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Boeing Michigan Aeronautical Research Center (BOMARC), Final Remedial Action Report for Site RW-01, McGuire AFB, N.J.

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Executive Summary

On 7 June 1960, an explosion in a helium tank took place in Shelter 204 (Figure ES) causing a fire in a nuclear-tipped, liquid-fueled BOMARC missile at McGuire Air Force Base, N.J. The fire burned uninhibited for approximately 30 minutes. Fire-fighting activities were conducted for 15 hours using water as a suppressant. As a result, materials from the shelter flowed under the front shelter doors, down the asphalt apron and street between the row of shelters, and into the drainage ditch leading outside the site boundary fence. The primary material of concern is weapons grade plutonium (WGP), fissile material from the nuclear warhead. It was estimated that 300 g of WGP was not recovered from the initial accident response actions, which, in a dioxide chemical form, is about one fluid ounce. Initial surveys conducted shortly after the accident indicated that the water associated with the fire-fighting activities was responsible for the primary distribution of contaminants. While a wind from the north to northeast was present during the initial stages of the fire, evidence from the Remedial Investigation/Feasibility Study (RI/FS) and the Final Status Survey Report (conducted for secondary impacted areas) did not support any significant airborne transport. Though translocation of shelter contaminants was largely attributed to fire-fighting water (and later storm water run-offs), activities during the accident response and those post-accident (i.e., foot and vehicle traffic) were believed to be responsible for some cross-contamination of material, estimated at less than 0.1 % of the total residual. In 1972, the site ceased operational use. Since then, a number of radiological investigations were accomplished to assess the integrity of asphalt and concrete engineering controls

Figure ES. Shelter 204.

that were emplaced to limit the movement of radiological contaminants and reduce exposure risks to personnel accessing the site.

Post-accident recovery operations accomplished by Explosives Ordnance Disposal (EOD) and the Atomic Energy Commission (AEC) removed weapon debris that contained a significant fraction of the radiological material contained in the weapon. The materials were then shipped to Medina Base, San Antonio, TX. Though the original design amounts of the weapon remain classified, an estimate of the material remaining on site after the initial removal was made by Department of Energy (DOE) and Air Force scientists, which placed an upper limit at 300 grams of WGP. In the mid-1980's, the public and the State of New Jersey expressed interest in restoring the site, which prompted the Air Force to conduct a RI/FS consistent with the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). Under the Act and Executive Order 12580, the Air Force, as the lead federal authority, published a Record of Decision (ROD) in consultation with the State of New Jersey and Region II, Environmental Protection Agency (EPA). Under the ROD, the Air Force decided to pursue excavation and off-site disposal of contaminated waste, provided a disposal site was available and the absence of other events that would dramatically decrease the cost-effectiveness of this, the preferred option for the site (Vest 1992). The foundation of the ROD was the environmental impact statement (EIS) and RI/FS. The risk-based criterion established in the RI/FS for unrestricted-release of soils was 8 picocuries/gram (pCi/g) ^{239}Pu, as modeled with the Residual Radiation (RESRAD) computer-based risk modeling code developed by Argonne National Laboratory. These concentrations provide an annual dose of 4 millirem (mrem) to a maximally-exposed individual (MEI) and correspond to a lifetime excess cancer risk of 10^{-4} (70-year integrated exposure). A risk-based remediation goal was not established for structures; however, criteria in U.S. Nuclear Regulatory Commission (NRC) Regulatory Guide 1.86 were considered relevant and appropriate for an unrestricted release of debris generated from the demolition of impacted shelters.

Remediation of the primary contaminated areas, based on the Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) methodology and results of the 1997 site characterization, was conducted from March 2002 to June 2004 by Duratek Services, Inc, and Shaw Environmental and Infrastructure (E & I). A total waste volume of 21,998 cubic yards (yd^3) comprised of contaminated debris and soils was packaged, shipped, and disposed at Envirocare of Utah. Upper structures of shelters 202 and 206 were removed as part of the demolition of shelter 204 due to the anticipation of interference with shoring requirements of the excavation. Twenty-two survey units were established for the final status survey with sizes between 124 and 2,125 m^2. The total area was 3.7 hectares (9.1 acres) with an average survey unit of 1,674 m^2. A total of 829 systematic (i.e., fixed grid) soil samples and 374 biased (i.e., specifically targeted locations) and sub-surface samples were collected in support of the final status in-situ γ-radiation scanning surveys. The survey results demonstrated compliance with the ROD-based criterion for the primary contaminated areas.

During the remediation of the primary contaminated areas, anecdotal information on contamination identified in secondary areas was provided by Duratek Services, Inc. to technical staff of the Air Force Institute for Operational Health (AFIOH), Headquarters, Air Force Safety Center (HQ AFSC), and the Environmental Flight, 305 Civil Engineering Squadron (305 CES/CEV). Some of these areas were investigated by AFIOH personnel during the restoration of primary contaminated areas, however, HQ Air Mobility Command (AMC) decided to accomplish survey and restoration of secondary areas in a separate effort. Concerns regarding contamination in secondary areas focused

on the limited ability of field instruments to detect contamination at depth in soils, the mechanism of translocation of contaminants to other impacted areas, the discrete nature of the plutonium contaminant and its modeled risks, the extent of contamination in secondary areas, and potential excessive costs in achieving the ROD-recommend course of action. Five distinct activities were accomplished to answer these questions. An in-situ γ-spectroscopy scan of potentially impacted areas was completed by National Security Technologies, LLC, and AFIOH in early 2005. A historical site assessment was performed by Cabrera Services, Inc. in early 2006. A discrete particle removal operation was completed by Cabrera Services in August/September 2006. In addition, AFIOH and HQ AFSC performed a comparison of risks from the plutonium in discrete particle versus homogenously dispersed forms. The information synthesized by these activities provided confidence that remedial actions could be finished in a technically sound and cost-efficient manner. HQ AFSC estimated that about 0.1 % of the contaminant left after the 1960 accident recovery actions remained in secondary areas. In 2007, a final status survey and spot removal operation was conducted by Cabrera Services. The spot removal amassed a total of 65 yd^3 of contaminated waste, predominantly soil with lesser amounts of floor debris and asphalt. A small volume was generated from the 2005 and 2006 investigation activities. Seventy-eight Class 1 survey units were established for the final status survey with a total area of 42.3 acres, an average survey unit of 2175 m^2, and 100 % survey coverage. Class 2 survey areas encompassed 86.5 acres, with a coverage of 47 %, 40.3 acres (163, 146 m^2), while Class 3 areas encompassed 62.8 acres, with a coverage of 24 %, 14.8 acres (59,915 m^2). A total of 1,956 Class 1 and 823 Class 2 surface soil samples were collected, and 150 biased soil samples were collected in support of the final status in-situ γ-radiation scanning surveys. A total of 274 subsurface samples were collected at 113 biased and systematic locations across the site to investigate the potential for contamination at depth. The survey results demonstrated compliance with the ROD-based criterion for secondary areas, and that the contaminants were restricted to surface soils.

Two issues of interest by some members of the public were not fully remedied by the restoration efforts conducted between 2002 and 2007. First, no evidence was found to support an alternate location of the drainage culvert under Ocean County Highway 539. The original culvert, which carried contaminated fire-fighting water from the accident, was replaced after the accident; however, based on surveys that investigated the potential for an alternate water drainage pathway, the replacement culvert appears to be in the same location. The disposition of the original culvert is not known, though there is no supporting evidence to suggest it was buried on the BOMARC site, or adjacent property on the west side of Ocean County Hwy 539 (part of the Fort Dix Reservation). Second, disposition of the launcher from the missile involved in the accident is not known. Extensive magnetometry surveys conducted during the RI/FS and restoration activities throughout the 2000's failed to reveal information on its disposition. Thus, an on-site disposal is deemed improbable.

In conjunction with the final status survey and spot removal operation, AFIOH and HQ AFSC conducted surveys of buildings potentially impacted by the accident and response activities. The workplan for this effort developed a risk-based criteria using computer-based risk modeling similar to the one used for land areas, but specific to surface contamination in structures. In contrast to land areas, which had risks modeled for an unrestricted use scenario using "resident-farmer" assumptions, the shelters provide little to no practical use for future military missions and are not acceptable for unrestricted access to members of the public because of structural and other site hazards. Therefore,

health impacts of their use were modeled for storage and other uses by site workers and under a concrete demolition scenario, where concrete debris could be left on-site as recycled material. The survey found residual contamination levels well below acceptable levels developed and below the soils criterion, as comingled with concrete in a demolition scenario. Screening measurements were performed of the exterior surfaces of shelter roofs in the vicinity of Shelter 204 with unremarkable findings, confirming findings from the RI/FS.

The remedial actions conducted on the site successfully removed residual plutonium to the acceptable levels specified in the ROD and substantiated by the final status surveys. Thus, the preferred option recommended by the ROD has been met for the site; the site meets unrestricted uses with respect to the radiological contaminants. Other hazards, not part of the RW-01 ROD, currently exist on the site. For example, near the eastern fence boundary of the site a trichloroethylene (TCE) plume extending vertically about 55 feet below ground surface and laterally from the site in many directions (OT-16). Asbestos was used as insulation on interior pipes in the shelters and other structures, and possibly in floor tiles of some buildings. Also, the structural integrity of some ceilings and roofs is a concern for entrance and use of some buildings.

Response complete (RC) action under the Department of Defense (DoD) Restoration Management Information System (RMIS) is recommended. No long-term monitoring, or further operations and maintenance are required to support the ROD; site closeout actions are recommended for RW-01. Since a technical basis for a five year review neither exists nor was recommended in the ROD, a five year review described in the CERCLA process is not required.

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Acronyms

ADMS	Air Defense Missile Squadron
AEA	Atomic Energy Act
AEC	Atomic Energy Commission
AF	area factor
AFB	Air Force Base
AFI	Air Force Instruction
AFIERA	Air Force Institute for Environment, Safety and Occupational Health Risk Analysis
AFIOH	Air Force Institute for Operational Health
ALARA	as low as reasonably achievable
ARAR	applicable or relevant and appropriate requirements
Bkgd	Background
BOMARC	Boeing Michigan Aeronautical Research Center
Bq	Becquerel
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CI	confidence interval
Ci	Curie
cpm	counts per minute
DCF	dose conversion factor
DCGL	dose conversion guideline level
DEP	Department of Environmental Protection
DERP	Defense Environmental Restoration Program
DOE	Department of Energy
dpm	disintegration per minute
DTRA	Defense Threat Reduction Agency
DU	depleted uranium
EIS	environmental impact statement
EMC	elevated measurement comparison
EOD	explosive ordnance disposal
EPA	Environmental Protection Agency
FGR	Federal Guidance Report
FIDLER	field instrument for detection of low energy radiations

FS	feasibility study
FSS	final status survey
GI	gastrointestinal
HEU	highly enriched uranium
HpGe	hyperpure germaniun
HQ AFSC	Headquarters, Air Force Safety Center
HAS	historical site assessment
ICRP	International Commission on Radiological Protection
K_d	solid/aqueous phase partition coefficient
keV	kilo electron Volts
LASL	Los Alamos Scientific Laboratory
LLD	lower limit of detection
MagThor	magnesium-thorium alloy
MARSSIM	Multi-Agency Radiation Survey and Site Investigation Manual
μCi	microcurie
MDA	minimum detectable activity
MDC	minimum detectable concentration
MEI	maximally-exposed individual
MeV	Mega electron Volts
M&I	maintenance and inspection
NAES	Naval Air and Engineering Station
nCi	nanocurie
NCRP	National Council on Radiation Protection and Measurements
NEPA	National Environmental Policy Act
NESHAPS	National Emission Standard for Hazardous Air Pollutants
NIST	National Institute of Standards and Technology
NJAC	New Jersey Administrative Code
NPL	National Priority List
NRC	Nuclear Regulatory Commission
NST	Nuclear Security Technologies
NTS	Nevada Test Site
pCi	picocurie

rad	radiation absorbed dose
RAM	radioactive material
RC	response complete
RCRA	Resource Conservation and Recovery Act
rem	roentgen equivalent man
RESRAD	Residual Radiation
RHL	Radiological Health Laboratory
RI	remedial investigation
ROD	record of decision
RW	radiological waste
SDR	Radiation Surveillance Division
SDWA	Safe Drinking Water Act
SEM	scanning electron micrograph
SWDA	Solid Waste Disposal Act
SI	site investigation
TCE	trichloroethylene
LCLP	toxicity characteristic leaching procedure
TEDE	total effective dose equivalent
$^{Total}U$	total uranium
UNLV	University of Nevada Las Vegas
USAFOEHL	United States Air Force Occupational and Environmental Health Laboratory
USAFSAM	United States Air Force School of Aerospace Medicine
WGP	weapons grade plutonium
WIPP	Waste Isolation Pilot Plant

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1.0 Introduction

1.1 General History of the Site. In 1958, the 46th Air Defense Missile Squadron (ADMS) from McGuire Air Force Base (AFB), N.J., was authorized the use of approximately 220 acres of Fort Dix property for the construction of a missile facility. The site is about 11 miles from McGuire AFB, off the east side of Ocean County Highway 539 in Plumsted County (Figure A-1). Initial construction consisted of 56 missile shelters, missile maintenance facilities, a power generation plant, and other associated facilities in support of the mission. In 1962, the existing liquid-fueled Model A missiles were supplemented with 28 Model B, solid-fueled missiles. All missiles were designed to carry nuclear-tipped warheads that contained weapons grade plutonium (WGP) and other radioactive materials. [Missiles at some of the other BOMARC sites had conventional explosives warheads.] The missile shelter area is on the northern part of the site as shown in Figure A-2 (upper portion of figure), while maintenance and support facilities are on the southern part of the site. The Model B solid-fueled missiles are on the northernmost portion of the missile area which required the addition of fill material as part of the construction process in 1962. The figure notes the former location of shelter 204, the shelter involved in the accident.

1.2 The Accident.

On 7 June 1960, at approximately 1500 hours, sensors in shelter 204 detected a fire, where a missile and warhead were in a war "ready" state. Based on an evaluation of the shelter post accident, officials determined that the fire was most likely initiated by the explosion of a pressurized helium tank which evidently caused the rupture of the 80-octane and JP-X fuel tanks. This allowed their fluids to flow into the 42-inch deep missile launcher pit where a substantial portion of the launcher mechanism was located. Within three to five minutes, a McGuire AFB fire-fighting crew responded, however, the fire was unabated for over 30 minutes because of the distance from the base to the site. While a small amount of carbon dioxide was applied to the fire, more than 30,000 gallons of water were applied throughout the initial response (with the fire hose wedged between the front two shelter doors). Approximately fifteen minutes into the fire, response personnel reported a muffled explosion associated with the ignition of high explosives in the weapon. [In this action, bright flashes of light are normally emitted, which are sometimes referred to as "arcing."] However, according to an investigation conducted by Los Alamos Scientific Laboratory (LASL) weapons response team experts, the fuel fire initiated at the onset of the accident and produced the large black plume of smoke exhausted near the rear of the shelter (pit area), while the fire that ensued in the high explosive material of the warhead was separate in time and space [references in Crismon *et al.* (2001)]. Radiological material in the shelter was predominantly under the weapon with some contamination on the floor as expected from the large amounts of water used to mitigate the fire. However, contamination was not associated with the roof of the shelter or walls where the fuel fire had most violently exhausted in the initial stages of the accident. The LASL team reported that the center points of the two distinct fires were separated by about twenty feet, and the fuel fire was greatly diminished (or exhausted) by the time the fire in the high explosives liberated any plutonium. (See Figure A-3 for detail on the interior of the shelter.)

An hour after initiation, the explosives ordnance disposal (EOD) personnel entered the area to examine the shelter and ensuing fire. Shortly after, fire fighters were cleared to enter the area and apply fire-fighting water more directly on the warhead. By 1615, the fire was under control and continued at a low intensity until 1830. Operations were closed down at 2000 hours, but water was applied to the area for another eight hours. Support personnel from Fort Dix, Lakehurst Naval and Engineering Center, Griffiss AFB, and Wright-Patterson AFB also aided in the response. More details of the number of personnel involved in the response were described by Kimm (1997).

1.3 Immediate Post-Accident Remedial Actions.

Air sampling was conducted at the accident site the next day as well as radiological surveys of the shelter interiors, concrete pad, asphalt road in front of the shelter, and soil areas. Specialized instruments like the field instrument for detection of low-energy radiations (FIDLER) were not developed at the time of the accident. Therefore, contamination surveys were accomplished with the Eberline PAC-1S α-scintillation meter/probe combination. At some locations, contamination readings were in excess of two-million counts per minute (2M cpm), the maximum scale reading for the instrument. Warhead debris inside the shelter was placed in plastic bags and sealed in cans, and shipped to an Atomic Energy Commission (AEC), which is now part of the Department of Energy (DOE) complex. Cabrera (2006b) described the contradictory information on the AEC facility that the material was transported and stored, based on a number of documents. According to documents cited by Crismon *et al.* (2001), weapons debris was initially sent to Medina Base, TX and analyzed in the early 1980s at another DOE site in preparation for potential disposal at the Waste Isolation Pilot Plant (WIPP). Regardless of the ultimate fate of the material in the DOE complex, the material was removed from the site shortly after the accident which was customary for nuclear weapons accident recovery operations.

Contamination on the concrete pad and asphalt was washed down with water and allowed to dry. On 10 June 1960, 110 gallons of paint was applied to contaminated concrete surfaces on the interior of and in front of the shelter, and to contaminated asphalt areas. This was accomplished to fix (retain) contaminated material and thereby limit translocation of contamination to other areas and reduce airborne re-suspension. Later in 1960, a four-inch, steel-reinforced concrete cover was poured over the apron covering an area from Shelter 208 to the drainage ditch area, just west of the last shelter in this row, shelter 202. Asphalt was poured over contaminated soil areas in the drainage area adjacent to the pad between the rows of shelters, as illustrated in Figure A-4.

1.4 Physical Setting of the Site [Excerpted from Cabrera (2006b)].

The BOMARC Missile Site lies within the New Jersey Pinelands in an area that is generally semi-rural with several nearby towns including: New Egypt (6 miles), Wrightstown (10 miles), Whiting (5 miles), Lakehurst (6 miles), and Browns Mills (9 miles). The majority of the nearby land is owned by the military. A New Jersey Army National Guard post located about one mile west-northwest of the site is used for heavy land vehicle (e.g., tanks) training. The nearest private residence in 1992 was located just over one mile north-northwest of the site. The site is located along the northern boundary of the outer coastal plain section of the Atlantic Coastal Plain. The topography rolls gently, with elevations ranging between 60 and 180 feet above mean sea level. The area is generally low-lying with poor drainage and multiple swamps. Maximum elevation at the

BOMARC Missile Site is about 180 feet above mean sea level along the north-south road through the center of the shelter area. A major drainage divide separates the inner and outer coastal plains. The inner coastal plain drains into the Delaware River Basin, while the outer coastal plain drains into the Atlantic Ocean. The BOMARC Missile Site lies in the outer coastal plain just east of the drainage divide. The site drains to the Elisha Branch, which drains to the Toms River.

The Atlantic Coastal Plain is a gently seaward-sloping surface characterized by a series of poorly consolidated, marginal marine sediments that are underlain by metamorphic Precambrian crystalline rocks. Interbedded continental sands and marine clays dominate the stratigraphy of the BOMARC Missile Site. Stratigraphically, there is a relatively thin expression (40 feet or less) of the Cohansey Sand underlain by an unknown thickness of the Kirkwood Formation and then the Manasquan Formation. The Cohansey Sand is typically a light gray to yellowish-brown, well-sorted, cross-bedded, pebbly, fine- to coarse-grained, ilmenitic, partly arkosic quartz sand, often cemented locally with iron oxide (limonite). Limonite staining generally produces yellow-colored sand, but shades of red, brown, gray, and white are also found.

As a consequence of development and construction activities, the predominant category of soil on the site is mapped as "sandy urban land." The Lakewood Series is the predominant natural soil in the area surrounding the Site. This series consists of 7 to 10 inches of gray sand underlain by 20 to 25 inches of dark brown to yellowish-brown sand. The soils are excessively drained, coarse, conducive to rapid water percolation, have low soil moisture retention, and low nutrient content. Permeability ranges from 0.2 to 6.3 inches per hour. The sodium, calcium, and magnesium have been dissolved. The less soluble iron, aluminum, and titanium are partially leached and have precipitated into the subsoil. The only mineral resources of Ocean County include gravel pits that generally mine industrial sand or construction sand and gravel. In the early 1700s through the 1850s bog iron was mined from the Cohansey Sand and Kirkwood Formation. The Heritage Minerals, Inc. property, located off Route 70 in Manchester Township and Lakehurst Borough, Ocean County, NJ, mined natural thorium (Th-nat) ore and other rare earths until its 1990 closure. In addition to naturally high-levels of thorium, which is radioactive, these ores also have than average concentrations of uranium, another naturally-occurring radioactive material. Air Force Institute for Operational Health (AFIOH) survey personnel found isolated areas on the BOMARC site that contained thorium in concentrations much higher than the mean background for the area.

The radioanalytical laboratory and radiation consultant functions of the former AFIOH are currently part of the Radiation Health Branch, Occupational and Environmental Health Division, USAF School of Aerospace Medicine (USAFSAM). These functions were historically part of the following Air Force organizations:

a. Air Force Institute for Environment, Safety and Occupational Health Risk Analysis,
b. Bioenvironmental Division, Occupational and Environmental Health Directorate, Detachment 1, Human Systems Center (Det 1 HSC/OEB),
c. Bioenvironmental Division, Occupational and Environmental Health Directorate, Armstrong Laboratory (AL/OEB),
d. Air Force Occupational and Environmental Health Laboratory (AFOEHL),
e. USAF Occupational and Environmental Health Laboratory (USAFOEHL), and
f. Radiological Health Laboratory (RHL).

The Cohansey Sand and Kirkwood Formation are the formations of principal hydro geologic interest. These two formations are hydraulically connected locally and are found at the BOMARC Site. Groundwater at the site occurs at shallow depths that range between 12 and 55 feet. Water table elevations in the vicinity of the shelters range from 127.8 to 129.5 feet above mean sea level and are highest west of the shelters. The groundwater flow direction is difficult to determine due to a groundwater divide west of the shelters. It is predominantly to the northeast for the rest of the site. The site lies within the Atlantic Coastal drainage basin near the headwaters of the Toms River drainage system. This drainage system is the second largest in the Pinelands area, and occupies almost 500 square kilometers (about 200 square miles). There is no surface water flow on the site except during precipitation events. The nearest stream is the Elisha Branch of the Toms River, just southeast of the Site. The Elisha Branch joins the Success Branch east of the Site in the Colliers Mills Wildlife Management Area. There is also a small, unnamed stream northeast of the Site that flows eastward into the Success Branch. The Success Branch joins with progressively larger branches until they enter the Toms River, eventually reaching the Atlantic Ocean. The grading plan for the Site shows that the highest elevation is the north-south road in the center of the shelter area; precipitation falling in this area either flows east or west. On the east side of the road water flows east to the fence line, then it flows either east to the Success Branch or south to the Elisha Branch. Precipitation falling on the west side of the road is directed into a drainage channel flowing southwest off the Site. The water passes through ditches and culverts until it flows under Highway 539. A ponding area is located just west of Highway 539. Water entering the ponding area will evaporate, percolate downward to the water table, or continue flowing southward to the Elisha Branch. Precipitation falling on the southern portion of the Site runs off to the south and southeast, eventually entering the Elisha Branch.

Due to the immobile characteristics of the WGP and other radiological contaminants released in the accident, and the limited depths the contaminants were found on the site as compared to the water table, no additional information is provide here on groundwater flow patterns. Cabrera (2006b) and the RI/FS (Earth Tech 1992) have highly detailed discussions.

1.5 Radionuclides of Concern (ROC).

The primary ROC is WGP, with highly-enriched uranium (HEU) and depleted uranium (DU) lesser ROCs in rank order. Table A-1 provides mass fractions for the WGP at the site, estimated for 1958 from Rademacher (2001). Of the α-radiation emitting isotopes, ^{239}Pu and ^{240}Pu dominate radiologically and have the same dose-conversion factors for internal dosimetry and dose-modeling applications. Further, because the two radionuclides have similar α-particle energies (Table A-2), discrimination is not possible through α-spectroscopy, and analytical results will have them combined as $^{239+240}$Pu.

The HEU and DU are indiscriminant from one-another, as each has a varied activity fraction of ^{234}U, ^{235}U, and ^{238}U. Figure A-6 contains a plot of the ^{234}U to ^{238}U activity concentration ratio (Rademacher 1999b), based on data from the 1997 Characterization (OHM 1998). From the plot, it is clear that the HEU dominates DU in the overall isotopic characteristic. Among the three uranium isotopes, ^{234}U comprised about 90 % of the total activity, including naturally-occurring background sources. However, in comparison to the WGP, uranium isotopes provide negligible risk, where the $^{238+239+240}$Pu to $^{234+235+238}$U activity ratio was estimated at 469 in the waste-profiling process (Horton

and Rademacher 1998). This process used α-spectroscopy radionuclide data from the 1997 Characterization (OHM 1998). Another important point gleaned from the 1997 Characterization data is that the two elements are spatially co-located, as evidenced from Figure A-7, where generally the highest total uranium concentrations (i.e., $^{234+235+238}$U) are related to the highest $^{239+240}$Pu concentrations. Some scatter in the data is attributed to heterogeneity effects, due to analysis of uranium and plutonium from separate aliquots. Therefore, remedial actions targeting WGP will effectively remove the uranium co-contaminant.

1.6 $^{239+240}$Pu to ^{241}Am Activity Ratio. Direct assessment of $^{239+240}$Pu in soils at low activity concentration is difficult because both isotopes have infrequent, low-energy photon emissions as illustrated in Figure A-5. As well, laboratory analyses of soils using high-resolution γ-spectroscopy is hampered by the same issue, leaving chemical dissolution, separation, and alpha spectroscopy as the most common direct assessment method. For soils containing heterogeneously distributed contaminants, large uncertainties can be observed in reported concentrations due to limited aliquot size for this method (Bernhardt 1976). A practical indirect alternative involves assessment of ^{241}Am, the decay daughter of ^{241}Pu:

$$^{241}\mathrm{Pu} \rightarrow {}^{241}\mathrm{Am} + {}^{0}_{-1}\beta ,$$

and calculation of the $^{239+240}$Pu through an established relationship between the two. HQ AFSC reviewed historical information on the $^{239+240}$Pu to ^{241}Am ratio and provided technical recommendations for future assessments (Rademacher 1999a). At that time, the best estimate was 5.4 ± 16 % [90 % confidence interval], based on α-spectroscopy data from the 1997 Characterization. During the 2002 – 2004 remediation, another $^{239+240}$Pu to ^{241}Am ratio data set was generated (Figure A-8). Though the sample set was significantly smaller than that from the 1997 Characterization, the 90 % confidence interval of the estimate was over two-fold lower. The best point estimate from the two data sets is within 3% agreement, which is within the typical combined bias of Pu and Am chemical tracers used for these analyses.

1.7 Thorium. BOMARC missiles used magnesium-thorium (MagThor) alloys in critical locations on the missile body that were subject to extreme temperatures, due to the high melting point, high strength, and creep resistance. In preparation for the 1997 Characterization, thorium was listed as a potential ROC, though the temperature required to melt the alloy was unlikely achieved by the fuel fire. Also, thorium was alloyed at a few percent by mass with magnesium, and has a low specific activity compared to other radiological contaminants at the site, having little effect on concentrations of thorium naturally-existing in soils, even in the event some material was released to the environment. Among the 349 samples collected during the 1997 Characterization, separate analyses were performed for plutonium, uranium, americium, and thorium. Figure A-9 contains a plot of the ^{228}Th to ^{232}Th from the characterization. For mature thorium, the activity of the two isotopes should be in equilibrium, as illustrated by the solid blue line of the plot. For most of the samples (green circles), this is the case. For a few of the samples (red and blue circles), the discrepancy between the two isotopes from equilibrium, and/or total concentration (i.e., higher than that typical for background) was attributed to interference from the $^{239+240}$Pu, that has a specific activity almost six orders of magnitude higher than the ^{232}Th (Rademacher 1999c). $^{239+240}$Pu activity concentrations are annotated for samples that were believed to have biased thorium results. Therefore, for soil removal activities in the restoration phase, special attention was not provided to thorium, except for that

provided by high-resolution γ-spectroscopy analyses that were standard for all final status soil samples.

1.8 Long-Term Post-Accident Monitoring.

1.8.1 General. After remedial actions were conducted shortly after the accident, radiological monitoring was not conducted until 1966, when a Radiological Health Laboratory (RHL) team visited the site (Taschner 1966). Table A-3 contains a tabular list of key monitoring activities that have occurred between the accident and site restoration. Most of the surveys conducted over the years differentiated between impacted and non-impacted areas based on in-situ measurements with a field instrument for the detection of low-energy radiations (FIDLER), and surface soil sample collection and analysis. Due to the lack of data logging equipment, most of the early in-situ measurements were static on a fixed grid pattern. This methodology was useful in determining relative impact between various areas on the site, but was not effective in locating small isolated areas of contamination if they did not by chance fall on a fixed measurement point. The first type of scanning survey conducted was by EG&G (1974) using an aerial-based photon-sensitive, scintillator detection system. This system lacked the sensitivity of land-based measurements of the time, but provided generalized information on the locations of contamination and relative concentrations. Many of the reports noted limited changes in concentrations between measurement events, but the comparisons were qualitative in nature, as soil sampling had high variability introduced by the effects of the heterogeneous distribution of the contaminant and slight spatial differences between in-situ measurement locations. For example, for measurements conducted on the concrete pad, a measurement was typically higher if the detector was placed over a seam in the concrete pad rather than a continuous concrete cover area due the lower photon attenuation characteristic of material filling the expansion joint versus concrete. A number of surveys made note of contaminated soil protruding through seams in the concrete, which prompted the addition of two inches of concrete to a small portion of the shelter apron in 1967, which covered the manhole access to the power and communication bunkers directly in front of shelter 204. At that time, the launcher pit in shelter 204 was filled with soil excavated from behind the shelter.

1.8.2 Primary Contaminated Areas. The majority of contamination was retained under the concrete pad in front of shelters 202, 204 and 206 or in adjacent grassy areas near these same shelters, based on post-accident radiological monitoring surveys. Lower levels of contamination were retained in soils following the generalized flow pattern of water from shelter 204 to a ditch just west of the shelters, through a culvert under County Hwy 539, and to a broad ponding area to the west, as illustrated in Figure A-10. The six underground bunkers in front of shelters 202, 204, and 206 that contained power and communication line connections were known to be impacted by radiological contamination based on many of the surveys conducted. Plutonium concentration isopleths from the 1973 aerial survey is provided in Figure A-11. From the plot, apparent is the lack of detail on distributions of ^{241}Am beyond the primary contaminated area in the vicinity of shelter 204. Among static measurements at helicopter hover areas, only one, location 28 (as shown in Table A-5), clearly had an elevated count rate in the ^{241}Am channel. This location was over the ditch, just west of the Hwy 539. Depth distribution studies were completed at a number of soil areas. In general, most of the plutonium in the profiles was located in the top few inches of soil, but qualitatively some data indicated a difference in the profile of samples from the drainage ditch compared to other contaminated areas. It was speculated that the profiles in narrow sections of the drainage ditch had

vertical distributions affected more by deposition of contaminated silt from water run-off events than by vertical migration of plutonium. However, it was difficult to quantitatively compare data between locations because of the variability introduced by heterogeneity.

1.8.3 Secondary Contaminated Areas. Some contamination was identified in areas other than those impacted by water transport of plutonium. However, since the primary purpose of the monitoring efforts was to assess potential migration and off-site health concerns, they focused on evaluation of the integrity of the concrete pad and asphalt coverings, and their ability to retain the primary source of contamination. Little effort was devoted to the study of these areas because they did not have sufficient size and plutonium concentrations to warrant off-site health concerns.

1.8.4 Airborne Radioactivity. Some airborne radioactivity measurements were conducted post accident. Because the majority of contamination was retained by concrete and asphalt, limited health concern existed for resuspension of contaminated soil. The Army in 1972 collected air samples during their investigation. All samples were below the decision level for the method.

1.8.5 Groundwater and Surface Water. Minimal ground and surface water monitoring was conducted during the early monitoring efforts in the late 60's, 70's, and early 80's. In 1972, the Army collected samples from monitoring wells with negative results (USAEHL 1972). Renewed interest by the State of New Jersey in the mid-80's prompted a study of water from potable wells in the local area, monitoring wells on-site, and surface water bodies in the vicinity of the site. Among the 26 samples collected, all plutonium results were below the decision level for the method, with the highest gross α-radiation concentration at 1.6 pCi/L (Maher 1986). Besides water sampling during the Remedial Action/Feasibility Study (Earth Tech 1992), the only other significant water sampling effort was conducted in 2000 by the U.S. Geological Survey, based on interests of the State of New Jersey for additional evaluation. Ten on-site monitoring wells were sampled without any evidence of plutonium or americium.

2.0 Initiation of Restoration Activities

2.1 The Installation Restoration Program (IRP).

The Air Force conducts its IRP under the statutory authority of the Defense Environmental Restoration Program (DERP), which was established in 1984 to promote and coordinate efforts for the evaluation and cleanup of contamination at Department of Defense (DoD) sites. Under DERP, cleanup activities can be conducted under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980, the Solid Waste Disposal Act (SWDA), also called the Resource Conservation and Recovery Act (RCRA), the Atomic Energy Act (AEA), and under other federal, state, or local mandates. The residual radioactive material from the accident is covered under Chapter 9, Section 91, paragraph b of the 1954 AEA (NRC 2002), and are exempt from licensing requirements of the Nuclear Regulatory Commission (NRC) and the agreement states. Within the DoD, Directive 3150.2, "DoD Nuclear Weapon System Safety Program," 23 Dec 96, directs Department Secretaries to, "ensure the safety and security of all nuclear weapons and nuclear weapon systems for which the Military Department has a DoD life-cycle management responsibility." Under Air Force Policy Directive 91-1, "Nuclear Weapons and Systems Surety,"

1 Nov 99, Headquarters, Air Force Safety Center (HQ AFSC) was delegated the responsibility to set policy for the protection of personnel, property, and the environment from hazardous exposure to radioactive materials. RW-01 is one of many "Section 91b" sites that are permitted by HQ AFSC.

In the mid-1980's, the public and State of New Jersey had interest in the Air Force remediating the site, which initiated activities under the IRP. The Air Force chose to remediate the site using the CERCLA process.

