ERDC/EL TR-12-25

US Army Corps
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Army Range Technology Program

Large-Scale Physical Separation of Depleted Uranium from Soil

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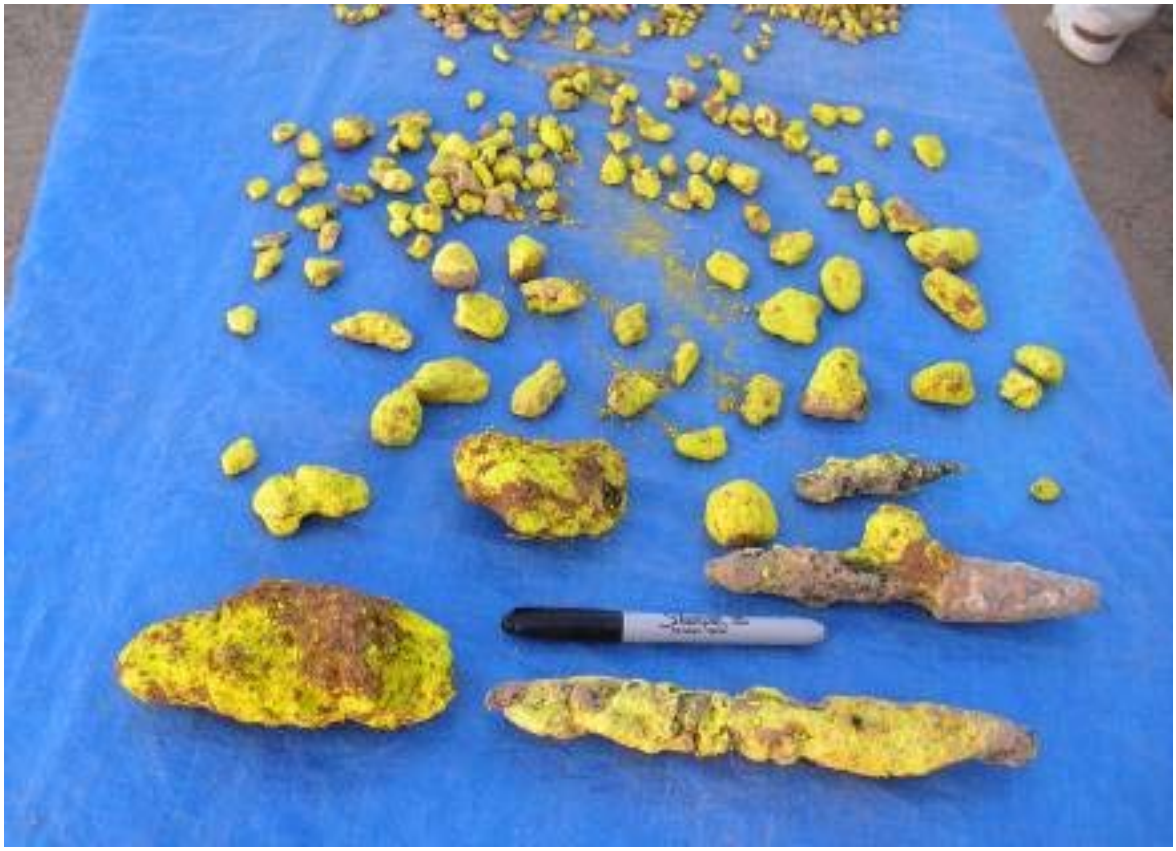
September 2012



Environmental Laboratory

ERDC/EL TR-12-25
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Final report

Prepared for U.S. Army Corps of Engineers
Washington, DC 20314-1000

Under Work Unit 33143

Monitored by U.S. Army Engineer Research and Development Center
3909 Halls Ferry Road, Vicksburg, MS 39180-6199

Abstract

Dry physical separation processes were tested at large-pilot scale (1,000 kg soil batches) at Yuma Proving Ground (YPG) to evaluate this technique for removal of depleted uranium (DU) metal from soil. Two sample locations, the Catch Box and the Buried DU Penetrator Test Site (DU Garden) were evaluated. These locations were chosen since previous small-scale testing confirmed that soils from these sites had varied uranium concentration, degrees of weathering, and aging of fired DU munition residues. Vibratory soil screening (dry sieve separation) was found to be effective for DU metal removal from Catch Box sand of YPG. On average, 50% of the mass of DU was removed with a single dry sieve separation of the Catch Box sand. The soil fines still contained DU, so control of fugitive dust emissions may be required. The degree of DU fragment weathering was found to be important to the success of the physical separation technology. The penetrator rod excavated from the DU Garden was highly weathered resulting in ineffective physical separation. The lesser degree of weathering of DU fragments in the Catch Box soil made successful physical separation possible. The difference in weathering of DU in the DU Garden versus the Catch Box could be due to increased exposure time (4 to 7 years in the garden versus approximately 18 months in the Catch Box); differences in soil chemistry (the DU garden was a desert soil, the Catch Box construction grade sand); and/or better aqueous drainage in the sandy Catch Box media. Non-uranium metals concentration were also increased in the DU Garden compared to both background soil concentrations and the concentrations detected in the Catch Box sands. Results indicate that periodic screening of Catch Box soils, coupled with dust control measures, could considerably increase the useful lifetime of Catch Box soil.

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Preface

This report was prepared as part of the Congressional Interest Army Range Technology Program (ARTP); Depleted Uranium (DU) Sensing, Containment, and Removal Focus Area. Research was conducted by the U.S. Army Engineer Research and Development Center (ERDC)-Environmental Laboratory (EL), Vicksburg, MS, and by cooperative agreement with the Mississippi State University-Institute for Clean Energy Technology (MSU-ICET), under the sponsorship of the U.S. Army Armament, Research, Development and Engineering Center (ARDEC), Picatinny Arsenal and the U.S. Army ARDEC Program Executive Office for Ammunition, Heavy Metals Office, Picatinny Arsenal. ERDC and MSU-ICET research activities were funded by MIPRs 8EGM009021 and 8EGM009202, respectively.

This project was performed under the general supervision of Dr. Elizabeth A. Ferguson, Technical Director, Military Environmental Engineering and Sciences, EL; John H. Ballard, Office of Technical Director and DU Program Manager, EL; and Dr. Steve L. Larson, Lead Principal Investigator, EL. In-house review was provided by W. Andy Martin, Chief, Environmental Engineering Branch (EP-E) and Susan Bailey, EP-E. The field assistance of Milton Beverly, Environmental Research and Development, Inc., David Carter, Alcorn State University, and the staff of the Yuma Proving Ground are all gratefully acknowledged.

This study was conducted under the direct supervision of W. Andy Martin, Branch Chief, EP-E, and under the general supervision of Warren P. Lorentz, Division Chief, Environmental Processes and Engineering Division, and Dr. Elizabeth C. Fleming, Director, EL. At the time of this study, COL Kevin J. Wilson was Commander of the ERDC, and Dr. Jeffery P. Holland was Director of the ERDC.

Unit Conversion Factors

Multiply	By	To Obtain
acres	4,046.873	square meters
acre-feet	1,233.5	cubic meters
cubic feet	0.02831685	cubic meters
cubic inches	1.6387064 E-05	cubic meters
cubic yards	0.7645549	cubic meters
feet	0.3048	meters
inches	0.0254	meters
microns	1.0 E-06	meters
pounds (mass)	0.45359237	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic meter
pounds (mass) per cubic inch	2.757990 E+04	kilograms per cubic meter
pounds (mass) per square foot	4.882428	kilograms per square meter
pounds (mass) per square yard	0.542492	kilograms per square meter
square feet	0.09290304	square meters
square inches	6.4516 E-04	square meters
square miles	2.589998 E+06	square meters
square yards	0.8361274	square meters
yards	0.9144	meters

Acronyms

ANOVA	Analysis of Variance
ARTP	Army Range Technology Program
bgs	below ground surface
CB	Catch Box
cm	centimeter
cpm	counts per minute
DU	depleted uranium
EL	Environmental Laboratory
ERDC	Engineer Research and Development Center
ICP-MS	Inductively coupled plasma- mass spectroscopy
ICP-OES	Inductively coupled plasma-optical emission spectroscopy
kg	killogram
mg	milligram
mm	millimeter
MS	Mass spectroscopy
MSU-ICET	Mississippi State University – Institute for Clean Energy Technology
na	not applicable
PEO-AMMO	Program Executive Office for Ammunition

RSD	relative standard deviation
SAFR	Small Arms Firing Range
US EPA	U.S. Environmental Protection Agency
WHO	World Health Organization
XRD	X-ray diffraction
YPG	Yuma Proving Ground
YTC	Yuma Test Center

Chemical Compounds

$(UO_2)_8O(OH)_{12} \bullet 12(H_2O)$	schoepite
UO_2	uranium dioxide (uraninite)

Metals

As	Arsenic
Ca	Calcium
Cr	Chromium
Cu	Copper
Fe	Iron
Mg	Magnesium
Mn	Manganese
Mo	Molybdenum
Ni	Nickel
Pb	lead

Sb	Antimony
U	Uranium
V	Vanadium
Zn	Zinc

1 Introduction

Depleted Uranium

Depleted uranium (DU) is uranium primarily composed of the isotope uranium-238 (U-238). Natural uranium is about 99.27 percent U-238, 0.72 percent U-235, and 0.0055 percent U-234. Because U-235 is used for fission in nuclear reactors and nuclear weapons, natural uranium is enriched in U-235 by separating the isotopes by mass. The byproduct of enrichment, called DU, contains less than one third as much U-235 and U-234 as natural uranium. Because U-234 accounts for about half the radioactivity of natural uranium, the external radiation dose from DU is about 60 percent of that from the same mass of natural uranium (World Health Organization (WHO) 2003, McClain and Miller 2007).

DU is useful for its very high density of 19.1 g/cm^3. Civilian uses of DU include counterweights in aircraft, radiation shielding in medical radiation therapy and industrial radiography equipment, and containers used to transport radioactive materials. Military uses include defensive armor plating and penetrating munitions. The chemical toxicity of DU in soil has raised health concerns world-wide due to its military deployment (Bleise et al. 2003, Burkart et al. 2005, Giannardi and Domenici 2003, McLaughlin 2005) as well as widespread civilian uses (Betti 2003, Hamilton 2001). This concern has generated interest in the remediation of soils contaminated with DU. Unique approaches are required due to the radiological, toxic heavy metal, and pyrophoric hazards associated with the use of metallic uranium.

The specific gravity of uranium is 18.95 g/cm^3. While the specific gravity of rock/soil/sand can vary, it can be approximated at 1.5 to 2.5 g/cm^3. Uranium oxidizes as it weathers, producing uranyl oxides and salts, evident as black and yellow coatings on the solid surface (Mellini and Riccobono 2005; Figure 1). The black substance has been identified by X-ray diffraction (XRD) analysis as uraninite, UO_2.

The amorphous yellow coating is composed of uranyl ions, hydroxyl compounds, and/or water, producing a compound that — as desccribed — is most likely schoepite, $UO_3 \cdot 2H_2O$ (Mellini and Riccobono 2005). These compounds have relatively high solubility in water (Meinrath et al. 2003).

Figure 1. Comparison of weathered and unweathered depleted uranium rods illustrating the formation of uranyl oxides and salts. Unfired penetrator rods can range from 10 to 50 cm in length, depending on the type of munition.

The density of uranium oxide is 10.96 g/cm^3 and supports gravimetric separation of DU corrosion uranyl compounds (separable by density) from soil. However, the uranium oxides have significant solubility in water, and the resulting ionic uranium can form uranium-based salts. These salts have lower densities that sorb to clays and organic matter in soil in complex interactions with soil particles (Johnson et al. 2004, Choy et al. 2006, Dong et al. 2006).

Uranium is a pyrophoric (combustible) metal, which means it is easily ignited when it reaches a high specific area ratio (as thin sections, fine particles, or molten states). Uranium in finely divided form is prone to ignition. Uranium also has an increased tendency to burn after prolonged exposure to moist air. A few metals, such as thorium, uranium, and plutonium, emit ionizing radiation that, when ignited, can complicate fire fighting and introduce a radioactive contamination problem (Burger and Slotte 2007). Under a dry, slightly oxidizing atmosphere, however, uranium corrodes quiescently. The heat generated from slow corrosion is not sufficient to ignite the uranium.

Dry Sieve Separation

As discussed in Larson et al. (2007), physical separation technologies are the most frequently utilized processes for one-time cleanup of closed small arms firing ranges (SAFRs), as well as for periodic removal of a metal such as lead (or DU) as a part of routine maintenance of active SAFRs. Most of the separation technologies and equipment used at ranges have been adapted from the mining industry and are readily available and relatively

inexpensive. In some cases, physical separation alone may be sufficient to reach treatment goals. In general, however, physical separation is simply the initial process in which the bulk of the DU is removed and is followed by additional cleanup technologies that either remove or stabilize the remaining DU fraction. Physical separation can also be an intermediate process for an advanced treatment train.

