metals from aqueous streams, and (c) phytostabilization - the use of plants to eliminate the bioavailability of toxic metals in soils.

Phytoextraction is used to reduce the concentration of contaminants in the soil to below regulatory standards. To achieve this goal, plants should concentrate elements of interest from the soil at a rate that will produce a "clean site" in a few years. The principal phytoextraction paradigm is shown in Figure 1. The main idea of phytoextraction is to exploit a plant's natural ability to accumulate elements of interest, e. g. remove them from the soil and concentrate in plant tissues.

Phytotech

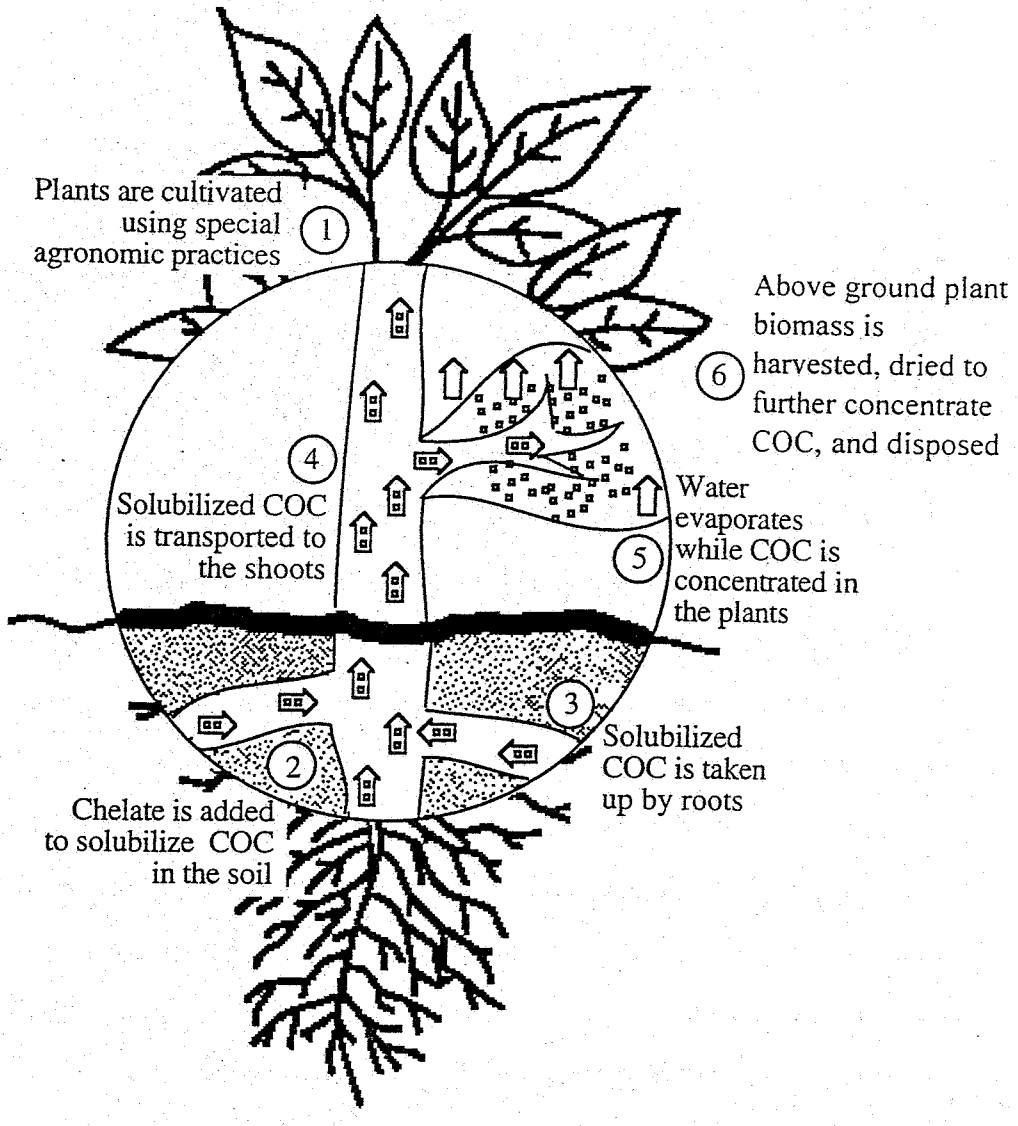

Figure 1. Phytoextraction paradigm.

The optimum plant for phytoextraction process should not only be able to tolerate and accumulate high levels of toxic metals in its harvestable parts, but must also have a rapid growth rate and the potential to produce a high biomass in the field, so that significant removal of the constituent of concern will occur in a few years. It is important that metal accumulating plants be responsive to agricultural practices to allow repeated planting and harvesting.

One of the severe limitations of phytoremediation is bioavailability of metal in soil. Metal uptake by roots is possible only through a water phase. Heavy metals are often presented in the soil in insoluble form highly bound to the soil particles. Acidification and other soil amendments are the chemical processes commonly used to bring sorbed metals into solution.

Following the phytoextraction process, harvested metal-enriched biomass could be ashed, incinerated, composted or even used for metal smelting to recycle the metal. The concentration process greatly reduces the amount of contaminated material that requires disposal, thereby decreasing the associated disposal fees. The metal-rich plant material can be safely harvested and removed from the site without extensive excavation, disposal costs, and loss of topsoil associated with traditional remediation practices. In many cases the metal extracted by the plants can be separated and recycled to reduce long-term liability concerns. Phytoextraction provides an efficient, cost effective and environmentally compatible means of addressing heavy metal and radionuclide contamination and significantly reduces the ecological risk associated with heavy metal and radionuclide soil contamination.

1.2.2. Phytoextraction of Uranium

Uranium is one of the most common radioactive contaminants in soils and is found primarily at former nuclear weapons processing facilities. By weight, natural U consists

of 99.283% ^{238}U, 0.71% ^{235}U, and 0.0054% ^{234}U having half-lives of 4.5×10^9 y, 7.1×10^8 y, and 2.47×10^5 y, respectively. Depleted and enriched U have lower and higher isotopic ratios of $^{234, 235}U$ to ^{238}U, respectively, to that found for natural U. In nature, U occurs mainly in ore deposits of uraninite (UO_2) or coffinite ($USiO_4$), which are mined for weapon and reactor-fuel production [Elless, 1998 #228]. Mine-tailing-process and spent fuel treatment wastes are the major sources of uranium contamination of soils.

Phytoremediation of any metal is heavily dependent on metal bioavailability in soil. Knowledge of the geochemical behavior of U is necessary to accurately assess the nature of soil amendment needed for inducing U hyperaccumulation in plants.

The geochemistry of uranium is quite complex. Not only is the solubility of uranium phases largely redox controlled, but also its aqueous speciation depends strongly on pH as well as the presence of both organic and inorganic ligands (Elles and Lee, 1998). Reduced uranium, U(IV), mainly present as the minerals coffinite and uraninite, are extremely insoluble (< 0.01 μg L^{-1}), whereas oxidized uranium, U(VI), mainly present in the minerals carnotite, rutherfordite, autunite, and uranophane, has greater solubilities. Speciation diagrams of oxidized uranium show that under acid conditions, uranium exists as the uncomplexed uranyl cation, UO_2^{2+}, which is free to participate in cation exchange and sorption reactions (Langmuir, 1978). As the pH rises to approximately slightly acid to neutral conditions, the uranyl cation becomes complexed with sulfate or orthophosphate oxyanions to form neutral species. As the pH approaches alkaline conditions, the uranyl cation becomes complexed with either a single carbonate (neutral species), a dicarbonate (anionic species), or a tricarbonate (anionic species) oxyanion. When existing as a neutral or anionic species, the uranyl cation does not participate in cation exchange reactions and because anion exchange is often low in most soils (only acid, tropical soils having high amounts of Fe/Mn oxides have significant anion exchange

capacities), these species do not participate strongly in any exchange or sorption phenomena.

Huang et al. (1998) demonstrated that citric acid is an efficient soil amendment in enhancing U desorption from soil to soil solution and triggering U hyperaccumulation in plants. The reduction in soil pH contributed only part of the enhanced soil U desorption and shoot U accumulation. Citric acid at low pH effectively removes coatings of amorphous Fe and Al sesquioxide from solid phase U particles, hence enhancing the dissolution and extraction of U from soil to soil solution. The reduction in soil pH coupled with chelation between U and citric acid may be the driving force behind the citric acid induced U accumulation by plants.

It was identified at Phytotech that the members of *Brassicaeae* family (*Brassica juncea* (L.) Czern., *Brassica narinosa* L., and *Brassica chinensis* L.) are efficient in accumulating uranium from soils (Huang, et al., 1998). The screening of new plant species for uranium accumulation is a continuing experiment at Phytotech facilities.

An integral part of this successful field application of phytoremediation is the assessment of soil specific characteristics affecting metal availability to the plants. Phytotech's treatability study is designed to provide information to project the level of success of phytoremediation at a particular site. The treatability study consists of an initial soil analysis to determine basic soil characteristics, i.e., total metal content (EPA Method 3050), soil pH, and electrical conductivity. Additional soil analyses, including a sequential extraction to assess metal associations with various soil fractions, are conducted to evaluate metal availability and provide information for the application of soil amendments to enhance metal uptake by plants. Finally, greenhouse studies are conducted using bulk soil samples to evaluate plant growth and metal uptake.

Overall plants grew very well in tested soil. The composite samples from both locations were capable of supporting good plant growth under agricultural practices developed by Phytotech.