2.2 The Remedial Investigation/Feasibility Study (RI/FS). A Preliminary Assessment (PA), under Stage 1 of the IRP program was an installation-wide [McGuire AFB] study to identify sites that had potential impacts to health and the environment. A Site Inspection (SI) is a follow-on Stage 1 IRP sampling effort to determine the existence and extent of actual site contamination. However, because the BOMARC site already had extensive site monitoring data, an SI was not necessary. The RI/FS under Stage 2 was initiated in 1989 and was completed in 1992 (Earth Tech 1992). The investigation conducted was the most extensive conducted to date. A summary of key field activities and the conclusions drawn are in Table 2.1. The general conclusions drawn from the RI/FS reinforced the findings from previous field monitoring efforts, but a greater degree of detail. Figure A-12 contains a radiological contamination contour map that was generated from the work. The most highly contaminated areas of this plot are similar to those in areal extent as identified in the 1973 aerial survey, but with detail on the lesser contaminated areas afforded by the 1973 survey. Some areas were identified with contamination that was not related to a water transport mechanism. For example, in Figure A-12, a small area between two shelters in the 300-series of shelters had low levels of contamination identified. The RI/FS had more survey work assessing contamination in shelter interiors than previous surveys. Removable contamination in excess of 20 dpm/100 cm^2 was identified only in shelters in the vicinity of shelter 204. The 20 dpm/100 cm^2 criterion was based on acceptable removable α-radiation for transuranics specified in US Atomic Energy Commission (AEC) Regulatory Guide 1.86 (AEC 1974), which at the time of the writing of the RI/FS had wide-spread use in industry, even for non-NRC licensed radioactive materials. Some correlation existed between the highest levels of removable and fixed contaminations at some locations, primarily shelter 204. However, Rademacher *et al.* (2007) noted a possible discrepancy in the documentation of some in-situ α-radiation concentrations. Many of the areas with contamination identified at lower concentrations lacked correlation between fixed and removable contamination. Rademacher *et al.* (2007) speculated that many of the reported in-situ α-radiation concentrations may have been biased high by a factor of five. One issue evaluated by RI/FS that was not addressed by previous surveys was the potential on-site burial of the contaminated launcher from shelter 204. No evidence was found from either the magnetometry or ground penetrating radar surveys.

2.3 The Record of Decision – Standard for Remediation.

At the conclusion of the RI/FS, the Air Force published a Record of Decision (Vest 1992). The Air Force decided excavation and off-site disposal at a radioactive waste site was the environmentally-preferred option if a disposal site was identified and deemed cost effective. At the time, a DOE disposal site was the only option because commercial sites could not accept wastes of this type. And, with the looming Low-Level Radioactive Waste Policy Amendments Act that took effect 1 January 1993, a commercial disposal site did not appear viable.

TABLE 2-1. Key RI/FS Field Activities and Conclusions.

Activity	Purpose	Conclusion
Magnetic profiling and ground-penetrating radar	Determine if potentially contaminated missile launcher structure or wastes were possibly buried on-site	No evidence of buried objects indicative of buried launcher or buried wastes.
Ground water from on-site monitoring wells	Determine if plutonium and/or americium were in ground water	No evidence of contamination in ground water, as sampled from wells.
Surface soil samples	Determine concentrations and extent of radiological contamination, and assess potential deposition pattern of airborne contamination from accident	Similar to previous surveys, the majority of contamination was under the concrete pad in front of shelters 202, 204, and 206. Contamination was located along drainage ditch along shelters, through the culvert under County Hwy 539, and on the west side of the highway. Contamination primarily the result of water transport. Some contamination identified from secondary transport mechanisms like vehicle and foot traffic.
In-situ FIDLER measurements		
In-situ HpGe measurements of soil areas around shelter 204		
Sub-surface soil samples	Determine vertical extent of contamination	Contamination in areas sampled was generally limited to the top foot. One sample had contamination detected at a the sampling strata of 22 – 24 feet below ground level.
Activity partitioning by physical sizing of soil	Assess activity available for airborne suspension	The majority of activity was in the less than 20 micron diameter soil fraction.
Air sampling in vicinity of shelter 204	Assess airborne radioactivity levels	α-radiation activity concentrations in the range of background for the area.
Swipe samples of surfaces on the interior of shelters	Assess removable contamination in levels shelters	Removable contamination above 20 dpm/100 cm^2 limited to shelters in the vicinity of shelter 204.
In-situ α-radiation on the interior surfaces of shelters	Assess fixed contamination levels in shelters	Most significant contamination identified in shelter 204, and shelters in vicinity of shelter 204. Shelters 127, 216, and 106 had a number of samples with activity concentrations greater than 100 dpm/100 cm^2. Some results are suspected to be biased high by a factor of five (Rademacher *et al.* 2007).

As an alternative, if the Air Force was denied use of a DOE disposal facility or if other events had a dramatic impact on the cost effectiveness, then the Air Force would maintain a "No Action" interim remedy in accordance with the National Environmental Policy Act (NEPA). In 1995, Envirocare, Utah, a commercial waste site became available that eventually was used for the disposal of all radiological wastes from the site. This site is now operated by Energy Solutions, Inc.

The RI/FS recognized that the primary health hazard at the site from the plutonium and americium contamination was long-term, low-level exposures that increase risks for delayed somatic effects, primarily cancer. The RI/FS evaluated the hypothetical maximally-exposed individual (MEI) under a resident-farmer exposure scenario, which is considered worst-case for possible unrestricted future use. Residual Radiation (RESRAD) computer modeling code, Version 4.10, was used (Gilbert *et al.* 1989) to model environmental transport and exposures to hypothetical receptors using key parameters listed in Table A-6. Table A-7 contains a summary of dose conversion factors used in the RESRAD modeling (DOE 1988) and those specified in various International Commission on Radiological Protection (ICRP) publications. The dose conversion factors chosen for the modeling were the most conservative, producing the maximum projected doses, regardless of the actual chemical form of the contaminant. While the modeling was conducted for ^{239}Pu, and ^{240}Pu comprises about 18 % of the total plutonium α-radiation activity, there is no difference in the dose conversion factor for the two isotopes. Figure 2-1 contains a scatterplot of projected dose equivalent over time from the ^{239}Pu and ^{241}Am and contaminants. From the plot, the projected dose at $t \simeq 0$ for

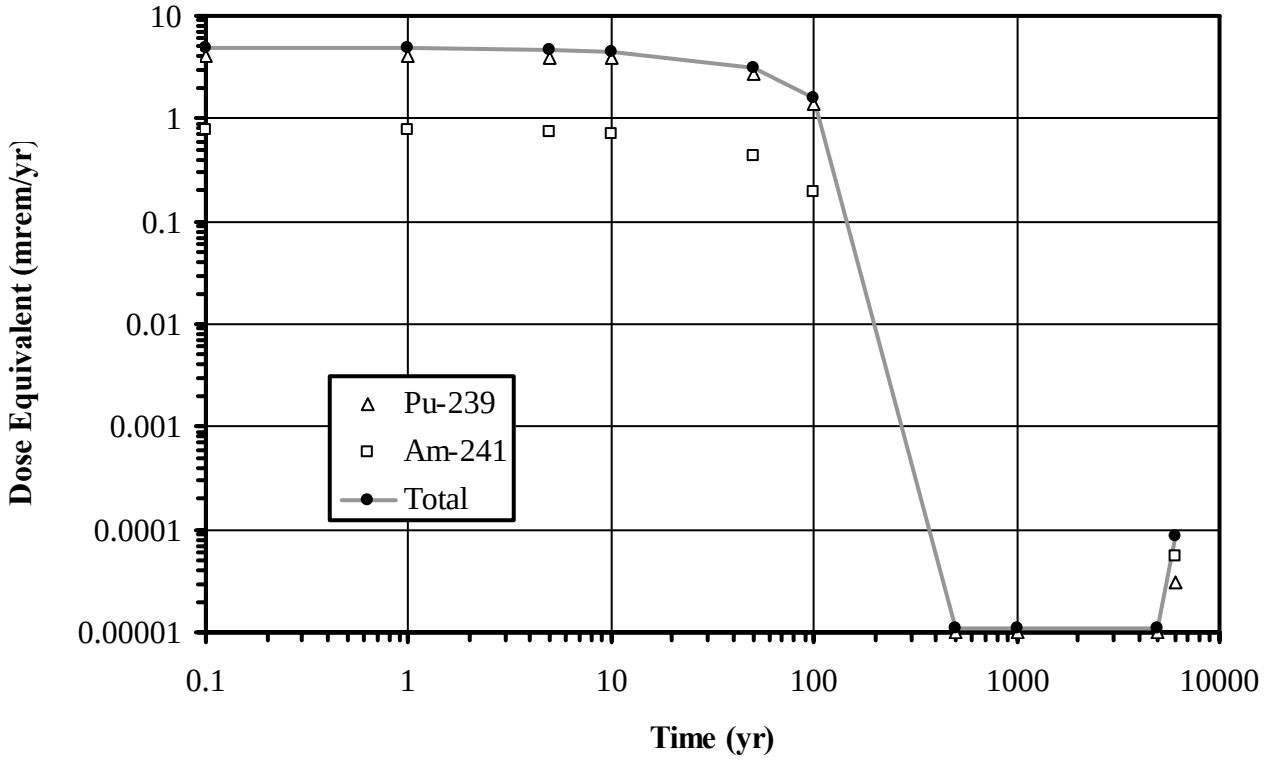

Figure 2-1. RESRAD Dose Summary Over Time [Data from RI/FS, Appendix J, Earth Tech (1992)]. [Note: ^{241}Am Modified for $^{239+240}$Pu to ^{241}Am Ratio of 5.4, and Average $^{239+240}$Pu Concentration of 8 pCi/g].

^{239}Pu was 4.8 mrem/yr. This level was deemed to be approximately equivalent to 4 mrem/yr, the post-remedial action goal. From the plot, projected dose equivalents are predominantly from ^{239}Pu, at a fraction almost equivalent to the fraction of total α-activity of the two isotopes combined. Among the modeled exposure routes, the inhalation route comprised about 76 % of the total dose equivalent, with the majority of the balance to soil ingestion (see Figure 2.2). Dose equivalent from plant consumption was a small modeled contributor, and external radiation an extremely small fraction, but primarily from ^{241}Am. Water-dependent pathways did not contribute significant dose equivalent for any time period considered by the model. However, from Figure 2.1, at about 6000 years, a very small dose equivalent from water-dependent pathways is projected, which is predominantly from ^{241}Am.

2.4 Pre-Remediation Action Characterization Studies.

Two pre-remedial action characterization studies were completed in 1996 and 1997. The objectives of the first study were to determine the depth of contamination in front of shelter 204 and along the drainage ditch west of shelter 204, evaluate the potential for mixed wastes inside the shelters and in groundwater from the existing trichloroethylene (TCE) plume, and better investigate surface anomolies identified in the RI/FS. The study came to some key conclusions. First, groundwaters in monitoring wells near shelter 204 were not impacted with TCE. Anomalous areas identified in the RI/FS were unremarkable for buried metal objects like roof panels and the launcher. Contamination was located at 20 feet below ground level in front of shelter 204 and at a depth of six feet at some locations in the drainage ditch. The 1996 characterization study estimated the volume of

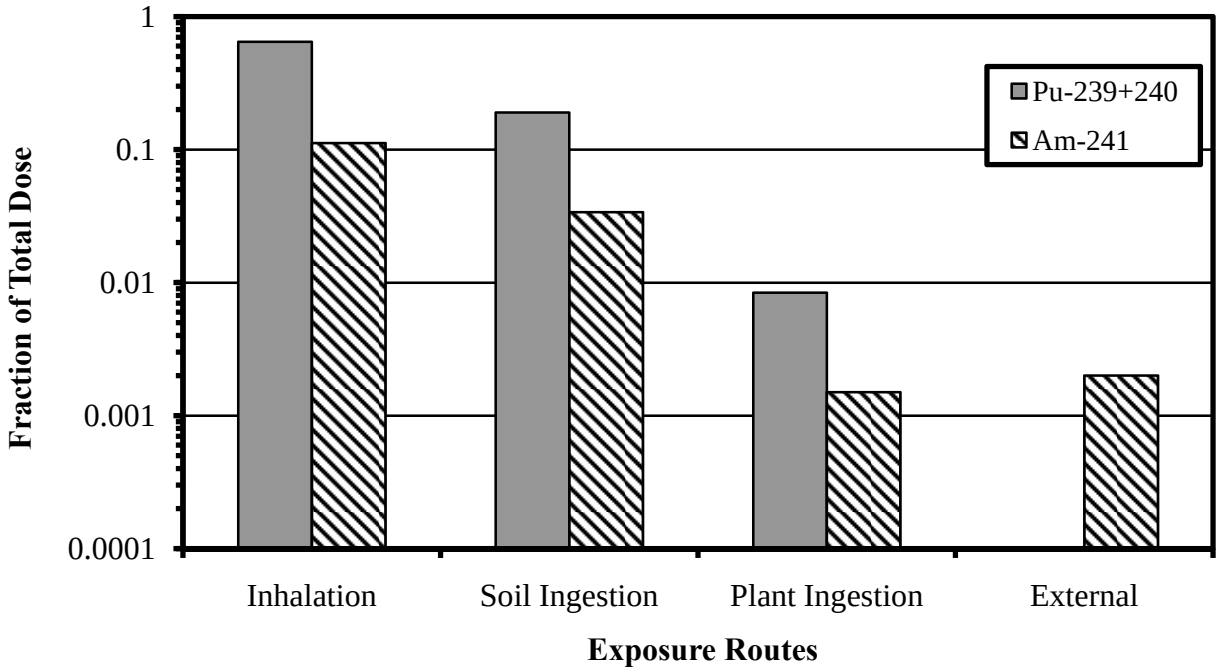

Figure 2-2. RESRAD Exposure Route Summary for t = 0 [Data from RI/FS, Appendix J, Earth Tech (1992)]. [Note: ^{241}Am Modified for $^{239+240}$Pu to ^{241}Am Ratio of 5.4].

contaminated soil and debris at 8,661 yd^3. The primary contaminated areas defined by the survey and shown in Figure A-13 closely corresponded to previous surveys.

The 1997 characterization study provided more in-depth analysis of the extent of contamination in the vicinity of shelter 204 and other areas around the concrete containment pad, contamination west of County Hwy 539, and around the culvert under the county highway. Sediment samples were also collected from Success and Brindle Lakes. Due to concern over lack of analysis in previous site surveys for thorium isotopes from the missile and uranium isotopes from the warhead, analyses for isotopic thorium and uranium were accomplished in additional to that for plutonium and americium. Sediment samples from the lakes were negative for plutonium. Thorium results for most samples were within background concentrations, but some had anomalous results that were attributed to interferences from plutonium (discussed above). Uranium concentrations, as expected, were in excess of background for a number of samples, but very low in comparison to the $^{239+240}Pu$ and ^{241}Am. Contamination was found at a depth of 24 feet in one area under the concrete cap between the rows of 200-series shelters, laterally between shelters 202 and 204. The total waste volume was refined to 12,500 yd^3, with the increase in estimated volume attributed to a greater lateral and vertical extent of the contamination zone.

2.5 Monitoring Well Water Sampling. In 2000, prior to remedial action, additional sampling was conducted in ten on-site monitoring wells. No evidence of radiological contamination was found (Zapreca *et al.* 2000).

3.0 Restoration – Primary Impacted Areas

3.1 Remedial Action.

The original contract to remediate the site was awarded in 1998. However, it was mutually agreed between Headquarters, Industrial Operations Command and the contractor to terminate the contract. In 1999, a contract was made between Chem-Nuclear Systems and IT Corporation to perform the clean-up. Public concern over the potential for transport of waste soils and debris by truck prompted a delay in the remedial efforts until transport issues were resolved. Eventually, a truck-rail transport option was negotiated with Lakehurst Naval Air and Engineering Station (NAES) and Fort Dix that afforded truck transport of metal waste containers completely on DoD property prior to their transfer to rail cars at a newly constructed rail spur on Lakehurst NAES. The option was deemed acceptable to local public officials and New Jersey DEP. Air Force and contractor project personnel briefed local community members on the modified transportation plans. Figure B-1 contains the local transportation route. The largest part of the 11.7 mile route was on Lakehurst NAES. Figures B-2 and B-3, respectively, are photographs of example intermodal metal containers and rail cars. A team from AFIERA performed a radiological baseline survey along the Lakehurst NAES portion of the truck transport route at the request of the Navy Radiological Affairs Support Office (RASO), Yorktown, VA. Results of the survey are contained in Rademacher *et al.* (2002). For laboratory analyses of 121 surface soil samples, the mean $^{239+240}Pu$ concentration was 11.8 fCi/g.

Prior to project mobilization in March 2002, Chem-Nuclear and IT Corporations were acquired by Duratek, Inc. and Shaw Environmental and Infrastructure (Shaw E&I), respectively. The contract

was honored by both firms. Operations were set-up as shown in Figure B-4. In the upper right portion of the figure is the primary excavation area, with soil and debris loading areas to the left in the figure between the low-numbered, 100-series missile shelters. Farther down this row of shelters, the contamination reduction zone (CRZ) was established. Initial remedial actions involved demolition of shelter 204, and demolition of the walls of shelters 202 and 206. The walls were torn down on these shelters to ensure that adequate shoring was left for the large excavation planned for soil areas in front of shelters 202 – 206. Metal materials from shelter 204 were disposed as waste, however, metals from shelters 202 and 206 were cleared for free release. Communication and power bunkers from these same shelters were removed along with the concrete and asphalt covers during soil excavation activities. The maximum excavation depth was 16 feet, at a location under the concrete cap between the row of 200-series shelters, laterally between shelters 202 and 204. Soil sampling during the 1997 characterization indicated contamination at a depth of 24-feet at this location; however, this was not confirmed during the excavation. It was speculated that samples collected below 16 feet in the 1997 characterization were cross-contaminated during the sampling with highly contaminated soils closer to the surface. After a little more than two years, project personnel demobilized from the site in June 2004.

3.2 Disposal Action. A total of 331 yd^3 of building debris was removed during restoration of primary contaminated areas. About 19,839 yd^3 of soil from the east side of County Hwy 539 was removed, while 2,159 yd^3 was removed from the west side of the highway (~ 10 % of the total contaminated soil volume). Soils removed from the launcher pit of shelter 204 were suspected to be contaminated with lead above the RCRA Toxicity Characteristic Leaching Procedure (TCLP) limit of 5 milligram per liter (mg/L). Samples from the soils were above this limit, requiring 57.6 yd^3 of soils to be segregated, shipped, and disposed as a mixed waste to the Envirocare facility.

3.3 Final Status Scanning Surveys and Soil Sample Analysis.

The excavated areas in the primary contaminated area encompassed 3.7 hectares (9.1 acres). Twenty-two survey units were established for the final status survey with sizes between 124 and 2,125m^2, and an average of 1,674m^2. For comparison, the Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) recommend a maximum of 2,000 m^2 for Class 1 survey units. Five of the 22 survey units exceeded this recommended maximum area; however, the survey unit with the largest area only exceeded it by 7 %. Figure B-5 contains the layout of the survey units (Duratek 2005). Fourteen were on the east side of County Hwy 539. Each survey unit was scanned with a FIDLER, with survey lines separated by about one meter, to ensure the scanning motion of the surveyor provided 100 % scan coverage. The scan rate was about one foot per second (ft/s).

Figures B-6 and B-7 contain scanning survey measurements from two of the survey units: EZ-5 and EZ-16. EZ-5 was the survey unit that encompassed the area with the highest amount of soil removed and the area excavated to a depth of 16 feet. This survey unit had four areas that required evaluation under the MARSSIM elevated measurement comparison (EMC) criterion, more than the other survey units. From the figure, elevated residual areas were between shelter 202 and 204, and in front of these shelters toward the asphalt drainage ditch. EZ-16, on the other hand, did not have any EMC areas and had the lowest mean final-status soil sampling ^{241}Am concentrations among the survey units. From Figure B-6, it is clear that the scanned area had a more uniform distribution of gross FIDLER readings.

Eight-hundred twenty-nine systematic soil samples were collected on a triangular grid pattern per recommendations of MARSSIM. A summary of the results are in Table B-1. All of the survey units passed the statistical tests under the MARSSIM protocols. Among the survey units, the highest average $^{239+240}$Pu concentration was observed in survey unit 2, based on ^{241}Am concentrations, and a $^{239+240}$Pu to ^{241}Am ratio 5.57. This survey unit also had the greatest number of samples with ^{241}Am concentrations greater than the average acceptable dose conversion guideline level ($DCGL_w$) for the survey units. Twelve survey units did not have any samples with ^{241}Am concentrations greater than the $DCGL_w$. Thirteen survey units had EMC areas that varied in number from a single to four areas. All survey units passed the EMC criterion, including the MARSSIM unity rule, based on area factors (AF) developed in consultation with the New Jersey DEP, and listed in Table 3-1. AFs relate the $DCGL_w$ to the $DCGL_{EMC}$: $DCGL_w$ x AF = $DCGL_{EMC}$.

TABLE 3-1. Area Factors under MARSSIM Protocol.

Area (m^2)	1	3	10	30	100	300	1,000	3,000	10,000
Area Factor	9.1	8.0	6.8	5.6	4.1	2.5	1.1	1.1	1.0
Acceptable $^{239+240}$Pu Concentrations (pCi/g)	73	64	54	45	33	20	8.8	8.8	8.0

4.0 Restoration – Secondary Impacted Areas

4.1 Introduction.

During 1998 discussions between the Air Force Institute for Environment, Safety and Occupational Health Risk Analysis [now AFIOH], HQ AFSC, and HQ Air Mobility Command, it was agreed that evaluation of areas outside of the primary contaminated area would be best accomplished after the greatest source of contamination was removed. This approach was chosen for a couple of reasons. First, there was concern that removal actions on the more highly contaminated areas could cross-contaminate adjacent areas that were previously uncontaminated. Second, there was a general belief that secondary contaminated areas would require minor soil removal, based on historical information.

During the remediation of the primary contaminated areas, anecdotal information on contamination identified in secondary areas was provided by Duratek Services, Inc. to technical staff of AFIOH, HQ AFSC, and 305 CES/CEV. Recently, functions of the 305 CES/CEV were realigned under the newly created 87th Air Base Wing, host wing to McGuire and installation support to Joint Base McGuire-Dix-Lakehurst. There was some concern that the amount and extent of the contamination was beyond an expectation of "minor contamination." As well, a number of other issues were raised. What was the mechanism for the translocation of the contamination? Was it possible that bulk contaminated soils were removed from the primary contaminated areas and used for backfill, and contaminated soils were covered with clean soil, limiting the ability of the in-situ survey

methodology to identify contaminated areas? Also, there was renewed concern over the discrete nature of the plutonium contamination and the risk modeling method that assumed a homogenous contaminant.

4.2 Air Force Institute for Operational Health and National Security Technologies, LLC Survey.

To address these concerns, the first step recommended by AFIOH was scanning surveys of the site to assess potentially impacted areas. National Security Technologies (NST) and AFIOH scanned numerous areas on the site with mobile scanning systems. The Kiwi system used by NST consisted of (8) 4x4x16-inch thallium-drifted sodium iodide [NaI(Tl)] detectors, while AFIOH used the Science Applications International Corporation Model GR-460 system that incorporates two 4 x4x16-inch NaI(Tl) detectors. Both systems used data collection software with global positioning systems (GPS). Figure C-1 contains a plot of the NST survey data. From the plot, the majority of the contaminated areas identified were along roads, with vehicle traffic being the most likely method of translocation. Figure C-2 contains a detailed view of the southern area. It was speculated that contamination in these areas was deposited during or shortly after the accident response from emergency vehicles like fire trucks. The most concentrated contamination was embedded between a thin, top-coat of asphalt (added after the accident) and the original asphalt laid during construction of the site. Information from the NST and AFIOH surveys were composited into Figure C-3, a simplified plot of potential impacted areas, which was part of a decision brief updating senior staff of McGuire AFB and HQ Air Mobility Command on progress of the remedial action (Archer 2005).

4.3. Phase 1 Characterization. Cabrera Services performed a characterization of discrete particles at select locations identified during the AFIOH and NST surveys. The purposes were to isolate and collect discrete particles for further analysis, assess particle depths, and assess activity concentrations of adjacent soil. The University of Las Vegas (UNLV) conducted physical and chemical characterizations of example soil and particles. In general, the majority of the discrete particles identified were located in the upper couple inches of soil. Table C-1 contains summary data from the UNLV distribution studies (Cabrera 2006b). Obvious from the comparison of activity concentrations in the various segments of the same sample is the marked variability due to the discrete particle characteristic. Five particles were analyzed by scanning electron microscopy (SEM), with an example in Figure C-4. The example particle had an estimated $^{239+240}$Pu activity of 0.8 μCi and a volume equivalent diameter of 122 microns, under the assumption that the particle is pure PuO_2 with a density of 11.5 g/cm^3. UNLV concluded that the majority of the activity in the samples analyzed from the BOMARC site reside in discrete particles, and exhibit a degree of pores and fractures that likely resulted during particle formation due to rapid cooling. And further stated, "the particles are chemically and physically stable and will likely remain in this form under normal environmental weathering." Based on these conclusions, the assumptions used in dose modeling were overly conservative - inhalation and ingestion dose conversion factors could have been based on less soluble physical forms. Further, it is clear that a significant fraction of activity in discrete particle form is aerodynamically too large for respiratory intakes.

4.4 Historical Site Assessment. A historical site assessment (HSA) was completed by Cabrera in 2006 (Cabrera 2006a) that documented existing information on the site, primarily with respect to the radiological contaminants, but with a good summary of non-radiological contaminants as well. Figure C-5 contains a comprehensive site overview from Cabrera (2006a) showing key facilities,

drainage areas, and primary vehicle traffic route used during the accident response. One of the primary concerns expressed in the HSA was the potential for parts of the primary contaminated area to be disturbed by construction activities. For example, as shown in Figure C-6, disturbed area A was a staging area during the construction of the 300-series shelters after the accident. The area where the 300-series shelters are located was at a lower grade than prior to construction, requiring fill material. The report speculated that some contaminant may have been used as fill or was covered by clean fill. It is important to note that while some minor contamination was identified at a few surface soil locations in the 300-series shelter area, there was neither evidence nor information to support the concern. As well, disturbed areas B and D are now wooded. The accident drainage flow went through the middle of area B, while area D contained contamination, based on the AFIOH survey in 2005. It was generally believed that these areas were cleared for the initial construction of the site, but were not disturbed post accident.

Figure C-7 contains a conceptual model of various contamination patterns in soil where there was an initial surface deposition. Sub-figure a is for an insoluble contaminant, like the WGP produced in this accident. Over time, there is a gradual downward migration of the contaminant, but concentrations, as depicted in the model, would be higher in surface layers as compared to layers at greater depth. Survey data from the site overwhelmingly supports this type of vertical deposition pattern. In contrast, sub-figure b depicts a more mobile contaminant where there is good vertical and lateral dispersion. Over time, as depicted in the model, layers at depth can have concentrations greater than those at the surface. From an in-situ radiological detection standpoint, this would be problematic for a ^{241}Am contaminant because detection relies on low-energy photons that are readily absorbed by thin layers of soil. Sub-figure c is similar to sub-figure a in an immobile contaminant assumption, but the contaminated area has been covered with clean fill. Like the case of sub-figure b, this is problematic from an in-situ radiological detection standpoint.

4.4 Discrete Particle Removal. Cabrera Services was contracted in 2006 to conduct a discrete particle removal operation with the purpose of reducing the source term on the site under the as low as is reasonably achievable (ALARA) principle. The initial plan was the removal of 200 discrete particles at priority locations, with suspect locations outside the fence first and within the confines of the fence second, in soil areas with highest elevated count rate from previous surveys. During the effort, 264 particles were removed from 60 separate locations. For each removal, depth was recorded and an estimate of the activity removed was made. Figure C-9 contains a map showing locations evaluated. In the plot, blue dots represent locations where an evaluation was made with portable survey instruments, but contamination could not be verified. Many of these locations are on the outside of the fence, with their original identification attributed to natural variations in background count rate. For many of the locations, as depicted by the orange circles, multiple discrete particles were removed. The vast majority of these targeted removal locations were located along roads and near structures involved in the accident response or related to routine operations after the accident. The 300-series shelter area only had one location with multiple particles and a handful of apparent single particle locations. Figure C-8 contains a plot of particle depth versus estimated particle activity. Notable from the plot is the abundance of particles between two and eight inches in depth. Particles with activity concentrations greater than 100 μCi were at depths greater than 4 inches, but generally no more than nine inches. The particle with the highest estimated activity was about 750 μCi, with the removal of about 15.9 mCi $^{239+240}$Pu in total. This represents about 0.07 % of the estimated total residual left on the site after the accident.

4.5 Discrete Contaminant Issues.

4.5.1 Definitions.

The terms “discrete particle,” “diffusely distributed,” “heterogeneous,” and “homogenous” have been used extensively throughout documents to describe the nature of the plutonium contaminant on the site, though no formal definition(s) have been provided. Other documents describing WGP plutonium have used similar terms. Defense Threat Reduction Agency (DTRA) in managing WGP on Johnston Atoll defined 1) “discrete, hot particles” as point sources with diameters greater than 45 μm with approximate activity of 135k pCi and 2) dispersed activity as particles with activity about 270 pCi and diameter about 10 μm (DTRA 2002).

The inconsistent use of the terms in the radiation protection field can lead to confusion. For example, the term “hot particle” in the radiation protection field is generally in reference to high, specific-activity fission product particles that pose an exposure risk for highly-localized skin dose and can be readily identified by a Geiger counter. The highly-localized dose is predominantly due to the β-particle emissions, while associated γ-emissions deposit their energy over a significantly larger tissue volume. Hot particle exposures are of particular interest in the nuclear power industry and were an issue of fallout from the Chernobyl accident. In this context, discrete plutonium particles do not behave in a similar manner, with the only external dose from low-energy, low-frequency emission x- and γ-radiations. For internal exposures through inhalation, plutonium particles can produce highly localized dose to adjacent tissue areas in the lung. In this case, the highly-localized energy deposition is from α-particles. However, in this exposure context, a DTRA-defined hot particle (i.e., diameters greater than 45 μm) cannot produce lung exposures since the particles are physically too large for respiratory intake under practical conditions. As such, use of the hot particle term has been discouraged for the WGP at the BOMARC site.

While PuO_2 is highly immobile and chemically very insoluble in most environments, theoretically, some fraction of the contamination will have been mobilized in an aqueous form. As disassociated ions, the plutonium can be incorporated into other chemical complexes (including dioxides) and subsequently have a more uniform distribution in the soil matrix. The degree that this condition is represented in soils at or below the $^{239+240}Pu$ remediation criterion is difficult to assess because discrete plutonium particles (which potentially exist in large numbers per sample) are difficult to isolate as point sources in sample matrices. This is in contrast to samples that contain a single high activity discrete particle, orders of magnitude above the criterion. Therefore, the $^{239+240}Pu$ in some samples may appear to be homogenously distributed, like that common to naturally occurring radionuclides in soils, but from an activity standpoint could be comprised primarily of numerous discrete particles distributed throughout the soil matrix. An important point regarding this issue is that high activity discrete particles are expected to be predominantly in a dioxide form, as they are chemically and physically stable (Cabrera 2006b). No physical mechanism exists for the natural environmental formation of high activity, relatively-pure plutonium particles of other chemical compounds (i.e., silicates, carbonates, nitrates). Rather, these compounds are more likely to exist in diffuse concentrations, as complexes with inert soil particles.

Figure C-10 provides conceptual diagrams of discrete plutonium contamination. The diagrams are identical in the type and size of discrete particles, and both provide a reasonably good illustration of

that observed in field studies. However, sub-figure b more closely correlates to laboratory analysis of soils, where there was an apparent low-level diffuse component of contamination liberated by dissolution processes, albeit very minor. The studies conducted by UNLV (Cabrera 2006b) and AFIERA (Rademacher 2001) corroborated this model.

4.5.2 Issues.

4.5.2.1 General. The discrete nature of the WGP on the BOMARC has created some issues germane to remediation of the site, whether real or perceived. As noted, recent interest in this issue has generated discussion in technical reports supporting this remediation, and is worth some limited discussion here. Table C-2 provides a brief summary of key issues of concern.

4.5.2.2 Laboratory Analysis.

Proper laboratory analysis of soils and other matrices supporting the remediation and FSS is critical to proper unrestricted radiological release of the site. The 1996 Characterization Study (OHM 1998) had significant variability in the $^{239+240}$Pu to ^{241}Am ratios distribution (Rademacher 1999b) that was attributed to heterogeneity. From that point forward, HQ AFSC only recommended α-spectroscopy for $^{239+240}$Pu to ^{241}Am ratio assessments, as the method was highly susceptible to variability when determining total activity. In 2000, the Department of Environmental Protection (DEP), State of New Jersey, requested that a fraction of FS soil samples be analyzed by α-spectroscopy. However, in response to the request, the Air Force convinced the DEP that the method could lead to high variability and confounding results. The only α-spectroscopy analyses conducted on samples from the site recently have been for confirmation of the $^{239+240}$Pu to ^{241}Am ratio during the 2002 – 2004 remediation (Duratek 2006), U.S. Geological Services for water samples (Zapecza *et al.* 2000), and for assessment of $^{239+240}$Pu in ashed composites of wipe samples (Rademacher *at al.* 2009).

HQ AFSC and AFIOH evaluated the effects of heterogeneity on γ-spectroscopy analysis of soil samples (Rademacher 1999a, 2001). Conjugate measurement of individual samples in plane-symmetrical containers (e.g., right cylindrical containers, Petri dishes, etc.) was recommended to reduce uncertainty in sample activity. Problems with heterogeneity in assessments of FSS samples of the Class 1 area were limited during the 2002 – 2004 remediation. Cabrera Services incorporated the method into FSS soil samples for the discrete particle removal and final status surveys conducted in 2007 (Cabrera 2008).

4.5.2.3 Sample Collection. Collection of soil samples representative to concentrations in soils in conjunction with in-situ γ-scanning are important in verifying that potentially impacted areas have met risk-based criterion. Heterogeneity can impact the ability to collect samples representative of the true contamination levels. While this issue was apparent and important during evaluation of pre-remediated soils (Earth Tech 1992), the effect on soils at or below the remediation criterion of 8 pCi/g $^{239+240}$Pu is significantly lower. From the 2002 – 2004 remediation FSS soil sampling results, the highest activity concentration observed was 95 pCi/g, only 12 times the criterion. To reduce the potential negative effects of heterogeneity in EMC areas, multiple samples were collected and analyzed.