Physical separation processes use soil particle characteristics such as size, shape, density and/or magnetism for separating particles (Battelle 1997). The two physical characteristics identified as providing the basis for separating particles from ranges are particle size (using sieving) and density (using gravity separation). Size separation is a mechanical process in which the soil material is applied to one or more chambers with progressively smaller openings. Material is sorted based on whether it passes through or is retained at each step. The process can be wet or dry, stationary or gyrating. Some common equipment types are screens, sieves and trommels. Particle shape, uniformity, agglomeration and blockage can affect the performance of these systems.

Dry sieving separation technologies use different size sieves or screens, often in a nested or sequential configuration, to segregate materials according to particle size. Dry sieving is an effective method for separating different sized particle fractions. Dry Sieving is also relatively efficient and cost-effective; it requires minimal mobilization effort, and does not generate a contaminated aqueous waste stream. Conventional dry sieving is effective for a wide range of particle sizes. However, sieve sizes smaller than 4.76 mm may require very dry soil (depending upon the soil silt and clay content) due to blinding and blockage of the screen. Hard clumps of soil may not break up, and thus may be retained intact on the larger screens. Dry sieving does not differentiate between organic, metallic, and geologic materials, and cannot separate bullets and bullet fragments, for example, from soil material of the same size (Larson et al. 2007).

Project Background

Originally established in 1943, the Yuma Proving Ground (YPG) encompasses approximately 1,300 square miles and is located near Yuma, AZ. It is operated by the Yuma Test Center (YTC) and serves as an Army arid environment test facility. The YPG was selected as the research site because of the diversity in age and weathering of DU projectiles.

The U.S. Army Engineer Research and Development Center (ERDC)-Vicksburg, Mississippi, executed the Army Range Technology Program (ARTP) research program with the Mississippi State University-Institute for Clean Energy Technology (MSU-ICET) under the sponsorship of the Program Executive Office for Ammunition (PEO-AMMO), Picatinny Arsenal and a Congressional Interest training range sustainment program. The objective of the ARTP was to develop and evaluate technologies for the detection and separation of depleted uranium (DU) penetrator projectiles and uranium oxide compounds from Catch Box and training range soils. The technologies under development are designed to provide engineered solutions that will allow continued and sustainable use of DU munitions on DoD test ranges.

The initial investigation studied four soil separation technologies: dry sieve, wet sieve, heavy liquid density separation, and water/momentum density separation (Larson et al. 2009). Four areas at YPG served as sample sites: the Catch B0x, the Retention Pond below the Catch Box area, Range 20, and the DU Garden. The DU Garden was an experimental area prepared in 2003/2004. In this area, fired and unfired penetrator rods were buried in rows at several depths ranging from near surface (0.00 to 2.54 cm), 15.24 cm and 91.44 cm (1, 6, and 36 inches, respectively) below ground surface (bgs) and allowed to weather. Additional studies were performed to optimize the field separation procedures. At the four locations, the DU munitions used for testing were penetrator ordnance of varying sizes. The uranium present in the soils consisted of metallic DU as well as uranium corrosion products, and the products of dissolution of those uranium oxides. The extent to which DU and DU residues from kinetic penetrators could be removed from the YPG soils depended on the extent of weathering the soils had undergone during the period between firing and separation activities.

As reported by Larson et al. (2009), dry separation of DU fragments from the surrounding sand was successfully and inexpensively achieved using simple vibratory or agitated screening techniques. For soils into which the DU had been recently fired (i.e. the Catch Box soil), these techniques were successful at removing greater than 70% of the total uranium present (by mass). For soils in which long periods of time had passed since firing, or for those that had been heavily weathered, the removal efficiency of this technique was somewhat lower. Approximately 50% of the >4.76 mm soil size fraction of DU Garden deep lifts and 16% of the >4.76 mm soil size

fraction of the Range 20 soil, and no uranium was removed from the Retention Pond soil using a 4.76 mm dry sieving process.

While the wet separation technologies tested at YPG (wet sieve separation, heavy liquid density separation, and water/momentum density separation) had the advantage of separating the fine uranium oxides observed in soils impacted with DU rounds from the less dense soils, their primary disadvantage was the production of a secondary waste stream contaminated with uranium. Techniques such as ion exchange filtration and zero valent iron or titanium oxide filtration might be adaptable to deal with water containing dissolved uranium. Wet separation of depleted uranium from the surrounding soil may be applicable in other climatic conditions than the desert environment of YPG.

Initial recommendations for sustainable management of DU at YPG, reported in Larson et al. (2009), were regular removal of DU fragments from the sand bed using dry separation techniques in order to remove the metallic DU present in these soils. This procedure would reduce the amount of time that metallic uranium could undergo corrosion and weathering as well as mediate any risks associated with the pyrophoric combustion of metallic, DU in the impact area.

Study Objectives

For this study, two of the YPG sampling areas were investigated, the Catch Box and the DU Garden. The objectives for this project were to:

- demonstrate simple vibratory screening as a rapid and effective technology for removing bulk- depleted uranium;
- perform this demonstration using field scale size samples on the order of 1,000 kg of soil or sand;
- evaluate the effect of repeated screenings from the sand/soil; and
- evaluate the removal/separation of DU from excavation of a buried penetrator rod.

2 Materials and Methods

Catch Box

Four sampling areas were randomly selected within the Catch Box (CB) and designated CB1 through CB4. For sampling CB1 - CB3, 1,000 kg of sand was excavated from each sampling area and placed in buckets (Figure 2A). The buckets were weighed and staged for dry sieve separation using a 4.76 mm sieve, #4 U.S. mesh (Figure 2B). The sieved sand was raked out onto a tarp and separated into 15 sampling zones. The 15 sub-samples were stored in pre-weighed plastic bags and scanned for radiation (Figure 2C). DU fragments retained on the 4.76 mm sieve were weighed and counted (Figure 2D) using a Geiger-Mueller counter (model TBM35) with a maximum count of 50,000 counts per minute (cpm). The DU fragments obtained from CB1-3 were added to the CB4 sample as described below.

Figure 2. Sample collection, soil sieve separation, and sample preparation sequence from Catch Box areas 1 through 3.

Soil from CB4 was excavated in the same manner as areas 1-3, and dry sieved to remove fragments over 4.76 mm in size. These fragments were weighed and counted and then returned to the soil along with the DU from CB sampling areas 1-3. The soil was thoroughly mixed and then sampled as for areas 1-3.

DU Garden

A fired DU penetrator rod was excavated from the DU Garden where it had been buried at a depth of 60.96 cm (2 ft.) for approximately 5 years. The entire mass of soil, 421.6 kg, was removed from the top of the penetrator. This soil was separated into two fractions by dry sieve separation (>4.76mm and <4.76 mm). The >4.76 mm fraction was counted and weighed (Figure 3), with large fragments being removed by hand for counting and weighing. Soil in the <4.76 mm fraction was homogenized and sub-sampled and returned to the laboratory for digestion and analysis.

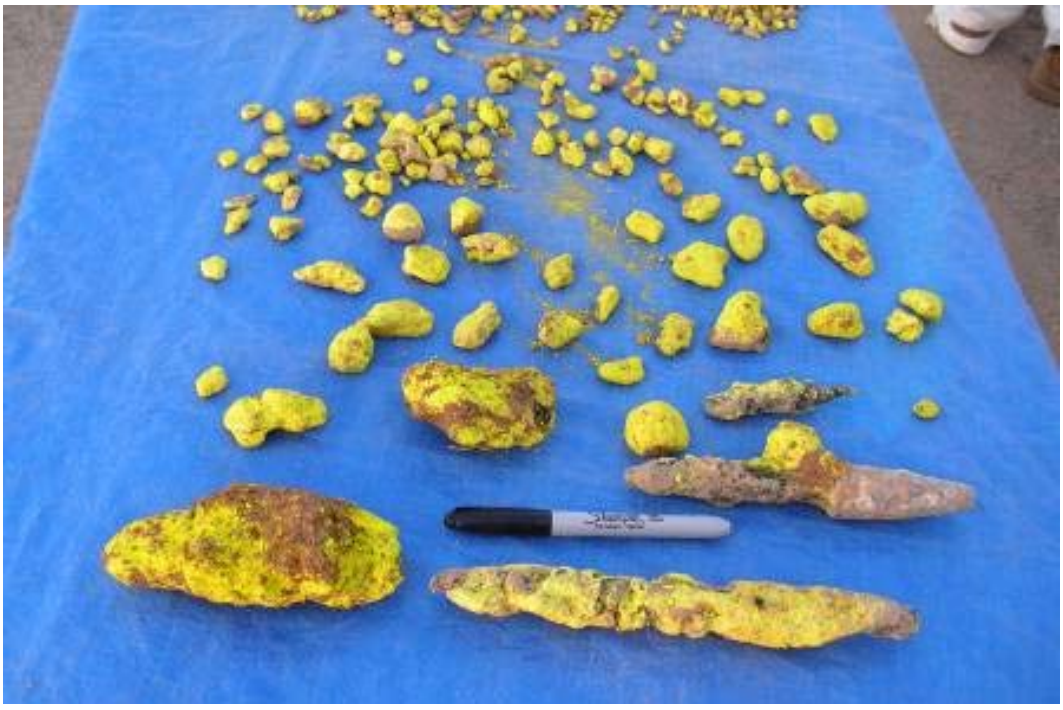

Figure 3. DU fragments from the >4.76 mm soil fraction of the DU Garden.

Sample Preparation

Following sieve separation, homogenization, screening by Geiger-Mueller counter, and sub-sampling in the field, soil samples were shipped to the ERDC-Vicksburg, MS for metals analysis. Metals in soil are known to be distributed heterogeneously (Larson et al. 2007). Therefore, upon arrival

at ERDC, the sub-samples were re-homogenized and then ground using the Fritsch Pulverisette 7 to pass a #400 mesh sieve (0.037 mm). All samples were digested and analyzed by inductively coupled plasma mass spectroscopy (ICP-MS) for metals in triplicate (Table 1).

Table 1. Analysis procedures for depleted uranium in YPG soil

Procedure	Method	Metal	Reporting Limit in Soil (mg/kg)
Soil digestion	SW-846-3051[a] SW-846-3015	Na	na[b]
ICP[c]	EPA Method 200.7[a]	Uranium (U)	5.0
		Lead (Pb)	5.0
		Nickel (Ni)	5.0
		Iron (Fe)	5.0
		Zinc (Zn)	5.0
		Manganese (Mn)	5.0
		Magnesium (Mg)	5.0
		Chromium (Cr)	5.0
		Copper (Cu)	5.0
		Vanadium (V)	5.0
		Calcium (Ca)	5.0

[a]US Environmental Protection Agency (US EPA), 1999

[b]na=not applicable

[c]ICP=inductively coupled plasma spectrometry

Chemical Analysis

Table 1 lists the procedures used during this study for analysis of the U in soil. Analysis was performed using ICP on a Perkins Elmer Optima 3000 or by ICP-MS on a Perkins Elmer Sciex 6000. Non-detect values are those that are below the ICP reporting limit. For data analysis purposes, the ICP reporting limit, 5.0 mg/kg, was used in place of non-detect. The calculated mass of DU is based on the concentration of uranium detected in the various soil samples under the assumption that all detected uranium is in the form of DU. Uranium concentration in the various soil size fractions by the different treatment procedures was reported as the average, standard deviation and relative standard deviation (RSD, %) using a 95% confidence interval. The sample size is indicated in the text and in the specific tables.

3 Results and Discussion

Catch Box

Soil sample characterization for DU

The soil from the four sampling areas of the Catch Box was separated, weighed, and counted. The results are shown in Table 2. The background Geiger-Mueller count was 100 cpm. The CB4 sampling area held all the DU >4.76 mm found in the sampling areas CB 1-3 as well as in CB 4.

Table 2. Catch Box soil sample characterization.

Parameter	Catch Box sampling sites			
	CB 1	CB 2	CB 3	CB 4
Initial mass (kg)	1,001.05	1,005.60	1,007.20	1,009.15
Rocks >4.76 mm (mass, kg)	2.15	2.75	2.40	1.50
DU >4.76 mm (mass, kg)	1.75	1.80	1.95	6.30
Soil <4.76 mm (mass, kg)	997.15	1001.05	1,002.85	1,001.35
Soil <4.76 mm Geiger-Mueller readings, cpm (avg, n=15)	Background*	Background	Background	Background

*2 of 15 responses were above background levels at 200 and 240 cpm

The concentration of uranium in the <4.76 mm size fraction of the soils from the four Catch Box sampling areas, as obtained by dry sieve separation, digestion and ICP analysis, is shown in Figure 4. The DU fragments from the >4.76 mm size fractions of all three sampling points were added to the CB4 sample before sieving. Statistical analysis using ANOVA on ranks, and the Tukey test, confirmed that the U concentration in the Catch Box sampling area 4 was significantly greater than that of Catch Box sample areas 1, 2, and 3 (p=0.001).

Based on the mass of soil and DU in the >4.76 mm soil size fraction, Catch Box sample areas 1, 2, and 3 had an average 76% DU by mass (Table 3). CB 4 is analyzed and reported separately as it had the added >4.76 mm DU from CB 1, 2, and 3.