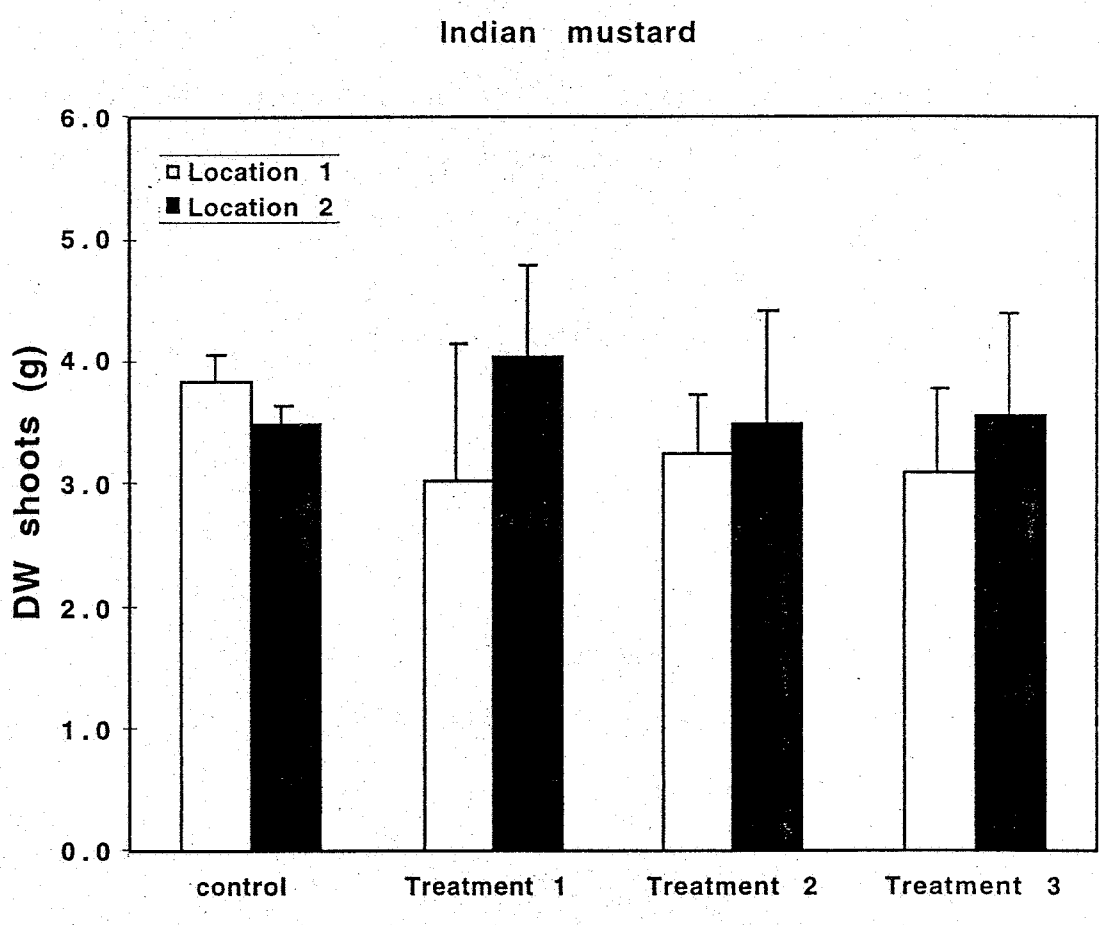

Figure 3. Above-ground biomass per pot of Indian mustard grown in the representative FEMP site soil sample (n=3).

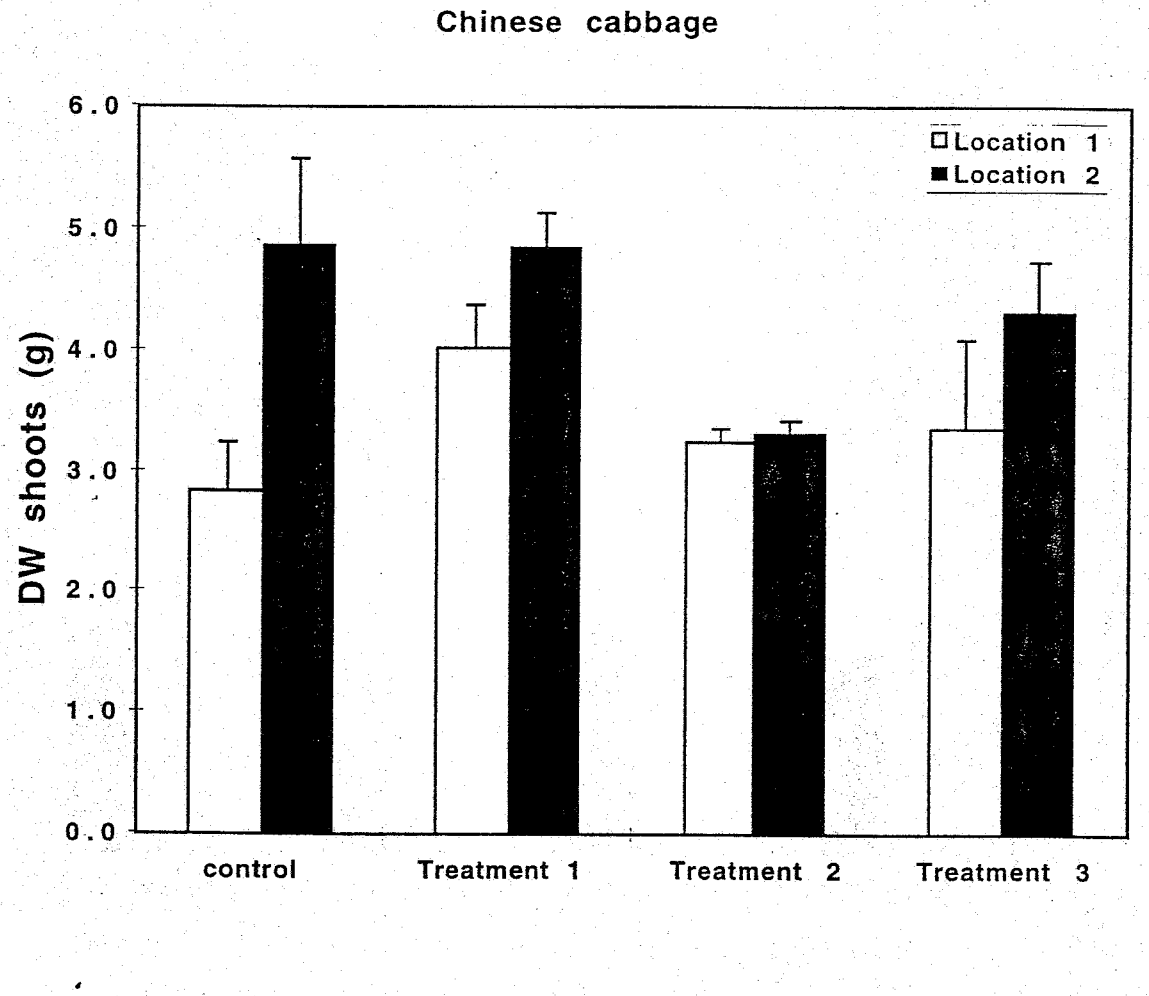

Figure 4. Above-ground biomass per pot of Chinese cabbage grown in the representative FEMP site soil sample (n=3).

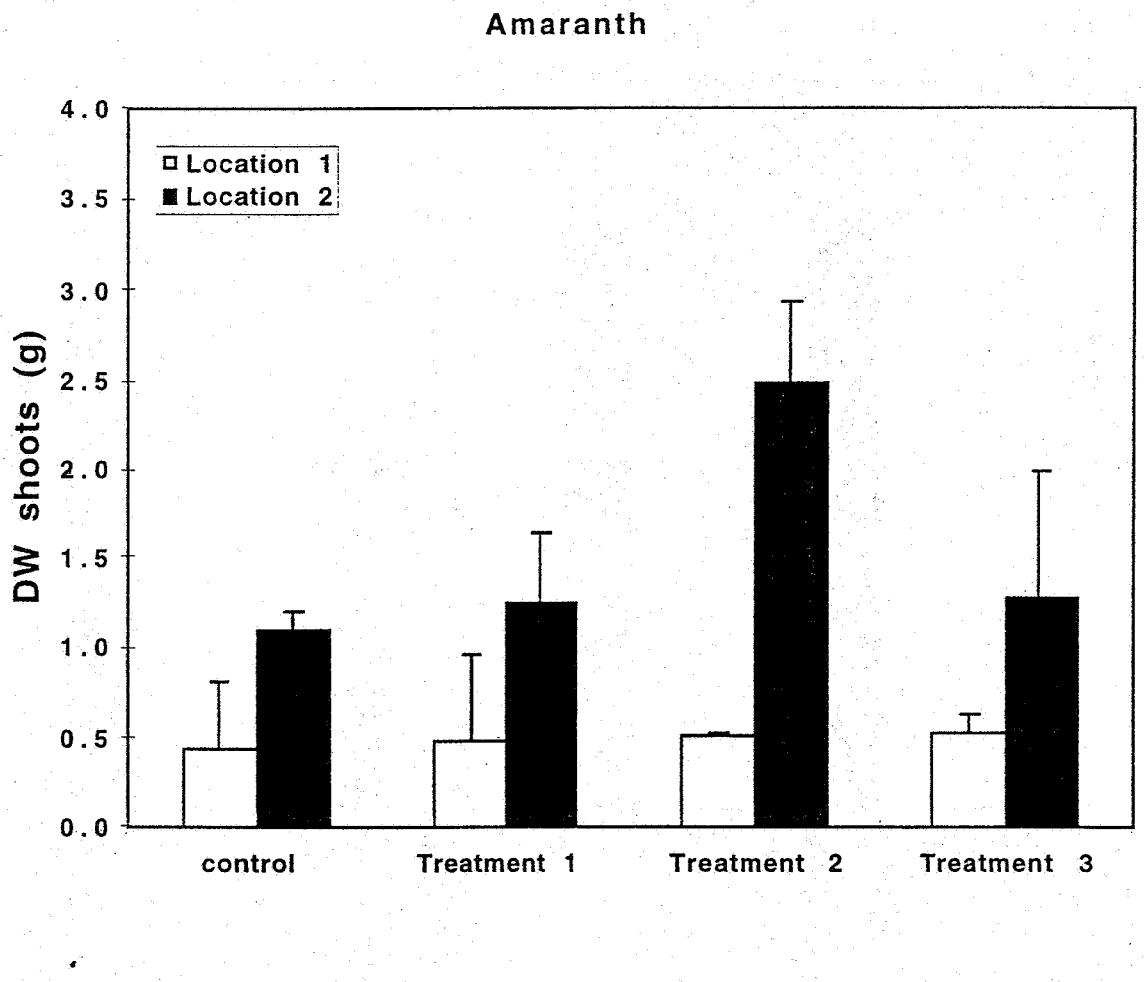

Figure 5. Above-ground biomass per pot of Amaranth grown in the representative FEMP site soil sample (n=3).

3.2. Uranium Accumulation in Plants

3.2.1. Soil Amendments

Following the representative FEMP site soil samples characterization and using previous Phytotech experience in U-contaminated soil phytoremediation, three combinations of soil amendment were selected for this study (Table 1). Sulfuric acid was added to reduce soil pH. Surfactant Triton-X-100 was used to disperse soil particles to the degree that overall surface area for U-citrate reactions will be increased.

Table 1. Soil Amendments Used in the Greenhouse Experiments with the Representative FEMP Site Soil Samples.