4.5.2.4 Inhalation.

Inhalation is the most important exposure pathway for the resident-farmer scenario. Heterogeneously distributed activity among particles greatly reduces projected doses because a fraction of the contaminant is unavailable for air-suspension and unable to penetrate to deep portions of the lung (alveolar region) where the greatest lung retention times are realized. Figure C-11 was generated for PuO_2 particles, under the assumption of 100 % PuO_2 composition, spherical shape, and density 11.5 g/cm^3. Aerodynamic equivalence was calculated with the equation from McClellan and Henderson (1989), using slip correction factors from the EPA (2007). The plot contains two data curves. The black line relates $^{239+240}$Pu activity to aerodynamic equivalent diameter, while the gray line relates volume and aerodynamic equivalent diameters. For volume equivalent diameters, greater than 0.5 μm, slip corrections are small and the primary factor relating the two diameters is:

$$\sqrt{\frac{\rho_0}{\rho_\rho}},$$

where ρ_0 is unit density and ρ_p is the density of the particle in question. The plot contains indices important to inhalation exposures. The green line represents a practical threshold for particle suspension in the environment (30 μm, aerodynamic equivalent diameter). The two blue lines represent an "approximate" demarcation between alveolar and tracheobronchial deposition and the red a minimum particle size separating tracheobronchial and naso-oropharynheal deposition (McClellan and Henderson 1989). From the plot, a maximum single particle activity available for deposition in the alveoli is 1.8 pCi (0.067 Bq), which the bolded values in parentheses for particles of shape factor equal to 1.6. Based on ICRP Report 54, about 60 % of Class Y (inhalation class) radiological material deposited in the alveoli region has long-term retention (ICRP 1987), which is responsible for the greatest modeled cancer risk to the lung. In contrast, for deposition in other portions of the respiratory tract, retention times are significantly lower and very small fractions of deposited radioactivity are transferred to other target organs of the body.

The most recent ICRP lung model, ICRP 66 (ICRP 1995), is more sophisticated than the model of ICRP 30, which dose conversion factors (DCFs) used in the RI/FS were derived. There has been a significant amount of computer-based modeling of variability and uncertainty associated with inhaled PuO_2, where there exists a stochastic intake paradigm of relatively small numbers of particles with high specific activity versus average intake (Aden and Scott 2003). In Aden and Scott's (2003) recent work using the ICRP 66 lung model, stochastic intakes of WGP were modeled, for single, 10, and 100 particles. The variability of deposited activity was highly dependent on the region of the respiratory tract of interest. The alveolar region had the least variability in deposited activity, with variability increasing for upper-more regions of the respiratory tract (Aden and Scott 2003). For the lower alveolar and tracheal/bronchial regions, under stochastic intake assumptions for WPG, the variability was low. However, for extrathoracic regions, much larger variability was observed and predominantly influenced by deposition of particles of large aerodynamic equivalent diameters. The implications of the paradigm were most marked for $^{238}PuO_2$ that is handled in the Department of Energy (DOE) complex, where the specific activity is about 240-fold higher than the WGP at the BOMARC site.

The RESRAD modeling conducted under ICRP 30 for the RI/FS assumes that the activity has a log-normal activity distribution with median aerodynamic diameter (AMAD) of 1 μm as a default, while 5 μm AMAD (log-normal) is the recommended default for occupational exposures under ICRP 66/68. In both cases, if the actual activity is distributed among particles of higher AMAD, DCF are lower. This is the expectation for the distribution of Pu activity on the BOMARC site and the case for relatively high activity discrete particles when stochastic intakes are of concern.

Application of the stochastic intake paradigm to WGP at the BOMARC site raises other paradigms. First, as already discussed, a significant fraction of the WGP left on-site after the accident was distributed in discrete particles, with aerodynamic equivalent diameters too large to afford respiratory intakes and for that matter airborne suspension. Even post remediation, some discrete particle characteristics may be present, but to a lesser degree than pre-remediation. And, for stochastic intake paradigm considerations of post-remediation soils, particle distributions will contain a reasonable fraction too large for suspension, making that fraction of activity unavailable for respiratory dose. Second, inhalation DCFs used in the 1992 risk modeling (Earth Tech 1992), assumed a Class W material. As noted above, a Class Y DCF, as applicable to PuO_2, was 40 % lower than the Class W DCF under Federal Guidance Report (FGR) 11. Under more recent ICRP guidance [Table A-7, (ICRP 1991, 1995)], a 30-year weighted PuO_2 DCF (termed "Type S") for the general public is about 10-fold lower than that used in the RI/FS risk modeling (Earth Tech 1992). As noted earlier, it is not plausible for high-activity $^{239+240}$Pu particles to exist on the site in a non-dioxide chemical form. If high-activity discrete particles are of concern, use of a DCF applicable to a more soluble and mobile form of Pu is not appropriate. In principle, the two considerations are mutually exclusive.

4.5.2.5 Ingestion.

Ingestion is the second most important pathway for the resident-farmer scenario and comprised an overall fraction of modeled risk of 22 %, or 2.2×10^{-5} over 70 years. The impact of heterogeneity (discrete particles) on modeled ingestion doses has similar type of paradigms to that of the case of inhalation. First, the existence of high-activity discrete particles and the dose modeling used for the ingestion exposure route contradicts the conservative use of Class D gastrointestinal tract uptake factor, f_1. Second, if one places great concern on potential ingestion of high-activity discrete particles, of necessity, an assumption must be made that a vast majority of residual activity in soils is comprised of such particles. Subsequently, inhalation risks would be virtually non-existent, as these particles would not be of proper aerodynamic equivalent diameter to allow air suspension.

To evaluate risks under the stochastic intake paradigm, data from the Class 1 FSS (Duratek 2006) were used to form a case study. This data set is most appropriate for review since it provides an extensive analysis of residuals from remediation, which comprise over a 1000 FSS samples. From Table B-2, survey unit 2 had the highest estimated mean residual concentration among systematic grid samples combined with area-weighting EMC concentrations among the survey units, with a mean of 3.24 pCi/g. Among the 154 samples, the highest total sample activity was 17 nCi, and is an estimate of the highest activity residual particle, assuming the entire sample activity is the result of a single particle. For a 2000 m^2 survey unit, monoactivity particles are assumed to be dispersed in the top 15 cm of soil, of density 1.5 g/cm^3. Per the RESRAD modeling, 35 g of soil is ingested per year by a site resident (see Table A-6). Table 4-1 contains summary calculations for the case study. Over

a 70-year period, the mean probability of ingesting a particle is 0.47. Table 4-1 contains probabilities of ingesting various particle numbers based on a Poisson probability distribution and DCFs from Table A-7. For various particle number and ingestion DCFs, 70-year cancer risks are listed under the assumption that there is an 8×10^{-4} cancer mortality risk per Rem (NAS/NRC 1990). From the data, the risks are very low compared to the overall lifetime cancer mortality risk goal of 1×10^{-4}, consistent with the range of 10^{-4} to 10^{-6} listed in the National Oil and Hazardous Substances Pollution Contingency Plan [40 CFR 430(e)(2)(i)(A)(2)]. As discussed above, the concern of stochastic intake of discrete particle is contradictory to the assumption of soluble-form gastrointestinal uptake factors, i.e. Class D under ICRP 30 and Type F under ICRP 72. Using a more appropriate dose conversion factor, Class Y, under ICRP 30/48 reduces calculated risks by a factor of 67, whereas under ICRPs 60/78 it is reduced by a factor of 106. Under ICRP 60/72, which is applicable to members of the public, the risk is reduced by a factor of 2.3, however, the assumption of an unspecified chemical form is made, which defaults to the most conservative gastrointestinal tract uptake factor.

TABLE 4-1. Estimated Risks for Stochastic Intake Paradigm for Ingestion of 17 nCi (0.017 μCi) Monoactivity $^{239+240}$Pu Particles (Mean 70-year Probability of Particle Ingestion = 0.47).

DCF Source	Class	Particle Number	70-yr Ingestion Probability	Ingested Activity (μCi)	Dose Conversion Factor (mrem/μCi)	Effective Dose Equivalent (mrem)	70-year Risks ($\times 10^{-4}$)*	
							Separate	Total
FGR 11 ICRP 26/30/48	D	1	0.293	0.017	$3.5 \times 10^{+3}$	60	0.14	0.22
		2	0.068	0.034		120	0.066	
		3	0.011	0.051		180	0.016	
		4	0.0012	0.068		240	0.0022	
		5	0.00012	0.085		300	2.9×10^{-4}	
	Y	1	0.293	0.017	52	0.88	0.0021	3.4×10^{-3}
		2	0.068	0.034		1.8	0.0010	
		3	0.011	0.051		2.7	0.00022	
		4	0.0012	0.068		3.5	5.4×10^{-5}	
		5	0.00012	0.085		4.4	4.3×10^{-6}	
ICRP 60/72 (Public)	M	1	0.293	0.017	$1.5 \times 10^{+3}$	26	0.061	0.096
		2	0.068	0.034		51	0.029	
		3	0.011	0.051		77	0.00067	
		4	0.0012	0.068		102	9.6×10^{-4}	
		5	0.00012	0.085		128	1.2×10^{-4}	
ICRP 68/60, 78 (Workers)	S	1	0.293	0.017	33	0.56	0.0013	2.1×10^{-3}
		2	0.068	0.034		1.12	0.00062	
		3	0.011	0.051		1.68	1.5×10^{-4}	
		4	0.0012	0.068		2.24	2.1×10^{-4}	
		5	0.00012	0.085		2.81	2.7×10^{-6}	

* Risks based on 8×10^{-4} excess cancer mortality/rem (NAS 1990), with overall risk being ingestion probability multiplied by risk of cancer mortality.

A probability function of ingested particles, derived from a broad distribution of particle activities, would have a mean ingested particle number significantly higher than the case presented here, but much lower in mean particle activity and less variability in total ingested activity. However, the probability of ingestion of high-activity particles would be significantly lower than described here. Most important, however, in this case study, inhalation doses are not possible because the minimum diameter of pure 17 nCi $^{239+240}$Pu particles is 34 μm, which equates to an aerodynamic equivalent diameter of 115 μm (spherical) - non-suspendable in typical outdoor environments. In summary, attributing a greater fraction of the residual radioactivity to high-activity discrete particles than to a more diffuse contaminant will increase the dose per particle ingestion event, but overall it will not increase the total risk because of a subsequent reduction in ingestion probability. Also, attributing more activity to high-activity particles will proportionately eliminate a source of activity for the inhalation pathway, which provides the largest modeled pathway of exposure.

4.5.2.6. Risk Modeling.

There has been some general scientific debate on whether discrete particle uptake and subsequent tissue exposure pose a significantly higher cancer risk compared to the same uptake and deposition from a more uniformly dispersed contaminant. In regard to exposure from BOMARC WGP, the implication is significant for inhalation exposures, because modeled gastrointestinal (GI) tract uptakes to the blood stream require contaminants to be in soluble form and WGP provides negligible dose to the GI tract during transit. Further, for WGP inhalation exposures, only depositions in the alveolar region of the lung are subject to significant spatially, non-uniform radiation exposures. Depositions of WGP in upper portions of the respiratory system are rapidly cleared predominantly to the GI tract, with a lesser amount to the circulatory system.

The ICRP has recommended application of average tissue doses in estimation of risk, even in the case of non-uniform exposures (ICRP 1991). NCRP Report No. 46 provided theoretical evaluation, and review of pertinent observations in animal and humans exposed to WGP (NCRP 1975). NCRP noted theoretical considerations for an inverse dose effect for spatially non-uniform exposure to ^{239}Pu particles in the lung and confirmation of the effect in animal studies of lung exposures to ^{238}Pu and ^{239}Pu. A recent literature review on the topic was conducted by Charles *et al*. that included Russian workers exposed to WGP (Charles *et al.* 2003). They concluded that the ICRP dose-averaging is likely to provide a reasonable estimate of carcinogenic risk. A recent review of animal studies data was completed by Raabe (2010), with the conclusion that heterogeneously distributed radiological particles in the lung leads to lower carcinogenic risk to the lung than a uniformly distributed contaminant.

4.5.3 Summary. Historical site investigations noted observation of a discrete particle plutonium contaminant nature. WGP involved in high-temperature ignition events in air have a propensity to form PuO_2 chemical forms. Dioxide forms of plutonium are the most stable chemical form under most soil conditions. Application of water to suppress the fire aided rapid condensation of plutonium. Recent SEM images provide conclusive evidence that this occurred in particles sampled from the site, and that the particles examined had limited surface degradation since formation. In this from, particles are chemically and physically stable, characteristic of a PuO_2 chemical form. Further evidence of this predominant chemical form was confirmed by strong acid challenges to contaminated soils. Use of the most conservative DCFs of FGR 11 provides an overestimate of risks

to a hypothetical future site inhabitant under the resident-farmer scenario. Further, the concern of stochastic intake of discrete particles under the most conservative FGR 11 DCFs is contradictory to this assumption. Evaluated with DCFs appropriate to dioxide forms are significantly lower, rendering the low probability exposure scenario insignificant. Overall, regardless of chemical form, recent ICRP recommendations for plutonium are less conservative than those used in the risk modeling that formed the basis of the ROD.

4.6 Final Status Survey and Spot Removal.

4.6.1 General. Spot removal of contamination and final status survey in secondary areas was accomplished in 2007 by Cabrera Services (Cabrera 2008). Figure C-12 is the breakdown of survey units based on remedial efforts conducted in the primary areas, findings from the HSA, NST and AFIOH surveys of secondary areas, and the discrete particle removal operation conducted in 2006. Generally, primary areas that were previously remediated were surrounded by a class 1 survey area (buffer). Because concern existed for drainage areas within the original fenced confines of the site, a class 1 survey area was designed between the original fence and County Hwy 539. Also, areas adjacent to transport routes were high priority for more detailed sampling due to previous surveys and logical translocation mechanisms. Other secondary areas within the confines of the site were considered priorities and buffer areas surrounding class 1 areas were designated class 2 areas as shown on the figure. A class 3 survey area was established beyond the class 2 survey areas.

4.6.2 Survey Methodology and Contamination Locations. Figure C-13 diagrams the survey protocol used by Cabrera (Cabrera 2008). From the diagram, systematic soil sampling and drive-over scanning were accomplished at the same time. Further survey work at select locations was determined by results of the soil sampling and scanning work. Either a reported soil sampling result with an ^{241}Am result over 1.2 pCi/g or a cluster of in-situ sampling points with z-score greater than 3 triggered additional investigation, sampling, and in some cases remedial action. Approximately 65 yd^3 of contaminated soils packaged and shipped as radioactive waste during this phase. Most of the waste was from removal operations conducted during this phase, with a small fraction of the total volume from waste generated during the 2005 AFIOH investigations, and shelter floor dirt removed by HQ AFSC and AFIOH during shelter investigations. Figure C-14 shows areas where contamination was removed during this phase of the remedial action. Most of the contamination removed was located along vehicle transport routes. The majority of the contamination removed from the vicinity of the former shelter 204 was that embedded in the asphalt surface of the road, and in soils adjacent to the road. Other prominent areas were in soils around Bldg 159, specifically the end that contained the restroom, and in soils along the road extending between the missile areas and Bldg 28, and in asphalt and soils around Bldg 28. This road was believed to have been used during the accident response for vehicles exiting the shelter area. A large volume of soil was removed from the area, annotated "storm water outfall," on the southern part of the site. Other locations on the figure were relatively discrete, with soil removals associated primarily with a single particle dominating the response of the FIDLER. Only a couple of removals were accomplished outside the currently fenced area (Note: the figure shows the 1972 fence).

4.6.3 Scanning Surveys. A summary of the scanning coverage is provided in Table 4-2. For class 1 areas, greater than 100 % coverage was attained (i.e., some overlap in scanned areas), but was reduced to 99 % to account for trees and some areas that could not be scanned due to excessive

terrain grades. Class 2 scans were 3 % short of the goal, while class 3 areas greatly exceeded the goals established.

TABLE 4-2. Summary of Driveover Scanning Coverage (Cabrera 2008).

Classification	Total Area (acres)	Prescribed Coverage		Actual Coverage	
		(acres)	(percent)	(acres)	(percent)
Class 1	42.3	42.3	100	41.9	99+
Class 2	86.5	43.25	50	40.3	47
Class 3	62.8	6.3	10	14.8	24

4.6.4 Systematic and Biased Surface Sampling in Support of Final Status Surveys.

Figure C-15 shows systematic soil sampling locations in support of the final status survey. The class 1 areas had 1956 samples among 78 individual survey units. A summary of the results are contained in Table C-3. For the vast majority of the survey units, no remedial actions were accomplished based on an elevated systematic soil sampling result, but rather based on scanning survey results. The table contains average $^{230+240}$Pu concentrations for each survey unit. Seven of the survey units (data highlighted in gray) had systematic sample(s) replacement, based on remedial efforts. The average concentrations in the survey units are based on pre-remedial action sampling, while the maximum concentrations listed reflect the value for pre-remedial and post-remedial action sampling. Among the systematic samples, the highest was 1000 pCi/g, and located in survey unit 43, in the vicinity of the 200-series shelter area. Figure C-16 shows individual survey unit locations. For survey unit 43, the pre-remedial action average $^{239+240}$Pu activity concentration was 37 pCi/g, but was almost entirely influenced by the sample with the maximum activity. From the re-sampling of this area, the average net $^{239+240}$Pu activity concentration among the samples was indistinguishable from background. Survey unit 43 was the only one with a pre-remedial action $^{239+240}$Pu activity concentration greater than the $DCGL_w$ of 8 pCi/g. Eight-hundred twenty-three samples were collected in the class 2 survey unit. Only 14 of the samples were above the decision level of the method for ^{241}Am, with the sample with the maximum calculated $^{239+240}$Pu at 5.1 pCi/g. All survey units passed the sign statistical test recommended by MARSSIM.

One-hundred fifty biased (i.e., by location) soil samples were collected to assess the potential for contamination in a number of suspect areas identified during scanning surveys and assess the effectiveness of remedial actions. Locations are shown in Figure C-17. The highest biased soil sample had a $^{239+240}$Pu activity concentration of 366 pCi/g. Post-removal samples were collected at locations requiring remedial action. Since remedial actions were iterative in some areas, some locations had multiple samples. A total of 517 post-removal samples were collected.

4.6.5 Sub-Surface Sampling. Sub-surface samples were collected primarily to assess if contamination existed in locations that had been covered with uncontaminated soil, or if contaminated soils were translocated to previously uncontaminated areas and used as fill. A number of locations previously identified with ^{241}Am above the screening level of 1.2 pCi/g were also sampled, as well as some systematic samples in class 1 survey units. A total of 274 samples were collected at 113 locations as shown in Figure C-18. From the figure, numerous locations were selected in the 300-

series shelter area and west of the drainage ditch that carried run-off water from the initial accident response. Only three of the 274 samples had positive detections for ^{241}Am. Sample 6007, at a location along the main road, south of the missile area had the highest calculated $^{239+240}$Pu, 17.7 pCi/g [the sample at 12 feet below ground surface (bgs)]. This sample was collected at a location that had existing surface contamination. To further investigate, four more direct push cores were collected, with four samples per core. Of the 16 additional samples, ^{241}Am activity concentrations were below the decision level for all but one sample, which had a calculated $^{239+240}$Pu activity concentration of 9.6 pCi/g, and too was in the 12 feet bgs lift. Overall, among the 20 samples collected in this area, the average was well below the $DCGL_w$ of 8 pCi/g, but it was widely believed that since contamination was identified in the bottom lift, and not any of the lifts below the surface-contaminated areas, that cross-contamination was the likely cause. Figure C-19 a photograph of the sampling of this area with the direct-push rig, while Figure C-20 contains a photograph of the same area, post sampling and contaminated soil removal. The other location with a positive finding was at location 6013, the area identified on the southern part of the figure as a "storm water outfall" area. The calculated $^{239+240}$Pu activity concentration for this location was 13.0 pCi/g, at a depth of 1 foot bgs, however, like the other location, this sample was in an area of surface contamination at the time of sampling. Other samples collected in close proximity to this location were unremarkable, as were post-remedial action samples. Most importantly, samples collected in areas with concern for contamination at depth, without accompanying surface contamination, were all unremarkable. Therefore, the sampling efforts during this phase discounted concern for contamination at depth.

4.6.6 Select Final Status and Biased Soil Samples Heterogeneity Evaluation.

Samples evaluated by Cabrera Services in 2007 in support of the spot removal and final status surveys were counted in a conjugate manner to reduce the effects of heterogeneity on sample activity assessments. The activity concentrations reported for individual samples were based on the integrated count of both sites of the sample. To qualitatively investigate heterogeneity in samples, biased and final status samples with mean activity concentration greater than 2 pCi/g were evaluated based on the assessed activity concentration for the conjugate measurement of each side of the "hockey puck" shaped sample containers. Figure C-21 contains a plot of the ratio of conjugate measurements versus the mean calculated $^{239+240}$Pu. The data was normalized to ratios greater than one for simplicity. The plot contains a red line at the remediation criterion of 8 pCi/g, and blue and green lines for the modeled 67th and 95th percentile ratio boundaries for a null hypothesis that the ^{241}Am contaminant is uniformly dispersed throughout the sample matrix. The variability represented is primarily due to the randomness of radioactive decay (i.e., counting statistics). These lines were modeled from a best-fit of uncertainty data from single conjugate measurements.

From the figure, the orange data point ($^{239+240}$Pu = 970 pCi/g, ratio = 5.4) was for the sample with the highest mean activity concentration. Based on previous work by Rademacher (1999a and 2001), the ratio approximates the theoretical maximum for this type of sample container, ignoring variability introduced by counting statistics. If the vast majority of the sample $^{239+240}$Pu activity is dominated by a single discrete particle, as evidenced by this data, the particle would contain about 300 nCi (sample mass = 314 g).

Overall, over the distribution of mean sample activity concentrations there is an apparent strong influence of heterogeneity. For samples below the criterion, the effects are to a lesser degree, with a

greater fraction of the samples falling below either the 67th or 95th percentile lines as compared to samples with greater activity. While this general trend was observed in previous studies (Rademacher 2001), heterogeneity for samples near or below the criterion are expected to have contamination in particles aerodynamically too large for respiratory intakes. For example, the sample with mean $^{239+240}$Pu = 8.2 pCi/g and ratio = 7.4 would have a particle activity of 2.8 nCi, if the sample activity was dominated by a single particle. For a pure PuO_2 form, the volume equivalent diameter would be about 18 μm and the aerodynamic equivalent diameter would be about 60 μm, if spherical (Figure C-11). Even with more oblong shape, a particle of this activity would not be suspendable under typical environmental conditions or capable of deposition in tracheal or deeper portions of the respiratory tract.

4.7 Summary of Actions on Secondary Impacted Areas. One-hundred ninety-two acres of land was evaluated in this phase of the project, with scanning effectively on 97 acres. Sixty-five cubic yards of waste were disposed, with an estimated total activity of 2.21 mCi, with about 1.9 mCi (26 mg, by mass) attributed to $^{239+240}$Pu. Added to the activity removed in 2006 by Cabrera (Cabrera 2006a), 15.9 mCi (0.22 g), this is 0.08 % of the total estimated residual mass, 300 g $^{239+240}$Pu. A continuing interest item among individuals monitoring progress on restoration of the BOMARC site is whether or not an activity found evidence of the damaged launcher from shelter 204. This activity did not uncover any evidence.

5.0 Scoping Surveys and Spot Remedial Actions in Shelters and Other Buildings.

5.1 Introduction.

Acceptable residual contamination criterion for the shelters and bunkers are predominantly based on potential future uses. The RI/FS and ROD were developed under CERCLA. The RI/FS predominantly focused on the extent of contamination in soils, current risks to the public, and risks to a future site inhabitant under the resident-farmer scenario. This unrestricted use scenario is generally considered a “worst-case” use because it encompasses the most significant potential exposure routes. While remediation of soils to an unrestricted residential use scenario was accomplished, a future use has not been determined, and may not be for some time. The shelters provide little to no practical use for future military missions, and are not acceptable for unrestricted access to members of the public because of structural and other site hazards. As such, an unrestricted future use would likely incorporate demolition of the structures, with concrete and steel being recycled or disposed. Over the past 37 years after the site was closed, a few shelters have been used to store investigation-derived waste and equipment during surveys and remediation. Similar future uses are plausible.

In general, CERCLA is not applicable to structures. The RI/FS did not establish a risk-based remediation goal for structures; however, criteria in U.S. Atomic Energy Commission (AEC) Regulatory Guide 1.86 (see Table D-1) were considered relevant and appropriate for an unrestricted release of debris, and recommended in the absence of a risk-based criterion (Earth Tech 1992). Sophisticated computer risk modeling codes, like RESRAD for exterior soils, had not been developed at the time of the RI/FS for building interiors. In the mid-1990s, a RESRAD model for building interiors, RESRAD-Build, was developed; the latest is Version 3.3 (Yu *et al.* 2003).

RESRAD-Build is used here to model doses to site workers that may intermittently use a shelter for storage. In one case examined here, 10 % occupancy for a 2,000 hour work year is assumed, with a 100 mrem annual exposure limit. If the shelters are demolished, the concrete rubble can serve a multitude of purposes including road-bed gravel fill, aggregate for new concrete, rip-rap, ground fill, etc. Any of these uses would effectively mix any surface contamination with uncontaminated portions of the bulk concrete. This is a logical evaluation criterion since deterioration of the concrete rubble over time would become part of the soil matrix. Under this condition, contaminated concrete can be treated with similarity to soil, in some respects. Buried concrete:

1) does not provides a contaminated surface suitable for airborne release to receptors and

2) if ever regenerated for a future use, the original contaminated surface would be mixed with other materials, lending to a more appropriate volumetric modeling, and lower risks.

5.2 Remedial Action Criterion for Buildings.

The summary results of the RESRAD modeling are provided in Table D-2 for $^{239+240}$Pu, and ^{241}Am, and the total. In the modeling, it was assumed that the $^{239+240}$Pu to ^{241}Am ratio was 5.4. An explanation for the use of this ratio rather than the 5.57 is provided in Rademacher *et al.* (2009). The modeling was conducted for various acceptable exposure levels. The most appropriate acceptable exposure level for a worker on-site is 100 mrem in a year, which is equivalent to the Nuclear Regulatory Commission (NRC) acceptable exposure limit for members of the public from licensed operations. This limit is broadly applicable to all ionizing radiation exposures in the Air Force – machine-generated or radioactive material, based on Air Force Instruction 48-148. In application of this limit to exposure of workers at the BOMARC site, it is important to understand that the exposure is under conditions of institutional control, where workers exposed below the criterion would be categorized as non-radiation workers and those with potential for exposures above as occupationally-exposed “radiation” workers.

The other cases are for a 4 mrem annual exposure, with the first limited to 4 mrem dose equivalent in the first year, and the second limited to a 30-year average of 4 mrem/yr. The distinction between the two is important for a WGP as a surface contaminant. The only appreciable exposure routes are inhalation and ingestion (Table D-2), which assumes a fraction of the contaminant is in a loose (removable) form. Air suspension of the contaminant in an unclosed system, like a shelter, allows for a slow depletion of the source. With RESRAD-Build default parameters applied to this case, the modeled 30-year dose-equivalent is 2 % of that of the first year. Under a lifetime integrated risk approach of CERCLA, average risk is more important than a very low increment of annual risk. Overall, the difference between them is a factor of two (2).

Table D-3 contains the parameters used for the RESRAD-Build modeling. Many of them are default parameters used in the code; some are specific to structures, like floor area and height, and others more specific to the expected future uses. For example, 192 h/y indoor fraction is deemed to be overly conservative for any conceivable future use of the shelters. As well, air exchange for the structure, 0.1/h, is on the minimum end for residential structures, with actual air exchanges much higher, as the structures were not designed to control air flow. The fraction released to the air, the air suspendable fraction, was assumed to be 0.1. This is overly conservative compared to the

RESRAD-Build cited value for oxidized plutonium of 0.001 (Yu *et al.* 2003). Another conservative assumption made in the model was the chemical form, FGR 11 Class W for inhalation and Class D for ingestion. As already discussed, due to the high temperature and highly oxidizing conditions existing during the accident, PuO_2 was the predominant form produced and still residual today. Table D-4 contains area factors for various elevated measurement comparison area (EMC) sizes and associated total α-radiation surface concentrations. Since the modeling code assumes complete mixing of the contaminant, regardless of the source area, acceptable surface concentrations are inversely proportional to the area. This is generally the case for surface contaminants that provide the vast majority of dose through internal exposure routes rather than external. Figure D-2 contains an example grid system for use during shelter scoping surveys. The grid was designed around existing facility features, with individual grid areas about two square meters and over 60 in number.

5.3 Bulk Contamination. Figure D-1 contains a plot of $^{239+240}$Pu surface concentrations vs. the averaging thickness of concrete. Under this approach, an assumption is made that with the release of surface contamination from the concrete (as a recycled material) there will be an accompanying degradation and a bulk release of concrete from surfaces. An alternate approach in meeting RI/FS-specified average soil concentrations of 8 pCi/g $^{239+240}$Pu for recycled concrete is effectively achieved by an inherent mixing with uncontaminated soil. The bulk thickness of clean mix is dictated by the surface concentration of Figure D-1. Under this scenario, bulk release of concrete from the surface is not a required assumption. For contaminated concrete recycled and used on site for base fill applications, this criterion is expected to be easily met for surface contamination levels in remaining shelters, as documented in the RI/FS (Earth Tech 1992).

5.4 Survey Findings for Remedial Actions Conducted in 2007 - 2009.

Surveys were conducted by AFIOH/SDR and HQ AFSC during the summer of 2007 (Rademacher *et al.* 2009). The surveys consisted of FIDLER screens of all missile shelter floors, and other select buildings that were in the vicinity of residual contamination identified and removed from secondary areas. Figure D-3 contains a photograph of shelter 208, an intact BOMARC Model A Missile Shelter, while Figure D-4 contains a photograph of shelter 202 that had its upper structure removed during the 2002 – 2004 remediation. Table D-5 contains a listing of shelters and other buildings with FIDLER screens. Figure D-5 contains a layout of shelters and other building in the missile area by number. Figure D-6 has detail on building in the non-missile area. Ten of the eleven shelters in close proximity to the location of former shelter 204 were investigated to greater degree with in-situ fixed and scanning α-radiation measurements, and wipe samples to assess removable contamination. Prior to the detailed measurements, the floors of the shelters were swept to remove dirt and other debris that would limit the effectiveness of the survey method. The dirt and debris were analyzed for radiological contamination. For shelters with evidence of high-activity discrete particles, removals were attempted prior to sweeping.

Table D-6 contains a summary of remarkable findings from FIDLER screens. Beyond those shelters in the vicinity of the former 204, only shelters 121, 123, 124, and 126 had some indication of possible impact, however upon more detailed evaluation, discrete particles could not be confirmed, nor could significant contamination be confirmed by in-situ α-radiation or wipe samples. For debris samples collected at suspect locations in the shelters, calculated $^{239+240}$Pu concentrations were below 8 pCi/g, with the highest being 6.2 pCi/g in shelter 123. For the shelters in the vicinity of the former

204, a number had high-activity discrete particles evidenced from the FIDLER surveys. From Table D-6, most were loose and easily removed, while some required a light abrasive treatment and others rotary hammer drill treatments to aid removal. For the latter, it was necessary primarily due to particles trapped in cracks in the floor of shelter 210. Based on the combination of field and a few laboratory measurements, the discrete particles identified and removed ranged from about 28 to 500 nCi.

Table D-7 contains a summary of debris γ-spectroscopy sampling findings. Gray-highlighted cells are for samples with $^{239+240}$Pu activity concentrations greater than the $DCGL_w$ of 8 pCi/g. The concentrations ranged from below the decision level for the method to 112.5 pCi/g. In general, the concentrations were greatest in those shelters with close proximity and lower for other at greater distance, with the highest in rank order: 208 (112.5 pCi/g), 209 (78.0 pCi/g), 203 (55.1 pCi/g), 205 (44.5 pCi/g), and 210 (33.0 pCi/g). Figure 5-1 provides a diagram of these shelters and respective concentrations from Table D-7. These concentrations would be somewhat different if discrete particle removals had been included. For example, in shelter 205, the debris contained 210 nCi $^{239+240}$Pu, while the discrete particle removed prior to sweeping and sampling had an estimated activity of 290 nCi, 58 % of the total debris activity. Only one of the equipment rooms, shelter 203, had debris greater than 8 pCi/g. While floor debris was removed during survey preparation, the total activity compared to the soils criterion was considerably lower than the acceptable elevated measurement comparison for a 1 m^2 land area containing soil. Subsequently, if removed and added to soils adjacent to shelters under a demolition scenario, the radiological risks would be low.

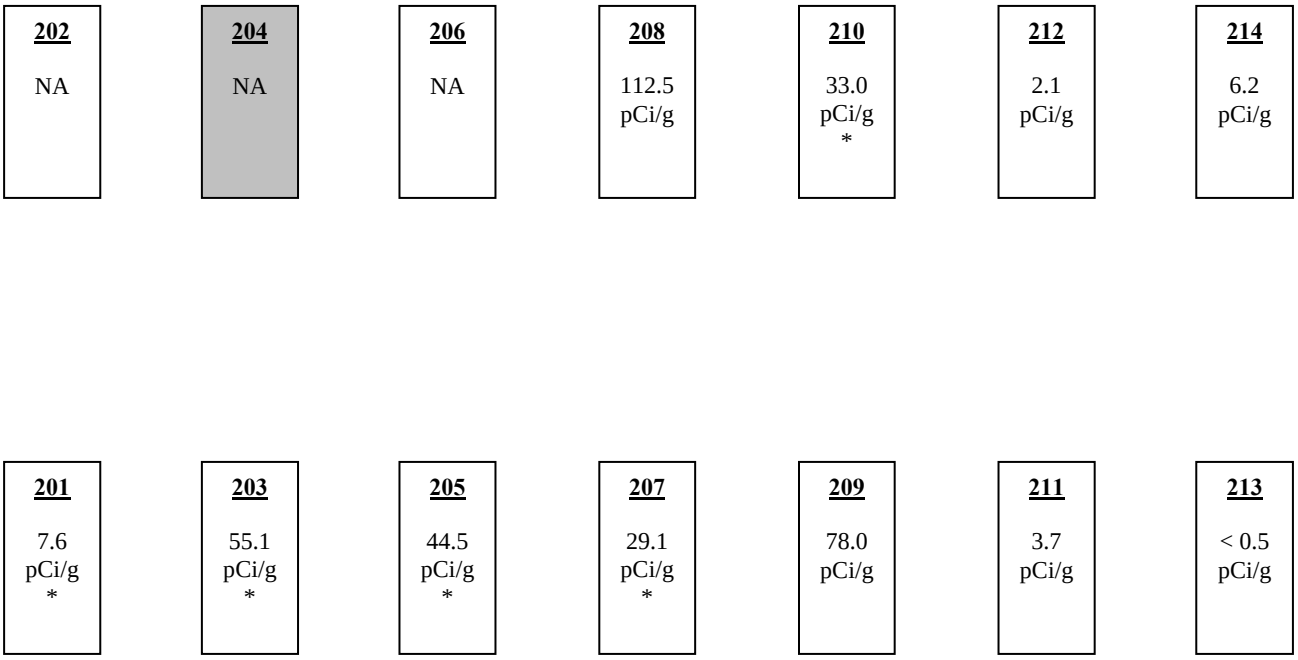

Figure 5-1. Shelter Configuration with $^{239+240}$Pu Activity Concentrations in Floor Debris of Main Shelters from First Debris Removal During 2007 Survey; [* Not Including Discrete Particles Removed, Data from Rademacher *et al.* (2009)].