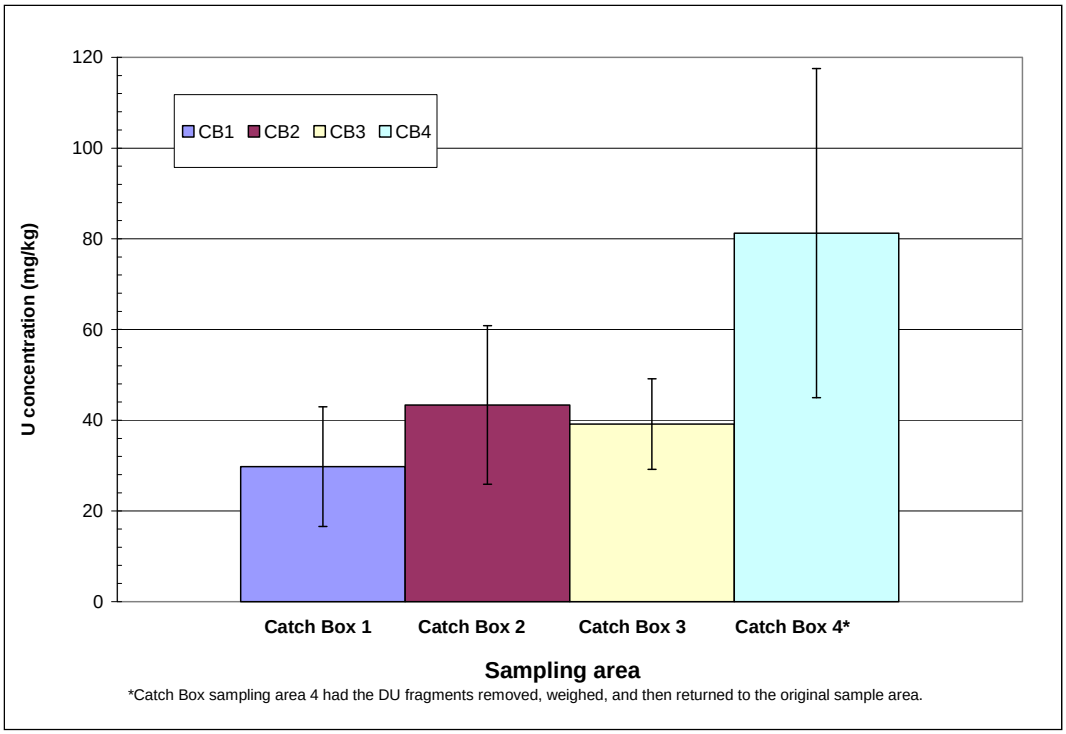

Figure 4. Concentration of U in <4.76 mm soil size fraction obtained through dry sieve separation.

Table 3. Mass of DU in the >4.76 mm and <4.76 mm soil size fractions of Catch Box sample areas 1, 2, and 3.

Sample area	Initial mass (kg)	>4.76 mm			<4.76 mm			
		Soil mass (kg)	DU mass (kg)	% DU in soil fraction	Soil mass (kg)	U concentration (mg/kg)	DU mass (kg)	% DU in soil fraction
CB 1	1001.5	2.15	1.75	81.40%	997.15	29.77	2.97	29.78%
CB 2	1005.6	2.75	1.80	65.45%	1,001.05	43.36	4.34	43.35%
CB 3	1007.2	2.40	1.95	81.25%	1,002.85	39.14	3.93	39.19%
Avg	*1004.77*	*2.43*	*1.83*	*76.03%*	*1,000.35*	*37.42*	*3.75*	*37.44%*
Stdev	*2.94*	*0.30*	*0.10*	*9.16*	*2.91*	*6.96*	*0.70*	*0.07*
RSD (%)	*0.29*	*12.39*	*5.68*	*12.05*	*0.29*	*18.59*	*18.77*	*18.56*

In comparison, the %DU by mass in the <4.76 mm soil size fraction was an average 37% (Table 3). Comparison of DU masses in the <4.76 mm soil size fraction from Catch Box sampling areas 1, 2, and 3 (n=45) after dry sieve separation and removal of the >4.76 mm size fraction (Table 4) showed the high degree of homogeneity in the distribution of the DU within the Catch Box area. The standard deviation and relative standard deviation (RSD) were 0.70 and 18.77%, respectively. This indicates both adequate sample preparation and the fact that the DU in the <4.76 mm size faction separates with the soil particle sizes.

Table 4. Comparison of DU masses in the <4.76 mm soil size fraction from Catch Box sampling areas 1, 2, and 3 (n=45) after dry sieve separation and removal of the >4.76 mm size fraction.

Sampling area	U concentration (avg, mg/kg)	Soil mass (kg)	DU mass (kg)
CB 1	29.77	1,000	2.97
CB 2	43.36	1,000	4.34
CB 3	39.14	1,000	3.93
Avg	*37.42*	*1,000*	*3.75*
Stdev	*6.96*	*3*	*0.70*
RSD (%)	*18.59*	*<1*	*18.77*

Separating the >4.76 mm sized DU fragments from the first three Catch Box sample areas and adding these fragments to the CB 4 area prior to dry sieve separation resulted in a DU mass in the <4.76 mm size fraction that had a lower standard deviation (0.06) but a greater RSD, 41%, than CB 1, 2, and 3 (Table 5). The DU fragments from CB 1, 2, and 3 were actually sieved twice, possibly separating finer sized particles of DU from the large fragments. This decreased the mass of the >4.76 mm size DU fragments over the additive mass expected, and increased the DU mass in the <4.76 mm size fraction in CB 4, as well as increasing the heterogeneity of the DU distribution.

Table 5. DU mass from Catch Box sampling area 4 in the soil size fraction <4.76 mm following dry sieve separation.

CB 4 sub-sample	U concentration (mg/kg, avg, n=3)	Soil mass (kg)	DU mass (kg)
1	71.31	2	0.14
2	84.91	2	0.16
3	53.05	2	0.10
4	58.31	2	0.10
5	147.43	2	0.24
6	67.90	2	0.13
7	47.89	2	0.09
8	47.82	2	0.17
9	66.21	2	0.16
10	64.01	2	0.09
11	86.35	2	0.14
12	68.41	2	0.12
13	181.97	2	0.33

CB 4 sub-sample	U concentration (mg/kg, avg, n=3)	Soil mass (kg)	DU mass (kg)
14	81.49	2	0.17
15	91.47	2	0.15
Avg (n=45)	*87.00*	*2*	*0.15*
Stdev	*37.83*	*<1*	*0.06*
RSD (%)	*43.49*	*8*	*40.82*

Non-uranium metals

The soil in the <4.76 mm size fraction of the Catch Box sampling areas was also analyzed for non-uranium metals (Figure 5 and Table 6). No lead (Pb), chromium (Cr), nickel (Ni), arsenic (As), antimony (Sb), or molybdenum (Mo) was detected in any of the sampling areas. There were two detections of copper (Cu) in CB 1 (2/45 samples), but no Cu was detected in any of the other sampling areas. With the exception of U, concentrations of the other metals were equal to, or less than, their mean background concentrations in US soils (Shacklette and Boerngen 1984).

Statistical analysis by ANOVA on ranks confirmed that there was no statistically significant difference between the non-uranium metal concentrations in the four Catch Box sampling areas. This is illustrated in

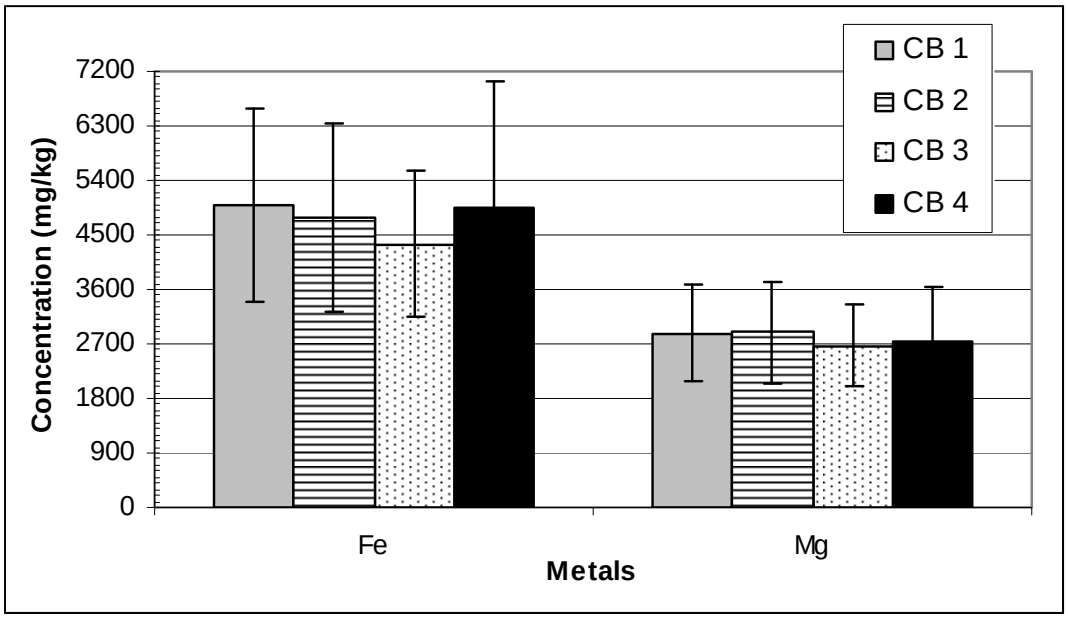

Figure 5. Concentrations of two non-uranium metals detected in the Catch Box sampling areas from the <4.76 mm soil size fraction obtained by dry sieve separation.

Table 6. Summary of the concentrations of uranium and non-uranium metals in the <4.76 mm size fraction of soils from the Catch Box.

	Concentration (mg/kg)											
	CB 1			CB 2			CB 3			CB 4		
Metal	Avg (n=45)	Stdev	RSD (%)	Avg (n=45)	Stdev	RSD (%)	Avg (n=45)	Stdev	RSD (%)	Avg (n=45)	Stdev	RSD (%)
U	30	13	44	43	17	40	39	10	26	81	36	45
Pb	5[b]	0.00	0.00	5[b]	0.00	0.00	5[b]	0.00	0.00	5[b]	0.00	0.00
Cr	5[b]	0.00	0.00	5[b]	0.00	0.00	5[b]	0.00	0.00	5[b]	0.00	0.00
Cu	5[b]	2	422	5[b]	0.00	0.00	5[b]	0.00	0.00	5[b]	0.00	0.00
Ni	5[b]	0.00	0.00	5[b]	0.00	0.00	5[b]	0.00	0.00	5[b]	0.00	0.00
Zn	10	8	75	7	7	100	5	6	113	9	9	92
Fe	5,000	1,600	32	4,800	1,600	32	4,400	1,200	27	5,000	2,000	42
Mn	150	24	16	140	26	18	130	19	14	146	29	20
Mo	5[b]	0.00	0.00	5[b]	0.00	0.00	5[b]	0.00	0.00	5[a]	0.00	0.00
Mg	2,900	790	27	2,900	800	29	2,700	700	25	2,700	900	34
V	12	6	50	9	8	86	8	7	92	9	9	94
Sb	5[b]	0.00	0.00	5[b]	0.00	0.00	5[b]	0.00	0.00	5[a]	0.00	0.00
As	5[b]	0.00	0.00	5[b]	0.00	0.00	5[b]	0.00	0.00	5[a]	0.00	0.00
Ca	9,700	600	6	9,000	400	5	8,700	400	4	10,400	300	3

[a]a single occurrence

[b]the method detection limit is used in place of “non-detect” for statistical analyses

Figure 5 using Fe and Mg, the two most abundant metals in the Catch Box sand. The concentrations for all the metals are detailed in Table 6. The concentration of Ca in the Catch Box sand is also listed in Table 6 as an example of a naturally occurring non-uranium metal. From this data, it appears that the addition of the previously sieved uranium fragments to the Catch Box 4 sample, where it underwent a second sieving, had no effect on any of the metals other than U. This is probably because the non-uranium metals are present in the same particle sizes as the soil itself. It appears that DU is the only metal appreciably present in the Catch Box with a particle size >4.76 mm.

Comparison of uranium and non-uranium metals detected in the Catch Box

As seen in Table 6, when the soils from Catch Box sampling areas 1, 2, and 3 were each treated by a single dry sieve separation (4.76 mm), the average concentration of U was 37.42 mg/kg with an average DU mass of 3.74 kg. When all of the separated DU >4.76 mm in size was returned to the soil of CB 4, sieved and analyzed, the concentration of U increased to 81 mg/kg, an increase of 2.16 times. The increase in DU concentration and mass was not additive as might be expected. The previously sieved DU fragments broke down further when sieved a second time, decreasing the DU mass in the larger size fraction and increasing the mass in the smaller size fraction. This implies that frequent, repeated screenings of the Catch Box soil will only remove less of the large fragments and increase the DU in the smaller size fractions.

Non-uranium metals were not detected in Catch Box sand at concentrations over U.S. background levels as reported by Shacklette and Boergnen (1984). There was also no increase in the non-uranium metals between Catch Box 1, 2, and 3 and CB 4 as was seen with uranium (Figure 5).

A single dry sieve soil separation, therefore, appears to be successful at separating approximately 50% of the DU from the Catch Box sand. Dry separation does not appear to separate the non-uranium metals from the soil.