Treatment	Soil amendments
Control	No soil amendments
Treatment 1	20 mM citric acid kg^{-1} soil
Treatment 2	20 mM citric acid kg^{-1} soil in combination with 20 mM sulfuric acid kg^{-1} soil
Treatment 3	20 mM citric acid kg^{-1} soil in combination with 2.5 mM Triton-X-100 kg^{-1} soil

Amendments were applied to the surface of the soil. Citric acid reacted with an excess of $CaCO_3$ in the soil that resulted in the release of CO_2 and formation of white foam on the soil surface.

$$CaCO_3 + \text{citric acid} = \text{Ca-citrate} + H_2O + CO_2\uparrow$$

One week after the amendment application, plants were harvested and analyzed for U content. Uranium concentration in the control plants was below the method

detection limit (<50 mg kg^{-1}) for both soils (Table 2). Addition of citric acid alone (Treatment 1) did not result in U hyperaccumulation in the plant shoots. For both representative soil samples U concentrations in plants treated with 20 mM of citric acid per kg of soil remained below MDL, except Amaranth in Location 1 soil (429±122 mg kg^{-1}). A combination of citric acid amendment with surfactant (Triton X-100) resulted in significant U accumulation in Amaranth (maximum of 1054 mg kg^{-1}) grown in the Location 1 representative soil sample. In Treatment 2 application of 20 mM kg^{-1} citric acid was supplemented with the addition of 20 mM kg^{-1} of sulfuric acid in an attempt to lower the soil pH. This treatment resulted in the highest U concentrations in the shoots of plants at both soils. The maximum U concentration was observed in Amaranth grown in Location 1 representative FEMP site soil sample (1347 mg kg^{-1}). Due to the very large pH buffering capacity of the FEMP soils, amendments did not significantly change the soil pH (Table 2). However, the profound effect of supplementing citric acid application with sulfuric acid was observed. Dispersing soil particles with the surfactant addition to the soil also resulted in high U accumulation in the plants.

Of three tested species grown in Location 1 representative FEMP site soil sample, Amaranth plants had the highest uranium accumulation in above-ground parts (Table 2). In Location 2 representative FEMP site soil sample, Chinese cabbage and Amaranth produced similar results. In general, the U concentrations in plants grown in the Location 1 representative FEMP site soil sample were significantly greater than the U concentrations in plants grown in the Location 2 representative FEMP site soil sample.

Table 2. Soil pH and Average Uranium Concentrations in Above-Ground Shoots of the Plants Grown in the Representative FEMP Site Soil Samples.

Species	Treatment	Uranium concentration in plants (mg kg^{-1})		Soil pH after harvest	
		Location 1	Location 2	Location 1	Location 2
Indian mustard	Control	<MDL	<MDL	6.56±0.04	6.95±0.09
	Treatment 1	<MDL	<MDL	6.39±0.05	6.97±0.03
	Treatment 2	77±16	<MDL	6.61±0.07	6.98±0.12
	Treatment 3	<MDL	<MDL	6.73±0.06	7.04±0.10
Chinese cabbage	Control	<MDL	<MDL	6.48±0.15	6.96±0.05
	Treatment 1	<MDL	<MDL	6.60±0.09	6.95±0.09
	Treatment 2	144±35	84±44	6.70±0.18	7.02±0.08
	Treatment 3	76±45	<MDL	6.75±0.19	7.04±0.06
Amaranth	Control	<MDL	<MDL	6.59±0.07	6.96±0.06
	Treatment 1	429±122	<MDL	6.43±0.21	6.95±0.03
	Treatment 2	941±496	77±39	6.61±0.09	6.92±0.11
	Treatment 3	899±168	<MDL	6.88±0.17	7.07±0.08

4. CONCLUSIONS

- The representative soil samples obtained from the FEMP site had near neutral pH and an EC at 0.50 dS/m. Average U concentrations were 955 mg kg^{-1} (20 mg kg^{-1} water soluble) and 336 mg kg^{-1} (2 mg kg^{-1} water soluble) for Location 1 and Location 2 soil, respectively.
- The majority of U was associated with the potentially plant available soil chemical fractions. However, no exchangeable U was detected and the acid-extractable residual fraction (i.e. that which can not be targeted by phytoremediation) constitutes 41% in the Location 1 representative soil sample and 38% in the Location 2 representative soil sample. Citric acid-extractable U in Location 1 representative soil sample averaged 186 mg U kg^{-1} soil, which represents approximately 20% of the total U content and approximately 50% of the uranium associated with the exchangeable and carbonate fractions, the two fractions considered the most labile and available fractions for plant uptake. Citric acid-extractable U in the Location 2 representative soil sample averaged 82 mg kg^{-1}, which represents approximately 25% of the total U content and approximately 75% of the uranium associated with the exchangeable and carbonate fractions.
- The composite representative FEMP site soil samples from both locations were capable of supporting good plant growth under agricultural practices developed by Phytotech.
- Application of soil amendments resulted in U hyperaccumulation, bringing U concentration in shoots of Amaranth up to 1347 mg kg^{-1}, at least two orders of magnitude above the control plant levels. However, effectiveness of soil amendments

was significantly limited by the high soil pH and buffer capacity of these carbonate-rich soils from the FEMP site.

- Due to the very large pH buffering capacity of the FEMP soils, amendments did not significantly change the soil pH (Table 2). However, the profound effect of supplementing citric acid application with sulfuric acid was observed. Dispersing soil particles with the surfactant addition to the soil also resulted in high U accumulation in the plants.

5. RECOMMENDATIONS

Analyses of U chemical association in the representative FEMP soils samples from both locations revealed that the majority of U was potentially associated with plant available fractions. However, high soil pH and buffer capacity of these carbonate-rich soils limited the effectiveness of the soil amendments used in the greenhouse experiments. Further optimization of the amendment formulation is required for optimal phytoextraction of U from such carbonate-rich soils.

Uranium concentration in plants achieved in this study (up to 1347 mg kg^{-1} in Amaranth) exceeded the U concentration in plants during the 1997 field trial east of RMI's historical uranium extrusion facility located in Ashtabula, Ohio. During the field trial, significant reduction of U concentration in the top 0.45 m of soil was achieved. It is reasonable to expect significant reduction in soil U concentration at the FEMP site, provided good plant growth and optimization of the soil amendment application can be achieved.

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7. Appendix A

7.1. Project Specific Plan for Soil Collection for Uranium in Soil Phytoremediation Greenhouse Study

PROJECT SPECIFIC PLAN FOR SOIL COLLECTION FOR URANIUM IN SOIL PHYTOREMEDIATION GREENHOUSE STUDY

Project No. 04.135

Revision 0
July 24, 1998

APPROVAL:

Carl T. Bishop 7/31/98

Carl Bishop, Project Lead
Technology Programs

Date

Mike Frank 8/4/98

Mike Frank, Environmental Monitoring
Soil and Miscellaneous Media Projects Section

Date

R Fiske 7-31-98

Reinhard Ffiske, Quality Assurance
Soil Charterization and Excavation Project

Date

ECDC No. 20300-PSP-0003
FERNALD ENVIRONMENTAL MANAGEMENT PROJECT

Fluor Daniel Fernald
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Cincinnati, Ohio 45253-8704

PROJECT SPECIFIC PLAN FOR SOIL COLLECTION FOR URANIUM IN SOIL PHYTOREMEDIATION GREENHOUSE STUDY

A. Identifying Information

1. **Project Background:** The purpose of this phytoremediation study is to determine how efficient the "Indian Mustard" plant (or some other plant species) would be, in removing uranium from soil when it is grown in that soil. Actual soil containing uranium above 20 mg/kg will be used in the study. Approximately 300 lbs. Of soil will be taken from an area known to contain about 1000 mg U/kg soil and will be sent to a company called "Phytotech." Phytotech will perform a greenhouse study of the phytoremediation process using the Fernald Soil.
2. **Project Name:** Phytoremediation of Uranium from Soils at Fernald Environmental Management Project
3. **Project No.:** ECDC 20300-PSP-0003/EM Project No. 04.135
4. **Material Description:** Surface Soil
5. **Source:** Area 3 at the Former Drum Baling Area (north of the former Bldg. 78)
6. **Sampling Locations:** Within the limits of the test location designated 3/H/HT in the HPGe Comparability Study (Attachment A).

B. Sampling Information

1. **General:** Enough surface soil (0-6") will be collected to fill six 5-gallon containers (equivalent to about 300 pounds) for off-site shipment to Phytotech. Soil should be taken from an area or areas where the uranium concentration is expected to be lower than average in the general area. Vegetation will be removed prior to sample collection to the extent possible. The container will have a plastic liner, and be sealed, and labeled. An alpha-beta screen will be collected from the soil placed in the containers prior to its release from the FEMP. The alpha/beta screen sample (~50cc) will be collected from the area of highest radiological readings. The area to be sampled has been previously characterized in the RTRAK *Applicability Measurements in locations of elevated radionuclide concentrations, addendum to the July 1998 RTRAK Applicability Study Report (September 1997).* Collection of gravel, in excess of 20 percent by volume will be avoided. The gravel content should be kept to a minimum.
2. **Preservation Method:** None
3. **Holding Time:** None
4. **Sampling Technique:** In accordance with "Solids Sampling Procedure," SMPL-01.
5. **Visual Inspection Performed?:** Yes
6. **Field Contact:** Carl Bishop 648-4302
7. **Charge No./Project Manager:** 6DDE2/Marv Gross
8. **Required QC Samples:** None