Table D-8 contains a summary of data from gridded fixed α-radiation measurements, scanning FIDLER measurements, and wipes. The key data in the table are the summary statistics for the static in-situ α-radiation and wipe samples, which are comparable to the release criterion. Among the static measurements, the highest was 82 cpm (shelter 209). Shelter 210 had the greatest degree of residual contamination among the ten evaluated. Further, regression analysis of fixed α-radiation measurements and paired wipes (see Figure D-7) indicated that the best estimate of the removable fraction was 2.4 %, over one-fourth lower than the default used in RESRAD-Build. Table D-9 contains a more refined summary of this data with respect to remedial action criteria developed with RESRAD-Build and Reg. Guide 1.86. The REDRAD-Build criteria were modified to accommodate the removable fraction, 2.4 %, as estimated during the survey. With this, residual contamination in the floors met the RESRAD-Build criterion using 4 mrem in year dose criterion and 100 % occupancy, the least restrictive use modeled for occupational use. The average net surface α-radiation concentration on the floor of shelter 210 was 31 dpm/100 cm^2, about one-seventh the 210 dpm/100 cm^2 criterion. The State of New Jersey requested that a residential use be evaluated against N.J. Administrative Code (NJAC) 7:29, which specifies a 15 mrem in a year dose-equivalent limit. Appropriate criteria for this dose limit are simply scaled from the 4 mrem in a year limit, using an 8,760 hour versus 2,000 hour occupancy for occupational use. All evaluated shelters have an average surface concentration well below the criteria, 181 dpm/100 cm^2 (2.4 % removable fraction).

Among the 900 fixed in-situ measurements collected on the grids, only one exceeded the 300 dpm/100 cm^2 "maximum" criterion of Reg. Guide 1.86, while only one of the 450 paired wipe samples collected on the sampling grids exceeded the 20 dpm/100 cm^2 removable contamination criteria. Overall, from review of the fixed grid, Reg. Guide 1.86 criteria were met for average concentrations on the floors.

Scanning α-radiation measurements identified a few additional areas not originally identified by FIDLER screens. Two shelters, 203 and 209, had additional areas identified by scanning measurements. The area in shelter 203 was about the size of a boot heel, while that in shelter 209 was about one square foot. While the maximum in-situ α-radiation count rate among the two was 181 cpm, neither area had a significant impact on the average fixed contamination levels for the shelters. Though not required, both areas were remediated with the rotary hammer based on the as low as is reasonably achievable (ALARA) principle.

5.5 Remedial Actions on Launcher Pits Conducted by Cabrera in 2008 - 2009. AFIOH/SDR and HQ AFSC recommended ALARA removal of debris from the launcher pits of 11 shelters in the vicinity of the former shelter 204. These pits were omitted from a hydraulic fluid removal operation in the mid-1990s due to concern for low-level radiological contamination.

5.6 Conclusions. The missile shelters had varying degrees of radiological impact dependent on proximity to the former location of shelter 204. The majority of residual contamination in impacted shelters was removed by a sweeping and in a few cases a rotary hammer. Surveys indicated residual contamination was significantly lower than the criterion established for expected future use as temporary storage, and acceptable for on-site demolition, with residuals in concrete meeting the acceptable soils criterion of 8 pCi/g $^{239+240}Pu$. Other future uses could be modeled and compared to residual concentrations. Due to the low residual concentrations, other uses are acceptable without radiological controls.

6.0 Launcher Pits.

6.1 General. The 200-series shelters contain a pit supporting the launcher hydraulic system, with an extension into the equipment room. Pipes traverse between the two areas, but a brick wall and pipe sealant prevents the transport of water and debris between the two areas. Because equipment rooms were better enclosed than launcher rooms, there was a lower potential for contamination in these than the latter. Contamination entering the pits was likely transferred from adjacent floor surfaces. Unless purposely removed, there is no reasonable natural mechanism for removal, contrary to that of floors which are affected by wind and foot traffic. Due to the general deterioration of shelter roofs, water intrusions occur during precipitation events in some of the shelters. Dependent on the amount of precipitation and evaporation rates, it is common to observe standing water in some of the pits. As well, some leakage of hydraulic fluids has occurred. When this occurred in wet pits, the hydraulic fluid formed a thin film on the water surface.

6.2 2009 Hydraulic Fluid Removals. Under sub-contract to Cabrera Services, Inc., Clean Harbors removed liquids from the pits between December 2008 and May 2009 (Cabrera 2009). The conditions of pits were highly varied. Figure E-1 contains a photograph of a launcher pit with large volumes of water that required pumping to allow access to pipes for removal of hydraulic fluid. All fluids pumped from the pits had the separation of oil and water phases (if applicable) and the filtration of particulates with physical dimensions larger than 5 microns (μm) by the equipment set-up shown in Figure E-2. Table E-1 contains a summary of pit conditions from the 2009 hydraulic fluid removal activity. More than half the pits were impacted by some water intrusion, with four having the addition of hydraulic fluid. Because shelters 202 and 206 only have residual slabs, pits were filled with water, but frozen over in the winter months. Most pits with standing water had water analyses. Many of the initial samples analyzed by γ-spectroscopy, which is sensitive to emissions from ^{241}Am, did not have adequate sensitivity, so they required isotopic plutonium analysis by α-spectroscopy. Results of the analyses are summarized on a column in Table E-1. All of the results were below the 15 pCi/L limit for ^{241}Am and $^{239+240}$Pu specified in the Safe Drinking Water Act (Federal Register 2000). [Note: as a comparison, the NRC effluent release limit for these isotopes is 20 pCi/L in water (NRC 2009)]. Sediment samples were collected from a number of the dry pit bottoms, composites of shelter floor debris, and composites of waste sediments removed from pits. All of the sediment and solid waste samples had $^{239+240}$Pu activity concentrations below 8 pCi/g, as summarized in Table E-1. The highest result, 6.2 pCi/g, was reported for sediment samples in pits of shelters 201 and 202. Similar to findings from sediments on floors and residual surface activity concentrations reported for shelter surveys, sediments in the launchers pits of shelters 211, 212, and 213 had the lowest $^{239+240}$Pu activity concentrations among this group of shelters. This is logical because of a greater distance from the pattern of plutonium contamination in soils. Volumes of water and hydraulic fluids pumped from the pits and hydraulic systems are listed in Table E-1. The largest volumes of water were removed from the pits of shelters 202 and 206. A total of 800 gallons of hydraulic fluid were transferred LORCO, Inc. for recycling at McGuire AFB (Cabrera 2009); specific amounts for some shelter hydraulic systems were not recorded.

6.3 HQ AFSC and USAFSAM Surveys. HQ AFSC and USAFSAM conducted fixed α-radiation measurements, wipes to assess removable contamination, and FIDLER screening scanning measurements in the launcher pits of shelters with the greatest potential for contamination (Rademacher *et al.* 2009). The surveys were conducted in March 2009, after the pumping of water

from most launcher pits, but prior to power-spray cleaning intended and completed by Clean Harbors in May 2009. Table E-2 contains a summary of the α-radiation measurements. Among the launcher pits in the six shelters targeted for survey, the pit in 210 had the highest average fixed α-contamination level, 12.5 counts per minute (cpm), which was dominated by a single measurement. The other shelters were significantly lower. The highest removable α-radiation concentration was 6.4 dpm/100 cm^2 and located in the pit of shelter 209. The vast majority of wipe samples were below the detection level of the method, 1.5 dpm/100 cm^2. Overall, contamination levels in the pits were lower than that of associated floors in these shelters. FIDLER surveys had unremarkable findings. Under ALARA, minor remedial actions were conducted at two locations of elevated contamination in the pit of shelter 210. Figure E-3 contains a mapping of measurements from the shelter 210 launcher pit.

6.4 Power-Spray Cleaning of Launcher Pits. In May 2009, launcher pits were power-sprayed with a citrus-based cleaner, and the assistance of brush cleaning in areas having more stubbornly-attached debris. The debris and cleaning solution in the pits and removed was pumped, filtered, and sampled, and disposed. Cabrera (2009) screened launcher pit floors with FIDLERs and collected and analyzed 10 wipes per pit evaluated. Wipe results are summarized in a column of Table E-1. FIDLER surveys had unremarkable findings.

6.5 Summary. Overall, residual radiological contamination levels in pits were lower than those associated with floors in shelters and well below release criteria established for shelter floor surfaces. Disposal of hydraulic fluids, oil/water mixtures, and filtered debris were made with radiological contaminants being below SDWA acceptable levels for fluids and the soils criterion established in the ROD, 8 pCi/g $^{239+240}Pu$.

7.0 Communication and Power Bunkers.

7.1 General. The RI/FS targeted removal of the communication and power bunkers associated with shelters 202 – 206, because they were contaminated by fire-fighting water used in the accident response. Bunkers at greater distances from shelter 204: 206, 208, to 214 are also progressively at higher grades than shelter 204 which precluded direct water intrusions through manhole covers of bunkers associated with shelters 208 through 214. From surveys of secondary-contaminated areas, described earlier in this document, contamination was translocated to other parts of the site, presumably due to vehicle and foot traffic during accident and after the accident response. Contamination translocated to asphalt surfaces was retained in the surface, or at a later time liberated from the surface allowing translocation to other areas, most notably adjacent soil areas. It was assumed that some may have entered bunkers through the small spaces between manhole cover and their steel bulkhead rims. Because bunkers had steel conduit pipes connecting shelters and the series of bunkers, there was some potential of contaminated water transported between bunkers. However, because the conduit entry points were about halfway up the wall of the bunkers (total height, 6 feet), due to the elevation of the terrain, it was believed that transport of water from the bunkers associated with shelter 206 would have been limited to 208 or 210. Scoping surveys were conducted to investigate the potential for transfer of contaminated water through conduits and surface contamination through manhole covers, and assess the degree of contamination.

7.2 Surveys. Survey measurements on shelter 208 bunkers were conducted by HQ AFSC and AFIOH during 2007, but because the bunkers contained about 22 inches of water, and shelter 210 and 212 bunkers were obstructed by the Cabrera Services, Inc. laboratory and office trailer, it was determined that more assessments should be conducted when the trailers were moved and a water pumping and filtration capability was available during hydraulic fluid removal activities. In 2009, in conjunction with hydraulic fluid removals, water content of shelter 208, 210, and 212 bunkers were pumped and filtered in a similar manner to that of the water from launcher pits, as shown in Figure E-4. Figure E-5 is a photograph of the interior of the shelter 208 power bunker, just after water removal. Clear in the image is the water line, about 22 inches high along the wall, and a thin film of sediment on the bottom. A couple of the bunkers had more sediment. Radiological measurements consisted of gross α-radiation on water, γ-spectroscopy on sediments, fixed and wipe samples on surfaces to assess α-radiation levels, and FIDLER screens to assess areas of high contamination, primarily discrete particles.

7.3 Survey Findings.

Table E-3 contains a summary of radiological data. The second column of the table contains gross α-radiation levels in water samples. As expected, all of the samples are well below the 15 pCi/L limit specified in the SDWA for $^{239+240}$Pu and ^{241}Am. Because the method is not specific to any radionuclide, it includes those in background like α-emitters in the natural uranium and thorium decay chains.

AFIOH and HQ AFSC collected sediments from shelter 208 bunkers in 2007. The sampling of sediment from each bunker was difficult because of the limited amount of sediment, 81 and 57 g, respectively, were collected from the communication and power bunkers. Based on γ-spectroscopy for the ^{241}Am, predicted $^{239+240}$Pu concentrations were < 1.4 and 34.2 pCi/g for the communication and power bunkers, respectively. Both shelters had isolated locations of elevated FIDLER response on the metal flanges on the bunker bulkheads, indicative that some contamination entered the bunker through this route. Cabrera Services, Inc., under contract to Cape (2009), conducted α-radiation measurements, fixed in-situ and wipes on interior surfaces of bunkers. Fixed in-situ measurements were targeted to locations of suspected contamination intrusion points: bulkheads, surfaces along walls in proximity to bulkheads, and below conduit pipe/bunker wall junctions. The range and mean surface concentrations, and sample number are summarized in Table E-3. Among the samples, those on the bulkhead consistently had the highest concentrations. Wall surfaces, including those near the conduit pipe/bunker wall junctions were low, confirming the bulkhead, as the reasonably apparent entry point for contaminated water, rather than conduit pipes connecting the series of bunkers. Average concentrations were progressively lower, in order, from 208, 210, to 212 bunkers. Wipe samples were targeted to floor debris and bulkhead location, with summary results in Table E-3. Among the results, the highest were attributable to debris wipes, with the highest measured concentration 20.9 dpm/100 cm^2. FIDLER screens conducted by Cabrera were unremarkable, except for a discrete particle located and removed from the floor of the shelter 212 communication bunker. Figure E-6 contains a select portion of Figure C-14. Evident from the figure are the vast number of discrete particles identified on the asphalt around shelters 209 – 214. Figure E-7 contains a photograph of the asphalt in the vicinity of the shelter 212 bunker's manhole covers. In the foreground of the image are locations and FIDLER readings of discrete particles located and removed in 2007 during restoration of secondary impacted areas. The finding is reasonable with

respect to the magnitude of the activity of the particle from the shelter 212 bunker, as it is within the range of FIDLER measurements on particles removed from the asphalt pavement. A composite debris sample from the shelter 210 and 212 power and shelter 212 communication bunkers had an 18.4 pCi/g estimated $^{239+240}$Pu activity concentration.

Cabrera Services, Inc. performed fixed, in-situ and wipes of the bulkheads on shelter 216, 218, and 220 bunkers, which are on the opposite site of the main road bisecting the missile area. The measurements were collected for the purpose of establishing background levels on bulkheads that were believed to be un-impacted. Some areas of elevated contamination were identified by fixed, in-situ and wipe measurements, the subject of some discussion in the next section.

7.4 Discussion.

The bunkers are physically small, have no practical occupancy scenario for any future use of the site, and meet the Occupational Safety and Health Administration (OSHA) definition of a confined space [29 CFR §1910.146(b)]. Power and communication bunkers for shelters 208, 210, and 212 had a low degree of impact from radiological contaminants. Though sampling was biased to areas of potentially greater degrees of contamination, average surface α-radiation concentrations were below criteria developed for shelters. Sediment volumes in the shelters were low, but contained $^{239+240}$Pu activity concentrations greater than the 8 pCi/g average concentration acceptable for soils. The same issue existed for small masses of debris removed when the floors of contaminated shelters were swept. In a demolition scenario, debris will reasonably be mixed with concrete debris, and have the potential to be a part of surface soils in a re-use scenario. Areas of elevated contamination are acceptable, based on area and concentration, provided the average for a survey unit des exceed 8 pCi/g and the unity rule (NRC 1997). From Table 3-1, 1 m^2 areas can have $^{239+240}$Pu activity concentrations as high as 73 pCi/g, about four times the composite debris sample from shelter 210 and 212 power and shelter 212 communication bunkers, though with volume a small fraction of that encompassed by a 1 m^2 area, 30 cm thick (300 L).

Of the remaining bunkers, those associated with shelters 208, 210, and 212 have the greatest potential for impact because the locations around the manhole covers for these bunkers had a high density of discrete particles, with some liberation from the surface and translocation to other areas, including the bunkers. In the general vicinity of these impacted asphalt areas are impacted soils, areas 1 and 2 (Figure E-6). Photographs of these areas, post restoration, are in Figures E-8 and E-9. These areas were most likely indirectly impacted by contamination that was initially on adjacent asphalt areas. From Figure E-6, asphalt areas in the vicinity of manhole covers to the bunkers of shelters 216, 218, and 220 had neither identifiable residual discrete particles nor adjacent impacted soil areas. Clearly, because these bulkheads had surface α-radiation contamination, they were impacted to some degree, but not to the same degree as the shelter 208, 210, and 212 bunkers. The bulkheads of shelter 216, 218, and 220 bunkers differed in construction from 208, 210, and 212. The former had a part of the bulkhead constructed from mortar and brick to meet grade requirements, as detailed in Figure E-10. These surfaces aided in retention of contamination to a greater degree than the relatively smooth surface of the completely formed concrete surface possessed by the bulkheads of shelter 208, 210, and 212 bulkheads. Nevertheless, due to the lower degree of contamination potential for shelter 216, 218, and 220 bunkers compared to that of shelter 208, 210, and 212 bunkers, the same conclusions apply for these bunkers.

8.0 Groundwater Quality.

Groundwater monitoring wells on the site have been sampled numerous times with unremarkable findings for $^{239+240}$Pu and ^{241}Am. Residual levels of these contaminants in surface soils are a small fraction of the $DCGL_w$, remediation criterion. For example, in the primary remediated areas, a conservative estimate of the average residual $^{239+240}$Pu was 1.82 pCi/g, less than 25 % of the remediation criterion (see Table B-1). The average residual contamination levels were much lower in class 1 survey units established in the secondary areas.

The modeled groundwater doses from $^{239+240}$Pu and ^{241}Am were very low for the time periods considered (Figures 2-1 and -2). For time periods greater than a few hundred years, it was effectively the only source, but more than four orders of magnitude lower than the projected dose at the remediation criterion. In the RESRAD modeling (Earth Tech 1992), the $^{239+240}$Pu and ^{241}Am soil solid/aqueous phase partition coefficients, K_d, used were based on site-specific values rather than default ones. As well, leach rates were set to zero, rather than the RESRAD defaults to force more surface retention, though default leach rates are 4.4×10^{-5} and 2.2×10^{-3} per year, respectively for $^{239+240}$Pu and ^{241}Am.

The Environmental Protection Agency cautions against using sorption measurements resulting in very high K_d values because they may have been affected by plutonium and americium precipitation reactions (EPA 1999 & 2004). To evaluate groundwater in a more conservative manner, low K_d values are more appropriate. For ^{241}Am, one author has suggested 4 cm^3/g (EPA 2004), as compared to the value of 400 cm^3/g used in the RI/FS. While for $^{239+240}$Pu, 20,000 cm^3/g was used in the RI/FS and 80 was the lower value among many sites evaluated by Glover *et al.* (1976). RESRAD modeling with these values would have greatly increased groundwater-dependent pathway doses, but not to a degree impacting the adherence to the 4 mrem/yr annual dose limit target of the restoration.

Colloid-facilitated transport of radiological contaminants has been of increased interest for sites containing radiological contaminants (EPA 1999b). Two DOE sites with $^{239+240}$Pu and ^{241}Am in waste burial pits had predicted transports of contaminants less than 10 meters (m) through groundwater, but were identified in groundwater over 1,000 m down gradient from the sites (EPA 2004). Some important distinction between these two sites and the BOMARC exist. First, the BOMARC has very low residual contamination levels compared to the other sites. Second, colloids of clay and humic (organic) acids are important to this transport process (EPA 2004), while the soils at the BOMARC (top 50 feet) are primary quartz sand, with little clay, silt, or peat (Earth Tech 1992). The EPA notes that little information is available on colloidal transport occurrence, its potential in other mineralogical conditions, the physicochemical properties of the transport process, or the conditions conducive to the generation of mobile colloids. However, due to:

1) the relatively low residual concentrations in surface soils and the 50 foot average depth to the aquifer at the site,

2) the fact that recent monitoring well samples (2000) were unremarkable for $^{239+240}$Pu and ^{241}Am with the 1960 post-accident plutonium and americium source terms intact, and

3) the current residual contamination is estimated to be less than 0.1 % of the 1960 estimated source term,

the mechanism of transport, while viable, is expected to provide an insignificant contribution to hypothetical doses to future site residents using on-site groundwater.

In summary, groundwater monitoring to assess impacts from residual $^{239+240}$Pu and ^{241}Am is not deemed necessary.

9.0 Five-Year Review. The draft Defense Environmental Restoration Program Manual discusses requirements for five year reviews (DoD 2008). Per the manual, "Sites where the response actions under the IRP or MMRP categories allow for unlimited and unrestricted exposure upon completion of the action do not require such reviews," provided the decision document under the provisions of CERCLA does not restrict the use of the property. It is important to note that a decision document generated for this CERCLA action does not itself allow unrestricted use or access, as other hazards currently exist at the site and the Air Force has not determined a future use. There are no current technical reasons to conduct a five year review for the radiological contaminants released by the 1960 BOMARC missile accident and follow-on actions.

10.0 Conclusions.

The Air Force signed a ROD under CERCLA for radioactive contaminants released from a fire in a nuclear-tipped, liquid-fueled BOMARC missile. The primary radioactive contaminants were $^{239+240}$Pu and ^{241}Am. Isotopes of uranium were also released during accident, but at an activity almost 500-fold lower than the $^{239+240}$Pu. The Air Force completed the preferred option specified in the ROD, which was removal of soils with $^{239+240}$Pu activity concentrations greater than 8 pCi/g and these structures: shelter 204 (which was extensively damaged and contaminated during the accident), the communication and power bunkers associated with shelter 204, the launcher from shelter 204 (if located), and contaminated asphalt and concrete from the pad and ditch. Due to the soil excavation and associated shoring requirements, the upper portions of shelters 202 and 206 and their associated bunkers were removed.

The primary remedial actions were conducted between 2002 and 2004, and accounted for the largest amount of radioactivity and debris removed from the site, with the exception of weapons debris removed shortly after the accident (see Table 10-1). The greatest amount of debris and contamination was removed from area between shelters 201 – 205 and 202 - 206, as shown in Figure 10-1, and the drainage ditch in Figure 10-2. Considerably smaller volumes and amounts of radioactive material were removed during additional investigations in 2006 and remediation of secondary impacted areas and shelters in 2007. Example photographs of these types of areas are shown in Figures 10-3 and -4. Over the 42 years between the accident and restoration, unquantified volumes of contaminated soils were removed for analysis. As such, some wastes were disposed under separate actions, while some was retained on-site and disposed with debris during either the primary and secondary restoration actions. The launcher was never located during any investigation or remedial actions, but it is unlikely to have been buried on the site. Final status surveys conducted

on soil and road areas during remediation of the primary and secondary impacted areas concluded that residual contamination was well below the 8 pCi/g criterion established in the ROD. Though

TABLE 10-1. Primary Radioactive Contamination Removal Operations on BOMARC.

Action	Type of Waste Stream	Estimated Volume (yd^3)	Estimated $^{239+240}Pu$ Mass (g)	Estimated $^{239+240}Pu$ Activity (Ci)
Accident Response (1960)	Weapon Debris	Unknown	Classified	Classified
Remediation of Primary Impacted Areas (2002 – 2004)	Concrete, Metal, & Asphalt Debris; Soils	22,329	300	21.9
Discrete Particle Removal in Secondary Areas (2006)	Soils	< 1	0.22	0.0159
Remediation of Secondary Impacted Areas (2007)	Asphalt & Soils	64	0.026	0.0019
Shelters Surveys (2007 – 2009)	Floor Debris	< 0.5	Negligible	Negligible
Hydraulic Fluid Removal and Pit Debris Removal (2008)	Water, Sediment	< 0.5*	Negligible	Negligible
Bunker Investigation (2009)	Water, Sediment	< 0.5*	Negligible	Negligible

* Excludes liquid volumes.

Figure 10-1. Primary Excavation Area between Shelters 201 – 205 and 202 – 206 (Duratek 2006).

Figure 10-2. Restored Drainage Ditch Area.

not specified in the ROD, final status surveys, risk-based area factors, and other principles of MARSSIM were applied upon agreement between the State of New Jersey and Air Force. Uranium concentrations in final status soil samples from both phases of restoration activities were unremarkable, attributable only to uranium that is naturally-occurring in soils.

Figure 10-3. Area Surrounding Concrete Pad Outside Restroom in Building 159, within Missile Area.

Figure 10-4. Restoration of Contaminated Soil, along Road.

Surveys of shelters and other targeted structures were conducted in 2007 by HQ AFSC and AFIOH. Risk-based criteria were developed for use scenarios similar to the shelter uses over the 27 years since closure. Surveys identified residual contamination on floors in a few shelters in proximity the former location of shelter 204. The majority of contamination was removed by floor sweeping actions. Among the ten shelters with extensive floor surveys, only four had residual contamination readily differentiable from background radiological conditions. All shelters were well below the residual contamination levels deemed acceptable for future uses, even for a 100 % occupancy of an occupationally-exposed individual or a member of the public in a residential scenario using the criterion from N.J.A.C. 7:29. The shelters met Reg. Guide 1.86, under reasonable interpretation of its criterion. In a demolition scenario, on-site re-use of concrete as fill rubble from impacted shelters is acceptable.

Underground power and communication bunkers have a low degree of radiological impacts, but are acceptable for unrestricted release. Future uses of the site may allow the bunkers to remain in-place. If excavation of areas with bunkers is necessary, demolition and re-use of concrete is a likely and an acceptable disposition option.

Radiological survey data collected over the years has demonstrated that a significant fraction of the plutonium contaminant is heterogeneously distributed over the site, and was evident in recent evaluations of final status soil samples. As such, the plutonium has significantly lower solubility than modeled in the development of acceptable remediation standards for soils and on surfaces in habitable structures, and subsequently a lower risk for adverse health effects for future site occupants.

No additional survey work or controls are necessary for residual radioactive materials on the site, though other hazards on the site require access controls. The ROD preferred actions are complete. Under the DoD RMIS, response complete (RC) action and site closeout are recommended. Since neither a technical basis for a five year review exists nor was recommended in the ROD, a five year review described in the CERCLA process is not required.

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Appendix A

Site Maps and Historical Data

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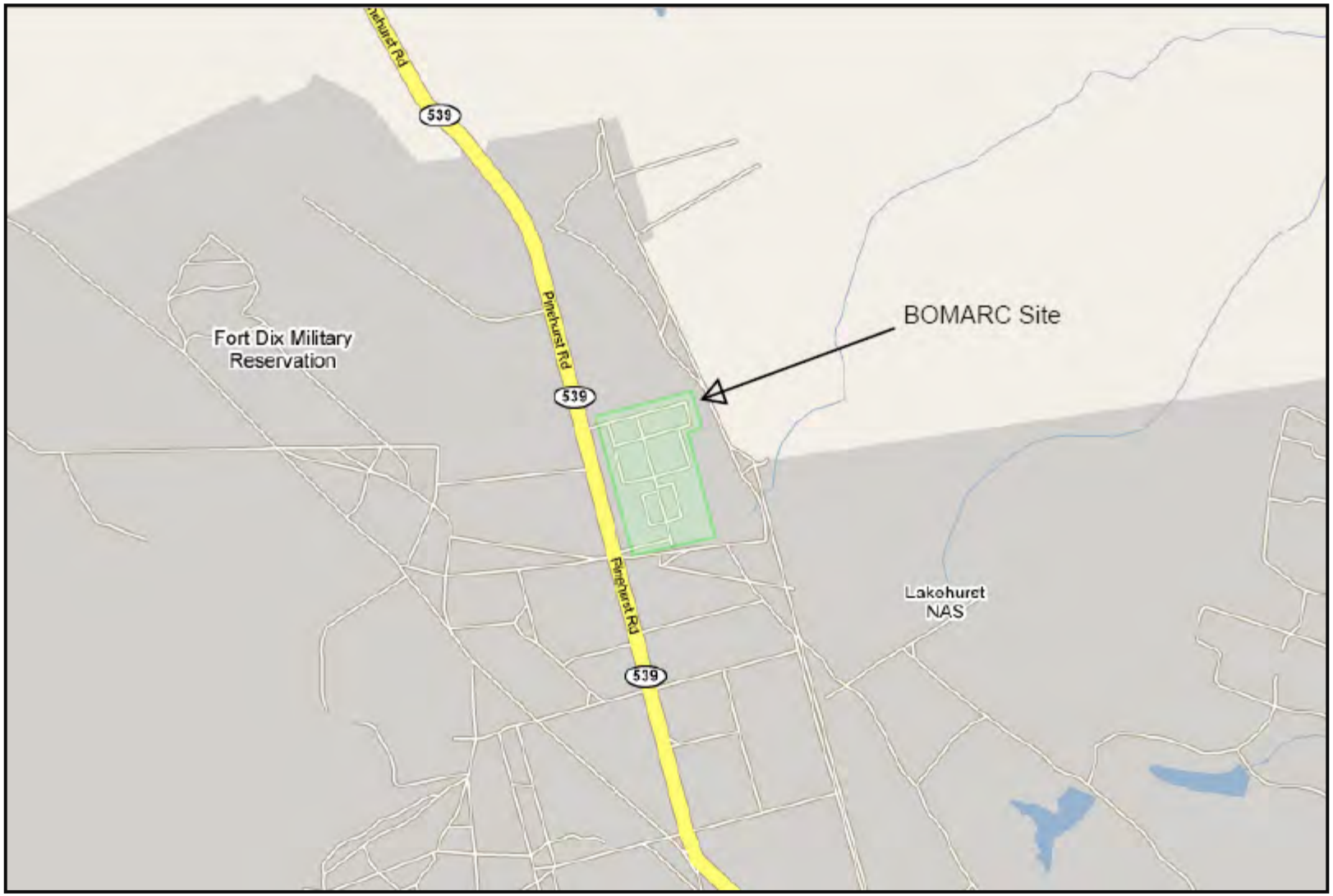

Figure A-1. Location of Site.

Figure A-2. Aerial Photograph of the BOMARC Site.

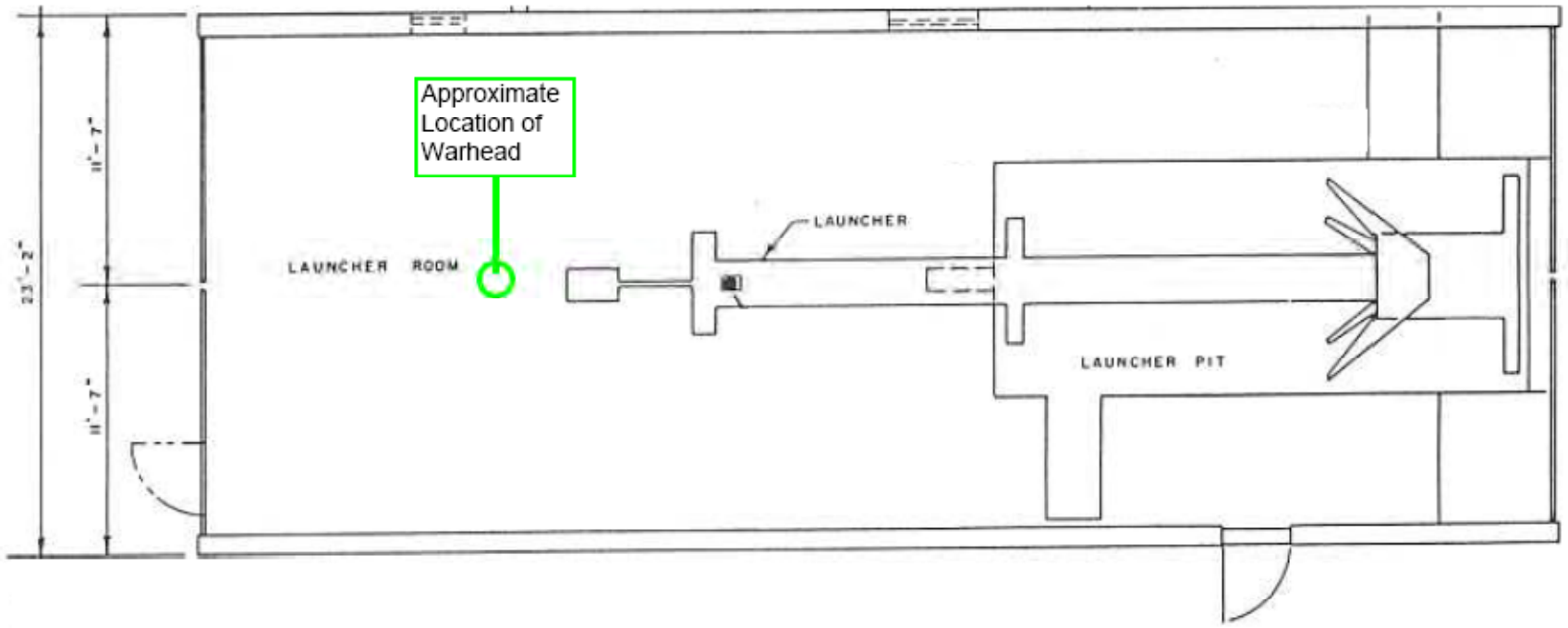

Figure A-3. Dimensions of Shelter Showing Simple Detail of Launcher Pit, Launcher, and Warhead Locations.

Figure A-4. Aerial Photograph of the BOMARC Site Indicating Areas Where Concrete and Asphalt were Poured.

TABLE A-1. Isotopic Composition of WGP in BOMARC Weapon Based on Los Alamos National Laboratory Estimates and Soil Analyses for 1958 (Rademacher 2001).

Isotope	Mass Percent	α-Activity Percent	Radiological Half-life (y)
Pu-238	0.0099	2.3	87.74
Pu-239	93.7	80.1	24,110
Pu-240	5.6	17.6	6,560
Pu-241	0.47	Not Applicable	14.35
Pu-242	Negligible	Negligible	376,000

TABLE A-2. Major Radiation Emissions of WGP Constituents (Scheien 1992).

Radionuclide	α-Particle Energies (MeV) & Frequency	β-Particle Energies (MeV) & Frequency	Photon Energies (MeV) & Frequency
Pu-239	5.155 (0.733) 5.143 (0.151) 5.105 (0.115)	None	0.113 (0.0005) 0.014 (0.044)
Pu-240	5.168 (0.735) 5.123 (0.264)	None	0.054 (0.0005) 0.014 (0.11)
Pu-241	None	0.021 (1.00)	None
Am-241	5.486 (0.852) 5.443 (0.128) 5.388 (0.014)	None	0.014 (0.427) 0.0595 (0.359) 0.026 (0.024)

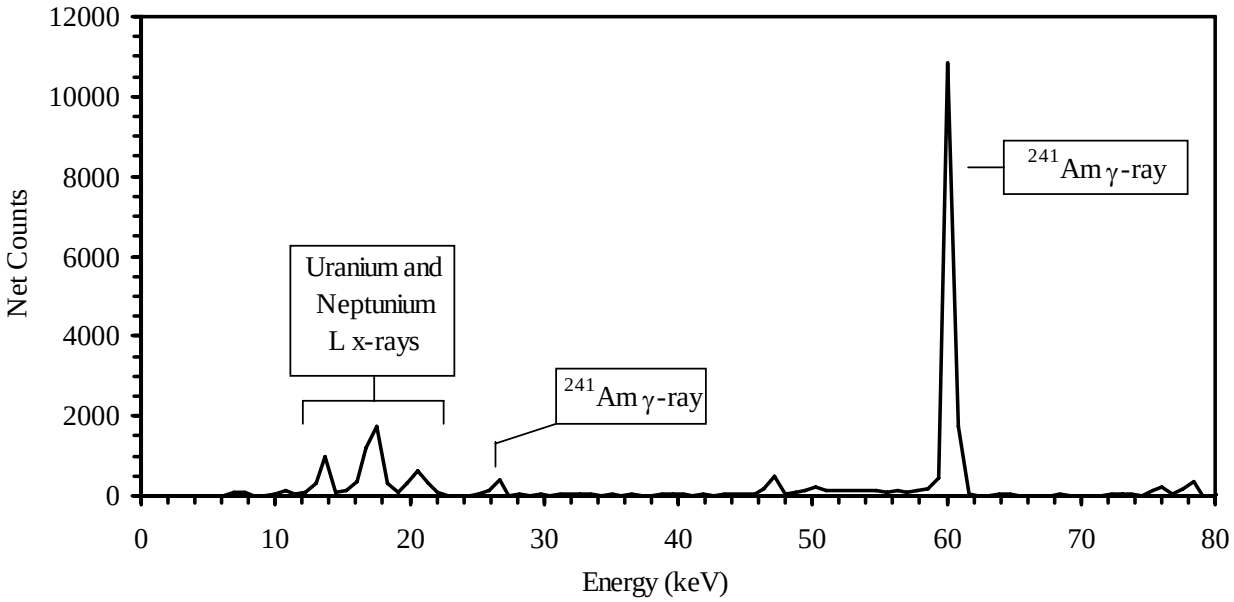

Figure A-5. Low-Energy Germanium Spectra for Discrete Particle Removed from a Shelter (Favret 2007).