DU Garden

Sample Characterization for DU

The initial total mass of the soil from the excavation of the buried penetrator rod was 426.25 kg. This soil mass was separated by dry sieve, producing two soil size fractions; the fraction that held soil particles sized >4.76 mm and the fraction sized <4.76 mm. The soil mass of the larger sized fraction was 160.70 kg; the portion of the total mass that was DU was 2.70 kg. The total soil mass of the smaller size fraction was 265.55 kg. This fraction was homogenized, sub-sampled (n=15), digested and analyzed for metals. The masses and Geiger-Mueller counts of each of the 15 sub-samples is detailed in Table 7. Compared to the background counts registered for the Catch Box samples, the DU Garden samples had an average of 5,500 cpm; this reflects the large quantity of DU present in the soil as particles <4.76 mm in size.

Table 7. Characterization of the soil in the <4.76 mm fraction produced from the DU Garden excavation.

Sub-sample	Soil mass (kg)	Soil Geiger-Mueller readings (cpm)
1	0.7	5,000
2	0.70	3,000
3	0.70	3,500
4	0.80	4,000
5	0.60	10,000
6	0.65	11,000
7	0.85	4,500
8	0.80	1,000
9	0.85	11,000
10	0.90	3,500
11	0.80	4,000
12	0.75	4,000
13	0.70	4,500
14	0.55	3,500
15	0.75	10,000
Avg	*0.74*	*5,500.00*
Stdev	*0.10*	*3,256.86*
RSD (%)	*13.07*	*59.22*

The average concentration of uranium in the<4.76 mm size fraction of the DU Garden soil, as obtained by triplicate digestion and ICP analysis of the 15 sub-samples, was 6,800 mg/kg. The mass of DU in each soil size fraction, as a percent of the total DU in the DU Garden soil, was calculated (Figure 6). The two soil size fractions had close percentages of DU, 60% and 40%, for the >4.76 mm and <4.76 mm size fractions, respectively.

Non-uranium metals

The soil in the <4.76 mm size fraction of the DU Garden sampling area was also analyzed for other, non-uranium, metals. Unlike the sand of the Catch Box, a full range of metals was found to be present in the DU Garden natural YPG soil. This data is illustrated in Figure 7 (metals present at low concentrations) and Figure 8 (metals present in higher concentrations). A summary comparing the DU Garden metal concentrations to the YPG background soil metals is provided in Table 8, where the shaded areas indicate those metals detected in the DU Garden at concentrations more than one standard deviation greater than the background levels.

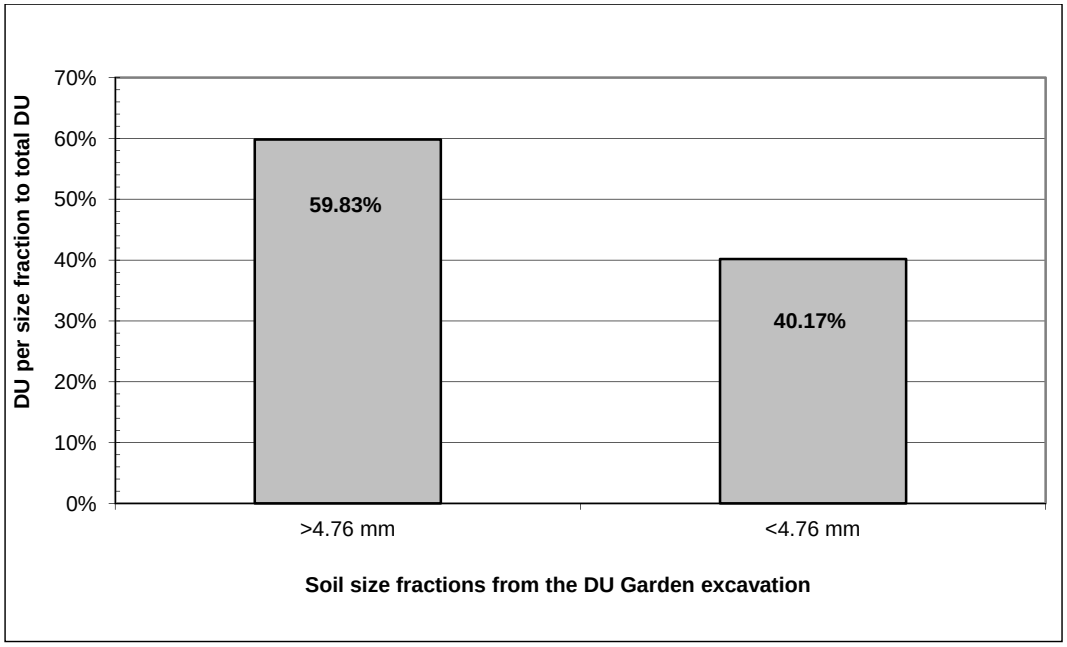

Figure 6. Ratio of DU mass in each soil size fraction to the total DU following dry sieve separation of soil from the DU Garden sampling site.

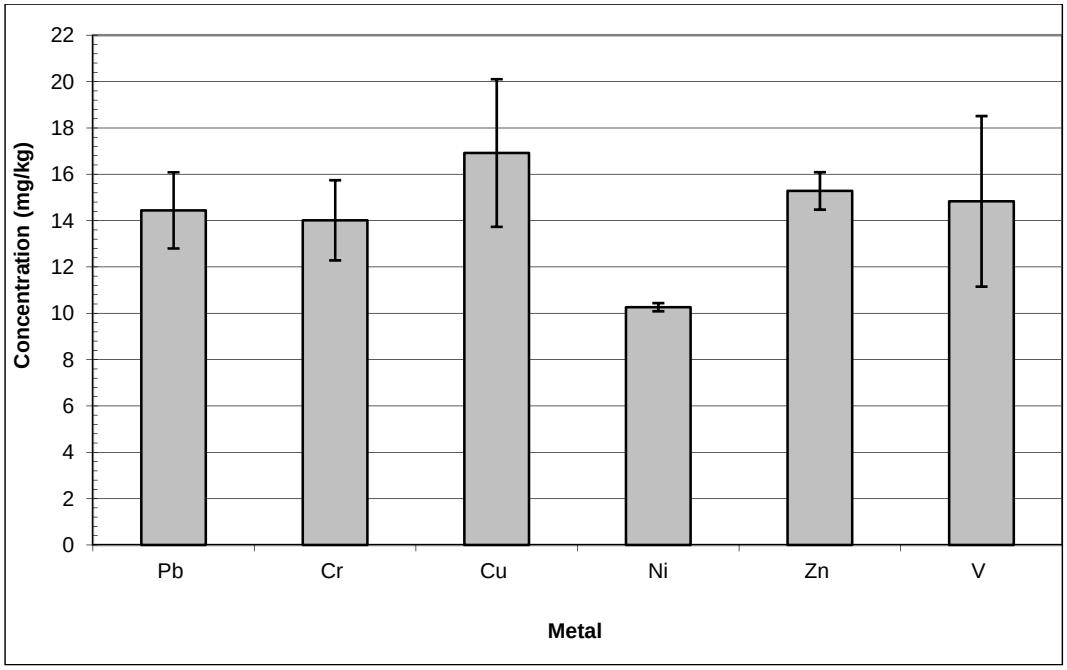

Figure 7. Low concentration munitions metals analyzed in the <4.76 mm size fraction of soil from the DU Garden excavation.

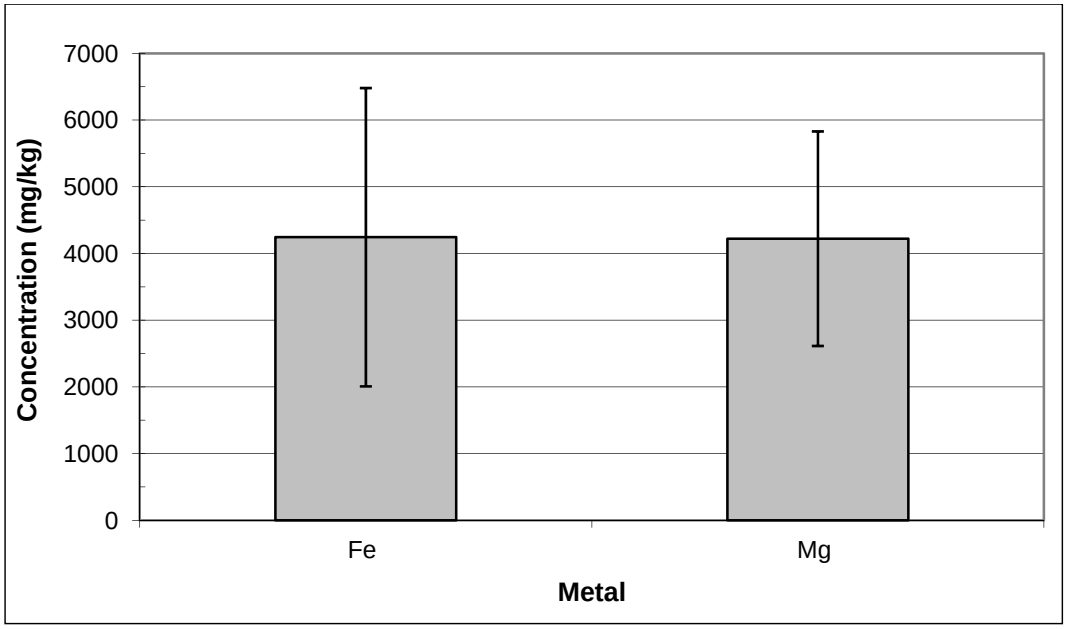

Figure 8. Concentration of iron and magnesium analyzed in the <4.76 mm size fraction of soil from the DU Garden excavation.

Table 8. Concentration summary of non-uranium metals in the <4.76 mm size soil fraction of soils of the DU Garden soil compared to background soil.[a]

	Concentration (mg/kg)					
	Background			DU Garden		
Metal	Avg (n=9)	Stdev	RSD (%)	Avg (n=45)	Stdev	RSD (%)
Pb	1[c]	4	288	14	2	11
Cr	5.00[b]	0.00	0.00	14	2	12
Cu	5.00[b]	0.00	0.00	17	3	19
Ni	5.00[b]	0.00	0.00	10	<1	2
Zn	18	8	45	15	1	5
Fe	5,000	2,200	45	4,200	2,200	53
Mn	170	65	39	170	26	16
Mo	5.00[b]	0.00	0.00	5.00[b]	0.00	0.00
V	8	6	75	15	4	25
Sb	5.00[b]	0.00	0.00	5.00[b]	0.00	0.00
As	5.00[b]	0.00	0.00	5.00[b]	0.00	0.00
Ca	5.00[b]	0.00	0.00	25,700	2,300	9

[a]Shaded values indicate an increase over one standard deviation in concentration over background levels.

[b]The method detection limit is used in place on “non-detect” for statistical analysis.

[c]1 of 9 samples

Comparison of uranium and non-uranium metals in the DU Garden soil

As seen in Table 7, and shown graphically in Figure 6, there was an increase in the concentration of U in the soil from the DU Garden over both the background and the Catch Box soil. However, dry sieve separation of DU Garden soil produced two fractions with almost equal masses of DU. The extended period of time the penetrator rod was exposed to weathering in the DU Garden over the Catch Box (4-7 years vs. 18 months) allowed DU oxides and carbonates to form and associate with small size soil particles.

In contrast to the background soil and the Catch Box sand, there was also an increase in some non-uranium metals in the DU Garden soil, particularly Pb, Cr, Cu, and Ni (Table 8).

Comparison of Catch Box and DU Garden soils

Dry sieving technologies use different size sieves or screens — often in a nested or sequential configuration — to segregate materials according to particle size. Dry sieving is an effective method for separating different sized particle fractions, is relatively efficient and cost-effective, and requires minimal mobilization effort. However, dry sieving does not differentiate between organic, metallic, and geologic materials, and cannot separate bullets and bullet fragments, for example, from soil material of the same size (Larson et al. 2007).

Characteristics of the >4.76 mm soil size fraction of the Catch Box and DU Garden sampling areas are summarized in Table 9. The Catch Box sand represents the type of uranium separation achievable if a dry sieve operation was performed periodically. As reported by Larson et al. (2009), the DU of the Catch Box sand, which was aged approximately 18 months at the time of sampling, was about 15% of the >4.76 mm size fraction. The large-scale separation reported here calculates the removal of an average 76% of the DU mass in the >4.76 mm soil size fraction of the Catch Box sand. This response is much greater than that initially proposed based on the preliminary small-scale separation efforts. The improved estimation of the percentage of 0.4.76 mm particles containing DU is most likely a result of the soil heterogeneity. In a previous study, small Catch Box soil samples were used (20 kg) compared to the 1000 kg soil masses separated in this study. The 50 x larger mass batch size allowed for a reduction in error based on sample representivity. Assuming all legal and regulatory requirements for returning soils have been met, this would leave the <4.76 mm fraction to be returned

to the Catch Box. The decreased DU mass in the Catch Box sand would decrease the chance of a spontaneous pyrophoric reaction during training exercises and increase the life of the Catch Box.

Table 9. Comparison of uranium concentration in the >4.76 mm soil fraction of the Catch Box and DU Garden soils.