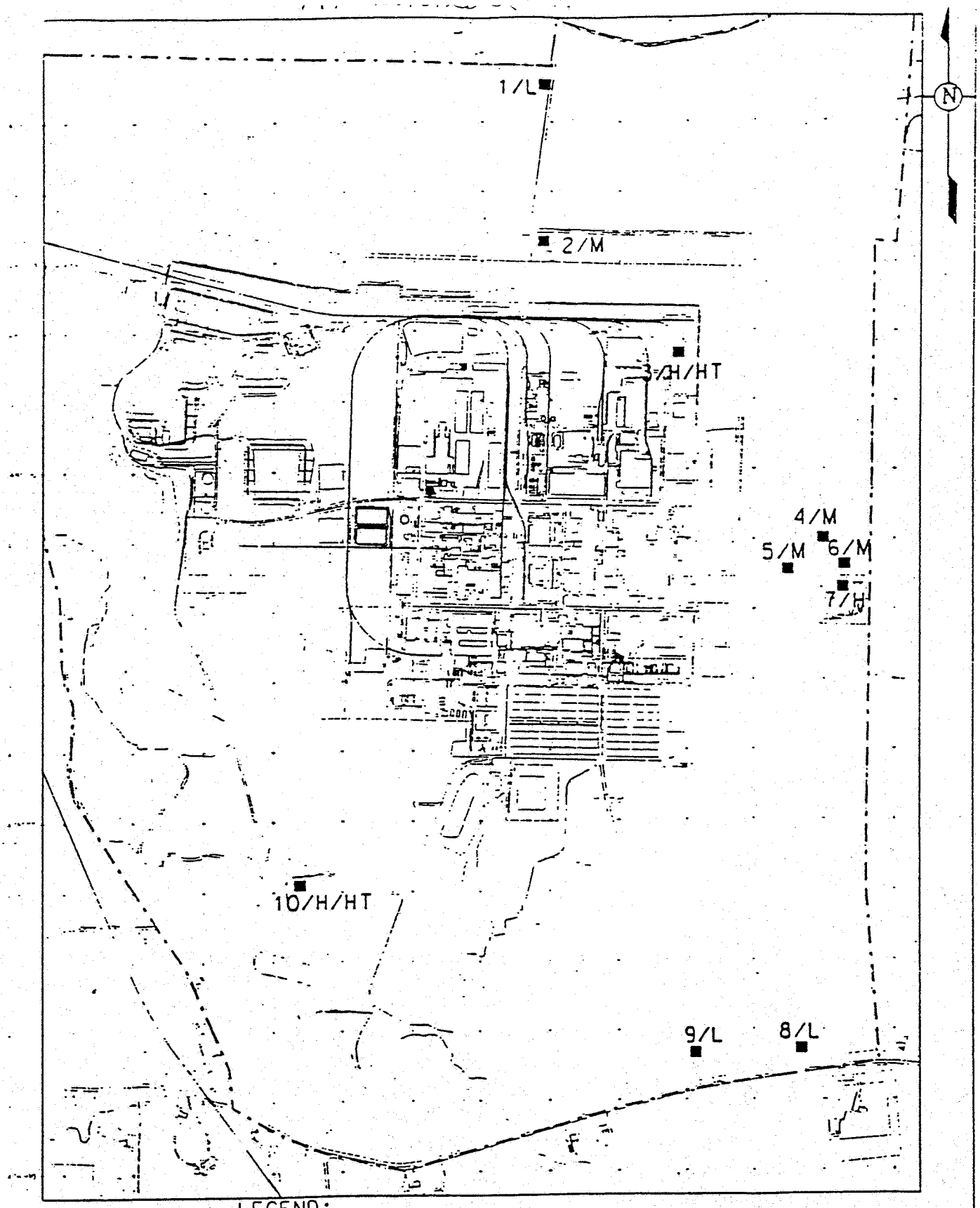

FIGURE 2-2. PART (B) COMPARABILITY STUDY TEST LOCATIONS

PROJECT SPECIFIC PLAN FOR SOIL COLLECTION FOR URANIUM IN SOIL PHYTOREMEDIATION GREENHOUSE STUDY

C. Sample Disposition

The soil samples are to be shipped to:

Slavik Dushenkov
Phytotech Inc.
1 Deer Park Drive, Ste. I
Monmouth Junction, NJ 08852

Phytotech will analyze the samples for uranium and will conduct greenhouse studies with these samples.

Chain of Custody documentation collected by the sampling team will be sent to Phytotech along with the samples.

D. Safety Concerns

Safety precautions included in the procedure "Solids Sampling (SMPL-01)" will be observed.

E. Project Specific Plan Changes

Changes to this Project Specific Plan will be provided through the variance process.

8. Appendix B

8.1. AnalyticalResultsTtables

8.1.1. Initial soil testing results for the FEMP Site

Flags:

U - indicates that the absolute value of the analyte in PB, ICB or CCB is less than PQL but grater than or equal to MDL

N - indicates that spike recovery (%R) is out of the control limit and the Spike Added is grater than or equal to one-fourth of the Sample Result.

* - indicates that the duplicate analysis for the analyte is out of control.

E - indicates that % Difference is greater than 10%.

ND - indicates that the value of the analyte is below MDL

Inorganic Data Reporting Forms

#	Title	Form
1	Inorganic Analyses Data Sheet	I-1
2	Initial Calibration Verification	I-2
3	Initial Calibration Blank	I-3
4	Continuing Calibration Verification	I-4
5	Continuing Calibration Blank	I-5
6	ICP Interference Check Sample ICSA	I-6
7	ICP Interference Check Sample ICSAB	I-7
8	Preparation Blank	I-8
9	Laboratory Control Sample Plant	I-9
10	Laboratory Control Sample Soil	I-10
11	ICP Serial Dilutions	I-11
12	Duplicates	I-12
13	Spike Sample Recovery Soil	I-13
14	Spike Sample Recovery Plant	I-14
15	Audit Sample Plant	I-15
16	Audit Sample Soil	I-16
17	Instrument Detection Limits	I-17
18	ICP Linear Rangers	I-18

Phytotech, Inc.

Analytical Method SW6010 Project 98019
Matrix Soil Sample #

Inorganic Analyses Data Sheet
Concentration Units (mg/kg)

Sample ID		Metals concentration in soil (mg.kg)										
		As	Ca	Cd	Co	Cr	Cu	Mn	Ni	Pb	U	Zn
Total metals												
Location 1	1	<MDL	>40,000	3	26	11	306	910	77	213	891	344
	2	<MDL	>40,000	4	28	<MDL	139	1,075	72	128	1,020	582
Location 2	1	<MDL	35,729	<MDL	13	12	56	580	32	56	335	133
	2	<MDL	35,138	<MDL	15	5	62	748	44	50	336	127
Water soluble												
Location 1		<MDL	142.5	<MDL	<MDL	<MDL	<MDL	0.1	<MDL	<MDL	20.3	0.1
Location 2		<MDL	107.6	<MDL	<MDL	<MDL	<MDL	0.0	<MDL	<MDL	2.1	0.5

Phytotech, Inc.

Analytical Method SW6010 Project 98019
Matrix PLANT Sample #

Initial Calibration Verification (ICV)
Concentration Units (mg/L)

Analyte	True	Found	% R
Aluminum			
Arsenic			
Boron			
Cadmium			
Calcium			
Chromium			
Cobalt			
Copper			
Iron			
Lead			
Magnesium			
Manganese			
Molybdenum			
Nickel			
Phosphorus			
Potassium			
Selenium			
Sodium			
Strontium			
Sulfur			
Uranium	4.000	4.132	103.3
Vanadium			
Zinc			

Control limit 90-110%

Phytotech, Inc.

Analytical Method SW6010 Project 98019
Matrix PLANT Sample #

Initial Calibration Blank (ICB)
Concentration Units (mg/L)

Analyte	PQL	Initial Calibration Blank (ICB)
Aluminum		
Arsenic		
Boron		
Cadmium		
Calcium		
Chromium		
Cobalt		
Copper		
Iron		
Lead		
Magnesium		
Manganese		
Molybdenum		
Nickel		
Phosphorus		
Potassium		
Selenium		
Sodium		
Strontium		
Sulfur		
Uranium	1.00	ND
Vanadium		
Zinc		

Phytotech, Inc.

Analytical Method SW6010 Project 98019
Matrix PLANT Sample #

Continuing Calibration Verification (CCV)
Concentration Units (mg/L)

Analyte	True	CCV-1		CCV-2		CCV-3		CCV-4		CCV-5	
		Found	% R	Found	% R	Found	% R	Found	% R	Found	% R
Aluminum											
Arsenic											
Boron											
Cadmium											
Calcium											
Chromium											
Cobalt											
Copper											
Iron											
Lead											
Magnesium											
Manganese											
Molybdenum											
Nickel											
Phosphorus											
Potassium											
Selenium											
Sodium											
Strontium											
Sulfur											
Uranium	10.0	9.498	95.0	9.248	92.5	9.042	90.4	9.145	91.4	9.126	91.3
Vanadium											
Zinc											

Control limit ±10%

Phytotech, Inc.

Analytical Method SW6010 Project 98019
Matrix PLANT Sample #

Continuing Calibration Verification (CCV)
Concentration Units (mg/L)

Analyte	True	CCV-6		CCV-7		CCV-8		CCV-9		CCV-10	
		Found	% R	Found	% R	Found	% R	Found	% R	Found	% R
Aluminum											
Arsenic											
Boron											
Cadmium											
Calcium											
Chromium											
Cobalt											
Copper											
Iron											
Lead											
Magnesium											
Manganese											
Molybdenum											
Nickel											
Phosphorus											
Potassium											
Selenium											
Sodium											
Strontium											
Sulfur											
Uranium	10.00	9.527	95.3								
Vanadium											
Zinc											

Control limit ±10%

Phytotech, Inc.

Analytical Method SW6010 Project 98019
Matrix PLANT Sample #

Continuing Calibration Blank (CCB)
Concentration Units (mg/L)

Analyte	PQL	Continuing Calibration Blank (CCB)							
		CCB-1	CCB-2	CCB-3	CCB-4	CCB-5	CCB-6	CCB-7	CCB-8
Aluminum									
Arsenic									
Boron									
Cadmium									
Calcium									
Chromium									
Cobalt									
Copper									
Iron									
Lead									
Magnesium									
Manganese									
Molybdenum									
Nickel									
Phosphorus									
Potassium									
Selenium									
Sodium									
Strontium									
Sulfur									
Uranium	1.00	ND	ND	ND	ND	ND	ND		
Vanadium									
Zinc									

Phytotech, Inc.

Analytical Method SW6010 Project 98019
Matrix PLANT Sample #

ICP Interference Check Sample ICSA
Concentrations Units (mg/L)

Analyte	True	Found	% R
Aluminum	500.0	485.9	97.2
Arsenic			
Boron			
Cadmium			
Calcium	500.0	480.3	96.1
Chromium			
Cobalt			
Copper			
Iron	200.0	184.2	92.1
Lead			
Magnesium	500.0	452.6	90.5
Manganese			
Molybdenum			
Nickel			
Phosphorus			
Potassium			
Selenium			
Sodium			
Strontium			
Sulfur			
Uranium			
Vanadium			
Zinc			

Control limit 80-120%

Phytotech, Inc.

Analytical Method SW6010 Project 98019
Matrix PLANT Sample #

ICP Interference Check Sample (ICSAB)
Concentration Units (mg/L)

Analyte	True	Found	% R
Aluminum	500.0	509.4	101.9
Arsenic			
Boron			
Cadmium			
Calcium	500.0	499.4	99.9
Chromium			
Cobalt			
Copper			
Iron	200.0	185.5	92.7
Lead			
Magnesium	500.0	467.3	93.5
Manganese			
Molybdenum			
Nickel			
Phosphorus			
Potassium			
Selenium			
Sodium			
Strontium			
Sulfur			
Uranium	4.00	4.382	109.6
Vanadium			
Zinc			

Control limit 80-120%

Phytotech, Inc.