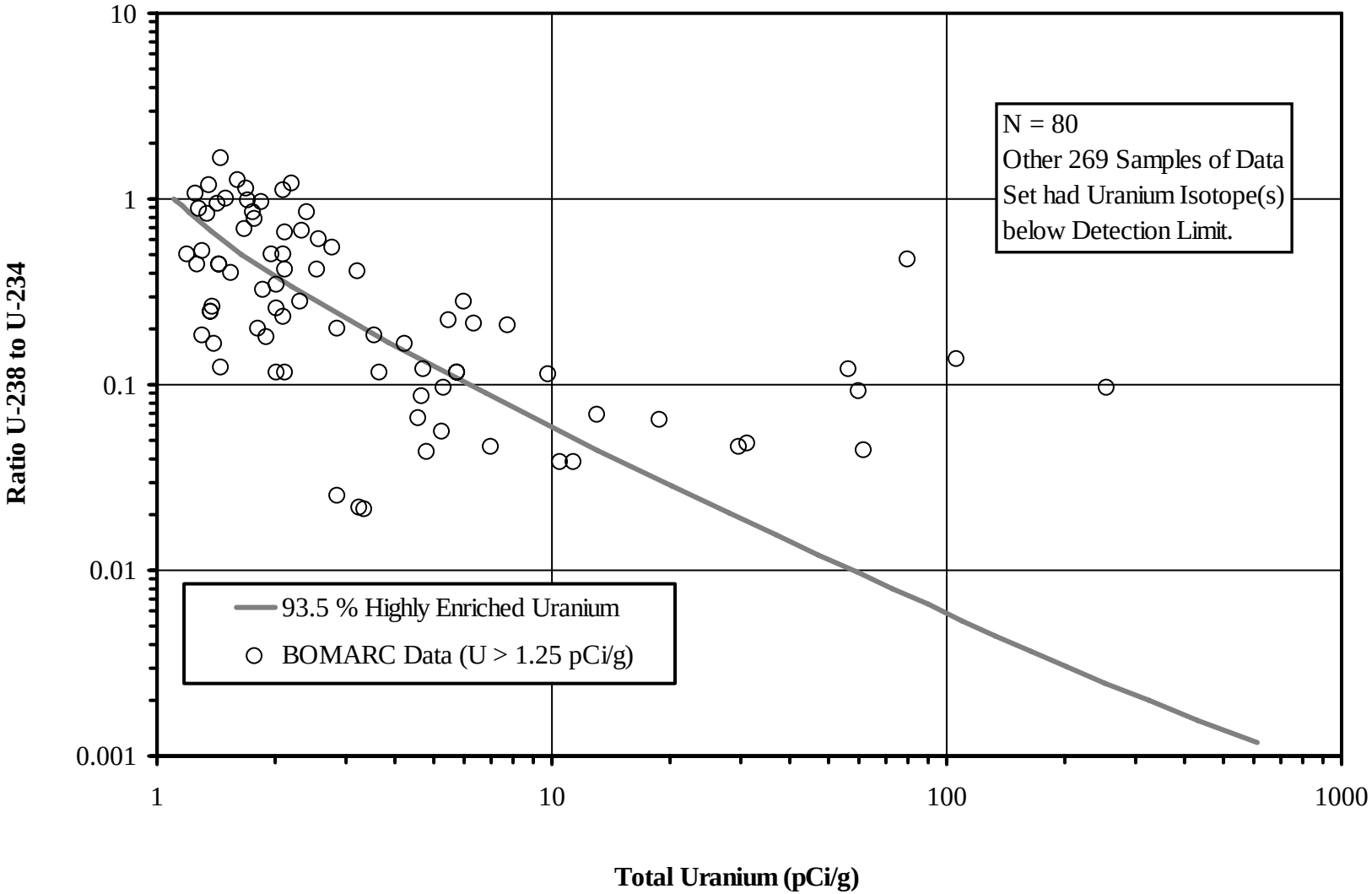

Figure A-6. ^{238}U to ^{234}U Ratios for Various Total Uranium Concentrations (Background = 1.1 pCi/g) Enriched Uranium Contaminant at BOMARC [Data from 1997 OHM Remediation] (Rademacher 2001).

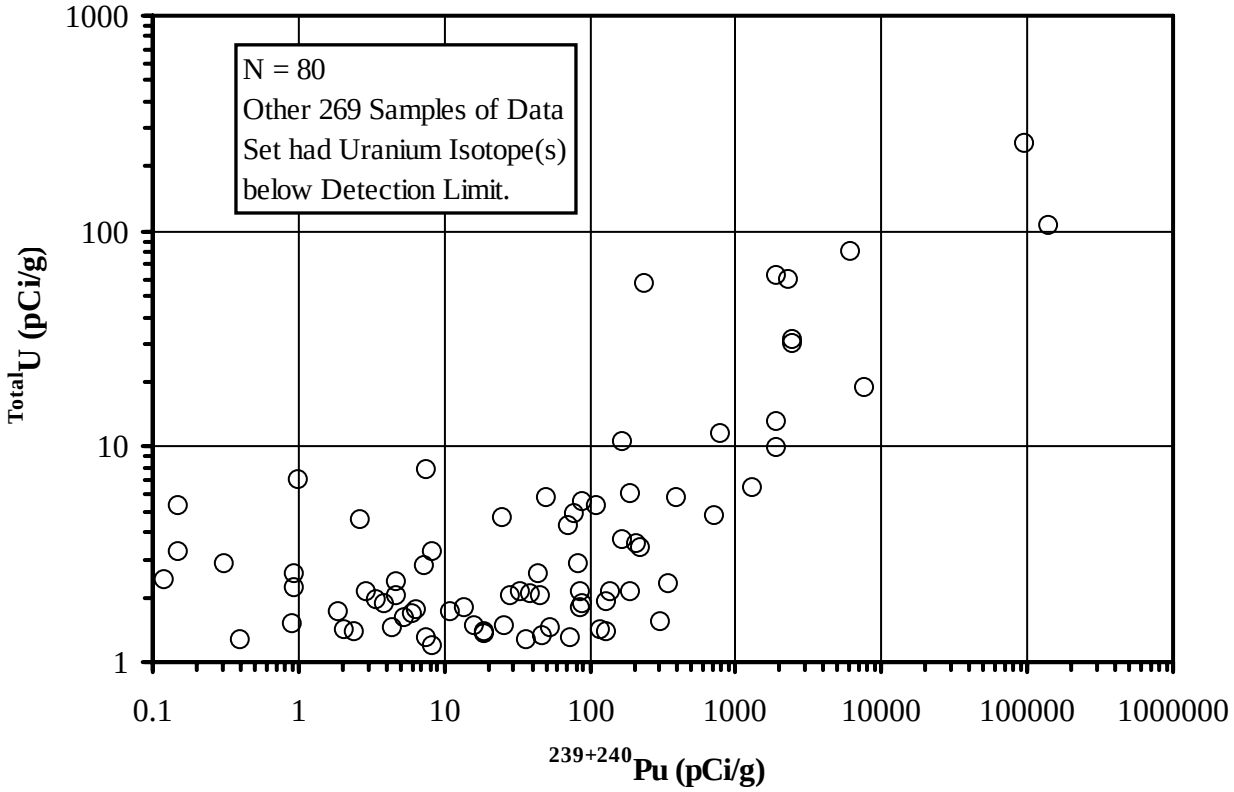

Figure A-7. Alpha Spectroscopy Data from 1997 Characterization (OHM 1998).

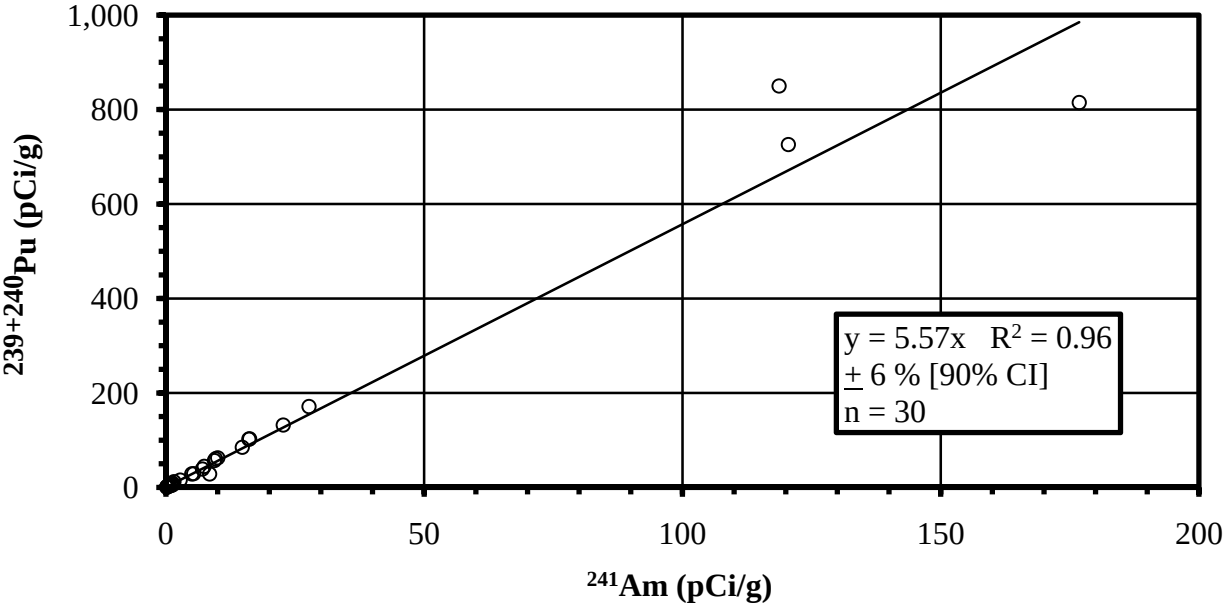

Figure A-8. $^{239+240}$Pu vs. ^{241}Am α-Spectroscopy [Data from Duratek (2006)].

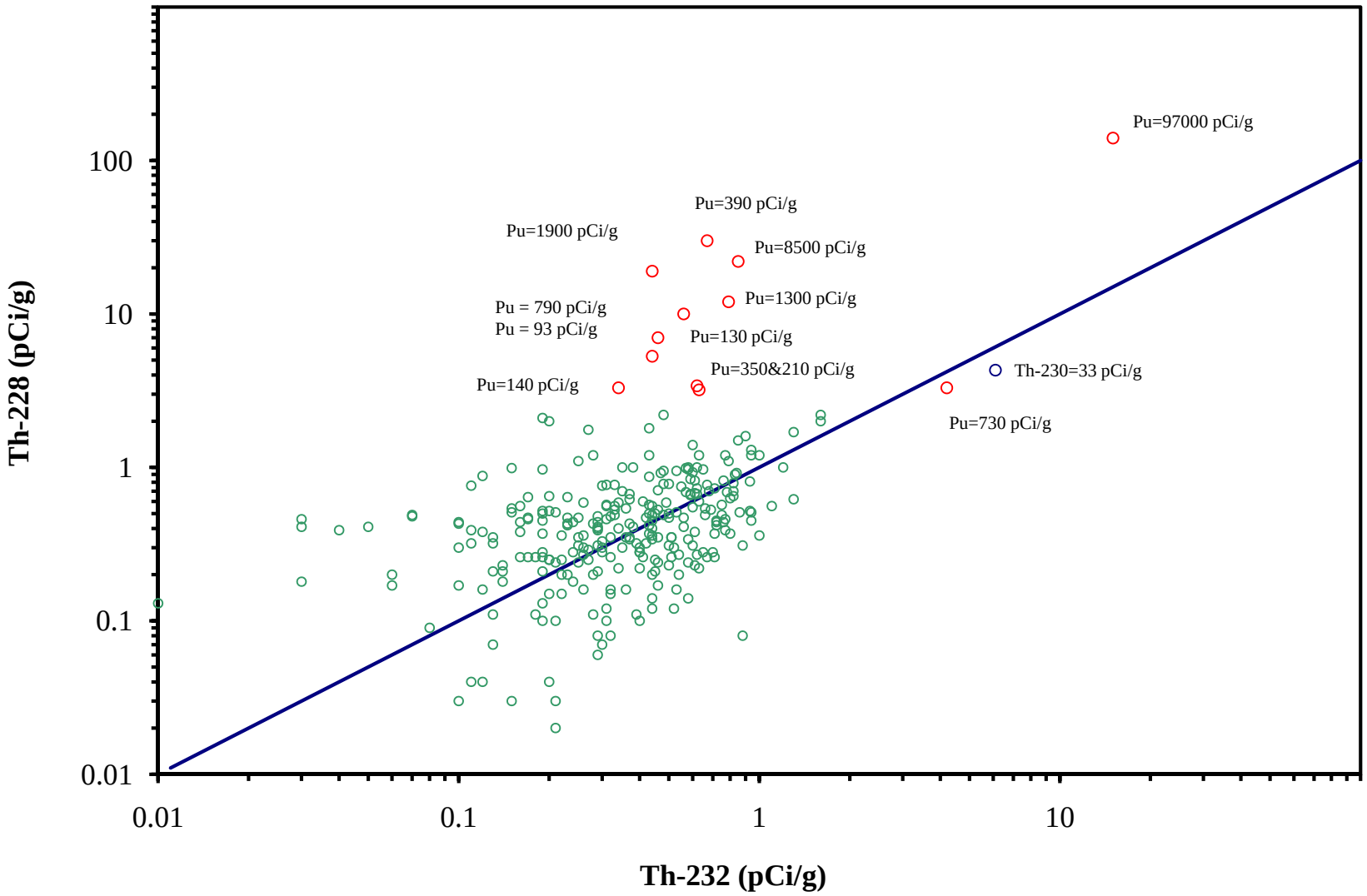

Figure A-9. ^{228}Th vs. ^{232}Th Concentrations for Samples Analyzed during the 1997 OHM Characterization Study [Atch 2, Rademacher (1999c)].

TABLE A-3. Summary of Long-Term Post Accident Monitoring
[Portions Excerpted from Cabrera (2008)].

Year	Type	Organization	Result
1966	Investigation	Air Force Radiological Health Laboratory, Wright-Patterson AFB (Taschner 1967)	Elevated Pu in soil along drainage ditch and around manholes at Shelter 204; localized "hot spot" in southwest corner of facility
1970, 1971, 1973	Radiological surveys	Air Force Radiological Health Laboratory, Wright-Patterson AFB (Kush and Case 1971, Kush and Case 1971, Kush and Case 1971, Case and Reed 1973)	Majority of site contamination contained under concrete pad near Shelter 204; some contamination in drainage ditch; Pu levels generally 10-30 micrograms per square meter ($\mu g/m^2$) outside exclusion fence; Pu in grassy-sandy areas adjacent to Shelters 201-208 with the majority confined to the upper 6 to 8 inches of soil; some originally deposited Pu was being dislodged and brought to the surface at joints in the concrete pad
1972	Radiological survey	U.S. Army Environmental Health Laboratory (USAEHL, 1972)	No detectable airborne radioactive material; no contamination of the water in the wells; detectable levels of radioactivity in the water from manhole at Shelter 202; no detectable removable/transferable radioactive material inside Shelters 203 and 204; at least 85 percent radioactivity in the upper 2 in of soil; at least 9 acres onsite and within 0.5 kilometer from the perimeter fence contained detectable levels of radioactive contamination
1973	Aerial radiation survey	EG&G (EG&G 1974)	Detected concentrations of ^{241}Am at levels of 0.04 $\mu g/m^2$ within 200-foot radius of Shelter 204; 60 kiloelectron volt (keV) gamma ray from ^{241}Am was used to detect Pu levels; elevated concentrations identified in a small area approximately 1400 ft from Shelter 204
1975	Radiological survey	Air Force Radiological Health Laboratory, Wright-Patterson AFB (Case & Reed 1975)	Unexpected elevated levels of Pu far removed from the "highly contaminated area" surrounding Shelter 204; relatively good agreement with previous survey results implied that the Pu was relatively immobile.
1976	Radiological survey	Air Force Radiological Health Laboratory, Wright-Patterson AFB (Case 1976, Case and Crisman 1976)	Findings similar to 1975 survey concerning radioactivity at the site; recommended establishing a controlled area, including Shelters 102, 104, 106, and 201 through 208, to limit access to the areas with the highest levels of surface soil Pu.

TABLE A-3. Summary of Long-Term Post Accident Monitoring (Continued)
[Portions Excerpted from Cabrera (2008)].

Year	Type	Organization	Result
1979, 1980	Radiological survey	USAF Occupational and Environmental Health Laboratory, Brooks AFB TX (Case 1981)	The general condition and extent of plutonium contamination distribution remains essentially unchanged for samples collected in 1975, 1976, and 1978. Offsite, measureable levels of plutonium continue to be found on both side of County Hwy 539, primarily in the vicinity of the drainage ditch. Some discrepancies between previous sampling results, but are attributable to nonhomogenous distribution.
1982	Radiological survey	U.S. Army Environmental Health Laboratory (USAEHL, 1982)	Soil samples collected along northern and western fence lines and drainage ditch that extends southwesterly from the southern edge of the Model A shelter area to under County Hwy 539; of the 15 soil samples collected only 1 sample exceeded EPA standard of 0.2 microcuries per square meter (uCi/m^2) for Pu.
1985	Radiological survey	USAF Occupational and Environmental Health Laboratory, Brooks AFB TX (Maher 1986)	Found that the Pu was relatively immobile; potable and non-potable water samples did not indicate presence of Pu in groundwater; postulated that runoff from Shelter 204 could transport low levels of Pu into the ditch and across CR539; relatively uniform vertical profiles and annual sampling indicated that Pu was still entering the ditch.
1985	Plume evaluation	USAF Occupational and Environmental Health Laboratory, Brooks AFB TX (Case 1985)	Evaluated plume mobility scenarios for the day of the incident; predicted worst-case plume touchdown at 0.6 mi, extending to 3.5 mi downwind of the shelter; concluded that plume touchdown would have occurred close to Shelter 204.
1986	Radiological survey	N. J. Department of Environmental Protection (White 1987)	Soil samples taken near Shelter 204 and in the drainage area west of County Hwy 539; 20 of 24 samples taken near Shelter 204 exceeded the screening criteria of 20 pCi/g; 4 samples had concentrations above 10,000 pCi/g. Only 1 of the 6 samples from west of County Hwy 539 exceeded the screening criteria. Water samples were collected from off-site wells and surface water locations, and on-site monitoring wells with plutonium results below the decision level for the method.

TABLE A-3. Summary of Long-Term Post Accident Monitoring (Continued)
[Portions Excerpted from Cabrera (2008)].

Year	Type	Organization	Result
1987	Radiological survey	USAF Occupational and Environmental Health Laboratory, Brooks AFB TX (Hunter 1988)	Fixed and removable alpha activity in Shelter 204 and soil samples from manholes and underground bunkers in front of Shelters 202, 206, 208, and 210 were all above acceptable levels; unfiltered non-potable water samples from the communication bunkers contained trace amounts of Pu; communications bunker in front of Shelter 202 had 1,180 pCi/g of ^{239}Pu while the water sample from the same location had 0.83 picocuries per liter (pCi/L); no removable activity was found inside the shelters surrounding Shelter 204.
1994	Radiological survey	Armstrong Laboratory, Brooks AFB TX (Montgomery 1994)	Highest ^{241}Am concentrations located in the apron cracks; theorized that wind and surface water erosion caused contaminated soil to accumulate in the cracks; concluded there was no evidence that a large-scale Pu migration was occurring.
2000	Radiological assessment of groundwater	United States Geological Service, Trenton, N.J. (Zapecza *et al.* 2000)	Investigation of 10 monitoring wells concluded no evidence of detectable Pu or Am contamination in any well bottom sediments, raw unfiltered or filtered water samples.

TABLE A-4. Summary of Survey, Monitoring, Analyses Supporting Restoration
[Portions Excerpted from Cabrera (2008)].

Year	Type	Organization	Result
1989	Radiological survey	Science Applications International Corporation (SAIC 1989a, 1989b)	Used *in situ* low energy photon detectors to collect over 400 gamma ray measurements; most activity located inside the concertina wire near Shelter 204 and in drainage ditch; some activity located following water drainage to the north and on main path to the south; largest measured activity level located at the edge of pavement where the road drainage first enters the ditch; second high activity area located just east of the concrete apron, where original decontamination presumably occurred.
1992	Remedial Investigation/ Feasibility Study (RI/FS)	Earth Technology Corp. (Watt and Collins 1992)	Pu identified in shallow soils, sediments, and structural materials, but not in groundwater, surface water, or air; Pu concentrations are consistent with previous survey results, indicating the Pu is not mobile in the environment. The current distribution of Pu at the site is primarily the result of the 1960 accident and subsequent fire-fighting efforts.
1996	Site Characterization	OHM Remediation Services (OHM 1996)	Objectives were to locate the lower boundary of Pu contamination in front of Shelter 204 and along the drainage ditch west of Shelter 204, evaluate corrugated metal pipes and concrete culverts, investigate potential mixed waste inside the shelters and in groundwater from the existing trichloroethylene (TCE) plume, and investigate subsurface anomalies identified by the 1992 RI/FS (described in Section 2.5 of this report): • Pu contamination estimated to be 20 ft deep in front of and surrounding Shelter 204 and 6 ft deep in the drainage ditch; • Elevated levels of Pu (>50 pCi/g) in surface soil near the corrugated metal pipes • Elevated levels of Pu (7.4 to 8.0 pCi/g) in the top 1 ft of soil at concrete culvert outlet on the west side of County Hwy 539 • Low concentrations of Pu (1.63 pCi/g) found in sediment from inside concrete culvert

TABLE A-4. Summary of Survey, Monitoring, Analyses Supporting Restoration (Continued)
[Portions Excerpted from Cabrera (2008)].

Year	Type	Organization	Result
1996	Site Characterization	OHM Remediation Services (OHM 1996) (Continued)	• Liquid samples from the Shelter 206 launcher support pit had 0.93 pCi/L of Pu and 800 milligrams per liter of 2-butanone • Liquid samples from the communication and power bunkers at Shelter 204 reported 573 and 126 pCi/L of Pu respectively • TCE was not identified in groundwater near Shelter 204; exposure rate readings of 100 microrem per hour (μrem/hr) were detected in the area between Shelters 211 and 213 during installation of one sampling well; the radioactivity was limited to 0 to 2 ft bgs • Investigation of subsurface anomalies did not locate the roof panels, doors, or launcher from Shelter 204; a level of 1.72 pCi/g of Pu reported in one subsurface soil sample 2.5 ft bgs from Site 4 Anomaly 2 located east of Goddard Boulevard, northeast of Shelter 214 and northwest of Shelter 216
1997	Site Characterization Follow-up	OHM Remediation Services (OHM 1998)	Investigated: (1) the areas surrounding Shelter 204 (soils, concrete, and asphalt within the exclusion zone), (2) the area containing the drainage ditch from Shelter 204 to the corrugated metal pipe, (3) the area surrounding the corrugated metal pipe, (4) the area surrounding the concrete culvert, and (5) the area between Shelters 211 and 213; evaluated the potential for Pu contamination in soils west of County Hwy 539 and sediments from Success Lake and Brindle Lake; and completed defining the extent of Pu contamination in Shelter 204 and subsurface support buildings for Shelters 202, 204, and 206. Alpha spectroscopy analyses performed for Pu, U, Am, and Th based on greater interest in uranium and thorium concentrations. • Soil sample results ranged from the detection limit to 140,000 pCi/g for Pu • Highest concentrations corresponded in the exclusion zone surrounding Shelter 204

TABLE A-4. Summary of Survey, Monitoring, Analyses Supporting Restoration (Continued)
[Portions Excerpted from Cabrera (2008)].

Year	Type	Organization	Result
1997	Site Characterization Follow-up	OHM Remediation Services (OHM 1998) (Continued)	• In the drainage ditch, highest Pu concentrations were found in the ditch, in the corrugated metal pipe, in the concrete culvert, and west of CR539 at 3,700 pCi/g, 22 pCi/g, 1.8 pCi/g, and 46 pCi/g, respectively • Concrete core samples and subsurface soil samples were collected from the apron south of Shelter 204; Pu concentrations ranged from less than the reporting limits to 140,000 pCi/g; reportable concentrations of Pu were discovered at depths up to 24 ft bgs • Concrete cores, chips, and liquid samples from Shelters 202, 204, 206 had Pu concentrations from below reporting limits to 97,000 pCi/g for volumetric samples and from below reporting limits to 47,000 decays per minute per 100 square centimeters ($dpm/100cm^2$) for surface samples • None of the 16 lake sediment samples contained Pu concentrations above the reporting limit
1999	Pu to Am Isotopic Ratios Analysis	HQ Air Force Safety Center, Kirtland AFB NM (Rademacher 1999b)	Review of $^{239+240}$Pu to ^{241}Am ratio of historical site surveys, characterization survey, and other related sites impacted with weapons grade plutonium. Concluded remediation should implement specific methodology for more accurate estimate.
1999	Heterogeneity study	HQ Air Force Safety Center, Kirtland AFB NM (Rademacher 1999a)	Determined that plutonium dispersed on site had potential for highly variable γ-spectroscopy results due to effects of heterogeneity. Recommended conjugate counting method to counter effect and provide qualitative measure of effect.
2000	Heterogeneity study	AF Institute for Environment, Safety, and Occupational Health Risk Analysis (Rademacher 2001)	Determined that plutonium dispersed on site had highly variable γ-spectroscopy results due to effects of heterogeneity. Effect was more pronounced for samples of higher activity concentration, but effect was observed in samples of low activity concentration.

TABLE A-4. Summary of Survey, Monitoring, Analyses Supporting Restoration (Continued)
[Portions Excerpted from Cabrera (2008)].

Year	Type	Organization	Result
2002	Radiological survey	AF Institute for Environment, Safety, and Occupational Health Risk Analysis (Rademacher *et al.* 2001)	Documented background conditions for portable survey instruments along BOMARC truck shipping route on Lakehurst Naval Air and Engineering Station (NAES). Soil sample collected and analyzed had mean $^{239+240}$Pu ~ 11 fCi/g.
2005	Radiological survey	AF Institute for Operational Health & National Securities Technologies (NST 2006)	Characterized extent of measurable discrete particle contamination: • Discovered 52 discrete particle areas within and outside the fenced boundary of the BOMARC Site.
2005	Phase I characterization of secondary contaminated areas	Cabrera Services (Cabrera 2006c)	Included radiological surveys to identify discrete particle locations in surface soil, subsurface soil sampling, and downhole gamma measurements to ascertain depth profile and intensity of additional discrete particles; study at University of Nevada Las Vegas (UNLV) evaluated chemical and physical forms of the Pu particles, environmental fate, and transport of discrete Pu particles • 9 areas surveyed for gamma radiation • Contamination was located in 6 of 9 areas • 5 areas were previously labeled as contaminated; • Previously unidentified area was directly behind Building 43 • UNLV study found that majority of Pu activity distributed as discrete particles with relatively large physical dimensions • UNLV study found the Pu particles are chemically and physically stable, could remain in current form with normal environmental weathering conditions, the particle forms are non-respirable (100 – 500 micrometers in diameter), and are highly insoluble • Approximately 90 percent of particles occur in the top 5 centimeters (cm) of soil • Approximately 10 percent of particles occur at an depth of 7 cm

Figure A-10. General Flow Pattern of Water from Accident and Follow-on Storm Run-Off Surmised from Post-Accident Radiological Monitoring Activities.

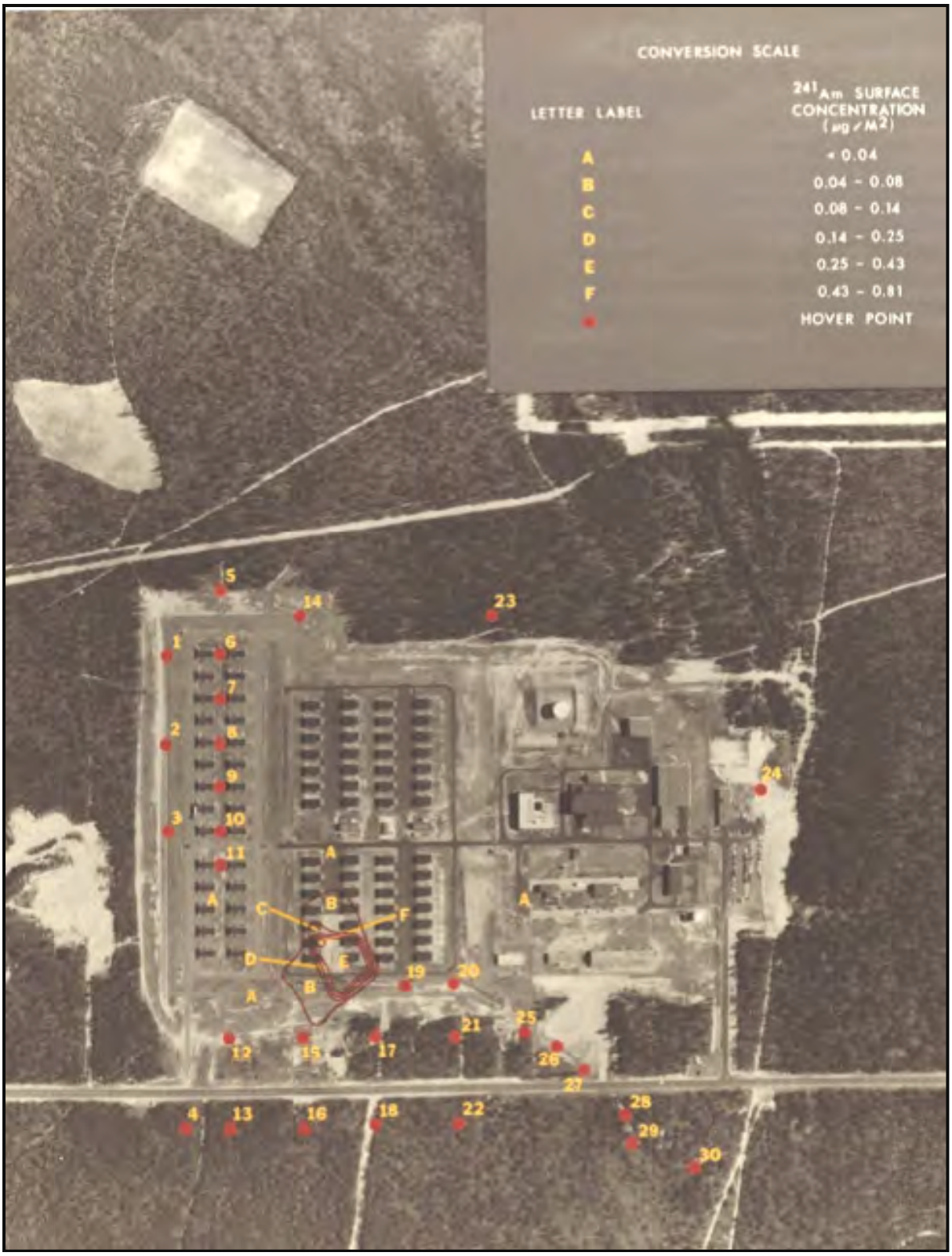

Figure A-11. ^{241}Am Concentration Isopleths (μg/m^2) from 1973 Aerial Survey (EG&G 1974), [Hover Point Count Rates in TABLE A-5].

TABLE A-5. Hover Point Count Rates [Table 1, EG&G 1974)].

Hover Location	Window (counts per minute)			Ratio: $\frac{B}{A+C}$	Standard Deviation from Average
	A	B	C		
	40 – 50 keV	50 – 70 keV	70 – 80 keV		
1	10229	29450	18140	1.0381	-0.77
2	10670	32114	19910	1.0502	-0.032
3	11561	35164	22057	1.0451	-0.34
4	16114	45768	27754	1.0437	-0.43
5	10342	29177	17656	1.0421	-0.52
6	11265	33682	20873	1.0480	-0.16
7	10742	32006	20280	1.0317	-1.16
8	10520	32327	20386	1.0460	-0.29
9	11233	34241	21682	1.0403	-0.63
10	11557	34883	22493	1.0245	-1.6
11	10553	31807	20167	1.0354	-0.93
12	11862	35185	21112	1.0671	1.00
13	16206	45162	26934	1.0469	-0.23
14	12032	36435	22629	1.0512	0.029
15	10674	30507	18412	1.0489	-0.11
16	13469	36632	21030	1.0618	0.68
17	10873	30573	17727	1.0690	1.12
18	13715	38535	22678	1.0589	0.50
19	10746	32375	19840	1.0585	0.48
20	10658	31987	19259	1.0692	1.13
21	9582	26117	15107	1.0578	0.44
22	11307	30745	17768	1.0568	0.37
23	10212	27556	15703	1.0633	0.77
24	8392	23491	14339	1.0334	-1.05
25	9520	29324	18693	1.0394	-0.69
26	8044	23812	14974	1.0345	-0.99
27	8069	23986	14791	1.0493	-0.088
28	9732	28183	15705	1.1080	3.49
29	9370	25698	14689	1.0681	1.06
30	8201	23197	14235	1.0339	-1.02
	Location identified with possible ^{241}Am.				