Sample site	Age of DU	% DU mass in the >4.76 mm soil size fraction	
		Small-scale study[a]	Field study
Catch box	18 month	15%	76%
DU Garden Excavation samples	5 years	73-75%[b]	60%[c]

[a]Larson et al. (2009)

[b]separate lifts based on depth below-ground-surface (bgs)

[c]combined mass of soil

The samples obtained from the excavation of an intact penetrator buried in the DU Garden at a depth of 30.48 cm (12-in), 5 years prior to sample collection, represented a system in which a penetrator lies undisturbed for an extended period of time in the subsurface. While no uranium was found in the upper lifts of the DU Garden penetrator rod excavation, when the levels were reached that surrounded the rod, the U in the largest size fraction increased to 73-75%, by mass (Larson et al. 2009). The current study examined the results of penetrator excavation as it would occur normally in the field. These conditions are important as this type of DU residue is one that can be detected readily using state-of-the-art DU location tools (Etheridge et al. 2009). Once located, the entire area of soil surrounding the penetrator can be excavated and combined as a single sample, digested and analyzed as it was in this study. In this situation, the >4.76 mm size fraction contained 60% of the DU by mass (Table 9). However, the small total mass of soil excavated compared to the overall uranium content indicated that the 40% of the original uranium that was present in the < 4.76 mm size fraction represented a significant amount of uranium soil contamination. Dry sieve separation of these residues in this manner may be useful for long-term range management activities in order to reduce the spatial distribution of uranium on the range. This might be useful if short time periods between deposition and location/excavation could be achieved. Assuming all legal and regulatory requirements for returning soils have been met, this would leave the <4.76 mm fraction to be returned to the range or Catch Box.

There were many more heavy metals detected from DU Garden soil than in Catch Box sand. There are several possible explanations:

- The soil from the DU Garden area may sorb the heavy metals to a greater extent than the construction grade sand of the Catch Box.
- The anoxic conditions of the subsurface promote migration of the metals from the penetrator and sorption to soil.
- The impact media (sand) of the Catch Box may have been purchased specifically for this application.

4 Conclusions and Recommendations

- Simple vibratory soil screening is effective for DU metal removal from both Catch Box sand and the soil surrounding a buried penetrator at YPG.
- The Catch Box soil fines still contain DU, so dust suppression will be required for range management.
- This investigation — as well as others — indicates that DU metals are readily corroded (Johnson et al. 2004, Larson et al. 2009). The oxidation products are more mobile than the metal parent and can be transformed in the environment (Johnson et al. 2004). The corrosion of the uranium metal should be studied, along with the role microbial processes play. If the corrosion process can be retarded, then the mechanism for transport of uranium metal will be limited to that of physical movement of metal fragments. Since the density of DU metal is extremely high, migration will be minimal. Therefore, time is important to the success/failure of the physical separation technology:

    - The 4-7 years of heavy weathering that the penetrator rod underwent in the DU Garden made dry sieve separation increasingly less effective.
    - The lighter weathering of DU fragments in the Catch Box soil made successful physical separation possible.

- Periodic screening of Catch Box soils, coupled with dust control measures, will considerably increase the useful lifetime of Catch Box soil.

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Appendix A: Catch Box Data

Table A1. Concentrations of metals (mg/kg) detected in the <4.76 mm size fraction of soil from Catch Box Sample Area 1 following dry sieve separation.

	Metal concentration (mg/kg)															
Sample	Pb	Cr	Cu	Ni	Zn	Fe	Mn	Mo	V	Sb	W	Ca	As	Mg	Cd	U
1-1	5.00*	5.00*	5.00*	5.00*	21.17	6796.00	187.20	5.00*	16.74	5.00*	5.00*	10570.00	5.00*	3535.00	5.00*	27.66
1-2	5.00*	5.00*	5.00*	5.00*	18.34	6020.00	173.40	5.00*	15.24	5.00*	5.00*	10780.00	5.00*	3235.00	5.00*	24.62
1-3	5.00*	5.00*	5.00*	5.00*	19.90	6642.00	181.10	5.00*	16.45	5.00*	5.00*	10550.00	5.00*	3462.00	5.00*	27.64
2-1	5.00*	5.00*	5.00*	5.00*	16.71	5566.00	160.80	5.00*	13.82	5.00*	5.00*	10880.00	5.00*	2980.00	5.00*	25.10
2-2	5.00*	5.00*	5.00*	5.00*	15.82	5377.00	157.10	5.00*	13.47	5.00*	5.00*	10600.00	5.00*	2879.00	5.00*	30.79
2-3	5.00*	5.00*	5.00*	5.00*	17.37	5846.00	165.90	5.00*	14.67	5.00*	5.00*	10810.00	5.00*	3135.00	5.00*	23.67
3-1	5.00*	5.00*	5.00*	5.00*	17.28	5912.00	162.70	5.00*	14.92	5.00*	5.00*	10190.00	5.00*	3166.00	5.00*	24.71
3-2	5.00*	5.00*	5.00*	5.00*	16.09	5559.00	157.60	5.00*	14.12	5.00*	5.00*	10020.00	5.00*	3017.00	5.00*	24.54
3-3	5.00*	5.00*	5.00*	5.00*	14.96	5226.00	159.40	5.00*	13.53	5.00*	5.00*	10560.00	5.00*	2946.00	5.00*	23.67
4-1	5.00*	5.00*	5.00*	5.00*	15.57	5463.00	162.00	5.00*	14.07	5.00*	5.00*	10310.00	5.00*	3125.00	5.00*	21.83
4-2	5.00*	5.00*	5.00*	5.00*	16.49	5885.00	166.50	5.00*	14.87	5.00*	5.00*	10250.00	5.00*	3270.00	5.00*	21.32
4-3	5.00*	5.00*	5.00*	5.00*	17.00	6154.00	172.10	5.00*	15.35	5.00*	5.00*	10220.00	5.00*	3448.00	5.00*	25.40
5-1	5.00*	5.00*	5.00*	5.00*	14.41	5183.00	154.70	5.00*	13.53	5.00*	5.00*	9797.00	5.00*	2956.00	5.00*	26.56
5-2	5.00*	5.00*	5.00*	5.00*	15.97	5830.00	163.30	5.00*	14.72	5.00*	5.00*	9371.00	5.00*	3397.00	5.00*	23.57
5-3	5.00*	5.00*	5.00*	5.00*	15.94	5863.00	170.00	5.00*	14.96	5.00*	5.00*	9666.00	5.00*	3361.00	5.00*	24.37
6-1	5.00*	5.00*	5.00*	5.00*	14.74	5386.00	152.70	5.00*	14.01	5.00*	5.00*	8722.00	5.00*	3163.00	5.00*	39.29
6-2	5.00*	5.00*	5.00*	5.00*	5.00*	3762.00	126.30	5.00*	10.73	5.00*	5.00*	9130.00	5.00*	2251.00	5.00*	35.12
6-3	5.00*	5.00*	5.00*	5.00*	11.57	4479.00	142.60	5.00*	12.45	5.00*	5.00*	9511.00	5.00*	2705.00	5.00*	34.84
7-1	5.00*	5.00*	5.00*	5.00*	11.20	4367.00	141.40	5.00*	12.03	5.00*	5.00*	9121.00	5.00*	2649.00	5.00*	17.19
7-2	5.00*	5.00*	5.00*	5.00*	10.77	4203.00	140.00	5.00*	11.73	5.00*	5.00*	9283.00	5.00*	2562.00	5.00*	17.80
7-3	5.00*	5.00*	5.00*	5.00*	11.29	4391.00	140.00	5.00*	12.50	5.00*	5.00*	9415.00	5.00*	2706.00	5.00*	19.85
8-1	5.00*	5.00*	5.00*	5.00*	5.00*	3643.00	126.60	5.00*	10.52	5.00*	5.00*	9191.00	5.00*	2239.00	5.00*	20.70
8-2	5.00*	5.00*	5.00*	5.00*	5.00*	3911.00	129.70	5.00*	11.27	5.00*	5.00*	9185.00	5.00*	2414.00	5.00*	22.69
8-3	5.00*	5.00*	5.00*	5.00*	11.03	4354.00	137.30	5.00*	12.18	5.00*	5.00*	9133.00	5.00*	2695.00	5.00*	23.70
9-1	5.00*	5.00*	5.00*	5.00*	10.99	4285.00	140.70	5.00*	12.01	5.00*	5.00*	9414.00	5.00*	2663.00	5.00*	33.73
9-2	5.00*	5.00*	5.00*	5.00*	12.69	4427.00	138.30	5.00*	12.23	5.00*	5.00*	9089.00	5.00*	2749.00	5.00*	33.54
9-3	5.00*	5.00*	5.00*	5.00*	10.33	4254.00	137.00	5.00*	11.82	5.00*	5.00*	9209.00	5.00*	2637.00	5.00*	32.40
10-1	5.00*	5.00*	5.00*	5.00*	5.00*	3536.00	127.80	5.00*	10.59	5.00*	5.00*	9758.00	5.00*	2178.00	5.00*	19.34

Sample	Metal concentration (mg/kg)															
	Pb	Cr	Cu	Ni	Zn	Fe	Mn	Mo	V	Sb	W	Ca	As	Mg	Cd	U
10-2	5.00*	5.00*	5.00*	5.00*	5.00*	3697.00	128.10	5.00*	10.68	5.00*	5.00*	9268.00	5.00*	2293.00	5.00*	20.42
10-3	5.00*	5.00*	5.00*	5.00*	5.00*	4072.00	136.70	5.00*	11.61	5.00*	5.00*	9507.00	5.00*	2547.00	5.00*	21.56
11-1	5.00*	5.00*	5.00*	5.00*	5.00*	3552.00	134.20	5.00*	10.61	5.00*	5.00*	9466.00	5.00*	2227.00	5.00*	21.87
11-2	5.00*	5.00*	5.00*	5.00*	5.00*	3692.00	134.00	5.00*	10.59	5.00*	5.00*	9431.00	5.00*	2299.00	5.00*	20.42
11-3	5.00*	5.00*	5.00*	5.00*	5.00*	2754.00	115.40	5.00*	5.00*	5.00*	5.00*	9350.00	5.00*	1671.00	5.00*	19.25
12-1	5.00*	5.00*	5.00*	5.00*	5.00*	2487.00	109.20	5.00*	5.00*	5.00*	5.00*	9205.00	5.00*	1519.00	5.00*	32.00
12-2	5.00*	5.00*	5.00*	5.00*	5.00*	3189.00	119.80	5.00*	5.00*	5.00*	5.00*	9245.00	5.00*	1972.00	5.00*	30.81
12-3	5.00*	5.00*	5.00*	5.00*	5.00*	2851.00	116.80	5.00*	5.00*	5.00*	5.00*	9216.00	5.00*	1762.00	5.00*	31.26
13-1	5.00*	5.00*	5.00*	5.00*	5.00*	2563.00	113.80	5.00*	5.00*	5.00*	5.00*	9325.00	5.00*	1581.00	5.00*	17.97
13-2	5.00*	5.00*	5.00*	5.00*	5.00*	3378.00	127.30	5.00*	5.00*	5.00*	5.00*	9592.00	5.00*	2089.00	5.00*	22.07
13-3	5.00*	5.00*	5.00*	5.00*	5.00*	3064.00	122.10	5.00*	5.00*	5.00*	5.00*	9651.00	5.00*	1906.00	5.00*	22.25
14-1	5.00*	5.00*	5.00*	5.00*	18.94	8265.00	190.50	5.00*	21.54	5.00*	5.00*	9537.00	5.00*	4508.00	5.00*	52.05
14-2	5.00*	5.00*	10.18	5.00*	19.07	8065.00	186.80	5.00*	21.55	5.00*	5.00*	9494.00	5.00*	4457.00	5.00*	51.16
14-3	5.00*	5.00*	10.05	5.00*	19.52	8156.00	190.50	5.00*	21.67	5.00*	5.00*	9417.00	5.00*	4511.00	5.00*	47.60
15-1	5.00*	5.00*	5.00*	5.00*	18.39	7853.00	185.40	5.00*	20.82	5.00*	5.00*	9301.00	5.00*	4335.00	5.00*	71.95
15-2	5.00*	5.00*	5.00*	5.00*	17.32	6841.00	175.00	5.00*	18.57	5.00*	5.00*	9449.00	5.00*	4026.00	5.00*	60.53
15-3	5.00*	5.00*	5.00*	5.00*	18.22	7707.00	183.70	5.00*	20.66	5.00*	5.00*	9475.00	5.00*	4323.00	5.00*	70.81
Avg	5.00	5.00	5.23	5.00	12.09	4989.02	149.86	5.00	12.84	5.00	5.00	9659.20	5.00	2878.87	5.00	29.77
Stdev	0.00	0.00	1.07	0.00	5.67	1583.18	23.51	0.00	4.58	0.00	0.00	550.63	0.00	787.14	0.00	13.17
%RSD	0.00	0.00	20.39	0.00	46.88	31.73	15.69	0.00	35.66	0.00	0.00	5.70	0.00	27.34	0.00	44.26

*method detection limit is substituted for non-detect for statistical analysis

Table A2. Concentrations of metals (mg/kg) detected in the <4.76 mm size fraction of soil from Catch Box Sample Area 2 following dry sieve separation.