Analytical Method SW6010 Project 98019
Matrix PLANT Sample #

Preparation Blank

Analyte	PQL	Found
Aluminum	0.15	
Arsenic	0.38	
Boron	0.11	
Cadmium	0.05	
Calcium	1.00	
Chromium	0.12	
Cobalt	0.05	
Copper	0.10	
Iron	0.20	
Lead	0.25	
Magnesium	1.00	
Manganese	0.02	
Molybdenum	0.10	
Nickel	0.20	
Phosphorus	0.50	
Potassium	1.00	
Selenium	0.60	
Sodium	1.00	
Strontium	0.02	
Sulfur	0.50	
Uranium	1.00	ND
Vanadium	0.10	
Zinc	0.10	

Phytotech, Inc.

Analytical Method 3050 Project 98019
Matrix Plant Sample #

Laboratory Control Sample (LCSP)
Concentration Units (mg/kg)

Analyte	True	Found	Control Limit
Aluminum			
Arsenic			
Boron			
Cadmium			
Calcium			
Chromium			
Cobalt			
Copper			
Iron			
Lead			
Magnesium			
Manganese			
Molybdenum			
Nickel			
Phosphorus			
Potassium			
Selenium			
Sodium			
Strontium			
Sulfur			
Uranium	2158	1928	89.3%
Vanadium			
Zinc			

Control limit 80-120%

Phytotech, Inc.

Analytical Method SW6010 Project 98019
Matrix Soil Sample #

Laboratory Control Sample (LCSS)
Concentration Units (mg/kg)

Analyte	True	Found	Control Limit
Aluminum			
Arsenic			
Boron			
Calcium			
Cadmium			
Cobalt			
Copper			
Chromium			
Iron			
Potassium			
Magnesium			
Manganese			
Molybdenum			
Sodium			
Nickel			
Phosphorus			
Lead			
Selenium			
Sulfur			
Strontium			
Uranium	675	698	103.4
Vanadium			
Zinc			

Control limit 80-120%

Phytotech, Inc.

Analytical Method SW6010 Project 98019
Matrix PLANT Sample # 9807996

ICP Serial Dilutions
Concentration Units (mg/kg)

Analyte	Initial Sample Result	Serial Dilution Result	% Difference
Aluminum			
Arsenic			
Boron			
Calcium			
Cadmium			
Cobalt			
Copper			
Chromium			
Iron			
Potassium			
Magnesium			
Manganese			
Molybdenum			
Sodium			
Nickel			
Phosphorus			
Lead			
Selenium			
Sulfur			
Strontium			
Uranium	ND	ND	
Vanadium			
Zinc			

Control limit ±10%

Phytotech, Inc.

Analytical Method SW6010 Project 98019
Matrix PLANT Sample # 9807996

Duplicates
Concentration Units (mg/kg)

Analyte	Sample	Duplicate	% RPD
Aluminum			
Arsenic			
Boron			
Calcium			
Cadmium			
Cobalt			
Copper			
Chromium			
Iron			
Potassium			
Magnesium			
Manganese			
Molybdenum			
Sodium			
Nickel			
Phosphorus			
Lead			
Selenium			
Sulfur			
Strontium			
Uranium	ND	ND	
Vanadium			
Zinc			

Control limit ±20%

Phytotech, Inc.

Analytical Method SW6010 Project 98019
Matrix PLANT Sample # 9808034

Duplicates
Concentration Units (mg/kg)

Analyte	Sample	Duplicate	% RPD
Aluminum			
Arsenic			
Boron			
Calcium			
Cadmium			
Cobalt			
Copper			
Chromium			
Iron			
Potassium			
Magnesium			
Manganese			
Molybdenum			
Sodium			
Nickel			
Phosphorus			
Lead			
Selenium			
Sulfur			
Strontium			
Uranium	33	32	3.6
Vanadium			
Zinc			

Control limit ±20%

Phytotech, Inc.

Analytical Method SW6010 Project 98019
Matrix Sample #

Instrument Detection Limits
Concentration Units mg/L

Analyte	MDL	PQL	Wavelength (nm)
Aluminum	0.009	0.15	208.22
Arsenic	0.037	0.38	193.76
Boron	0.010	0.11	249.68
Calcium	0.010	1.00	317.93
Cadmium	0.004	0.05	226.50
Cobalt	0.005	0.05	228.62
Copper	0.010	0.10	205.55
Chromium	0.012	0.12	324.75
Iron	0.010	0.20	259.94
Potassium	0.004	1.00	766.49
Magnesium	0.002	1.00	279.08
Manganese	0.001	0.02	257.61
Molybdenum	0.001	0.10	202.03
Sodium	0.005	1.00	589.59
Nickel	0.004	0.20	231.60
Phosphorus	0.017	0.50	178.29
Lead	0.027	0.25	220.35
Sulfur	0.005	0.60	182.03
Selenium	0.019	0.50	196.09
Strontium	0.001	0.02	407.77
Uranium	0.012	1.00	385.96
Vanadium	0.001	0.10	309.31
Zinc	0.003	0.10	213.85

8.1.2. Plants metal uptake for the for the FEMP Site

Phytotech, Inc.

Analytical Method SW6010 Project 98019
Matrix Plant Sample #

Inorganic Analyses Data Sheet
Concentration Units (mg/kg)

Location 1 soil

Lab #	Species	Treatment		DW	Metal concentrations (mg/kg)											
					As	Ca	Cd	Co	Cr	Cu	Mn	Ni	P	Pb	U	Zn
9808032	Indian Mustard	Control	1	3.721	<MDL	37,330	15	<MDL	<MDL	76	32	39	6,736	<MDL	<MDL	89
9808033			2	4.102	<MDL	42,490	18	<MDL	<MDL	126	42	65	5,733	<MDL	<MDL	87
9808034			3	3.746	<MDL	47,383	13	<MDL	<MDL	93	34	62	5,278	<MDL	<MDL	73
9808035		Treatment 1	1	2.815	<MDL	55,379	14	<MDL	<MDL	78	39	59	7,400	<MDL	<MDL	73
9808036			2	4.234	<MDL	41,202	13	<MDL	<MDL	88	31	53	6,500	<MDL	<MDL	73
9808037			3	2.035	<MDL	38,956	12	<MDL	<MDL	68	43	35	8,539	<MDL	<MDL	93
9808038		Treatment 2	1	3.786	<MDL	35,869	18	3	<MDL	103	99	74	7,350	<MDL	86	87
9808039			2	2.882	<MDL	40,075	15	<MDL	<MDL	60	58	43	6,795	<MDL	86	80
9808040			3	3.072	<MDL	37,339	14	3	<MDL	63	48	50	8,765	<MDL	59	83
9808041		Treatment 3	1	2.279	<MDL	30,996	10	<MDL	<MDL	41	28	25	7,557	<MDL	<MDL	66
9808042			2	3.339	<MDL	31,529	11	<MDL	<MDL	35	45	14	7,282	<MDL	<MDL	75
9808043			3	3.632	<MDL	35,702	15	<MDL	<MDL	66	47	36	7,652	<MDL	<MDL	80
9808044	Chinese cabbage	Control	1	3.287	<MDL	37,889	7	<MDL	<MDL	35	36	17	7,134	<MDL	<MDL	73
9808045			2	2.517	<MDL	30,729	5	<MDL	<MDL	23	49	<MDL	8,822	<MDL	<MDL	73
9808046			3	2.763	<MDL	31,844	9	<MDL	<MDL	33	52	22	8,083	<MDL	<MDL	95
9808047		Treatment 1	1	4.418	<MDL	34,593	8	<MDL	<MDL	32	62	18	7,718	<MDL	<MDL	83
9808048			2	3.763	<MDL	30,653	7	<MDL	<MDL	22	48	<MDL	7,286	<MDL	<MDL	77
9808049			3	3.854	<MDL	35,182	9	<MDL	<MDL	38	50	18	7,296	<MDL	<MDL	87

Phytotech, Inc.

Analytical Method SW6010 Project 98019
Matrix Plant Sample #

Inorganic Analyses Data Sheet
Concentration Units (mg/kg)

Location 1 soil

Lab #	Species	Treatment		DW	Metal concentrations (mg/kg)											
					As	Ca	Cd	Co	Cr	Cu	Mn	Ni	P	Pb	U	Zn
9808050	Chinese cabbage	Treatment 2	1	3.128	<MDL	37,313	10	3	<MDL	43	79	36	7,757	<MDL	109	82
9808051			2	3.356	<MDL	35,634	10	7	<MDL	34	86	36	7,087	<MDL	179	78
9808052			3	3.252	<MDL	39,515	12	5	<MDL	58	75	52	7,116	<MDL	145	90
9808053		Treatment 3	1	3.861	<MDL	40,004	9	4	<MDL	40	84	36	6,896	<MDL	128	82
9808054			2	3.701	<MDL	33,677	8	<MDL	<MDL	46	62	31	8,649	<MDL	48	88
9808055			3	2.506	<MDL	31,882	7	<MDL	<MDL	30	108	17	7,293	<MDL	52	77
9808056	Amaranth	Control	1	0.121	<MDL	46,157	<MDL	<MDL	<MDL	48	20	<MDL	8,157	<MDL	<MDL	80
9808057			2	0.846	<MDL	40,844	5	<MDL	9	27	20	18	9,563	<MDL	<MDL	137
9808058			3	0.388	<MDL	37,288	5	<MDL	<MDL	29	20	22	9,382	<MDL	<MDL	76
9808059		Treatment 1	1	0.236	<MDL	52,465	9	<MDL	<MDL	42	93	36	5,943	<MDL	376	89
9808060			2	0.195	<MDL	44,537	<MDL	<MDL	<MDL	44	120	<MDL	8,942	<MDL	343	107
9808061			3	1.042	<MDL	49,218	12	8	9	70	171	60	6,826	21	570	136
9808062		Treatment 2	1	0.526	<MDL	52,324	13	15	<MDL	48	200	78	6,065	<MDL	1,087	98
9808063			2	0.504	<MDL	53,926	14	19	<MDL	74	317	93	6,514	<MDL	1,347	114
9808064			3	0.523	<MDL	44,493	8	4	<MDL	28	79	27	7,912	<MDL	389	130
9808065		Treatment 3	1	0.659	<MDL	45,399	13	13	<MDL	75	260	67	7,523	<MDL	921	113
9808066			2	0.439	<MDL	46,394	10	8	<MDL	37	128	52	8,305	<MDL	720	118
9808067			3	0.480	<MDL	49,391	13	12	<MDL	42	120	88	6,805	<MDL	1,054	107

Phytotech, Inc.