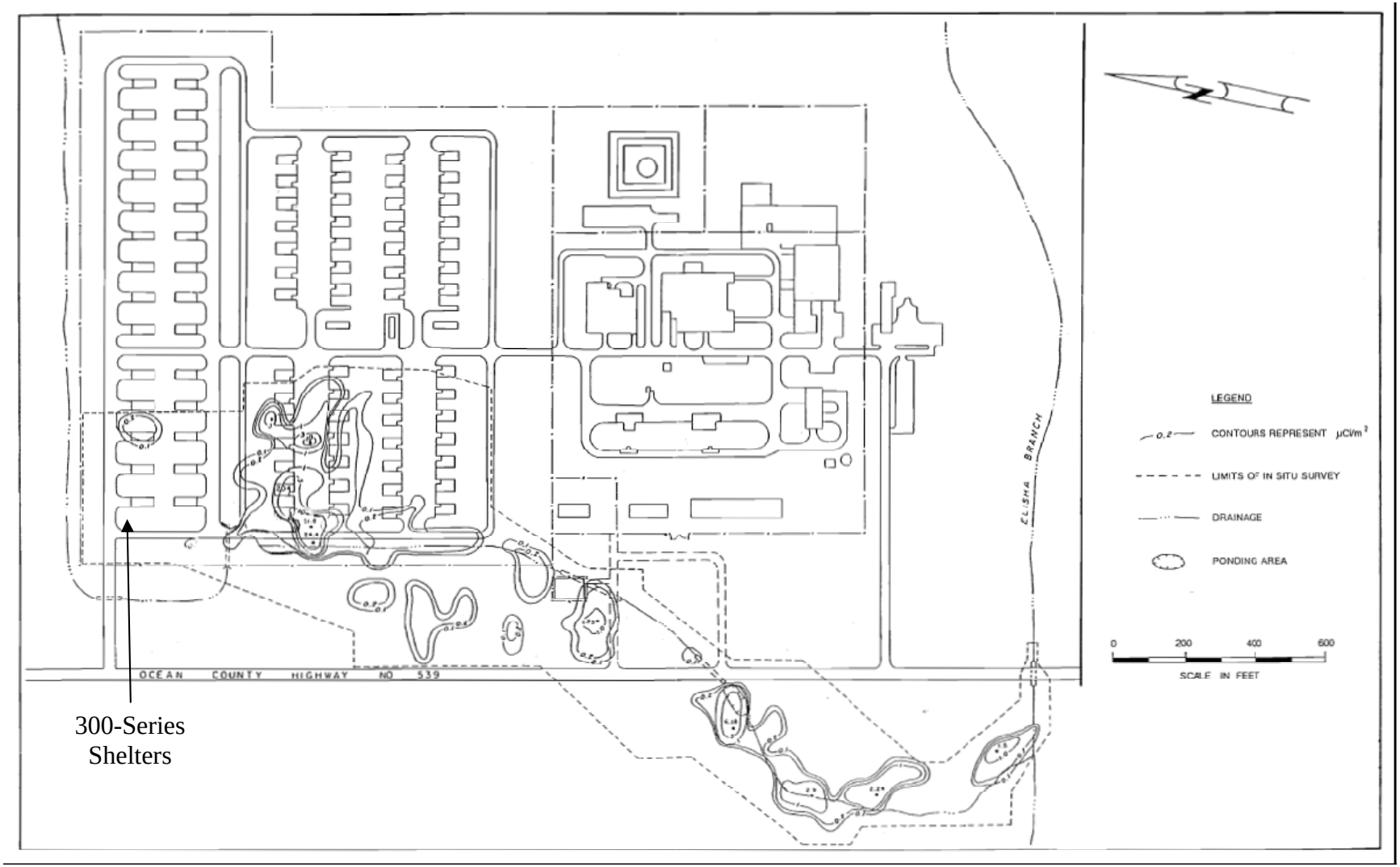

Figure A-12. Radiological Contamination Contour Map from RI/FS [Figure ES-11, Earth Tech (1992)].

TABLE A-6. Key RESRAD Parameters Used to Model Environmental Transport and Exposure to Receptors [RI/FS, Appendix J, Earth Tech (1992).

Parameter (units)	Value	Parameter (units)	Value
Area of contaminated zone (m^2)	16,000	Thickness of contaminated zone (m)	0.152
Length parallel to aquifer (m)	175	Basic radiation dose limit (mrem/yr)	4
Principal radionuclides	^{239}Pu, ^{241}Am	Ratio of Pu to Am	5.9
Cover depth (m)	0	Density of contaminated zone (g/cm^3)	1.6
Contaminated zone erosion rate (m/yr)	0.001	Contaminated zone total porosity	0.41
Contaminated zone effective porosity	0.32	Contaminated zone hydraulic conductivity (m/yr)	490
Contaminated zone b parameter	4.38		
Evapotranspiration coefficient	0.61	Precipitation (m/yr)	1.1
Runoff coefficient	0.5	Watershed area for nearby stream pond (m^2)	1×10^6
Density of saturated zone (g/cm^3)	1.6		
Contaminated zone total porosity	0.41	Contaminated zone effective porosity	0.32
Contaminated zone hydraulic conductivity (m/yr)	4,900	Saturated zone hydraulic gradient	0.0167
		Contaminated zone b parameter	4.38
Water table drop rate (m/yr)	0.001	Well pump intake depth (meters below water table)	3.6
Individual's use of groundwater (m^3/yr)	150		
Unsaturated zone thickness (m)	13	Unsaturated zone soil density (g/cm^3)	1.6
Unsaturated zone total porosity	0.41	Unsaturated zone effective porosity	0.32
Unsaturated zone specific b parameter	4.38	Unsaturated zone hydraulic conductivity (m/yr)	4,900
Am distribution coefficients (cm^3/g) [contaminated, unsaturated, saturated]	400	Inhalation rate (m^3/yr)	7,000
Pu distribution coefficients (cm^3/g) [contaminated, unsaturated, saturated]	20,000	Mass loading for inhalation (g/m^3)	0.0002
Occupancy factor, inhalation	0.55	Dilution length for airborne dust, inhalation (m)	3.0
Pu leach rate (/yr)	0.0	Am leach rate (/yr)	0.0
Occupancy and shielding factor, external γ-radiation	0.60	Fruits, vegetables, and grain consumption (kg/yr)	28.7
Leafy vegetable consumption (kg/yr)	14.0	Milk consumption (L/yr)	102
Meat and poultry consumption (kg/yr)	26.3	Soil ingestion rate (g/yr)	35
Fraction of drinking water from site	1.0	Livestock fodder intake for meat (kg/d)	68
Livestock fodder intake for milk (kg/d)	55	Livestock water intake for meat (L/d)	55
Livestock water intake for milk (L/d)	160	Mass loading for foliar deposition (g/m^3)	0.0001
Drinking, livestock, irrigation water fraction from ground water	1.0	Depth of roots (m)	0.9
		Depth of soil mixing layer (m)	0.15

TABLE A-7. Comparison of RI/FS and ICRP Dose Conversion Coefficients for $^{239+240}Pu$.

Application		Inhalation Factors		Ingestion Factors		
		DCF (EDE) (mrem/μCi)	f_1	DCF (EDE) (mrem/μCi)	f_1	
	RI/FS (DOE-EH-0071, 1988)	5.1E+05		4.3E+03		Compounds
Workers	ICRP 26/30/48 [FGR 11] (Class D)	NA	NA	3.5E+03	1.0E-03	
	ICRP 26/30/48 [FGR 11] (Class W)	4.3E+05	1.0E-03	3.7E+02	1.0E-04	All but PuO_2
	ICRP 26/30/48 [FGR 11] (Class Y)	3.1E+05	1.0E-05	5.2E+01	1.0E-05	PuO_2
	ICRP 60/30/48 (Class D)	NA	NA	2.1E+03	1.0E-03	
	ICRP 60/30/48 (Class W)	2.5E+05	1.0E-03	2.3E+02	1.0E-04	All but PuO_2
	ICRP 60/30/48 (Class Y)	2.4E+05	1.0E-05	4.5E+01	1.0E-05	PuO_2
	ICRP 68/60	NA	NA	9.3E+02	5.0E-04	Unspecified
	ICRP 68/60 (Type M, Unspecified Compounds)	1.2E+05	5.0E-04	2.0E+02	1.0E-04	Nitrates
	ICRP 60/68 (Type S, Insoluble Oxides)	3.1E+04	1.0E-05	3.3E+01	1.0E-05	Insoluble Oxides
	ICRP 78	NA	NA	9.3E+02	5.0E-04	Unspecified
	ICRP 78 (Type M, Unspecified Compunds)	1.1E+05	5.0E-04	2.0E+02	1.0E-04	Nitrates
	ICRP 78 (Type S, Insoluble Oxides)	4.1E+04	1.0E-05	3.3E+01	1.0E-05	Insoluble Oxides
General Public	ICRP 60/72 (Type F, 3 months old)	7.8E+05	5.0E-04			
	ICRP 60/72 (Type F, 1 year old)	7.4E+05	5.0E-04			
	ICRP 60/72 (Type F, 5 year old)	5.6E+05	5.0E-04			
	ICRP 60/72 (Type F, 10 year old)	4.4E+05	5.0E-04			
	ICRP 60/72 (Type F, 15 year old)	4.1E+05	5.0E-04			
	ICRP 60/72 (Type F, 25 year old)	4.4E+05	5.0E-04			
	ICRP 60/72 (Type M, 3 months old)	3.0E+05	5.0E-04	1.6E+04	5.0E-04	30-yr Weighted Mean = 1.5E+03
	ICRP 60/72 (Type M, 1 year old)	2.9E+05	5.0E-04	1.6E+03	5.0E-04	
	ICRP 60/72 (Type M, 5 year old)	2.2E+05	5.0E-04	1.2E+03	5.0E-04	
	ICRP 60/72 (Type M, 10 year old)	1.8E+05	5.0E-04	1.0E+03	5.0E-04	
	ICRP 60/72 (Type M, 15 year old)	1.7E+05	5.0E-04	9.1E+02	5.0E-04	
	ICRP 60/72 (Type M, 25 year old)	1.9E+05	5.0E-04	9.3E+02	5.0E-04	
	ICRP 60/72 (Type S, 3 months old)	1.6E+05	1.0E-05	30-yr Weighted Mean = 4.8E+04		
	ICRP 60/72 (Type S, 1 year old)	1.4E+05	1.0E-05			
	ICRP 60/72 (Type S, 5 year old)	1.0E+04	1.0E-05			Used for ROD
	ICRP 60/72 (Type S, 10 year old)	7.0E+04	1.0E-05			
	ICRP 60/72 (Type S, 15 year old)	6.3E+03	1.0E-05			Most applicable of respective models

Figure A-13. 1996 Characterization Results (OHM 1996).

Appendix B

Restoration of Primary Contaminated Areas

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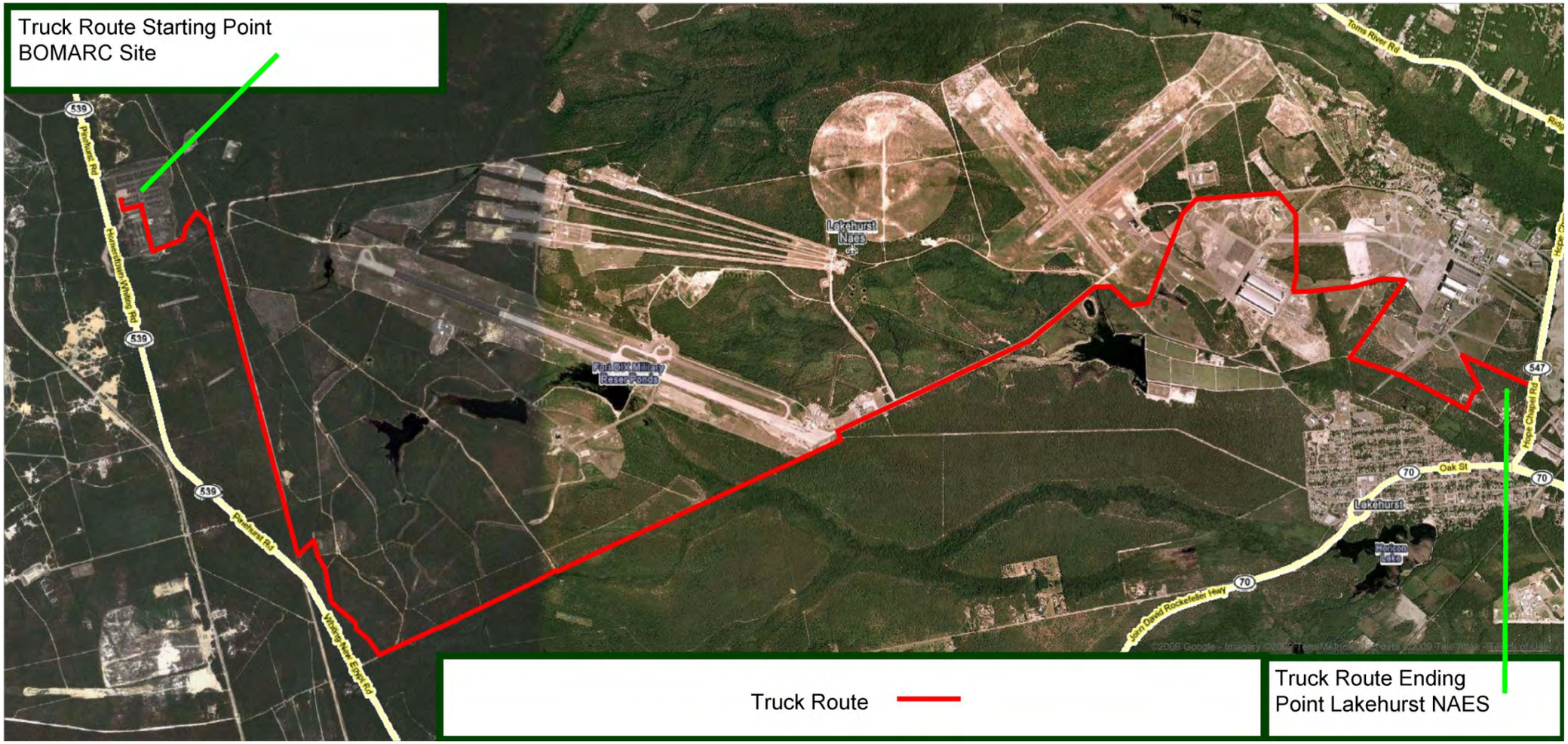
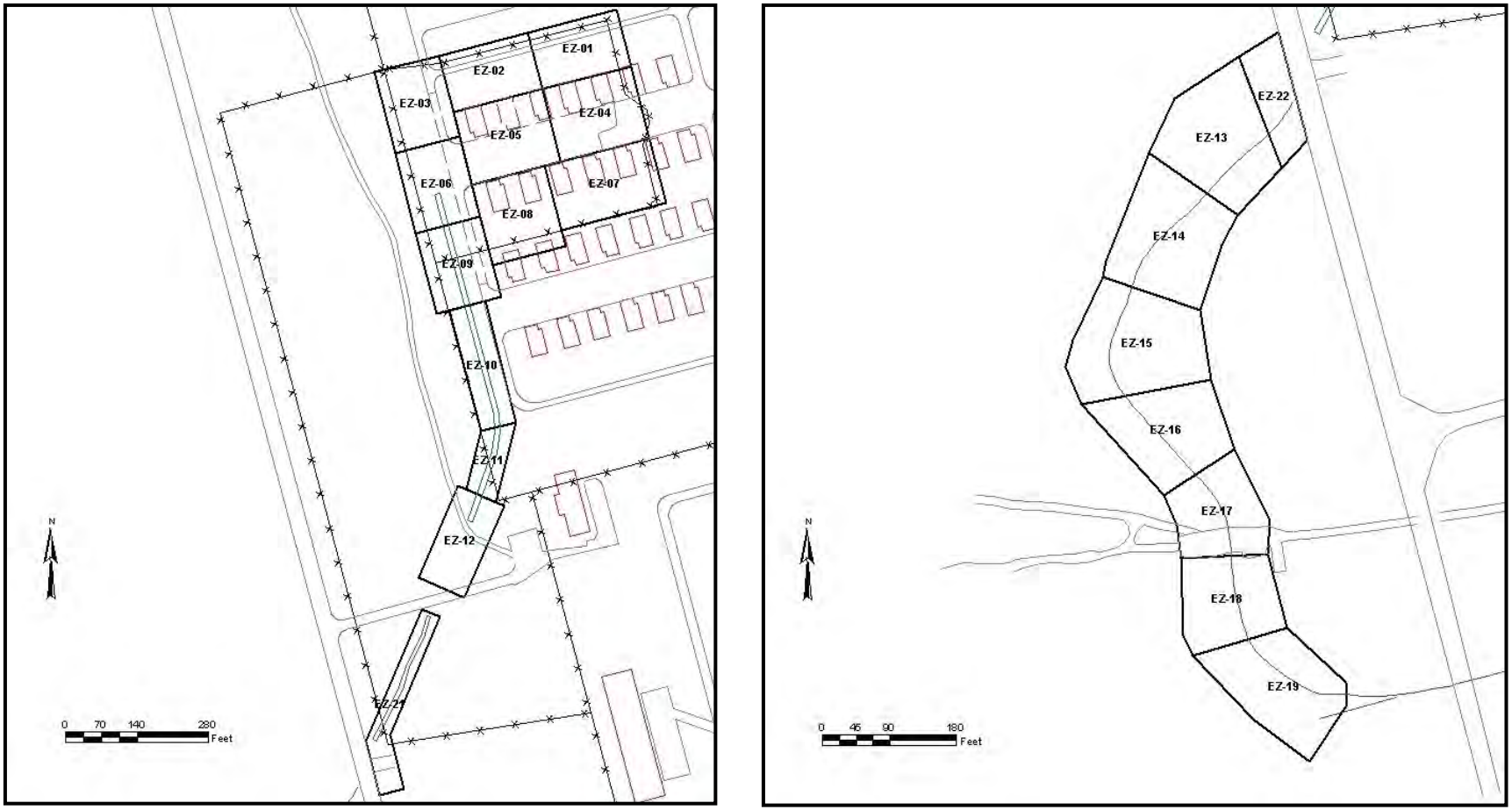


Figure B-1. Local Truck Transportation Route for Contaminated Soils and Debris.

Figure B-2. Photograph of an Intermodal Container.

Figure B-3. Flatbed Rail Car used to Carry Four Intermodal Containers.

Figure B-4. Site Layout for Primary Areas Restoration (Duratek 2005).



a. East Side of County Hwy 539.

b. West Side of Hwy 539.

Figure B-5. Survey Units for Primary Areas Restoration (Duratek 2005).

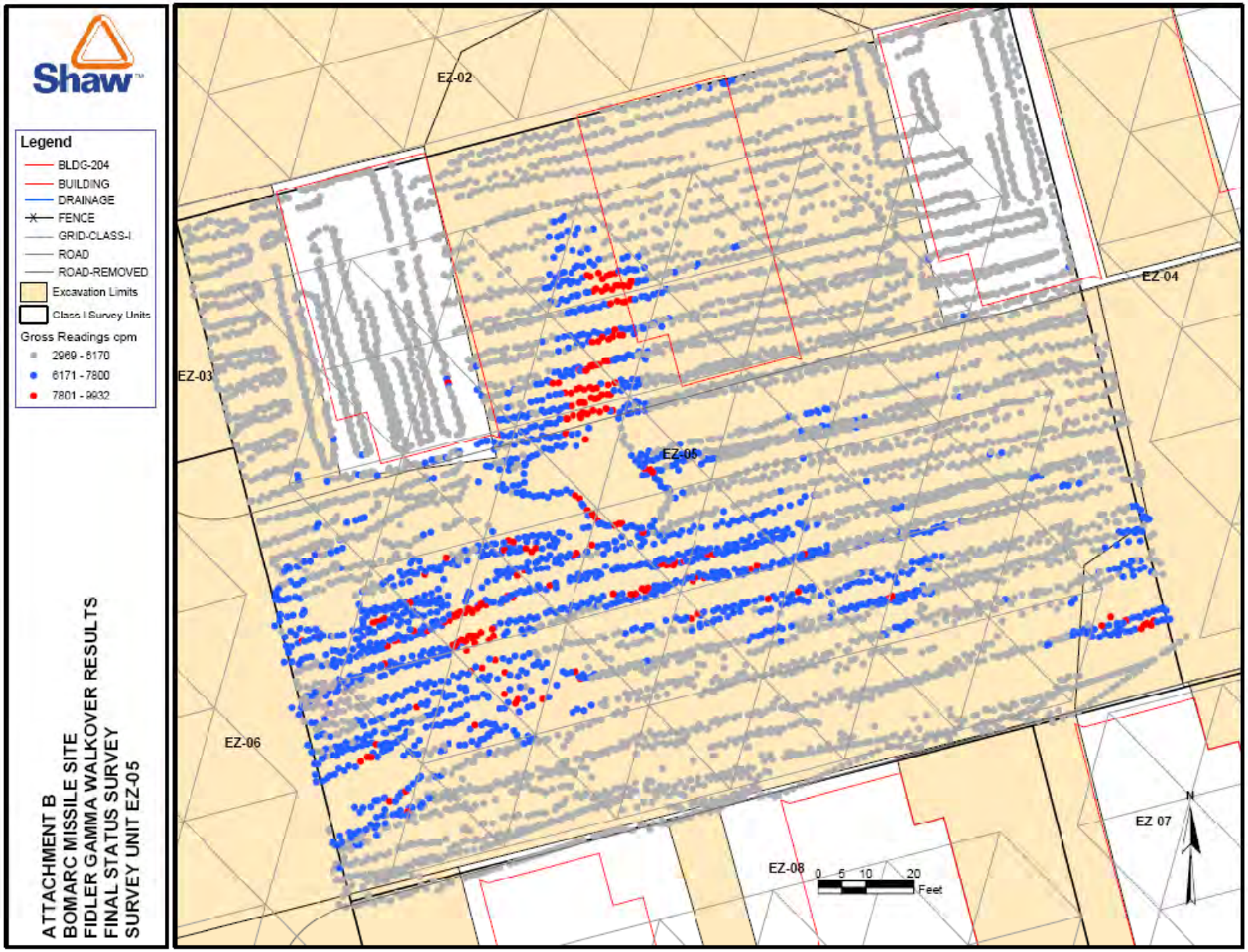


Figure B-6. Example FIDLER Scan Data for Survey Unit EZ-5 (Duratek 2005).

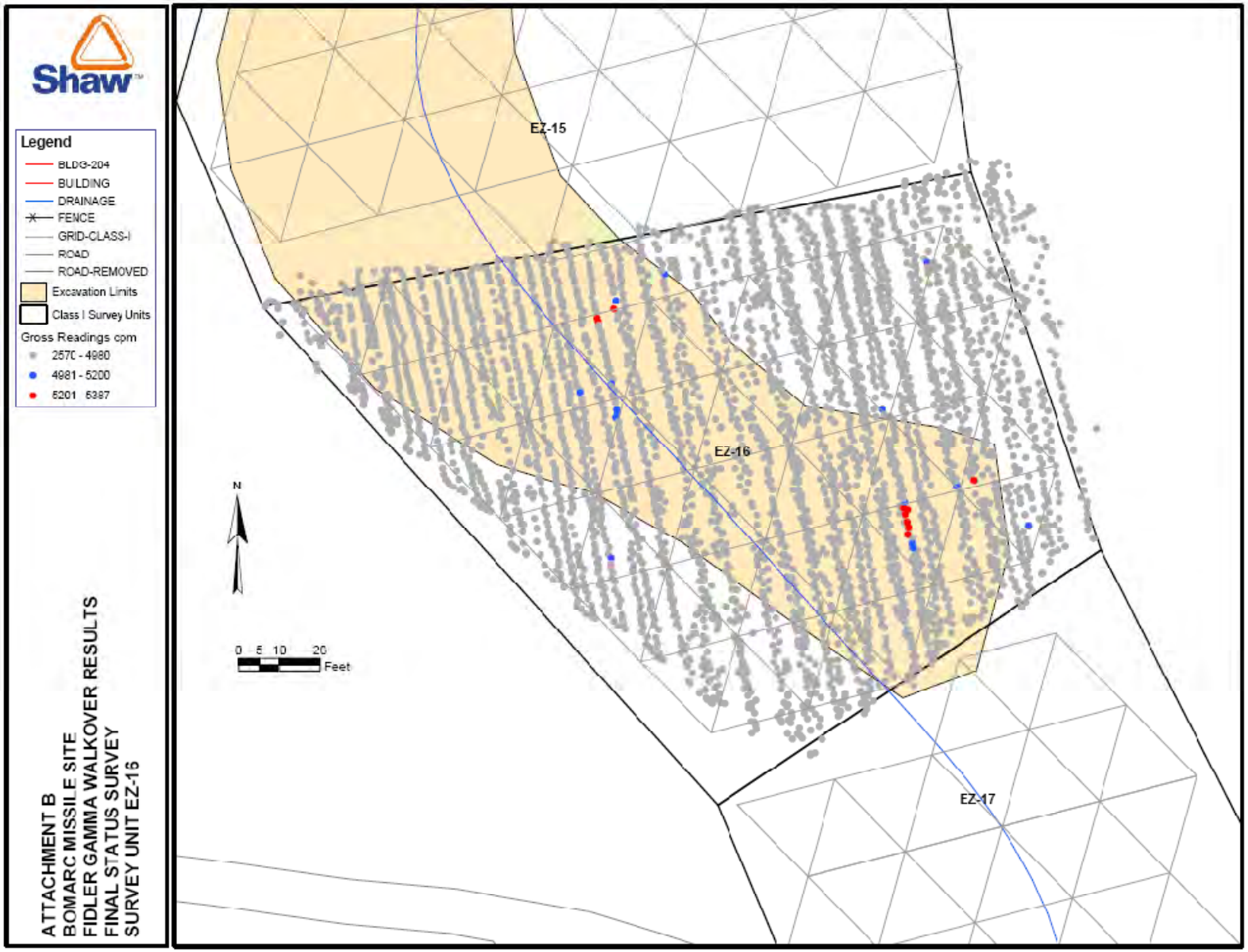


Figure B-7. Example FIDLER Scan Data for Survey Unit EZ-16 (Duratek 2005).

TABLE B-1. Final Status Survey Soil Analysis Results for Remediation of Primary Contaminated Areas.

Survey Unit Number	Survey Unit Size (m^2)	Systematic-Grid Samples		Mean $^{239+240}Pu$ (pCi/g)	EMC 1		EMC 2		EMC 3		EMC 4	
		Number	# > DCGL		pCi/g	Area (m^2)	pCi/g	Area (m^2)	pCi/g	Area (m^2)	pCi/g	Area (m^2)
1	1925	45	2	2.1	14.9	18.2	4.1	10.7				
2	1925	45	4	2.9	13.3	37.0	5	22.8	7.3	10.7		
3	2000	40	0	1.2	23.4	29.8						
4	2018	44	0	1.2								
5	2125	43	2	2.0	6.5	85.3	4.3	2.7	2.8	85.3	6.4	114
6	2000	44	2	2.21	8.1	47.4	8.2	94.8				
7	2022	55	0	1.7								
8	1785	38	3	2.7	8.1	75.8	9.2	2.7	8.8	2.7		
9	2000	43	1	2.3	10.4	2.7						
10	1658	36	1	1.6	10.8	28.4	27.9	7.4				
11	833	19	0	1.6	7.3	42.9						
12	1800	39	0	1.5								
13	1959	42	1	2.3	3.9	2.7	8.7	2.7				
14	2031	45	1	2.2	4.4	339	3.8	2.7				
15	2143	48	0	1.3								
16	1654	36	0	1.1								
17	1304	27	0	1.6								
18	1406	31	2	2.1	6.2	10.7	8.1	10.7				
19	1835	40	0	1.6								
20	124	17	0	1.91								
21	1504	34	0	1.1	9.5	2.7	10.6	6.8				
22	766	18	0	1.4								
Totals	36817	829	Area-Weighted Mean	1.82								

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Appendix C

Restoration of Secondary Contaminated Areas

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Figure C-1. National Securities Technologies Survey, Conducted 4 – 12 April 2005 (NST 2005).

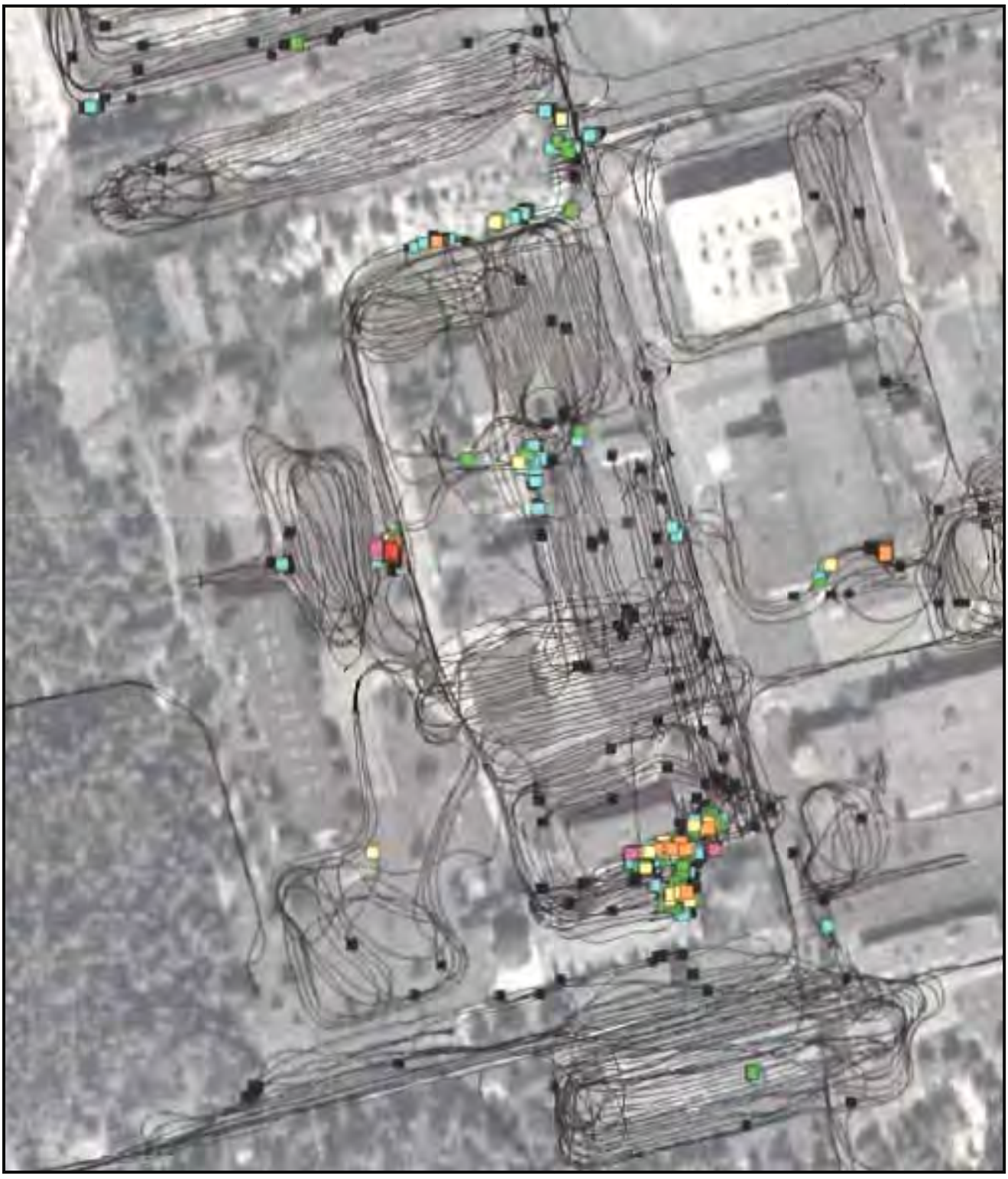


Figure C-2. Detailed Section of Figure C-1.

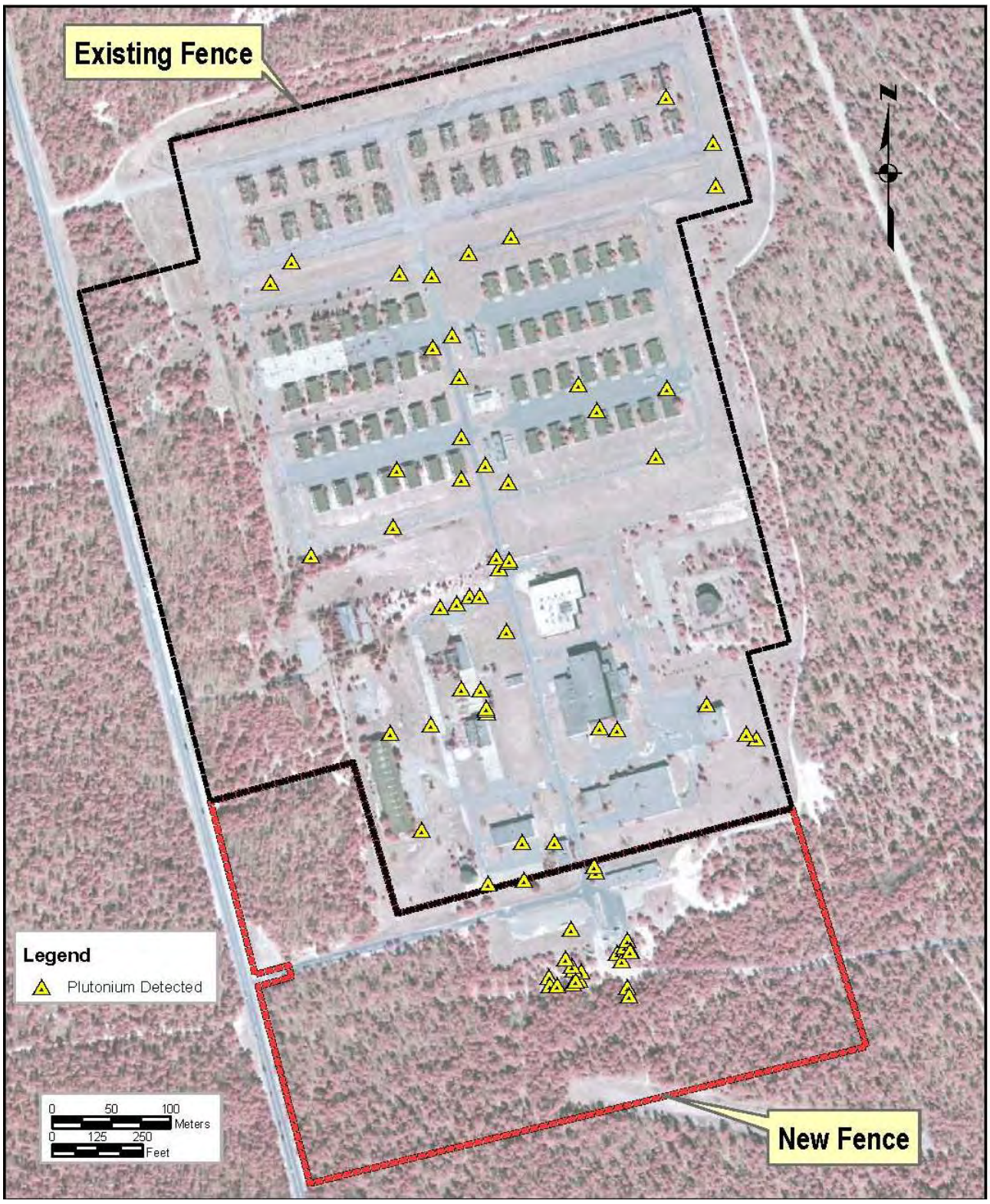


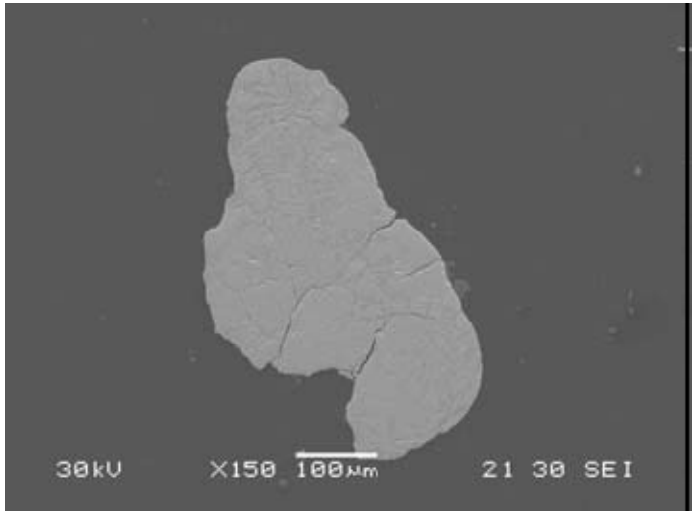
Figure C-3. Suspect Areas for Contamination in Secondary Contaminated Areas (Archer 2005).