	Metal concentration (mg/kg)															
Sample	Pb	Cr	Cu	Ni	Zn	Fe	Mn	Mo	V	Sb	W	Ca	As	Mg	Cd	U
1-1	5.00*	5.00*	5.00*	5.00*	14.42	5982.00	167.50	5.00*	15.51	5.00*	5.00*	9968.00	5.00*	3614.00	5.00*	51.05
1-2	5.00	5.00	5.00	5.00	11.52	4770.00	148.10	5.00	12.76	5.00	5.00	9416.00	5.00	2920.00	5.00	46.26
1-3	5.00	5.00	5.00	5.00	13.98	5777.00	161.70	5.00	15.04	5.00	5.00	9522.00	5.00	3465.00	5.00	47.85
2-1	5.00	5.00	5.00	5.00	16.21	6712.00	176.00	5.00	17.62	5.00	5.00	9496.00	5.00	3924.00	5.00	39.21
2-2	5.00	5.00	5.00	5.00	13.17	5448.00	158.30	5.00	14.25	5.00	5.00	9575.00	5.00	3338.00	5.00	35.92
2-3	5.00	5.00	5.00	5.00	12.78	5320.00	156.80	5.00	14.49	5.00	5.00	9354.00	5.00	3237.00	5.00	32.31
3-1	5.00	5.00	5.00	5.00	13.83	5750.00	170.70	5.00	15.54	5.00	5.00	9498.00	5.00	3482.00	5.00	40.48
3-2	5.00	5.00	5.00	5.00	15.44	6571.00	180.00	5.00	17.26	5.00	5.00	9503.00	5.00	3857.00	5.00	40.39
3-3	5.00	5.00	5.00	5.00	15.28	6415.00	177.10	5.00	16.62	5.00	5.00	9516.00	5.00	3831.00	5.00	38.42
4-1	5.00	5.00	5.00	5.00	13.85	5896.00	168.20	5.00	15.64	5.00	5.00	9561.00	5.00	3508.00	5.00	78.24
4-2	5.00	5.00	5.00	5.00	15.69	5842.00	166.30	5.00	15.58	5.00	5.00	9515.00	5.00	3527.00	5.00	77.77
4-3	5.00	5.00	5.00	5.00	12.07	5127.00	156.30	5.00	13.86	5.00	5.00	9444.00	5.00	3142.00	5.00	82.23
5-1	5.00	5.00	5.00	5.00	12.96	5492.00	161.10	5.00	14.48	5.00	5.00	9886.00	5.00	3357.00	5.00	40.79
5-2	5.00	5.00	5.00	5.00	14.64	6149.00	169.50	5.00	16.43	5.00	5.00	9828.00	5.00	3713.00	5.00	42.00
5-3	5.00	5.00	5.00	5.00	13.28	5674.00	165.90	5.00	14.80	5.00	5.00	9938.00	5.00	3468.00	5.00	42.17
6-1	5.00	5.00	5.00	5.00	12.42	5300.00	156.50	5.00	14.33	5.00	5.00	9600.00	5.00	3295.00	5.00	47.29
6-2	5.00	5.00	5.00	5.00	5.00	3027.00	115.70	5.00	5.00	5.00	5.00	9093.00	5.00	1877.00	5.00	38.87
6-3	5.00	5.00	5.00	5.00	5.00	3441.00	123.80	5.00	5.00	5.00	5.00	9442.00	5.00	2169.00	5.00	36.75
7-1	5.00	5.00	5.00	5.00	5.00	3200.00	119.40	5.00	5.00	5.00	5.00	9033.00	5.00	1978.00	5.00	79.59
7-2	5.00	5.00	5.00	5.00	5.00	3593.00	128.80	5.00	5.00	5.00	5.00	9312.00	5.00	2230.00	5.00	77.27
7-3	5.00	5.00	5.00	5.00	5.00	3695.00	129.90	5.00	5.00	5.00	5.00	9063.00	5.00	2312.00	5.00	76.22
8-1	5.00	5.00	5.00	5.00	5.00	3227.00	115.80	5.00	5.00	5.00	5.00	8890.00	5.00	2037.00	5.00	22.77
8-2	5.00	5.00	5.00	5.00	5.00	3644.00	118.80	5.00	10.13	5.00	5.00	8531.00	5.00	2292.00	5.00	23.65
8-3	5.00	5.00	5.00	5.00	5.00	4550.00	135.40	5.00	11.59	5.00	5.00	8686.00	5.00	2802.00	5.00	26.90
9-1	5.00	5.00	5.00	5.00	5.00	3255.00	116.80	5.00	5.00	5.00	5.00	8551.00	5.00	2028.00	5.00	55.98
9-2	5.00	5.00	5.00	5.00	5.00	4222.00	135.00	5.00	11.03	5.00	5.00	8872.00	5.00	2613.00	5.00	61.22
9-3	5.00	5.00	5.00	5.00	5.00	3462.00	118.80	5.00	5.00	5.00	5.00	8226.00	5.00	2153.00	5.00	54.68
10-1	5.00	5.00	5.00	5.00	5.00	3095.00	111.90	5.00	5.00	5.00	5.00	8513.00	5.00	1926.00	5.00	22.42
10-2	5.00	5.00	5.00	5.00	5.00	4440.00	140.70	5.00	11.53	5.00	5.00	9344.00	5.00	2790.00	5.00	23.53
10-3	5.00	5.00	5.00	5.00	5.00	3845.00	128.70	5.00	10.20	5.00	5.00	9251.00	5.00	2396.00	5.00	20.51
11-1	5.00	5.00	5.00	5.00	5.00	3540.00	125.60	5.00	5.00	5.00	5.00	9011.00	5.00	2205.00	5.00	20.82

Sample	Metal concentration (mg/kg)															
	Pb	Cr	Cu	Ni	Zn	Fe	Mn	Mo	V	Sb	W	Ca	As	Mg	Cd	U
11-2	5.00	5.00	5.00	5.00	5.00	3620.00	122.00	5.00	5.00	5.00	5.00	8474.00	5.00	2218.00	5.00	23.86
11-3	5.00	5.00	5.00	5.00	5.00	3358.00	120.00	5.00	5.00	5.00	5.00	8773.00	5.00	2106.00	5.00	20.42
12-1	5.00	5.00	5.00	5.00	5.00	3257.00	110.80	5.00	5.00	5.00	5.00	8510.00	5.00	2033.00	5.00	23.89
12-2	5.00	5.00	5.00	5.00	5.00	3246.00	115.70	5.00	5.00	5.00	5.00	8981.00	5.00	2035.00	5.00	26.77
12-3	5.00	5.00	5.00	5.00	5.00	3110.00	114.90	5.00	5.00	5.00	5.00	9083.00	5.00	1969.00	5.00	25.83
13-1	5.00	5.00	5.00	5.00	5.00	2744.00	111.60	5.00	5.00	5.00	5.00	8937.00	5.00	1742.00	5.00	42.75
13-2	5.00	5.00	5.00	5.00	5.00	2783.00	110.40	5.00	5.00	5.00	5.00	8711.00	5.00	1771.00	5.00	39.84
13-3	5.00	5.00	5.00	5.00	5.00	2712.00	111.80	5.00	5.00	5.00	5.00	8680.00	5.00	1718.00	5.00	38.89
14-1	5.00	5.00	5.00	5.00	15.59	7126.00	175.60	5.00	19.57	5.00	5.00	8969.00	5.00	4100.00	5.00	45.47
14-2	5.00	5.00	5.00	5.00	16.00	7687.00	177.90	5.00	20.77	5.00	5.00	8941.00	5.00	4276.00	5.00	47.15
14-3	5.00	5.00	5.00	5.00	16.29	7531.00	180.70	5.00	20.44	5.00	5.00	9100.00	5.00	4248.00	5.00	48.68
15-1	5.00	5.00	5.00	5.00	15.16	7043.00	170.50	5.00	18.81	5.00	5.00	8626.00	5.00	3952.00	5.00	46.93
15-2	5.00	5.00	5.00	5.00	16.18	7636.00	184.00	5.00	20.56	5.00	5.00	9106.00	5.00	4300.00	5.00	50.12
15-3	5.00	5.00	5.00	5.00	15.20	7002.00	174.30	5.00	18.86	5.00	5.00	9077.00	5.00	4070.00	5.00	47.17
Avg	5.00	5.00	5.00	5.00	9.58	4784.80	144.12	5.00	11.28	5.00	5.00	9142.36	5.00	2889.42	5.00	43.36
Stdev	0.00	0.00	0.00	0.00	4.84	1552.83	25.56	0.00	5.71	0.00	0.00	432.67	0.00	839.09	0.00	17.48
%RSD	0.00	0.00	0.00	0.00	50.52	32.45	17.74	0.00	50.60	0.00	0.00	4.73	0.00	29.04	0.00	40.30

*method detection limit is substituted for non-detect for statistical analysis

Table A3. Concentrations of metals (mg/kg) detected in the <4.76 mm size fraction of soil from Catch Box Sample Area 3 following dry sieve separation.

	Metal concentration (mg/kg)															
Sample	Pb	Cr	Cu	Ni	Zn	Fe	Mn	Mo	V	Sb	W	Ca	As	Mg	Cd	U
1-1	5.00*	5.00*	5.00*	5.00*	10.53	4982.00	136.00	5.00*	13.23	5.00*	5.00*	7761.00	5.00*	2990.00	5.00*	39.28
1-2	5.00	5.00	5.00	5.00	5.00	4625.00	135.00	5.00	12.07	5.00	5.00	8230.00	5.00	2848.00	5.00	37.74
1-3	5.00	5.00	5.00	5.00	12.91	5972.00	163.10	5.00	15.84	5.00	5.00	8826.00	5.00	3598.00	5.00	44.99
2-1	5.00	5.00	5.00	5.00	11.22	5186.00	140.70	5.00	13.37	5.00	5.00	8402.00	5.00	3162.00	5.00	35.35
2-2	5.00	5.00	5.00	5.00	5.00	4591.00	135.20	5.00	12.19	5.00	5.00	8735.00	5.00	2864.00	5.00	39.40
2-3	5.00	5.00	5.00	5.00	12.60	5689.00	156.60	5.00	15.32	5.00	5.00	9273.00	5.00	3480.00	5.00	37.81
3-1	5.00	5.00	5.00	5.00	11.34	5192.00	150.70	5.00	13.52	5.00	5.00	9341.00	5.00	3236.00	5.00	38.30
3-2	5.00	5.00	5.00	5.00	12.65	5850.00	155.10	5.00	15.68	5.00	5.00	8631.00	5.00	3502.00	5.00	42.67
3-3	5.00	5.00	5.00	5.00	13.25	6033.00	160.40	5.00	15.98	5.00	5.00	8964.00	5.00	3638.00	5.00	42.95
4-1	5.00	5.00	5.00	5.00	11.14	5047.00	145.00	5.00	13.32	5.00	5.00	9031.00	5.00	3110.00	5.00	35.80
4-2	5.00	5.00	5.00	5.00	10.74	5032.00	144.20	5.00	13.14	5.00	5.00	8512.00	5.00	3092.00	5.00	33.40
4-3	5.00	5.00	5.00	5.00	10.92	5082.00	145.30	5.00	13.06	5.00	5.00	8672.00	5.00	3118.00	5.00	41.56
5-1	5.00	5.00	5.00	5.00	11.09	5120.00	141.10	5.00	13.11	5.00	5.00	8671.00	5.00	3184.00	5.00	32.81
5-2	5.00	5.00	5.00	5.00	11.86	4558.00	138.10	5.00	11.92	5.00	5.00	9538.00	5.00	2891.00	5.00	32.23
5-3	5.00	5.00	5.00	5.00	11.86	4558.00	138.10	5.00	11.92	5.00	5.00	9538.00	5.00	2891.00	5.00	41.18
6-1	5.00	5.00	5.00	5.00	12.30	5521.00	152.60	5.00	14.66	5.00	5.00	8940.00	5.00	3376.00	5.00	45.32
6-2	5.00	5.00	5.00	5.00	5.00	3877.00	127.50	5.00	10.12	5.00	5.00	8641.00	5.00	2415.00	5.00	40.39
6-3	5.00	5.00	5.00	5.00	5.00	3733.00	125.00	5.00	5.00	5.00	5.00	8835.00	5.00	2321.00	5.00	33.87
7-1	5.00	5.00	5.00	5.00	5.00	3432.00	117.20	5.00	5.00	5.00	5.00	9230.00	5.00	2135.00	5.00	31.10
7-2	5.00	5.00	5.00	5.00	5.00	3919.00	126.10	5.00	10.19	5.00	5.00	8893.00	5.00	2437.00	5.00	30.94
7-3	5.00	5.00	5.00	5.00	5.00	3450.00	115.40	5.00	5.00	5.00	5.00	8683.00	5.00	2140.00	5.00	27.74
8-1	5.00	5.00	5.00	5.00	5.00	3074.00	112.60	5.00	5.00	5.00	5.00	8947.00	5.00	1913.00	5.00	28.92
8-2	5.00	5.00	5.00	5.00	5.00	3501.00	118.00	5.00	5.00	5.00	5.00	8685.00	5.00	2175.00	5.00	29.94
8-3	5.00	5.00	5.00	5.00	5.00	3513.00	122.50	5.00	5.00	5.00	5.00	9198.00	5.00	2193.00	5.00	30.03
9-1	5.00	5.00	5.00	5.00	5.00	3379.00	121.20	5.00	5.00	5.00	5.00	9082.00	5.00	2122.00	5.00	45.05
9-2	5.00	5.00	5.00	5.00	5.00	3719.00	122.90	5.00	5.00	5.00	5.00	8920.00	5.00	2342.00	5.00	47.63
9-3	5.00	5.00	5.00	5.00	5.00	4091.00	130.20	5.00	10.87	5.00	5.00	8786.00	5.00	2569.00	5.00	72.82
10-1	5.00	5.00	5.00	5.00	5.00	2709.00	101.80	5.00	5.00	5.00	5.00	8813.00	5.00	1710.00	5.00	22.33
10-2	5.00	5.00	5.00	5.00	5.00	3184.00	109.00	5.00	5.00	5.00	5.00	8489.00	5.00	2000.00	5.00	25.23
10-3	5.00	5.00	5.00	5.00	5.00	2941.00	105.90	5.00	5.00	5.00	5.00	8576.00	5.00	1851.00	5.00	21.75
11-1	5.00	5.00	5.00	5.00	5.00	3111.00	114.20	5.00	5.00	5.00	5.00	8639.00	5.00	1930.00	5.00	37.46