Analytical Method SW6010 Project 98019
Matrix Plant Sample #

Inorganic Analyses Data Sheet
Concentration Units (mg/kg)

Location 2 soil

Lab #	Species	Treatment	DW	Metal concentrations (mg/kg)											
				As	Ca	Cd	Co	Cr	Cu	Mn	Ni	P	Pb	U	Zn
9807996	Indian Mustard	Control	1 3.437	<MDL	42,921	<MDL	<MDL	<MDL	25	31	<MDL	6,744	<MDL	<MDL	52
9807997			2 3.342	<MDL	36,190	<MDL	<MDL	<MDL	16	27	<MDL	6,748	<MDL	<MDL	47
9807998			3 3.666	<MDL	37,251	<MDL	<MDL	<MDL	18	62	<MDL	7,123	<MDL	<MDL	46
9807999		Treatment 1	1 4.896	<MDL	38,784	<MDL	<MDL	<MDL	15	22	<MDL	5,484	<MDL	<MDL	42
9808000			2 3.458	<MDL	37,437	<MDL	<MDL	<MDL	16	22	<MDL	6,718	<MDL	<MDL	49
9808001			3 3.774	<MDL	38,233	<MDL	<MDL	<MDL	18	34	11	6,404	<MDL	<MDL	95
9808002		Treatment 2	1 2.688	<MDL	31,534	<MDL	<MDL	<MDL	14	31	<MDL	7,111	<MDL	<MDL	50
9808003			2 3.240	<MDL	30,984	<MDL	<MDL	<MDL	15	31	<MDL	7,153	<MDL	<MDL	48
9808004			3 4.525	<MDL	38,559	<MDL	<MDL	<MDL	17	33	<MDL	6,259	<MDL	<MDL	45
9808005		Treatment 3	1 2.809	<MDL	32,337	<MDL	<MDL	<MDL	18	28	<MDL	5,881	<MDL	<MDL	47
9808006			2 3.396	<MDL	39,060	<MDL	<MDL	<MDL	17	36	<MDL	7,396	<MDL	<MDL	54
9808007			3 4.481	<MDL	37,113	<MDL	<MDL	<MDL	15	45	<MDL	4,772	<MDL	<MDL	42
9808008	Chinese cabbage	Control	1 4.681	<MDL	40,019	<MDL	<MDL	<MDL	14	43	<MDL	4,674	<MDL	<MDL	37
9808009			2 4.291	<MDL	36,309	<MDL	<MDL	<MDL	14	21	<MDL	5,298	<MDL	<MDL	33
9808010			3 5.646	<MDL	35,870	<MDL	<MDL	<MDL	21	43	13	5,024	<MDL	<MDL	42
9808011		Treatment 1	1 5.087	<MDL	36,985	<MDL	<MDL	<MDL	16	34	<MDL	5,574	<MDL	<MDL	39
9808012			2 4.926	<MDL	33,499	<MDL	<MDL	<MDL	13	36	<MDL	5,036	<MDL	<MDL	35
9808013			3 4.542	<MDL	36,146	<MDL	<MDL	<MDL	10	28	<MDL	4,900	<MDL	<MDL	33

Phytotech, Inc.

Analytical Method SW6010 Project 98019
Matrix Plant Sample #

Inorganic Analyses Data Sheet
Concentration Units (mg/kg)

Location 2 soil

Lab #	Species	Treatment	DW	Metal concentrations (mg/kg)											
				As	Ca	Cd	Co	Cr	Cu	Mn	Ni	P	Pb	U	Zn
9808014	Chinese cabbage	Treatment 2	1 3.228	<MDL	36,825	<MDL	3	<MDL	20	59	14	4,121	<MDL	123	33
9808015			2 3.332	<MDL	32,195	<MDL	3	<MDL	19	62	12	5,651	<MDL	94	41
9808016			3 3.396	<MDL	31,035	<MDL	<MDL	<MDL	13	42	<MDL	4,526	<MDL	37	34
9808017		Treatment 3	1 4.078	<MDL	36,603	<MDL	<MDL	<MDL	12	32	<MDL	5,994	<MDL	<MDL	38
9808018			2 4.061	<MDL	32,923	<MDL	<MDL	<MDL	10	32	<MDL	5,313	<MDL	<MDL	35
9808019			3 4.800	<MDL	32,016	<MDL	<MDL	<MDL	17	35	<MDL	6,258	<MDL	<MDL	39
9808020	Amaranth	Control	1 0.993	<MDL	41,432	<MDL	<MDL	<MDL	16	13	<MDL	7,992	<MDL	<MDL	49
9808021			2 1.141	<MDL	42,499	<MDL	<MDL	<MDL	15	14	<MDL	8,080	<MDL	<MDL	57
9808022			3 1.177	<MDL	41,075	<MDL	<MDL	<MDL	18	13	<MDL	7,327	<MDL	<MDL	52
9808023		Treatment 1	1 1.306	<MDL	37,290	<MDL	<MDL	<MDL	12	20	<MDL	7,887	<MDL	<MDL	48
9808024			2 1.623	<MDL	41,146	<MDL	<MDL	<MDL	16	19	<MDL	5,548	<MDL	<MDL	36
9808025			3 0.860	<MDL	42,792	<MDL	<MDL	<MDL	22	48	<MDL	6,923	<MDL	<MDL	59
9808026		Treatment 2	1 2.125	<MDL	29,758	<MDL	<MDL	<MDL	16	56	<MDL	5,489	<MDL	97	34
9808027			2 2.986	<MDL	29,910	<MDL	<MDL	<MDL	18	43	<MDL	4,067	<MDL	101	30
9808028			3 2.386	<MDL	30,590	<MDL	<MDL	<MDL	14	34	<MDL	4,684	<MDL	31	30
9808029		Treatment 3	1 0.771	<MDL	37,796	<MDL	<MDL	<MDL	MDL	41	<MDL	7,707	<MDL	<MDL	57
9808030			2 0.996	<MDL	38,385	<MDL	<MDL	<MDL	16	28	<MDL	6,952	<MDL	<MDL	59
9808031			3 2.085	<MDL	34,839	<MDL	<MDL	6	20	35	<MDL	7,039	<MDL	<MDL	42

Phytotech, Inc.

Analytical Method SW6010 Project 98019
Matrix Soil Sample #

Initial Calibration Verification (ICV)
Concentration Units (mg/L)

Analyte	True	Found	% R
Aluminum			
Arsenic			
Boron			
Cadmium			
Calcium			
Chromium			
Cobalt			
Copper			
Iron			
Lead			
Magnesium			
Manganese			
Molybdenum			
Nickel			
Phosphorus			
Potassium			
Selenium			
Sodium			
Strontium			
Sulfur			
Uranium	4.000	3.898	97.4
Vanadium			
Zinc			

Control limit 90-110%

Phytotech, Inc.

Analytical Method SW6010 Project 98019
Matrix Soil Sample #

Initial Calibration Blank (ICB)
Concentration Units (mg/L)

Analyte	PQL	Initial Calibration Blank (ICB)
Aluminum		
Arsenic		
Boron		
Cadmium		
Calcium		
Chromium		
Cobalt		
Copper		
Iron		
Lead		
Magnesium		
Manganese		
Molybdenum		
Nickel		
Phosphorus		
Potassium		
Selenium		
Sodium		
Strontium		
Sulfur		
Uranium	1.00	ND
Vanadium		
Zinc		

Phytotech, Inc.

Analytical Method SW6010 Project 98019
Matrix Soil Sample #

Continuing Calibration Verification (CCV)
Concentration Units (mg/L)

Analyte	True	CCV-1		CCV-2		CCV-3		CCV-4		CCV-5	
		Found	% R	Found	% R	Found	% R	Found	% R	Found	% R
Aluminum											
Arsenic											
Boron											
Cadmium											
Calcium											
Chromium											
Cobalt											
Copper											
Iron											
Lead											
Magnesium											
Manganese											
Molybdenum											
Nickel											
Phosphorus											
Potassium											
Selenium											
Sodium											
Strontium											
Sulfur											
Uranium	10.00	9.643	96.4	9.698	97.0	9.452	94.5				
Vanadium											
Zinc											

Control limit ±10%

Phytotech, Inc.

Analytical Method SW6010 Project 98019
Matrix Soil Sample #

Continuing Calibration Blank (CCB)
Concentration Units (mg/L)

Analyte	PQL	Continuing Calibration Blank (CCB)							
		CCB-1	CCB-2	CCB-3	CCB-4	CCB-5	CCB-6	CCB-7	CCB-8
Aluminum									
Arsenic									
Boron									
Cadmium									
Calcium									
Chromium									
Cobalt									
Copper									
Iron									
Lead									
Magnesium									
Manganese									
Molybdenum									
Nickel									
Phosphorus									
Potassium									
Selenium									
Sodium									
Strontium									
Sulfur									
Uranium	1.00	ND	ND	ND					
Vanadium									
Zinc									

Phytotech, Inc.

Analytical Method SW6010 Project 98019
Matrix Soil Sample #

ICP Interference Check Sample ICSA
Concentrations Units (mg/L)

Analyte	True	Found	% R
Aluminum	500.0	490.3	98.1
Arsenic			
Boron			
Cadmium			
Calcium	500.0	495.3	99.1
Chromium			
Cobalt			
Copper			
Iron	200.0	186.7	93.3
Lead			
Magnesium	500.0	471.6	94.3
Manganese			
Molybdenum			
Nickel			
Phosphorus			
Potassium			
Selenium			
Sodium			
Strontium			
Sulfur			
Uranium			
Vanadium			
Zinc			

Control limit 80-120%

Phytotech, Inc.

Analytical Method SW6010 Project 98019
Matrix Soil Sample #

ICP Interference Check Sample (ICSAB)
Concentration Units (mg/L)

Analyte	True	Found	% R
Aluminum	500.0	495.5	99.1
Arsenic			
Boron			
Cadmium			
Calcium	500.0	491.8	98.3
Chromium			
Cobalt			
Copper			
Iron	200.0	186.9	99.3
Lead			
Magnesium	500.0	468.8	93.6
Manganese			
Molybdenum			
Nickel			
Phosphorus			
Potassium			
Selenium			
Sodium			
Strontium			
Sulfur			
Uranium	4.000	4.294	107.3
Vanadium			
Zinc			

Control limit 80-120%

Phytotech, Inc.

Analytical Method SW6010 Project 98019
Matrix Soil Sample #

Preparation Blank

Analyte	PQL	Found
Aluminum		
Arsenic		
Boron		
Cadmium		
Calcium		
Chromium		
Cobalt		
Copper		
Iron		
Lead		
Magnesium		
Manganese		
Molybdenum		
Nickel		
Phosphorus		
Potassium		
Selenium		
Sodium		
Strontium		
Sulfur		
Uranium	1.00	ND
Vanadium		
Zinc		

Phytotech, Inc.

Analytical Method SW6010 Project 98019
Matrix Soil Sample # 9807292

ICP Serial Dilutions
Concentration Units (mg/kg)

Analyte	Initial Sample Result	Serial Dilution Result	% Difference
Aluminum			
Arsenic			
Boron			
Calcium			
Cadmium			
Cobalt			
Copper			
Chromium			
Iron			
Potassium			
Magnesium			
Manganese			
Molybdenum			
Sodium			
Nickel			
Phosphorus			
Lead			
Selenium			
Sulfur			
Strontium			
Uranium	335	379	13.1E
Vanadium			
Zinc			

Control limit ±10%

Phytotech, Inc.