TABLE C-1. Estimated Activity Concentrations of Sample Segments from 5 cm Cores, Assuming $^{239+240}$Pu:^{241}Am: 5.4, 38 g per Vertical Segments; 13.3 g(A), 14.8 g(B), 6.2 g(C), and 4.8 g(D) per Horizontal Segments [Data from Cabrera 2006b, Appendix E].

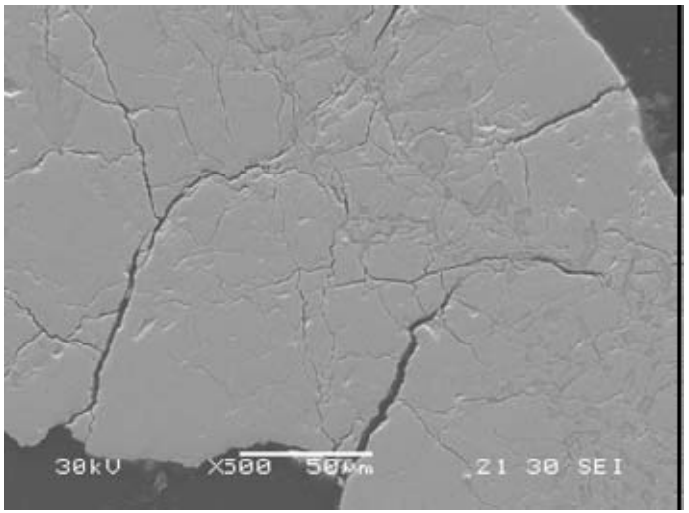
Sample Number	Estimated Vertical Segment $^{239+240}$Pu Activity Concentration (pCi/g)							
	1	2	3	4	5	6	7	8
4-C	1.2E+01	8.3E+05	6.1E+02	9.6E+00	7.9E+00			
5-F	0.0E+00	8.2E-01	6.4E-01	1.2E+05	3.1E+01	3.2E+00	0.0E+00	4.6E+01
9-F	0.0E+00	2.4E-01	3.2E-01	2.7E-01	4.7E-01	3.5E-01	3.6E+03	1.4E+01
10-F	8.6E+00	1.6E+00	3.0E+00	2.9E+00	2.3E+00	3.3E+00	2.1E+04	1.3E+01
11-F	7.3E-01	2.4E-01	2.0E-01	3.6E-01	1.5E+00	1.1E+01	4.5E+04	1.7E+00
12-F	6.2E-01	1.3E+00	2.1E+00	2.7E+00	1.4E+01	3.2E+04	1.2E+02	3.4E+01
15-D	0.0E+00	8.8E+02	2.9E+03	6.6E+03	7.3E+04			
16-D	6.5E+01	8.9E+01	5.3E+02	1.1E+04	1.5E+05			

Sample Number	Estimated Horizontal Segment $^{239+240}$Pu Activity Concentration (pCi/g)				Sample Number	Estimated Horizontal Segment $^{239+240}$Pu Activity Concentration (pCi/g)			
	A	B	C	D		A	B	C	D
4-C-1	3.9E+00	6.4E+00	4.7E+01	8.2E+00	10-F-8	1.1E+00	5.9E+00	1.1E+01	8.4E+01
4-C-2	1.8E+01	3.6E+02	5.1E+06	4.1E+01	11-F-6	2.0E+01	6.2E+00	4.8E+00	5.1E+00
4-C-3	5.4E+01	8.2E+01	5.1E+01	2.0E+01	11-F-7	7.6E+01	1.2E+05	3.5E+00	4.9E+00
5-F-3	0.0E+00	0.0E+00	0.0E+00	6.5E+00	12-F-5	2.8E+00	2.6E+00	4.5E+01	5.1E+01
5-F-4	0.0E+00	5.6E+00	7.2E+05	6.0E+02	12-F-6	1.3E+01	2.0E+01	1.9E+05	2.5E+03
5-F-5	0.0E+00	3.5E+01	3.0E+01	1.3E+02	12-F-7	6.6E+00	2.4E+01	5.0E+02	3.0E+02
9-F-6	0.0E+00	0.0E+00	1.6E+00	8.6E-01	15-D-4	4.0E+02	9.1E+02	2.2E+04	2.6E+04
9-F-7	9.6E-01	1.2E+00	4.0E+00	3.6E+04	15-D-5	2.4E+02	2.4E+02	4.4E+05	9.3E+02
9-F-8	5.3E+00	1.2E+01	1.6E+01	5.4E+01	16-D-4	1.5E+03	1.1E+03	1.3E+03	9.5E+04
10-F-6	1.2E+00	1.4E+00	3.3E+00	1.8E+01	16-D-5	1.0E+04	1.0E+02	9.1E+05	3.3E+02
10-F-7	5.5E+00	1.4E+01	1.7E+01	2.2E+05					

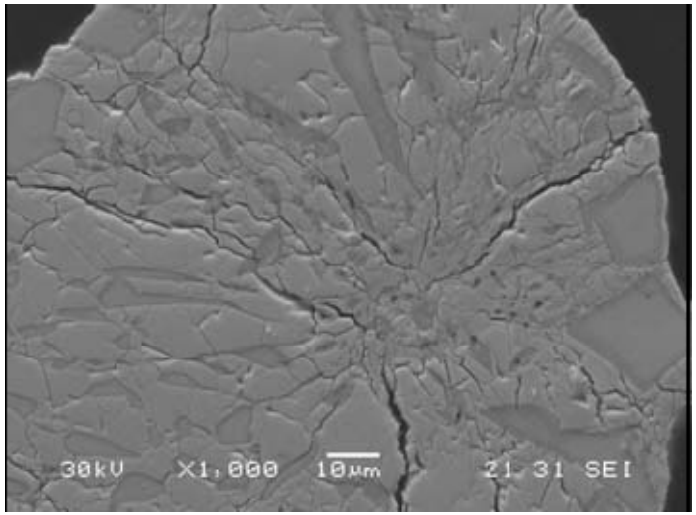
0 – **8**	**8** – 80	80 – 800	800 – 8k	8k – 80k	> 80k	pCi/g



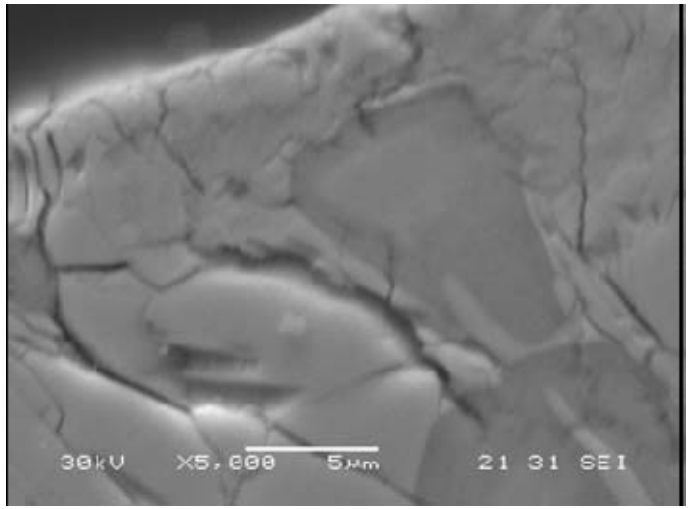
a. SEI x150



b. SEI x50



c. SEI x1000

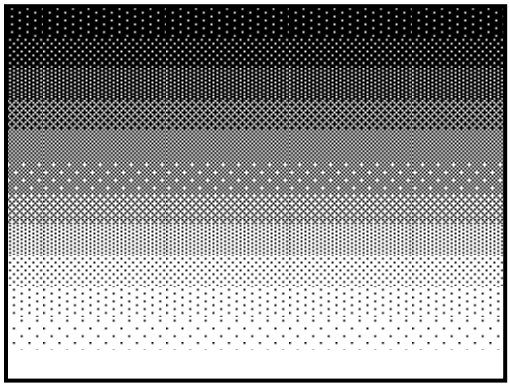


d. SEI x5000

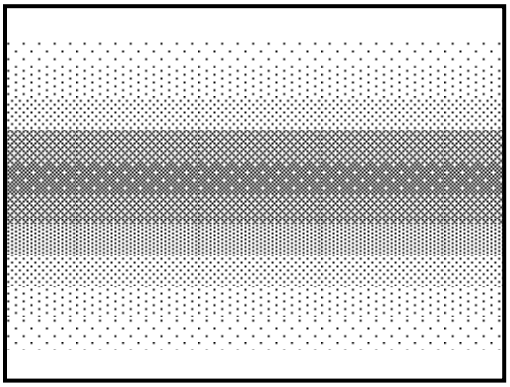
Figure C-4. Scanning Electron Microscopy (SEM) Image, 0.8 µCi $^{239+240}$Pu Particle Evaluated by Radiochemistry Research Group, Harry Reid Center and Department of Chemistry, University of Nevada, Las Vegas, NV [Figure 13, Appendix E, (Cabrera 2006c)].

Figure C-5. Comprehensive Site Overview, Historical Site Assessment (Cabrera 2006a).

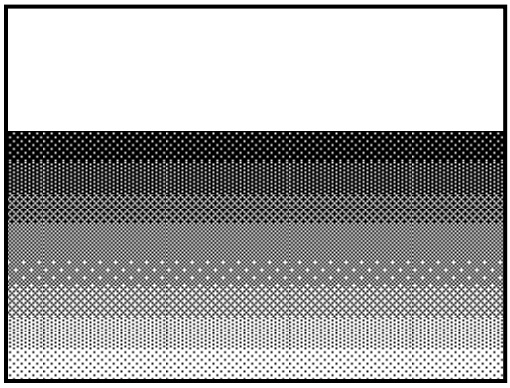
Figure C-6. 1963 Aerial Photograph of BOMARC Missile Site with Highlighted Area of Apparent Disturbance (Cabrera 2006a).



a. Pattern for Highly Insoluble (Immobile) Contaminant.



b. Pattern for Soluble (Mobile) Contaminant.



c. Pattern for Insoluble Contaminant with Uncontaminated Overburden.

Figure C-7. Conceptual Model of Various Contaminant Depth Profiles in Soils.

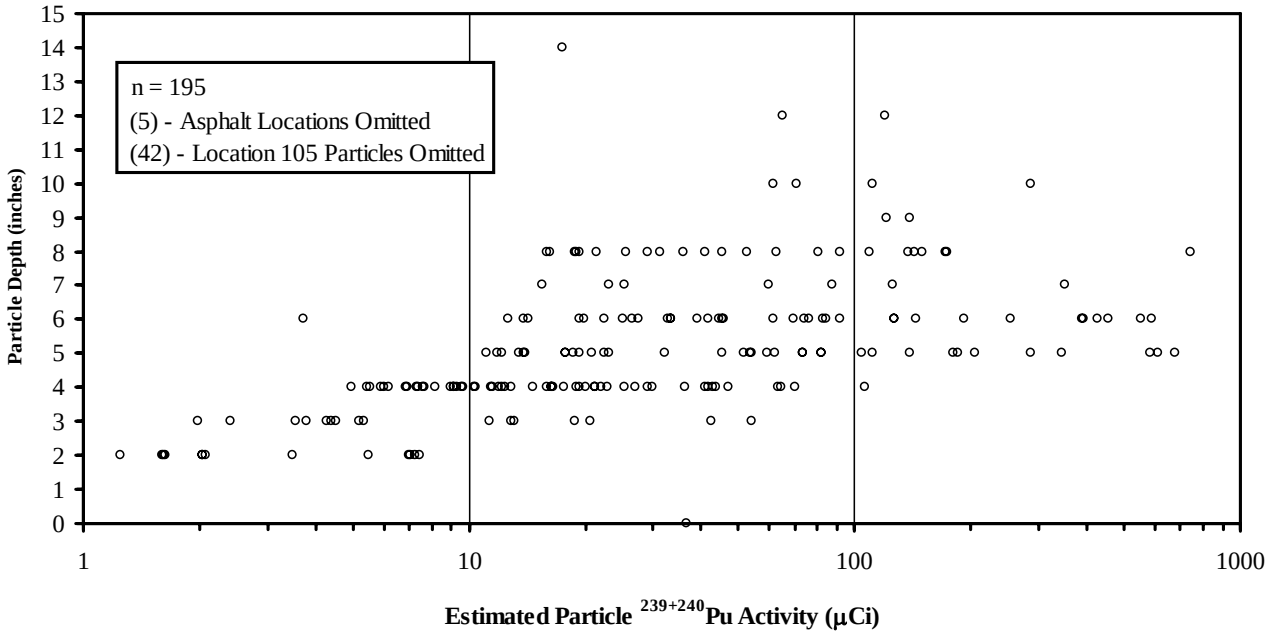
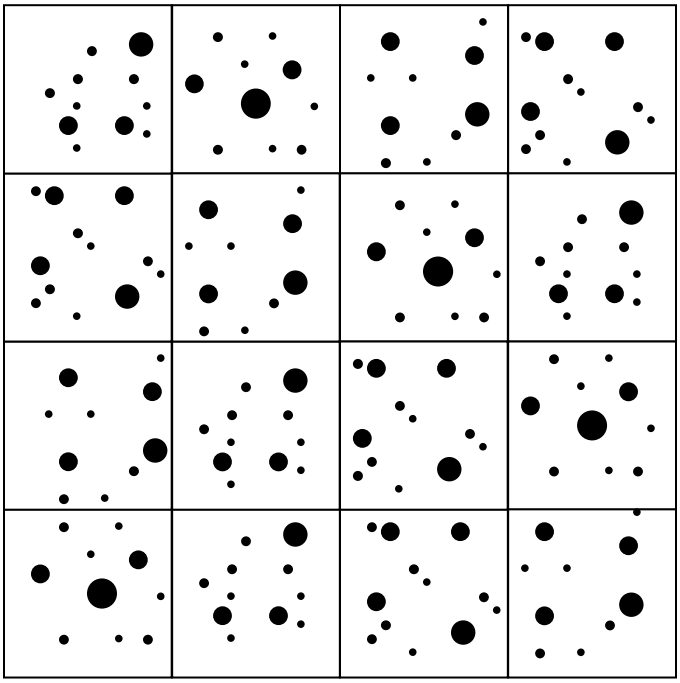
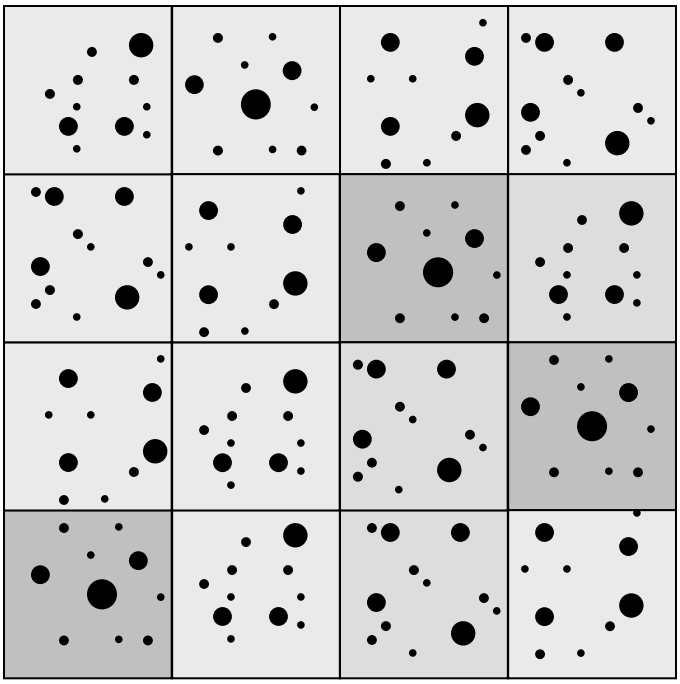


Figure C-8. Estimated Particle $^{239+240}$Pu Activities vs. Depth (Data from Cabrera 2006a).

Figure C-9. Particle Locations Evaluated by Cabrera (2006a).



a. Discrete Particle Form.



b. Discrete Particle Form with Diffuse Component.

Figure C-10. Plutonium Contaminant Conceptual Diagram [Adapted from Rademacher *et al.* (2007)].

TABLE C-2. Issues Related to Homogenous and Heterogeneous WGP Contaminant Distributions.

Context		Homogenous	Heterogeneous
Laboratory Analysis of Samples	α-Spectroscopy	Reasonable reproducible analytical results among sub-sample aliquots/split samples	Questionable reproducibility among sub-aliquots/split samples due to small aliquot sizes. Relationships between co-distributed contaminants reasonable if serial extraction method is used.
	γ-Spectroscopy (^{241}Am Target Analyte)	Reasonable reproducible analytical results among sub-sample aliquots/split samples.	Better reproducibility among sub-aliquots/split samples than α-spectroscopy, due to significantly larger aliquot size. Variability in reported activity concentration can be minimized with conjugate counting.
Sample Collection		No special provisions for sampling.	Variability in sampled activity is reduced for larger sample sizes.
In-situ γ-Scanning of Site		Good agreement to modeled instrument response.	Modeled response should account for homogenous and discrete particle response. High activity discrete particles in contaminant make identification of impacted areas easier than the case of a homogenous contaminant.
Exposure Routes [Dose equivalent fractions from RI/FS, Appendix J (Earth Tech 1992)]	Inhalation (76 %)	Standard dose model algorithms assume fairly uniform exposure to homogenous contaminant distributions. Models normally assume 100 % of contaminant is of respirable particle size.	Heterogeneous distributions could have widely varied modeled doses. Assumption of 100 % respirable contaminant is poor. Mean doses will be lower than modeled.
	Soil Ingestion (22 %)	Standard dose model algorithms assume fairly uniform exposure to contaminants, as the case for a homogenous contaminant.	Heterogeneous distributions could have widely varied modeled doses, dependent on the relative particle distribution.
	Plant (1 %)	Standard dose model algorithms assume fairly uniform aqueous partition of contaminant, which exists for homogenous cases.	Heterogeneous distributions should not have widely varied overall aqueous partition of contaminant. Aqueous phase should be lower for large activity, discrete particles than homogenous, due to lower surface to volume ratio.
Risk Modeling	Lung Intake	Primary source for risk modeling.	ICRP models are applicable to discrete particle exposures [(Harrison 2003); (Charles *et al.* 2003)].
	GI Intake	Primary source for risk modeling.	PuO_2 has insignificant dose to GI tract in-transit. Transport to internal organs requires soluble form; discrete particles in bone and liver not applicable to GI intakes. Large activity, discrete particles are expected to have lower GI uptakes than homogenous form, due to lower surface to volume ratio.

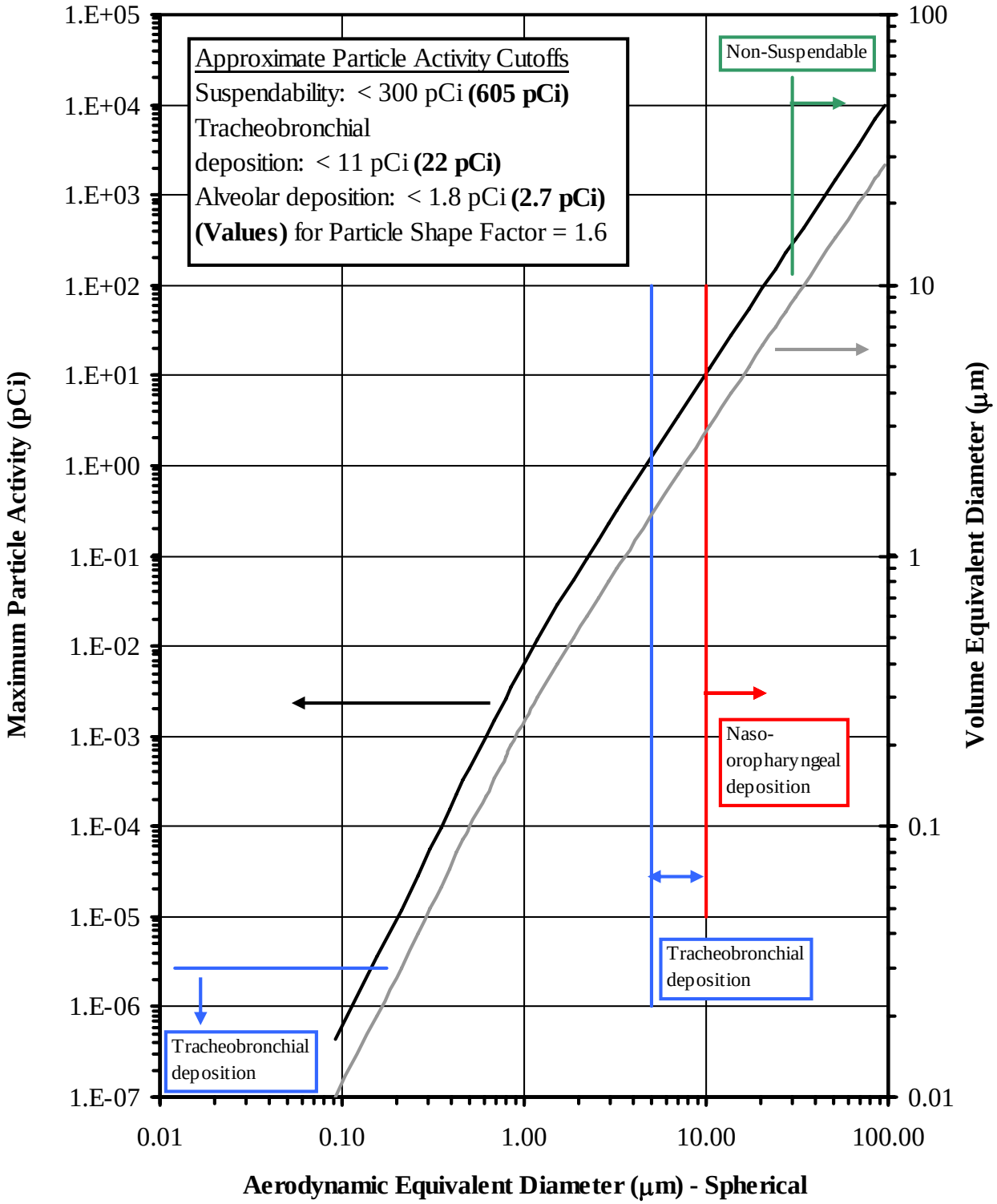


Figure C-11. Maximum Particle Activities and Volume Equivalent Diameters for Aerodynamic Equivalent Diameter (Spherical) PuO_2 Particles.

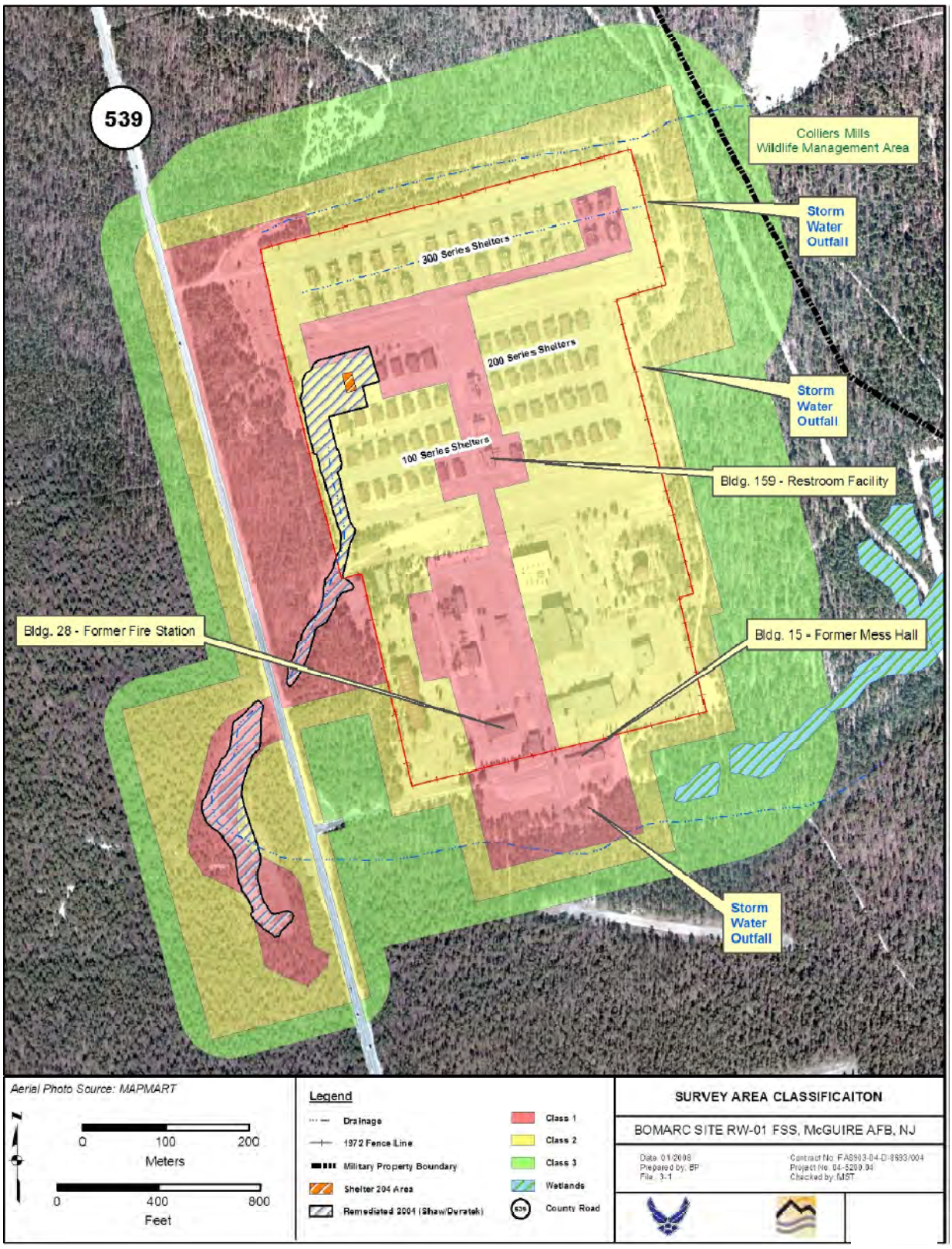


Figure C-12. Survey Area Classification Used for Secondary Areas (Cabrera 2008).

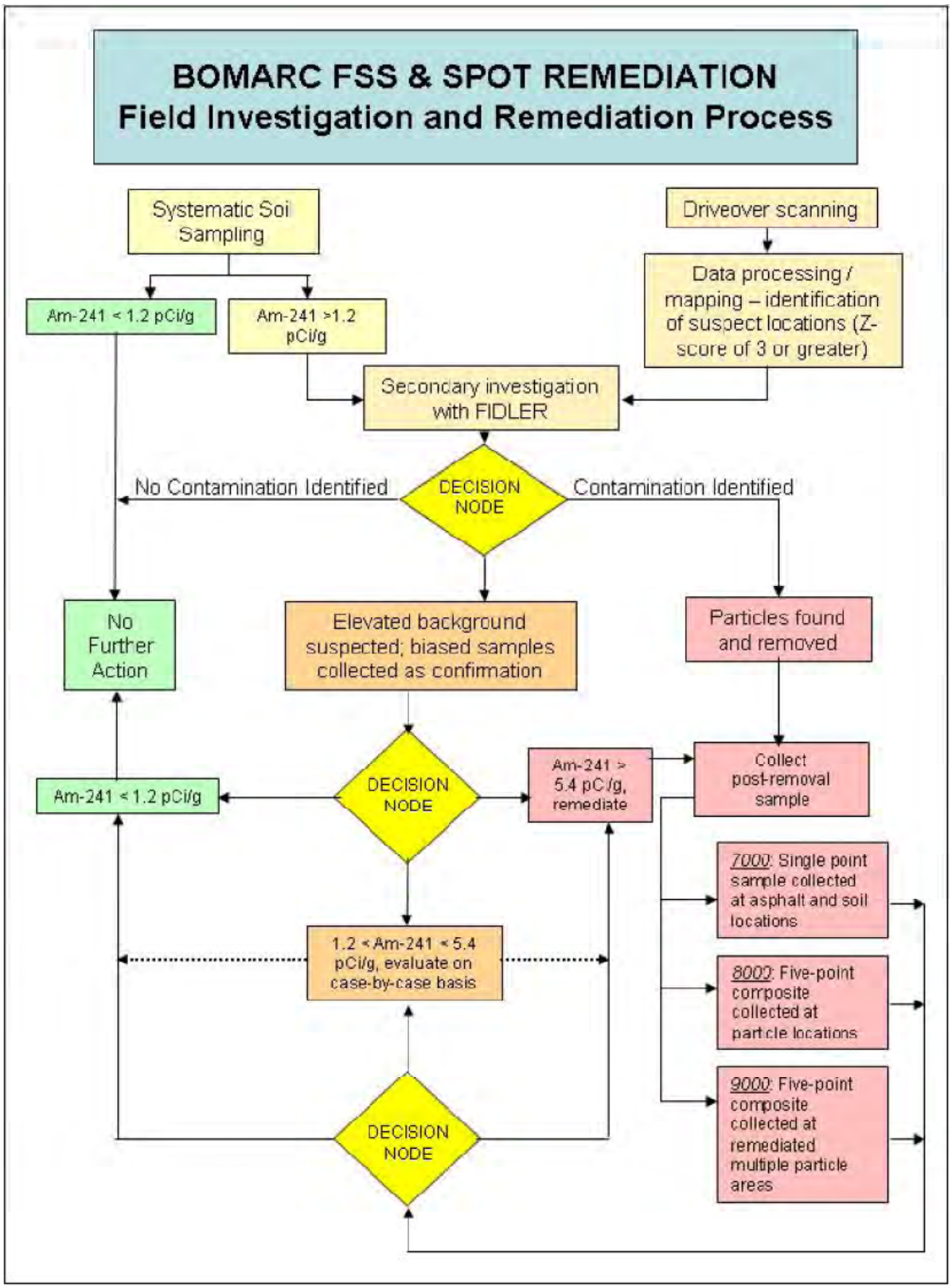


Figure C-13. Investigation, Remediation, and Resurvey Process Used for Secondary Areas (Cabrera 2008).

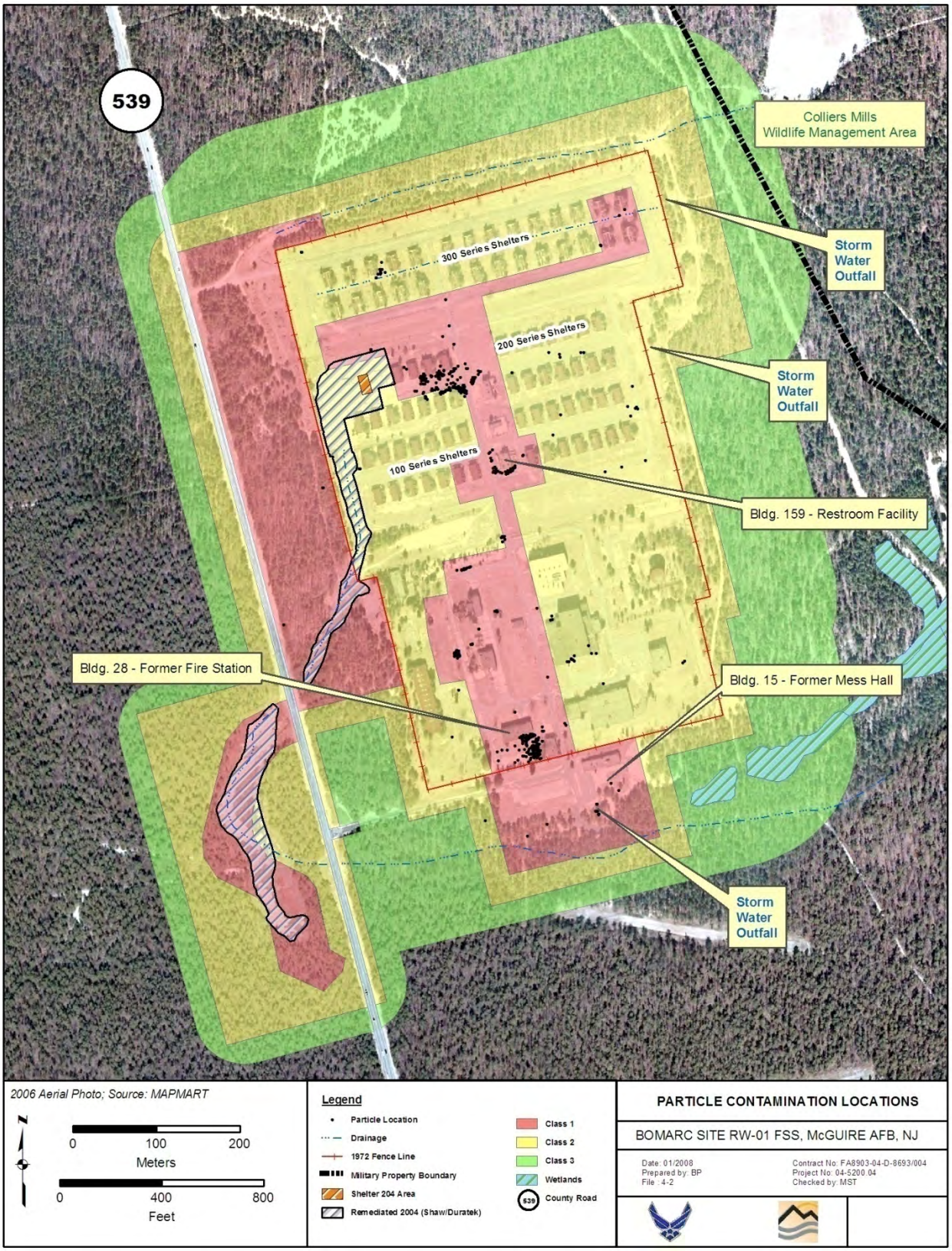


Figure C-14. Particle Contamination Areas (Cabrera 2008).