Sample	Metal concentration (mg/kg)															
	Pb	Cr	Cu	Ni	Zn	Fe	Mn	Mo	V	Sb	W	Ca	As	Mg	Cd	U
11-2	5.00	5.00	5.00	5.00	5.00	3109.00	112.20	5.00	5.00	5.00	5.00	8193.00	5.00	1937.00	5.00	37.95
11-3	5.00	5.00	5.00	5.00	5.00	2952.00	109.60	5.00	5.00	5.00	5.00	8383.00	5.00	1825.00	5.00	36.01
12-1	5.00	5.00	5.00	5.00	5.00	2890.00	106.70	5.00	5.00	5.00	5.00	8425.00	5.00	1794.00	5.00	43.23
12-2	5.00	5.00	5.00	5.00	5.00	2771.00	106.10	5.00	5.00	5.00	5.00	8286.00	5.00	1724.00	5.00	46.85
12-3	5.00	5.00	5.00	5.00	5.00	2777.00	104.80	5.00	5.00	5.00	5.00	8239.00	5.00	1729.00	5.00	42.38
13-1	5.00	5.00	5.00	5.00	5.00	3239.00	111.10	5.00	5.00	5.00	5.00	8385.00	5.00	2030.00	5.00	33.70
13-2	5.00	5.00	5.00	5.00	5.00	3437.00	116.30	5.00	5.00	5.00	5.00	8656.00	5.00	2146.00	5.00	29.18
13-3	5.00	5.00	5.00	5.00	5.00	3353.00	113.30	5.00	5.00	5.00	5.00	8534.00	5.00	2095.00	5.00	31.21
14-1	5.00	5.00	5.00	5.00	12.69	6150.00	156.90	5.00	15.94	5.00	5.00	8905.00	5.00	3647.00	5.00	42.59
14-2	5.00	5.00	5.00	5.00	12.54	6091.00	155.40	5.00	15.97	5.00	5.00	8716.00	5.00	3578.00	5.00	58.94
14-3	5.00	5.00	5.00	5.00	12.86	6157.00	155.70	5.00	15.99	5.00	5.00	8697.00	5.00	3613.00	5.00	58.12
15-1	5.00	5.00	5.00	5.00	13.73	6895.00	166.20	5.00	18.31	5.00	5.00	8708.00	5.00	3888.00	5.00	54.31
15-2	5.00	5.00	5.00	5.00	11.53	5687.00	145.90	5.00	14.53	5.00	5.00	8401.00	5.00	3392.00	5.00	50.08
15-3	5.00	5.00	5.00	5.00	11.40	5650.00	145.40	5.00	14.70	5.00	5.00	8341.00	5.00	3369.00	5.00	50.84
Avg	*5.00*	*5.00*	*5.00*	*5.00*	*8.09*	*4351.76*	*131.38*	*5.00*	*9.89*	*5.00*	*5.00*	*8718.91*	*5.00*	*2666.67*	*5.00*	*39.14*
Stdev	*0.00*	*0.00*	*0.00*	*0.00*	*3.55*	*1192.82*	*18.82*	*0.00*	*4.67*	*0.00*	*0.00*	*361.46*	*0.00*	*676.71*	*0.00*	*9.98*
%RSD	*0.00*	*0.00*	*0.00*	*0.00*	*43.84*	*27.41*	*14.32*	*0.00*	*47.27*	*0.00*	*0.00*	*4.15*	*0.00*	*25.38*	*0.00*	*25.51*

*method detection limit is substituted for non-detect for statistical analysis

Table A4. Concentrations of metals (mg/kg) detected in the <4.76 mm size fraction of soil from Catch Box Sample Area 4 following dry sieve separation and return of the >4.76 mm DU fragments to the soil.

	Metal concentration (mg/kg)															
Sample	Pb	Cr	Cu	Ni	Zn	Fe	Mn	Mo	V	Sb	W	Ca	As	Mg	Cd	U
1-1	5.00*	5.00*	5.00*	5.00*	16.51	5972.00	166.70	5.00*	15.89	5.00*	5.00	10720.00	5.00*	3413.00	5.00*	70.38
1-2	5.00	5.00	5.00	5.00	16.39	5992.00	158.80	5.00	15.66	5.00	5.00	9990.00	5.00	3400.00	5.00	71.63
1-3	5.00	5.00	5.00	5.00	16.10	5910.00	163.70	5.00	15.52	5.00	5.00	10520.00	5.00	3371.00	5.00	71.91
2-1	5.00	5.00	5.00	5.00	15.09	5515.00	161.20	5.00	15.00	5.00	5.00	10560.00	5.00	3187.00	5.00	82.38
2-2	5.00	5.00	5.00	5.00	16.54	6004.00	170.40	5.00	16.26	5.00	5.00	10830.00	5.00	3461.00	5.00	86.82
2-3	5.00	5.00	5.00	5.00	18.27	6613.00	174.20	5.00	17.60	5.00	5.00	10730.00	5.00	3753.00	5.00	85.52
3-1	5.00	5.00	5.00	5.00	14.01	5156.00	151.20	5.00	13.79	5.00	5.00	10830.00	5.00	2983.00	5.00	48.18
3-2	5.00	5.00	5.00	5.00	16.78	6234.00	169.40	5.00	16.27	5.00	5.00	10670.00	5.00	3530.00	5.00	54.99
3-3	5.00	5.00	5.00	5.00	17.66	6488.00	170.00	5.00	17.45	5.00	5.00	10600.00	5.00	3651.00	5.00	55.98
4-1	5.00	5.00	5.00	5.00	12.80	4811.00	142.60	5.00	12.90	5.00	5.00	10170.00	5.00	2799.00	5.00	54.08
4-2	5.00	5.00	5.00	5.00	16.10	5824.00	163.10	5.00	15.31	5.00	5.00	10450.00	5.00	3338.00	5.00	61.73
4-3	5.00	5.00	5.00	5.00	14.20	5227.00	149.00	5.00	13.71	5.00	5.00	10460.00	5.00	3024.00	5.00	59.13
5-1	5.00	5.00	5.00	5.00	13.41	5077.00	148.90	5.00	13.14	5.00	5.00	10260.00	5.00	2979.00	5.00	141.20
5-2	5.00	5.00	5.00	5.00	13.82	5275.00	150.70	5.00	13.73	5.00	5.00	10550.00	5.00	3044.00	5.00	149.60
5-3	5.00	5.00	5.00	5.00	12.95	5008.00	149.80	5.00	13.32	5.00	5.00	10620.00	5.00	2900.00	5.00	151.50
6-1	5.00	5.00	5.00	5.00	16.44	6085.00	164.50	5.00	15.74	5.00	5.00	10770.00	5.00	3475.00	5.00	71.70
6-2	5.00	5.00	5.00	5.00	10.16	3977.00	134.20	5.00	10.63	5.00	5.00	10720.00	5.00	2307.00	5.00	67.80
6-3	5.00	5.00	5.00	5.00	5.00	3757.00	130.70	5.00	5.00	5.00	5.00	10510.00	5.00	2184.00	5.00	64.21
7-1	5.00	5.00	5.00	5.00	5.00	3815.00	127.10	5.00	5.00	5.00	5.00	10050.00	5.00	2214.00	5.00	44.61
7-2	5.00	5.00	5.00	5.00	10.08	4027.00	132.50	5.00	10.02	5.00	5.00	10060.00	5.00	2333.00	5.00	45.42
7-3	5.00	5.00	5.00	5.00	10.57	4155.00	134.10	5.00	10.63	5.00	5.00	10100.00	5.00	2404.00	5.00	53.65
8-1	5.00	5.00	5.00	5.00	5.00	3409.00	120.50	5.00	5.00	5.00	5.00	10140.00	5.00	1985.00	5.00	47.89
8-2	5.00	5.00	5.00	5.00	5.00	3519.00	123.70	5.00	5.00	5.00	5.00	10230.00	5.00	2037.00	5.00	49.25
8-3	5.00	5.00	5.00	5.00	5.00	2867.00	113.40	5.00	5.00	5.00	5.00	9979.00	5.00	1656.00	5.00	46.32
9-1	5.00	5.00	5.00	5.00	5.00	3051.00	118.90	5.00	5.00	5.00	5.00	10230.00	5.00	1768.00	5.00	62.82
9-2	5.00	5.00	5.00	5.00	5.00	3382.00	123.70	5.00	5.00	5.00	5.00	10190.00	5.00	1962.00	5.00	68.55
9-3	5.00	5.00	5.00	5.00	5.00	3818.00	131.40	5.00	5.00	5.00	5.00	10290.00	5.00	2206.00	5.00	67.26
10-1	5.00	5.00	5.00	5.00	5.00	3296.00	118.90	5.00	5.00	5.00	5.00	10230.00	5.00	1898.00	5.00	61.25
10-2	5.00	5.00	5.00	5.00	10.36	4084.00	131.20	5.00	10.25	5.00	5.00	10120.00	5.00	2366.00	5.00	66.52
10-3	5.00	5.00	5.00	5.00	5.00	3236.00	118.60	5.00	5.00	5.00	5.00	10120.00	5.00	1870.00	5.00	64.25
11-1	5.00	5.00	5.00	5.00	5.00	3105.00	116.60	5.00	5.00	5.00	5.00	10000.00	5.00	1774.00	5.00	91.28

Sample	Metal concentration (mg/kg)															
	Pb	Cr	Cu	Ni	Zn	Fe	Mn	Mo	V	Sb	W	Ca	As	Mg	Cd	U
11-2	5.00	5.00	5.00	5.00	5.00	2645.00	110.50	5.00	5.00	5.00	5.00	9845.00	5.00	1496.00	5.00	83.69
11-3	5.00	5.00	5.00	5.00	5.00	2854.00	111.60	5.00	5.00	5.00	5.00	10130.00	5.00	1632.00	5.00	84.07
12-1	5.00	5.00	5.00	5.00	5.00	2797.00	112.70	5.00	5.00	5.00	5.00	10300.00	5.00	1582.00	5.00	67.20
12-2	5.00	5.00	5.00	5.00	5.00	3037.00	116.20	5.00	5.00	5.00	5.00	10480.00	5.00	1729.00	5.00	70.38
12-3	5.00	5.00	5.00	5.00	5.00	3061.00	115.20	5.00	5.00	5.00	5.00	9917.00	5.00	1743.00	5.00	67.66
13-1	5.00	5.00	5.00	5.00	5.00	3116.00	117.80	5.00	5.00	5.00	5.00	10060.00	5.00	1777.00	5.00	176.00
13-2	5.00	5.00	5.00	5.00	5.00	3008.00	118.00	5.00	5.00	5.00	5.00	10110.00	5.00	1702.00	5.00	181.20
13-3	5.00	5.00	5.00	5.00	5.00	2979.00	117.80	5.00	5.00	5.00	5.00	10450.00	5.00	1683.00	5.00	188.70
14-1	5.00	5.00	5.00	5.00	21.80	8915.00	196.20	5.00	22.66	5.00	5.00	10260.00	5.00	4249.00	5.00	77.07
14-2	5.00	5.00	5.00	5.00	22.56	9165.00	199.50	5.00	23.41	5.00	5.00	10530.00	5.00	4323.00	5.00	83.62
14-3	5.00	5.00	5.00	5.00	22.48	9314.00	199.60	5.00	24.49	5.00	5.00	10530.00	5.00	4317.00	5.00	83.77
15-1	5.00	5.00	5.00	5.00	22.59	9506.00	207.20	5.00	24.60	5.00	5.00	10930.00	5.00	4369.00	5.00	93.44
15-2	5.00	5.00	5.00	5.00	21.95	9141.00	199.80	5.00	23.16	5.00	5.00	10590.00	5.00	4240.00	5.00	88.47
15-3	5.00	5.00	5.00	5.00	22.72	9370.00	204.60	5.00	24.23	5.00	5.00	10830.00	5.00	4387.00	5.00	92.49
Avg	*5.00*	*5.00*	*5.00*	*5.00*	*11.50*	*4968.82*	*145.70*	*5.00*	*11.56*	*5.00*	*5.00*	*10370.24*	*5.00*	*2722.24*	*5.00*	*81.23*
Stdev	*0.00*	*0.00*	*0.00*	*0.00*	*6.41*	*2064.96*	*29.29*	*0.00*	*6.66*	*0.00*	*0.00*	*289.35*	*0.00*	*923.12*	*0.00*	*36.30*
%RSD	*0.00*	*0.00*	*0.00*	*0.00*	*55.76*	*41.56*	*20.10*	*0.00*	*57.59*	*0.00*	*0.00*	*2.79*	*0.00*	*33.91*	*0.00*	*44.68*

*method detection limit is substituted for non-detect for statistical analysis

Appendix B: DU Garden Data

Table B1. Concentrations of metals (mg/kg) detected in the <4.76 mm size fraction of soil from DU Garden following dry sieve separation.