Analytical Method SW6010 Project 98019
Matrix Soil Sample # 9807292

Duplicates
Concentration Units (mg/kg)

Analyte	Sample	Duplicate	% RPD
Aluminum			
Arsenic			
Boron			
Calcium			
Cadmium			
Cobalt			
Copper			
Chromium			
Iron			
Potassium			
Magnesium			
Manganese			
Molybdenum			
Sodium			
Nickel			
Phosphorus			
Lead			
Selenium			
Sulfur			
Strontium			
Uranium	335	336	0.3
Vanadium			
Zinc			

Control limit ±20%

Phytotech, Inc.

Analytical Method SW6010 Project 98019
Matrix Soil Sample # 9807293

Duplicates
Concentration Units (mg/kg)

Analyte	Sample	Duplicate	% RPD
Aluminum			
Arsenic			
Boron			
Calcium			
Cadmium			
Cobalt			
Copper			
Chromium			
Iron			
Potassium			
Magnesium			
Manganese			
Molybdenum			
Sodium			
Nickel			
Phosphorus			
Lead			
Selenium			
Sulfur			
Strontium			
Uranium	891	1020	13.5
Vanadium			
Zinc			

Control limit ±20%

Phytotech, Inc.

Analytical Method SW6010 Project 98019
Matrix Soil Sample # 9807292

Spike Sample Recovery
Concentration Units (mg/kg)

Analyte	Spike Sample Result	Sample Result	Spike Added	% R
Aluminum				
Arsenic				
Boron				
Calcium				
Cadmium				
Cobalt				
Copper				
Chromium				
Iron				
Potassium				
Magnesium				
Manganese				
Molybdenum				
Sodium				
Nickel				
Phosphorus				
Lead				
Selenium				
Sulfur				
Strontium				
Uranium	335	574	250	95.6
Vanadium				
Zinc				

Control limit 75-125%

9. Appendix C

9.1. QA/QC Protocol

9.1.1. Sample Custody

Each person having custody of the samples recorded on the report will sign and date the form certifying transfer of custody or receipt of the samples. The tracking form will be transmitted with the samples. The last person to sign the form should be the laboratory operator in charge of the analysis. Upon arrival at the laboratory and completion of log-in procedures, the original form will be transmitted to the PI, and a copy will remain with the analytical laboratory records.

9.1.2. Calibration Procedures And Frequency

Each instrument will be calibrated in a manner consistent with standard operating procedures. Analytical problems with the calibration procedure will result in corrective actions recommended by the Principal Investigator before analysis continues.

9.1.2.1. Conductivity Meter:

The Conductivity meter will be calibrated daily using commercially purchased 990 µS/cm solution. The calibration will be checked first by using commercially purchased 107.2 µS/cm, and after every 10 samples using a calibration check sample (Farm soil amended with 600 ppm Pb). If calibration check samples are not within 90-110 percent of the known value, the instrument will be re-calibrated and last 10 samples will be rerun. Conductivity will be measured before pH.

9.1.2.2. pH

The pH meter will be calibrated daily using commercially purchased pH 4, pH 7, and pH 10 buffer solutions. The calibration will be checked first by using commercially purchased pH 8, and after every 10 samples using a calibration check sample (Farm soil amended with 600 ppm Pb). If calibration check samples are not within 90-110 percent of the known value, the instrument will be re-calibrated and last 10 samples will be rerun.

9.1.2.3. Analytical Balances

Analytical balances will be calibrated on a routine basis with a set of certified weights and records which will be kept in a log book. The laboratory has yearly service contracts on all balances.

9.1.4.1. Duplicates and Matrix Spikes

On a daily basis, duplicate analyses will be performed on 5% (1 in 20) of samples listed on one request form (e.g., if less than 20 samples listed, then 1 sample, if 100 samples are listed on a form then 5 duplicate samples). This includes plant, soil TM, and soil WE.

In all analyses, duplicate samples will be spiked with standard material and percentage recovery and relative error will be calculated. The objective of duplicate spiking of samples is to determine the extent of matrix bias or interference on analyte recovery (accuracy) and sample-to sample precision (EPA, 1986).

In each analytical batch (defined as any number of samples of the same matrix type which are prepared simultaneously), one duplicate sample will be used. Choice of the samples for duplicates and spiking will be selected in a random, unbiased manner.

The spiking solution (SPEX CertiPrep- cat # PHXY-5) contains 100 mg/L of the following elements: As, Ag, Be, Cd, Co, Cu, Cr, Mn, Mo, Ni, Pb, Se, Sn, Sr, U, V, Zn.

Plant samples: Add 1 mL solution to weighed plant material before adding nitric acid.
Soil samples: Add 2.5 mL solution to weighed soil material before adding nitric acid.

9.1.4.2. Blanks

To ensure that contamination from glassware, other materials, or reagents are not interfering with accurate sample analysis, a reagent blank will be run prior to any sample run. For this reagent blank, all analytical operations using the specified materials and reagents will be performed in the absence of the sample substrate. A reagent blank will be run for every analytical batch. If the reagent blank shows significant interference(i.e. if the concentration of the reagent blank is above the contract required detection limit), materials and reagents will be replaced before additional samples are prepared. Samples out of control will be flagged. Samples prepared with contaminated reagents will be discarded, and fresh samples will be processed.

9.1.4.3. Laboratory Check Sample

Each analytical batch will contain one laboratory check sample (LCS). The LCS consists of a sample of equivalent matrix background as the actual samples with known analyte concentration. The LCS is carried through the same sample preparation, extraction procedures, and analysis as the actual samples.

Plant samples (LCSP): QC metal 2- for all samples
U control- additional for uranium samples

Soil samples (LCSS): Montana soil, NIST 2711.

9.1.4.4. Acidification

All water extracted samples, Cal WET, TCLP samples, and all others that are not digested should be filtered and acidified to pH 2 before submission to ICP analysis.

10. Appendix D

10.1. Chain of custody records

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Sample Chain of Custody / Analysis Request

Project ID: _____ Task ID: Ferrol Treatability Date: 8/17/98

Samples Submitted By: MPE Report Results To: MPE

Lab Sample #: 9807292 To 9807293

Page #: 54 Controls: Samples doubled, 293S, NIST, BLANK

Analytical Parameters

Sample Matrix: Plant (Soil) Water Other (Specify): _____

Test Code: (TM) (WE) SE TCLP EDTA Other (specify): _____

Physical Properties:	Spectroscopy:		Chromatography:	
Conductivity ☒	ICP ☒	AA ☐	HPLC ☐	
pH ☒	Element(s) U	Element	Compound	
Other				

Comments: _____

Laboratory Traffic Report

Relinquished by: (signature)	Date	Received by: (signature)	Date	Reason for exchange
[signature]	8/17/98	[signature]	8/17/98	Sample Prep/Sieving
[signature]	8/31	Lisa S. Morra	8/31	sample prep
[signature]	9/2	M. Lucas	9/2/98	ICP
Relinquished by: (signature)	Date	Received by: (signature)	Date	Reason for exchange
Relinquished by: (signature)	Date	Received by: (signature)	Date	Reason for exchange

Task: Phyto 97 ICP File: ME0902 HPLC file: _____

Notes: *Please indicate any special handling instructions or any known hazards:*

1) _____
2) _____
3) _____

1 Deer Park Drive, Suite I, Monmouth Junction NJ 08852 (732) 438-0900 ex 20 Fax (732) 438-1209

Phytotech

Sample Chain of Custody / Analysis Request

Project ID: 98019 Task ID: Treat2b1y

Samples Submitted By: Chris Date: 10/1/98

Lab Sample #: 9807996 To 9808067 Report Results To: Shay

Page #: Controls:

Analytical Parameters

Sample Matrix: (Plant) Soil Water Other (Specify):

Test Code: (TM) WE SE TCLP EDTA Other (specify):

Physical Properties:
Conductivity ☐
pH
Other

Spectroscopy:
ICP ☑
Element(s) U
AA ☐
Element

Chromatography:
HPLC ☐
Compound

Comments:

Laboratory Traffic Report

Relinquished by: (signature)	Date	Received by: (signature)	Date	Reason for exchange
	10/1/98	M. Lorow	10/1/98	trays
Relinquished by: (signature)	Date	Received by: (signature)	Date	Reason for exchange
		M Lutz	10/5/98	ICP
Relinquished by: (signature)	Date	Received by: (signature)	Date	Reason for exchange
Relinquished by: (signature)	Date	Received by: (signature)	Date	Reason for exchange
Relinquished by: (signature)	Date	Received by: (signature)	Date	Reason for exchange

Task: Mg97 ICP File: SD015 HPLC file:

Notes: *Please indicate any special handling instructions or any known hazards:*

1)
2)
3)

1 Deer Park Drive, Suite I, Monmouth Junction NJ 08852 (732) 438-0900 ex 20 Fax (732) 438-1209

Phytotech

Priority

Sample Chain of Custody / Analysis Request

Project ID: 98019 Task ID: Transkey Date: 10/7/98

Samples Submitted By: Chris Report Results To: Slavik

Lab Sample #: 9807996 To 9808061

Page #:_____ Controls: _____

Analytical Parameters

Sample Matrix: (Plant) Soil Water Other (Specify): _____

Test Code: (TM) WE SE TCLP EDTA Other (specify): _____

Physical Properties:	Spectroscopy:		Chromatography:
Conductivity ☐	ICP ☑	AA ☐	HPLC ☐
pH ☐	Element(s) U	Element	Compound
Other			

Comments: _____

Laboratory Traffic Report

Relinquished by: (signature)	Date	Received by: (signature)	Date	Reason for exchange
[signature]	10/7/98	M. Lerow	10/14/98	Proj
Relinquished by: (signature)	Date	Received by: (signature)	Date	Reason for exchange
		M Lutz	10/15/98	ICP
Relinquished by: (signature)	Date	Received by: (signature)	Date	Reason for exchange
Relinquished by: (signature)	Date	Received by: (signature)	Date	Reason for exchange
Relinquished by: (signature)	Date	Received by: (signature)	Date	Reason for exchange

Task: May 97 ICP File: SD015 HPLC file: _____

Notes: *Please indicate any special handling instructions or any known hazards:*

1) _____
2) _____
3) _____

1.3. Project goals and objectives

1.3.1. Goals

The goals of the Phytoremediation of Uranium Contaminated Soils at the Fernald Environmental Management Project (FEMP) Site project included the followings:

- further evaluation of U phytoextraction using soils from FEMP;
- report the results of the evaluation of U phytoextraction from FEMP site soil.