	Metal concentration (mg/kg)															
Sample	Pb	Cr	Cu	Ni	Zn	Fe	Mn	Mo	V	Sb	W	Ca	As	Mg	Cd	U
1-1	15.82	5.00*	16.01	5.00*	5.00*	1777.00	142.60	5.00*	12.32	5.00*	5.00*	29160.00	5.00*	2418.00	5.00*	7556.00
1-2	15.33	5.00*	16.89	5.00*	5.00*	2572.00	155.70	5.00*	13.25	5.00*	5.00*	29560.00	5.00*	3018.00	5.00*	7495.00
1-3	16.03	5.00*	17.03	5.00*	5.00*	2914.00	161.10	5.00*	13.71	5.00*	5.00*	29270.00	5.00*	3281.00	5.00*	7544.00
2-1	12.29	5.00*	11.85	5.00*	5.00*	1789.00	142.60	5.00*	5.00*	5.00*	5.00*	28460.00	5.00*	2400.00	5.00*	4975.00
2-2	12.95	5.00*	12.09	5.00*	5.00*	1829.00	141.50	5.00*	10.17	5.00*	5.00*	28340.00	5.00*	2434.00	5.00*	5062.00
2-3	12.38	5.00*	12.38	5.00*	5.00*	2348.00	151.50	5.00*	10.76	5.00*	5.00*	28910.00	5.00*	2830.00	5.00*	4951.00
3-1	13.78	5.00*	14.65	5.00*	5.00*	2865.00	162.90	5.00*	12.30	5.00*	5.00*	28600.00	5.00*	3220.00	5.00*	5679.00
3-2	13.94	5.00*	13.83	5.00*	5.00*	2350.00	156.20	5.00*	11.29	5.00*	5.00*	28640.00	5.00*	2824.00	5.00*	5781.00
3-3	13.94	5.00*	12.96	5.00*	5.00*	1535.00	139.10	5.00*	10.62	5.00*	5.00*	28530.00	5.00*	2190.00	5.00*	5745.00
4-1	13.62	5.00*	13.97	5.00*	5.00*	2165.00	149.80	5.00*	11.47	5.00*	5.00*	28450.00	5.00*	2648.00	5.00*	5782.00
4-2	13.90	5.00*	14.64	5.00*	5.00*	2855.00	160.00	5.00*	12.09	5.00*	5.00*	28700.00	5.00*	3146.00	5.00*	5836.00
4-3	13.07	5.00*	13.84	5.00*	5.00*	2361.00	153.30	5.00*	11.62	5.00*	5.00*	29220.00	5.00*	2781.00	5.00*	5762.00
5-1	16.04	5.00*	16.27	5.00*	5.00*	1537.00	136.30	5.00*	12.02	5.00*	5.00*	28580.00	5.00*	2144.00	5.00*	7397.00
5-2	16.00	5.00*	17.15	5.00*	5.00*	2406.00	154.50	5.00*	13.10	5.00*	5.00*	28830.00	5.00*	2784.00	5.00*	7540.00
5-3	16.05	5.00*	17.44	5.00*	5.00*	2561.00	155.70	5.00*	13.28	5.00*	5.00*	28960.00	5.00*	2930.00	5.00*	7683.00
6-1	17.63	10.01	19.44	5.00*	5.00*	2097.00	138.70	5.00*	13.67	5.00*	5.00*	26270.00	5.00*	2661.00	5.00*	9367.00
6-2	17.17	11.20	20.11	5.00*	5.00*	2961.00	150.20	5.00*	14.47	5.00*	5.00*	25220.00	5.00*	3414.00	5.00*	9679.00
6-3	17.52	11.11	19.81	5.00*	5.00*	2740.00	144.00	5.00*	14.01	5.00*	5.00*	25140.00	5.00*	3217.00	5.00*	9466.00
7-1	11.77	5.00*	12.75	5.00*	5.00*	2823.00	147.80	5.00*	10.67	5.00*	5.00*	24760.00	5.00*	3322.00	5.00*	5039.00
7-2	12.14	5.00*	12.64	5.00*	5.00*	3109.00	150.50	5.00*	10.67	5.00*	5.00*	24150.00	5.00*	3525.00	5.00*	4952.00
7-3	12.14	5.00*	12.67	5.00*	5.00*	2904.00	148.30	5.00*	10.28	5.00*	5.00*	24490.00	5.00*	3377.00	5.00*	5039.00
8-1	13.20	5.00*	14.74	5.00*	5.00*	3209.00	150.30	5.00*	11.91	5.00*	5.00*	23570.00	5.00*	3521.00	5.00*	6257.00
8-2	13.65	5.00*	14.09	5.00*	5.00*	2794.00	145.30	5.00*	11.32	5.00*	5.00*	23600.00	5.00*	3234.00	5.00*	6245.00
8-3	13.01	5.00*	14.33	5.00*	5.00*	3041.00	148.40	5.00*	11.75	5.00*	5.00*	23400.00	5.00*	3421.00	5.00*	6196.00
9-1	14.79	5.00*	15.31	5.00*	5.00*	2306.00	134.90	5.00*	11.52	5.00*	5.00*	23700.00	5.00*	2831.00	5.00*	7446.00
9-2	14.89	5.00*	16.51	5.00*	5.00*	2763.00	144.50	5.00*	12.45	5.00*	5.00*	23710.00	5.00*	3217.00	5.00*	7465.00
9-3	14.79	5.00*	16.07	5.00*	5.00*	2416.00	139.60	5.00*	11.55	5.00*	5.00*	23950.00	5.00*	2950.00	5.00*	7665.00

	Metal concentration (mg/kg)															
Sample	Pb	Cr	Cu	Ni	Zn	Fe	Mn	Mo	V	Sb	W	Ca	As	Mg	Cd	U
10-1	13.56	12.83	17.82	5.00*	14.60	6217.00	192.00	5.00*	17.12	5.00*	5.00*	23920.00	5.00*	5863.00	5.00*	6208.00
10-2	13.87	13.68	17.57	5.00*	15.61	6842.00	193.20	5.00*	18.02	5.00*	5.00*	23420.00	5.00*	6108.00	5.00*	6087.00
10-3	13.64	14.69	18.66	10.27	16.73	7692.00	201.50	5.00*	19.70	5.00*	5.00*	23540.00	5.00*	6504.00	5.00*	6197.00
11-1	14.65	14.72	19.65	5.00*	16.02	7177.00	196.70	5.00*	19.49	5.00*	5.00*	24460.00	5.00*	6258.00	5.00*	6862.00
11-2	14.28	14.29	19.57	5.00*	15.37	6726.00	194.50	5.00*	18.72	5.00*	5.00*	24690.00	5.00*	6099.00	5.00*	7006.00
11-3	14.37	13.73	19.05	5.00*	14.89	6527.00	195.50	5.00*	17.93	5.00*	5.00*	24810.00	5.00*	6000.00	5.00*	6888.00
12-1	14.64	14.23	19.64	5.00*	14.93	6728.00	192.10	5.00*	19.04	5.00*	5.00*	23500.00	5.00*	6021.00	5.00*	7255.00
12-2	15.11	14.10	19.58	5.00*	14.79	6486.00	190.20	5.00*	18.91	5.00*	5.00*	23720.00	5.00*	5915.00	5.00*	7220.00
12-3	14.27	13.39	19.10	5.00*	13.47	5895.00	186.00	5.00*	17.24	5.00*	5.00*	24110.00	5.00*	5615.00	5.00*	7237.00
13-1	14.55	14.26	20.03	5.00*	15.31	6983.00	194.90	5.00*	19.11	5.00*	5.00*	22590.00	5.00*	6143.00	5.00*	7375.00
13-2	15.16	15.42	20.85	10.15	15.56	7232.00	197.40	5.00*	20.27	5.00*	5.00*	23280.00	5.00*	6271.00	5.00*	7532.00
13-3	15.30	14.59	20.54	5.00*	14.96	6761.00	193.00	5.00*	19.13	5.00*	5.00*	22960.00	5.00*	6039.00	5.00*	7814.00
14-1	11.99	13.12	16.22	10.09	15.58	7137.00	203.80	5.00*	17.12	5.00*	5.00*	24660.00	5.00*	6328.00	5.00*	4765.00
14-2	12.33	16.90	15.95	5.00*	14.58	6526.00	198.00	5.00*	16.38	5.00*	5.00*	24530.00	5.00*	6025.00	5.00*	4931.00
14-3	12.54	14.09	16.57	10.58	16.84	7851.00	209.90	5.00*	18.36	5.00*	5.00*	24470.00	5.00*	6506.00	5.00*	5045.00
15-1	17.20	15.05	22.90	5.00*	14.58	6543.00	214.00	5.00*	20.16	5.00*	5.00*	24280.00	5.00*	5978.00	5.00*	9571.00
15-2	17.55	16.69	24.35	10.32	15.92	7540.00	216.40	5.00*	22.20	5.00*	5.00*	23760.00	5.00*	6315.00	5.00*	9817.00
15-3	17.03	16.18	23.79	10.18	15.32	7125.00	208.90	5.00*	21.54	5.00*	5.00*	23770.00	5.00*	6274.00	5.00*	9801.00
Avg	*14.44*	*9.21*	*16.92*	*5.72*	*9.11*	*4244.78*	*168.52*	*5.00*	*14.83*	*5.00*	*5.00*	*25658.67*	*5.00*	*4222.22*	*5.00*	*6827.00*
Stdev	*1.64*	*4.69*	*3.19*	*1.83*	*5.12*	*2236.23*	*26.21*	*0.00*	*3.68*	*0.00*	*0.00*	*2346.27*	*0.00*	*1608.06*	*0.00*	*1460.89*
%RSD	*11.38*	*50.99*	*18.84*	*31.98*	*56.17*	*52.68*	*15.55*	*0.00*	*24.81*	*0.00*	*0.00*	*9.14*	*0.00*	*38.09*	*0.00*	*21.40*

*method detection limit is substituted for non-detect for statistical analysis

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
September 2012	Final	

4. TITLE AND SUBTITLE

Large-Scale Physical Separation of Depleted Uranium from Soil

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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Applied Research Associates, Inc.
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8. PERFORMING ORGANIZATION REPORT NUMBER

ERDC/EL TR-12-25

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U.S. Army Corps of Engineers

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Dry physical separation processes were tested at large-pilot scale (1,000 kg soil batches) at Yuma Proving Ground (YPG) to evaluate this technique for removal of depleted uranium (DU) metal from soil. Two sample locations, the Catch Box and the Buried DU Penetrator Test Site (DU Garden) were evaluated. These locations were chosen since previous small-scale testing confirmed that soils from these sites had varied uranium concentration, degrees of weathering, and aging of fired DU munition residues. Vibratory soil screening (dry sieve separation) was found to be effective for DU metal removal from Catch Box sand of YPG. On average, 50% of the mass of DU was removed with a single dry sieve separation of the Catch Box sand. The soil fines still contained DU, so control of fugitive dust emissions may be required. The degree of DU fragment weathering was found to be important to the success of the physical separation technology. The penetrator rod excavated from the DU Garden was highly weathered resulting in ineffective physical separation. The lesser degree of weathering of DU fragments in the Catch Box soil made successful physical separation possible. The difference in weathering of DU in the DU Garden versus the Catch Box could be due to increased exposure time (4 to 7 years in the garden versus approximately 18 months in the Catch Box), differences in soil chemistry (the DU garden was a desert soil, the Catch Box construction grade sand), and/or better aqueous drainage in the sandy Catch Box media. Non-uranium metals concentration were also increased in the DU Garden compared to both background soil concentrations and the concentrations detected in the Catch Box sands. Results indicate that periodic screening of Catch Box soils, coupled with dust control measures, could considerably increase the useful lifetime of Catch Box soil.

15. SUBJECT TERMS

Buried DU Penetrator Test Site
Catch box
Depleted uranium (DU)
Dry sieve separation
Large-scale physical separation
U-234
Vibratory soil screening
Wet separation
Yuma Proving Ground (YPG)

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(include area code)*
Unclassified	Unclassified	Unclassified		44	