1.3.2. Objectives

The major objectives associated with the Phytoremediation of Uranium Contaminated Soils at the Fernald Environmental Management Project (FEMP) Site project were as follows:

- gather and assess environmental characterization data to select the most promising sites to demonstrate phytoextraction technology at FEMP;
- acquire bulk soil samples from the selected sites for evaluation of phytoextraction feasibility;
- characterize bulk soil samples for U availability;
- select the most promising plant species for U phytoextraction;
- optimize the soil amendment formulation for the FEMP site soil conditions;
- evaluate U accumulation in the above-ground plant biomass;
- assemble, interpret, and report the results of the above activities.

2. SOIL CHARACTERIZATION

2.1. Soil Sampling

Representative samples were collected by Fluor Daniel Fernald (FDF) personnel on August 5, 1998 according to the Project Specific Plan for soil collection for uranium in soil phytoremediation greenhouse study (ECDC 203000-PSP-0003/EM Project No. 04.135, July 24, 1998, see Appendix A for details). Surface soil (0-6") was collected from two locations (Location 1 - High contamination area and Location 2 - Low contamination area). The soil samples were placed in six sealed plastic containers, labeled, and shipped to Phytotech's Monmouth Junction facilities.

2.2. Soil analysis

Two bulk soil samples in six 5-gallon plastic containers with a total weight of 103 kg arrived at Phytotech's Monmouth Junction facilities on August 11, 1998. Containers 1 and 2 were labeled as Location 1 soil with high U content. Containers 3 to 6 were labeled as Location 2 soil with low U content. Soil containers from the same location were mixed together and treated as one representative sample. The composite soil was sieved to 2 mm, stored in sealed containers, and used for analysis. On August 28, 1998 one bucket of a total of 14 kg of the Location 2 soil was sent to the US Plant, Soil, and Nutrition Laboratory, USDA-ARS at Cornell University for uranium speciation analysis and further investigation of acidification and chelating agent effect on uranium solubilization from contaminated soils.

2.2.1. General Analysis

Soil pH for the representative soil samples was close to neutral for both locations, 7.1 and 7.0 for location 1 and 2 respectively. Soil EC was 0.50 dS m^{-1} for both representative samples.

Average U concentration was higher at location 1 (955±91 mg kg^{-1}) compared to location 2 (336±1 mg kg^{-1}). The levels of water extractable uranium in the representative soil samples were 20 mg kg^{-1} and 2 mg kg^{-1} for location 1 and 2, respectively.

2.2.2. Evaluation of Phytoextractable U

Additional analyses of the soil were conducted to evaluate phytoextractable metals and provide information for the application of soil amendments to enhance metal uptake by the plants. Sequential extraction of the FEMP site soil provides essential information concerning the chemical speciation of the constituent of concern within the soil matrix (e.g., associated with the exchange sites of clay minerals, carbonate minerals, oxide minerals, organic matter, and residual). Each step of the five-step procedure uses an extractant that is operationally defined as removing the constituent of concern (i.e., U) from a select soil fraction and each step in the procedure removes a more resistant or refractory form (Ramos, et al., 1994). Thus, the exchangeable and carbonate fractions represent the two fractions that contain the most available forms of the constituent of concern to plants, whereas the residual fraction represents that fraction of the constituent of concern which is not readily available.

Lee with colleagues (Lee, et al., 1993; Lee and Marsh, 1992) showed that the FEMP site soils are carbonate-rich and contain between 20 and 34% carbonate minerals in the incinerator area (IA) and storage pad area (SPA) soils; hence, uranium is not expected to exist as an uncomplexed exchangeable cation. This expectation was documented for the IA and SPA soils by Elless and Lee (1998) who showed exchangeable uranium to be < 0.003 meq UO_2^{2+}/100 g soil or < 4 mg U kg^{-1} soil.

Because of the strong affinity of the uranyl cation for carbonate in neutral to alkaline conditions, it is expected that the carbonate fraction in the sequential extraction would be the largest reservoir of contaminant uranium in carbonate-rich soils, with lesser amounts

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U Fractionation in Carbonate Rich, Uranium-Contaminated Soils

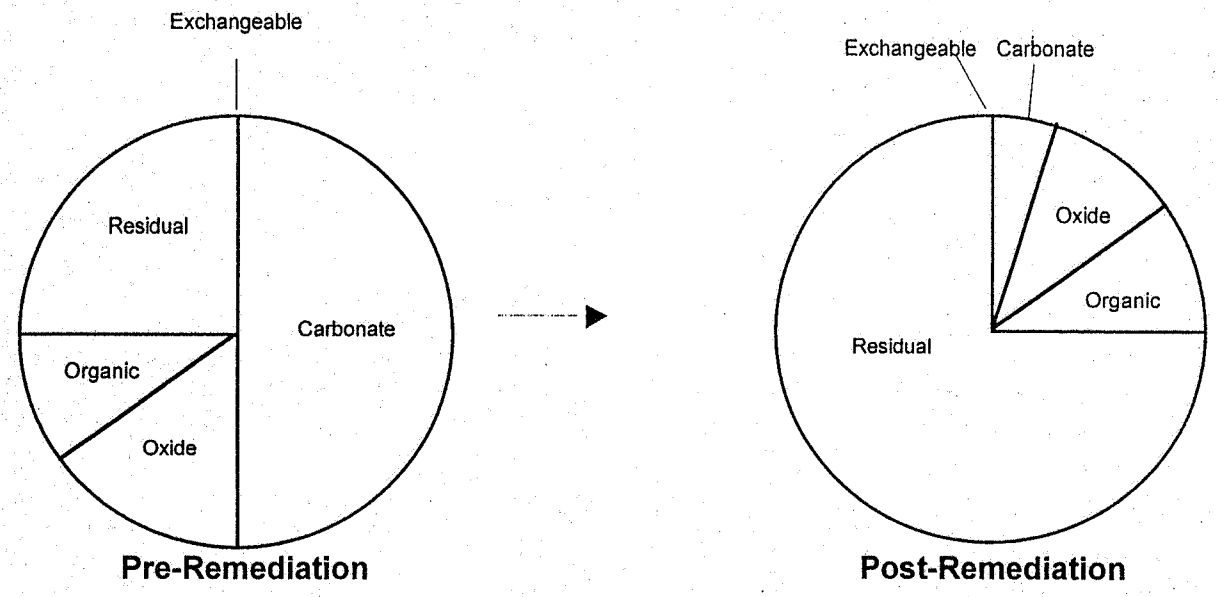

Figure 2. U Fractionation in carbonate rich, uranium-contaminated soils before and after phytoremediation.

associated with the oxide, organic, and residual fractions (Fig. 2). Following remediation that targets the carbonate fraction for removing uranium, the U partitioning would be reduced in this fraction as well as the other bioavailable fractions (i.e., the oxide and organic fractions) and increase in the nonavailable residual fraction (Fig. 2).

As expected for carbonate-rich soils, sequential extraction of Location 1 soil revealed the absence of exchangeable uranium, with the majority of the uranium existing in the carbonate and residual fractions. The lack of exchangeable uranium yet the presence of water-extractable uranium is explained by the fact that the sequential extraction is performed at a 10:1 solution:soil ratio whereas the water extraction is done at a 1:1 solution:soil ratio. Thus, the higher dilution caused the exchangeable uranium concentration to fall below detection although it is expected that the exchangeable fraction, being the first fraction extracted in the sequential extraction, would also extract water-soluble uranium. Extraction of U by citric acid, Phytotech's primary soil amendment for U-contaminated soils, averaged 186 mg U kg^{-1} soil, which represents approximately 20% of the total U and approximately 50% of the uranium associated with the exchangeable and carbonate fractions, the two fractions considered the most labile and available fractions for plant uptake.

Similar results were observed for Location 2 soil. Sequential extraction of this soil also revealed the absence of exchangeable uranium and the predominance of the carbonate and residual fractions for uranium partitioning. Again, the greater dilution associated with the sequential extraction compared to the water extraction allows for the presence of detectable water-extractable U yet undetectable U in the extraction of the exchangeable fraction. Citric acid-extractable U averaged 82 mg kg^{-1}, which represents approximately 25% of the total U content and approximately 75% of the uranium associated with the exchangeable and carbonate fractions.

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From earlier research, it is known that plants preferentially target contaminants associated with the exchangeable and carbonate fractions during phytoremediation. The lack of detectable uranium in the most available fraction may lead to poor uptake even though the uranium concentration associated with the carbonate fraction is relatively high. The reason for this prediction is due to the very large pH buffering capacity these soils have due to the presence of such high concentrations of carbonate minerals in these soils. A vital step in uranium phytoremediation is the reduction of soil pH in the rhizosphere, that is the volume of soil immediately adjacent to plant roots. This step shifts uranium species equilibrium to UO_2^{2+} cations that can be chelated with citric acid, taken up by plants and translocated to the above-ground parts. Acidification of rhizosphere may also stimulate destruction of Ca minerals and releasing U in the soil solution. Surfactants may also enhance U solubility via dispersion of soil particles.

3. GREENHOUSE STUDIES

The bulk composite samples were sieved, fertilized and planted with Indian mustard (*Brassica juncea* (L) Czern.), Chinese cabbage (*Brassica chinensis* L.), and Amaranth (*Amaranthus retroflexus* L.) for evaluation of plant growth and metal uptake. Three hundred grams of sieved soil were used per 9 cm diameter pot. Ten seeds of the selected plant were placed onto the soil surface in a circular patterned covered evenly with an additional 30 grams of soil. The seeded pots were put in trays and placed in a growth chamber at 25°C, 75% relative humidity, and a 16 h photoperiod (600 $\mu mol \cdot m^{-2} \cdot sec^{-1}$) provided by a combination of incandescent and cool-white fluorescent lights. Plants were watered and fertilized as needed. After germination, plant population was reduced to 4 healthy plants per pot. One week later the seedlings were thinned to two plants of equal size, growing in opposite sides of the pot. Amendments (Table 1) were supplied to soil to enhance metal accumulation in above-ground biomass. All treatments were made in three replicates After five weeks growth, the plants were harvested and analyzed for U concentration.

3.1. Plant Growth

Germination of seeds was 100% and the plants developed normally. The average plant dry weight (DW) per pot for the entire experiment was similar for Indian mustard (3.473±0.355 g) and Chinese cabbage (3.853±0.772 g). Overall, Amaranth had a lower DW per pot (1.017±0.699 g); however the difference in average DW are consistent with normal plant growth and development for tested species. For Indian mustard and Chinese cabbage no significant difference was observed in plant DW for different treatments or to the control (Fig. 3, 4). Amaranth grew better in the Location 2 soil compared to Location 1 soil (Fig. 5).