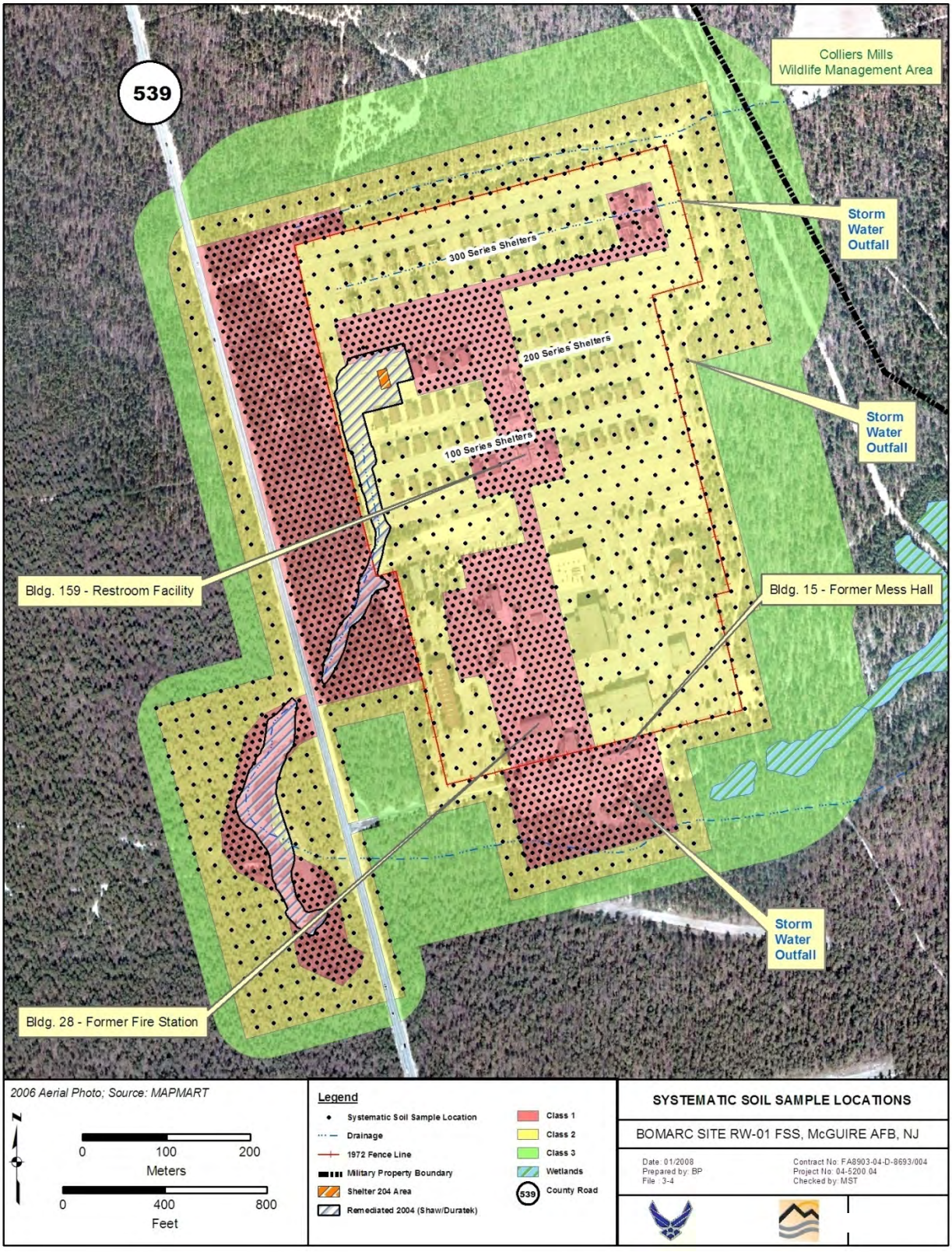


Figure C-15. Systematic Soil Sampling Locations Supporting Final Status Surveys in Secondary Areas (Cabrera 2008).

TABLE C-3. Final Status Survey Soil Analysis Results for Remediation of Secondary Contaminated Areas.

Survey Unit	Sample Number	$^{239+240}$Pu (pCi/g)		Number > DCGL	Survey Unit	Sample Number	$^{239+240}$Pu (pCi/g)		Number > DCGL
		Average	Maximum				Average	Maximum	
1	25	< 0.0	0.0	0	30	25	< 0.0	0.6	0
2	25	0.6	10.0	1	31	25	< 0.0	0.0	0
3	25	0.0	3.9	0	32	25	< 0.0	0.6	0
4	25	< 0.0	0.6	0	33	24	< 0.0	0.6	0
5	25	0.0	0.6	0	34	24	< 0.0	0.0	0
6	25	0.0	8.9	1	35	25	< 0.0	0.6	0
7	16	1.1	6.7	0	36	25	< 0.0	0.0	0
8	24	< 0.0	1.1	0	37	25	< 0.0	0.6	0
9	22	< 0.0	0.6	0	38	34	< 0.0	0.6	0
10	25	0.0	1.7	0	39	16	< 0.0	0.0	0
11	27	< 0.0	0.6	0	40	22	< 0.0	3.3	0
12	25	< 0.0	1.1	0	41	25	< 0.0	0.0	0
13	25	2.8	22	2	42	25	< 0.0	11	1
14	28	< 0.0	0.6	0	43	27	37	1000 (1.7)	1
15	25	< 0.0	4.5	0	44	25	< 0.0	0.6	0
16	24	< 0.0	0.6	0	45	24	0.0	10	1
17	25	< 0.0	0.6	0	46	25	< 0.0	1.7	0
18	25	0.0	2.8	0	47	25	0.0	5.6	0
19	25	< 0.0	2.8	0	48	25	1.7	14	1
20	25	0.0	1.1	0	49	27	1.7	36 (5.0)	1
21	25	0.0	3.3	0	50	23	2.2	41 (6.2)	1
22	24	0.6	7.2	0	51	25	0.0	10	1
23	25	0.0	4.5	0	52	25	1.7	23 (8.9)	2
24	25	< 0.0	2.2	0	53	25	< 0.0	1.1	0
25	27	0.0	4.5	0	54	24	0.0	10	1
26	25	0.0	8.4	1	55	25	0.6	10	2
27	25	< 0.0	0.6	0	56	26	< 0.0	1.7	0
28	25	< 0.0	0.6	0	57	24	< 0.0	0.6	0
29	24	< 0.0	1.1	0	58	25	< 0.0	0.6	0

TABLE C-3. Final Status Survey Soil Analysis Results for Remediation of Secondary Contaminated Areas (Continued).

Survey Unit	Sample Number	$^{239+240}$Pu (pCi/g)		Number > DCGL	Survey Unit	Sample Number	$^{239+240}$Pu (pCi/g)		Number > DCGL
		Average	Maximum				Average	Maximum	
59	24	0.0	5.6	0	69	25	< 0.0	0.0	0
60	26	< 0.0	0.6	0	70	24	< 0.0	0.0	0
61	25	< 0.0	6.1	0	71	25	< 0.0	0.0	0
62	26	1.7	58 (23)	1	72	25	< 0.0	0.6	0
63	25	0.0	8.4	0	73	24	< 0.0	1.1	0
64	25	0.0	13	1	74	29	< 0.0	1.1	0
65	33	< 0.0	1.1	0	75	25	0.6	8.4	1
66	24	3.3	45 (7.8)	3	76	26	0.6	7.2	0
67	26	5.6	71 (6.1)	3	77	25	0.0	5.0	0
68	24	< 0.0	0.6	0	78	22	0.0	2.2	0
	Spot removal of activity decreased average concentration; (values) based on post-remediation re-sampling.								

$^{239+240}$Pu to ^{241}Am ratio of 5.57.

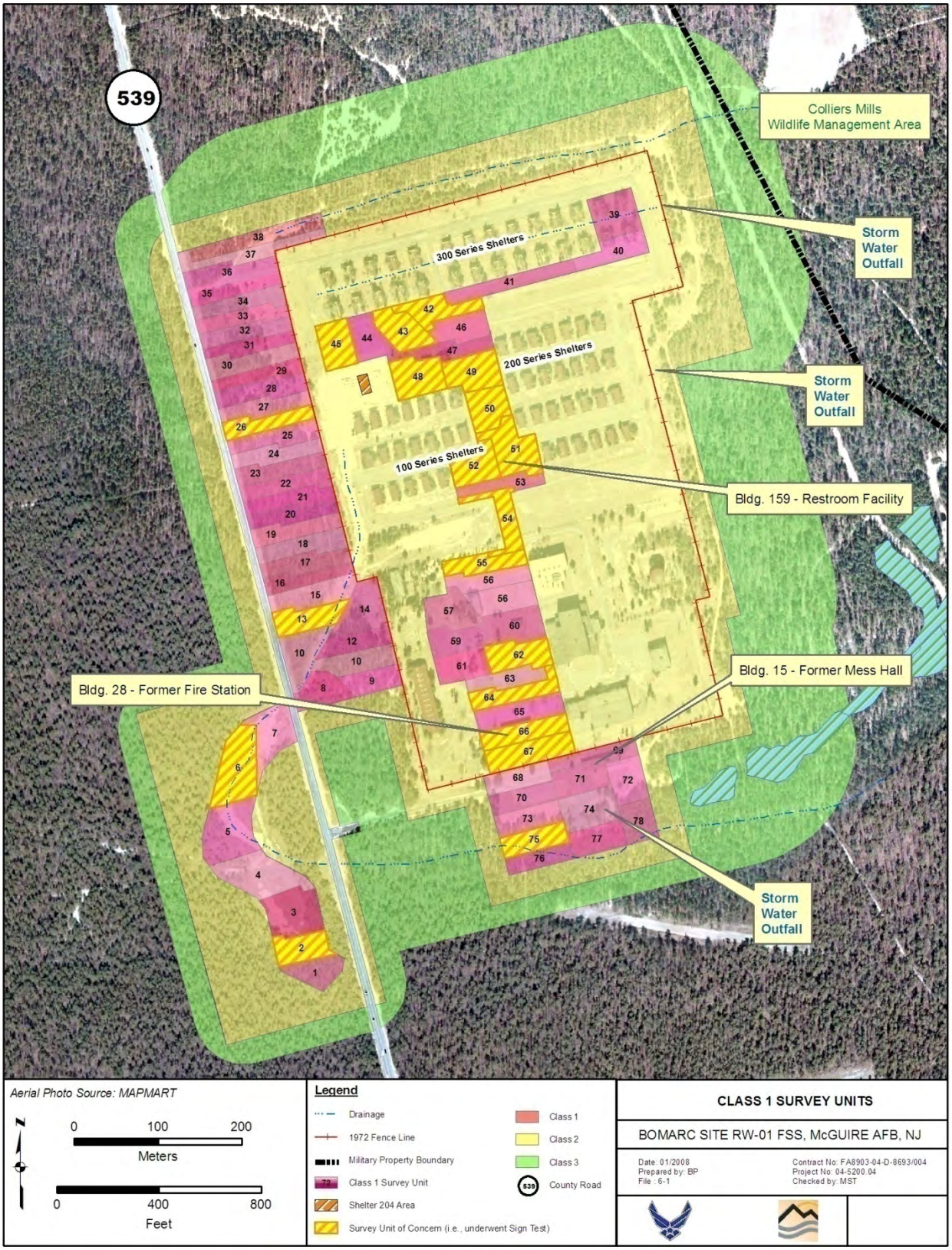


Figure C-16. Class 1 Survey Units (Cabrera 2008).

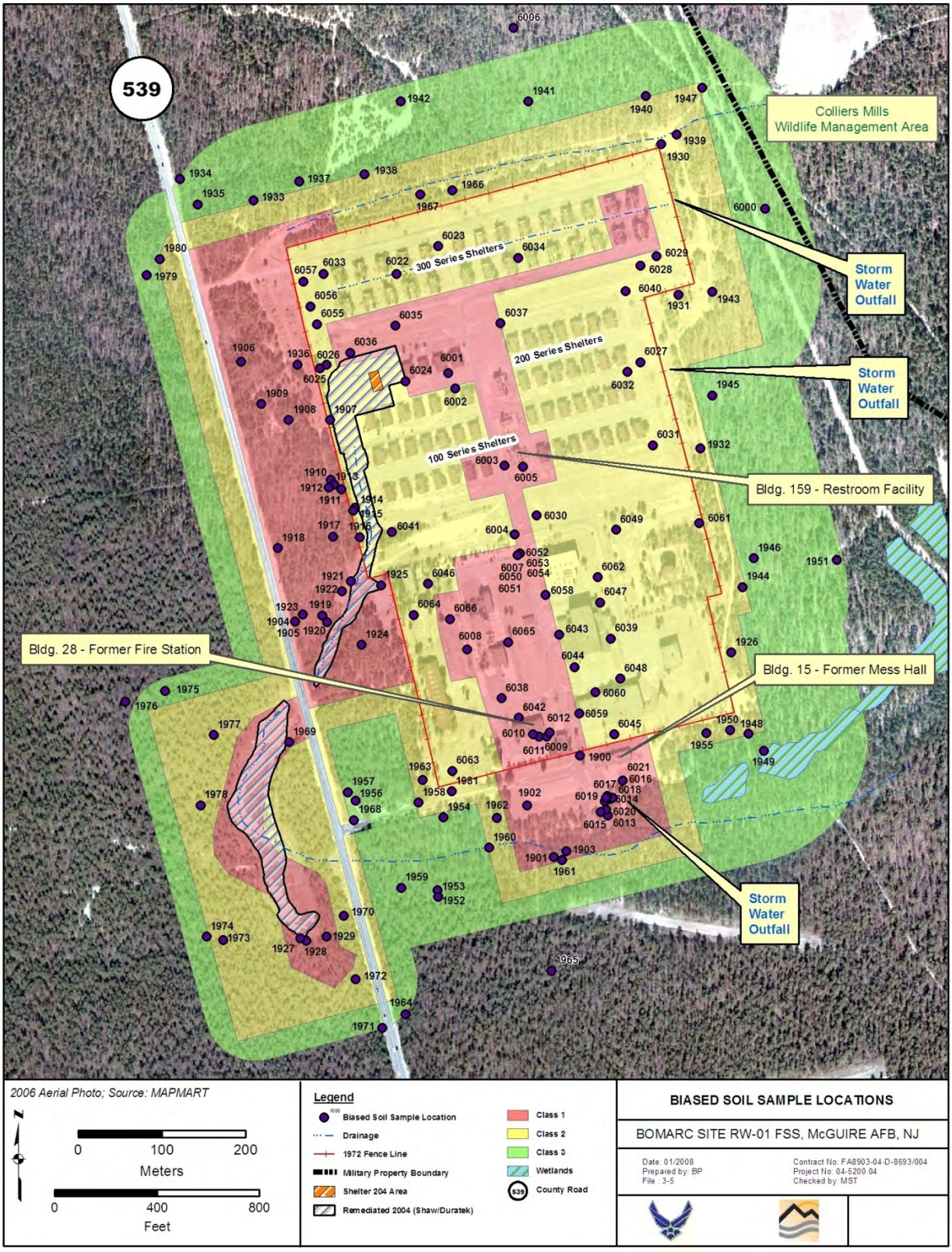


Figure C-17. Biased Soil Sampling Locations Supporting Final Status Surveys in Secondary Areas (Cabrera 2008).

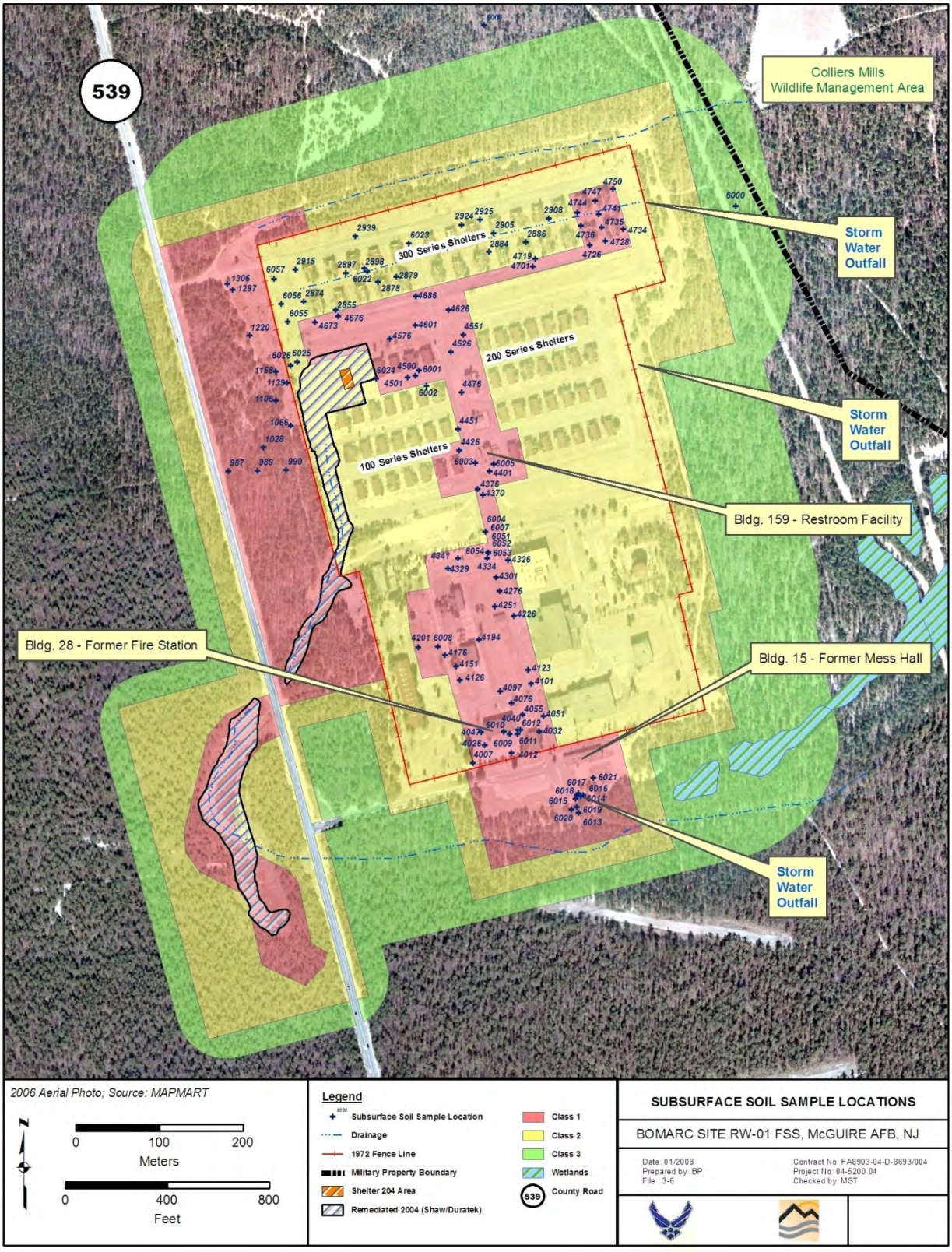


Figure C-18. Subsurface Soil Sampling Locations Supporting Final Status Surveys in Secondary Areas (Cabrera 2008).

Figure C-19. Direct-Push Rig Sampling Location with Positive ^{241}Am Finding, Along Road Edge, South of Missile Area Entrance Gate.

Figure C-20. Location Sampled in Figure C-19, Post Sampling and Remediation of Contaminated Soil, Just Along Edge of Road.

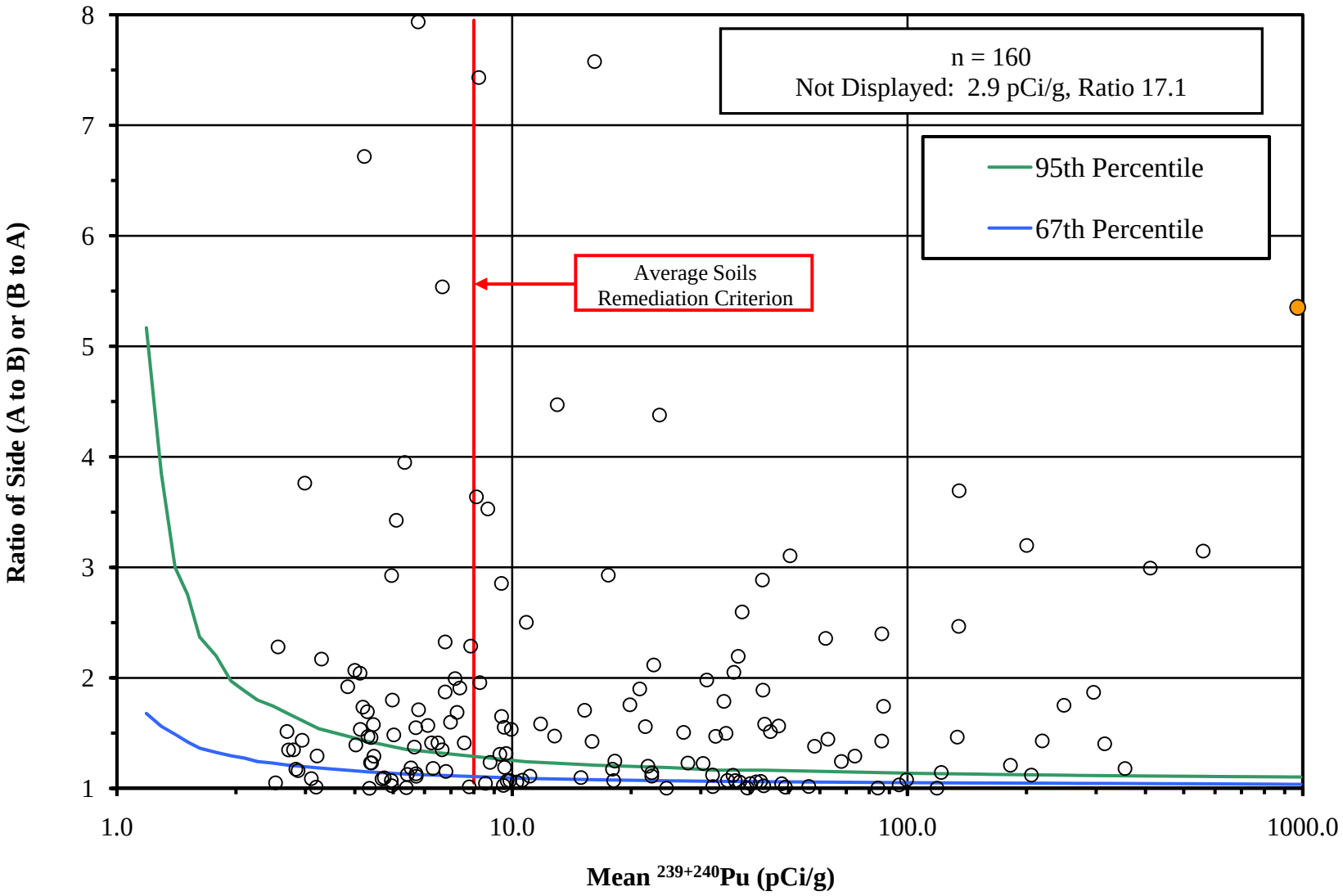


Figure C-21. Ratios of Activity Concentration for Conjugate Assessment of Select Final Status and Biased Soil Samples [Data from Cabrera (2008)].

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Appendix D

Risk-Modeling and Survey Data for Shelters

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TABLE D-1. AEC Reg. Guide 1.86, Excerpted from Rademacher (2005). [Bold for WGP + ^{241}Am].

Nuclide[a]	disintegrations/minute/100 square-centimeters (dpm/100 cm^2)		
	Average[b c f]	Maximum[b d f]	Removable[b e]
U-nat, ^{235}U, ^{238}U & associated decay products	5,000 (α)	15,000 (α)	1,000 (α)
Transuranics, ^{226}Ra, ^{228}Ra, ^{230Th}, ^{228Th}, ^{231}Pa, ^{227}Ac, ^{125}I, ^{129}I	100	300	20
Th-nat, ^{232}Th, ^{90}Sr, ^{223}Ra, ^{224}Ra, ^{232}U, ^{126}I, ^{131}I, ^{133}I	1,000	3,000	200
β–γ emitters (nuclides with decay modes other than α-emission or SF) except ^{90}Sr and others noted above	5,000 (β–γ)	15,000 (β–γ)	1,000 (β–γ)

Notes:

[a]Where surface contamination by both α- and β–γ-emitting nuclides exists, the limits established for α- and β/γ-emitting nuclides should apply independently. [The values apply to radioactive contamination deposited on, but not incorporated into the interior of, the contaminated item.]

[b]As used in this table, dpm means the rate of emission by radioactive material as determined by correcting the counts per minute observed by an appropriate detector for background, efficiency, and geometric factors associated with the instrumentation.

[c]Measurements of average contamination should not be averaged over more than 1 square meter. For objects of less surface area, the average should be derived for each such object.

[d]The maximum contamination level applies to an area of not more than 100 cm^2.

[e]The amount of removable radioactive material per 100 cm^2 of surface area should be determined by wiping that area with dry filter or soft absorbent material, applying moderate pressure, and assessing the amount of radioactive material on the wipe with an appropriate instrument of known efficiency. [The use of dry material may not be appropriate for tritium.] When removable contamination on objects of less surface area is determined, the pertinent levels should be reduced proportionally and the entire area should be wiped. [Except for transuranics and ^{228}Ra, ^{227}Ac, ^{228Th}, ^{230Th}, ^{231}Pa, and α-emitters, it is not necessary to use wiping techniques to measure removable contamination levels if direct scan surveys indicate that the total residual surface contamination (i.e. removable and fixed) are within the limits for removable contamination.]

[[f]The average and maximum radiation levels associated with surface contamination resulting from β–γ-emitting nuclides should not exceed 0.2 mrad/hr @ 1 cm and 1.0 mrad/hr @ 1 cm, respectively, measured through 7 milligrams per square centimeter (mg/cm^2) of total absorber.]

TABLE D-2. Summary of RESRAD-Build Dose Calculations for Contaminated Floor Surface of BOMARC Shelter (10 % Removable Fraction).

Annual Dose Equivalent (mrem)	α-Radiation (dpm/100 cm^2)		
	$^{239+240}$Pu	^{241}Am	Total
100 (t = 0)	10,700	2,000	12,700
4 (t = 0)	430	80	510
4 (30-year mean)	850	160	1,010
Route	Inhalation	Ingestion	External
Dose Percents	97.7	2.1	0.07

TABLE D-3. RESRAD-Build Parameters Used for Evaluations.

Parameter	Value	Parameter	Value
Total Time	10,950 d (30 y)	Inhalation Rate	18 m^3/d
Time Inside	192 h/y	Ingestion Dust	1 x 10^{-4} m^2/h
Fraction Inside	0.022	Deposition Velocity	1 x 10^{-2} m/s
Time to Remove Contaminant	10,950 d (30 y)	Resuspension Rate	5 x 10^{-7} 1/s
Building Area	130 m^2	Fraction Released to Air	0.1
Building Height	4.1 m	Removable Fraction	0.1
Building Floor Dimensions	7 m x 18.5 m	$^{239+240}$Pu to ^{241}Am Ratio	5.4
Air Exchange Rate	53.3 m^3/h	Inhalation DCF (mrem/μCi)	4.3 x 10^5 (W)
Air Exchanges per Hour	0.1	Ingestion DCF (mrem/μCi)	3.5 x 10^3 (D)

TABLE D-4. Summary of RESRAD-Build Area Factors for Values of Table B-2 and Main Shelter Area.

Categories	Area Factors for Various EMC-Sizes					
Geometry (m)	3.0 x 3.0	2.5 x 2.5	2.0 x 2.0	1.5 x 1.5	1.0 x 1.0	0.5 x 0.5
Area (m^2)	9.0	6.25	4.9	2.25	1.0	0.25
Area Factor	14	20	32	56	127	506
Acceptable [α] Concentration (cpm) for 100 mrem/yr	177k	254k	401k	715k	1,610k	6,430k

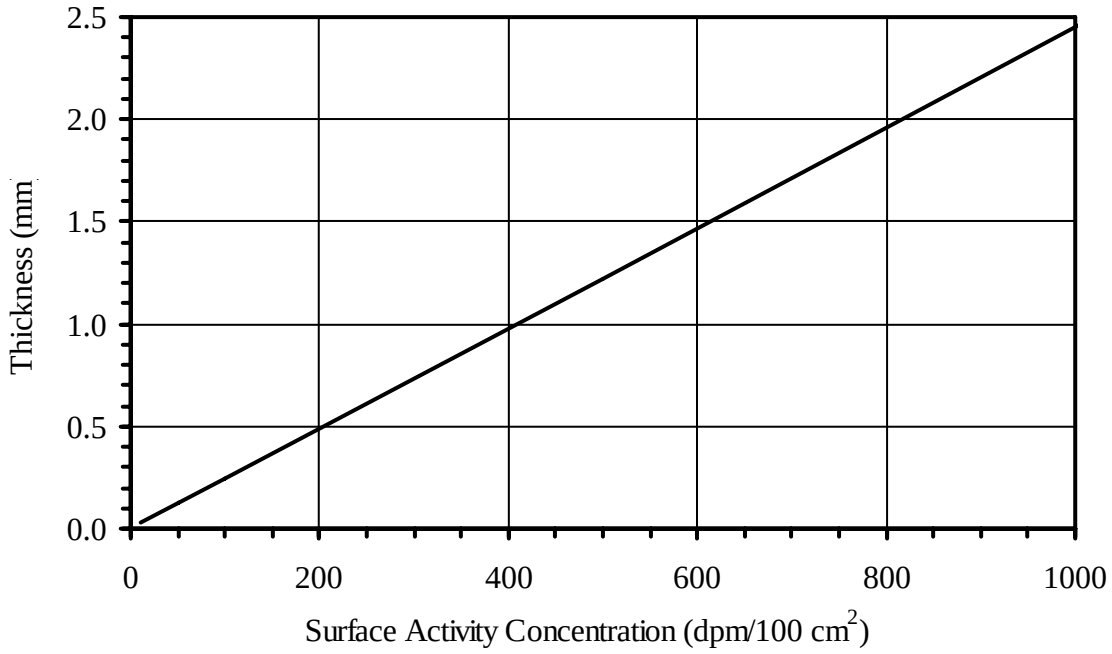

Figure D-1. Averaging Thickness of Concrete vs. Mean Surface Concentrations of $^{239+240}$Pu at 8 pCi/g.

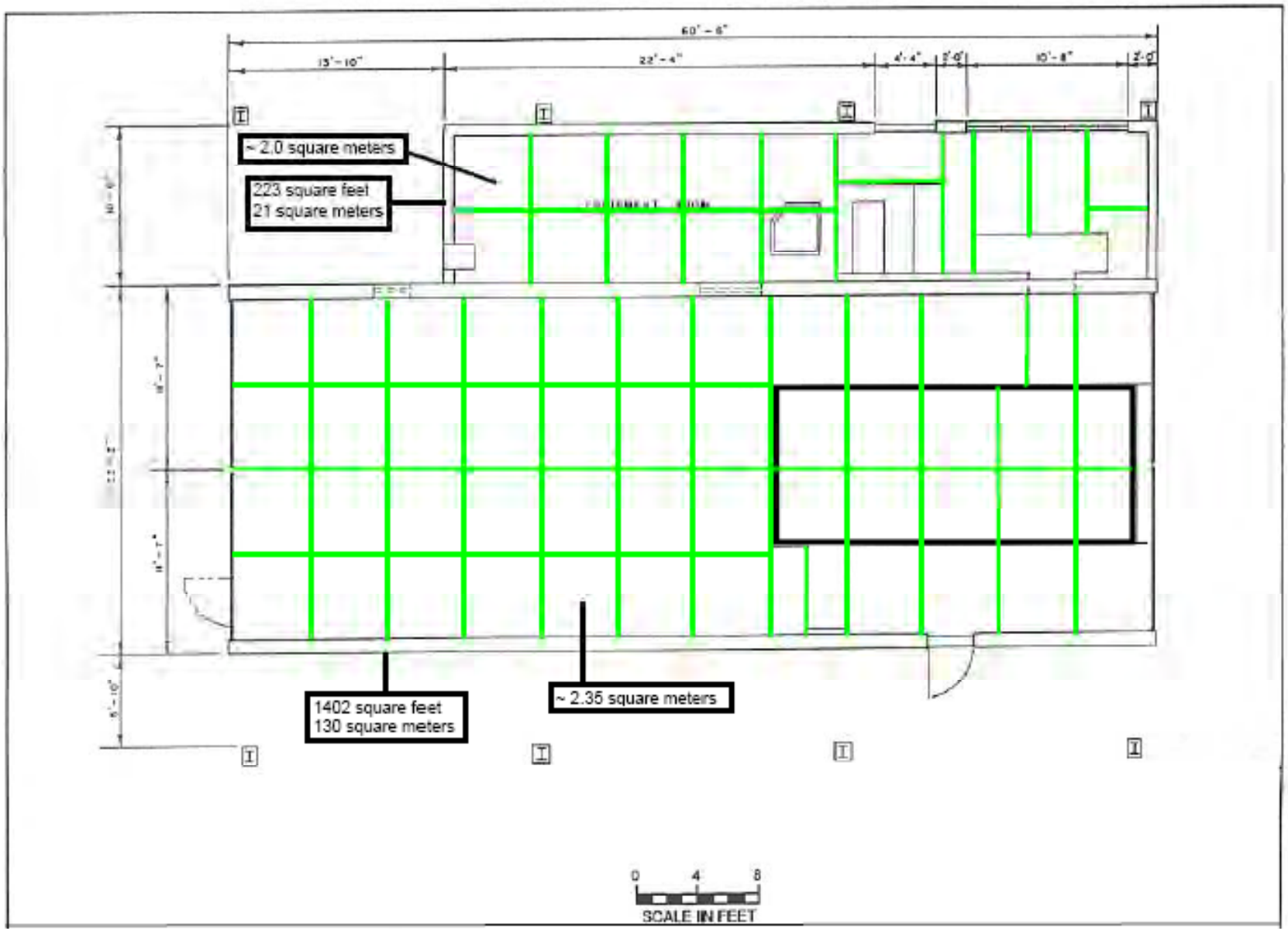

Figure D-2. Example Grid System for Shelter Floor and Pit Surveys.

Figure D-3. Photograph of Intact Model A Missile Shelter (208).

Figure D-4. Photograph of Residual Concrete Pads, Launchers, and Pits of Shelter 202.

TABLE D-5. Shelters and Buildings with FIDLER Screens (Rademacher *et al.* 2009).

Building Number	Note	Building Number	Note	Building Number	Note	Building Number	Note	Building Number	Note
101	--	115	--	201	--	215	--	301	--
102	--	116	2, 6	202	3, 5	216	5	302	--
103	--	117	--	203	--	217	--	303	--
104	--	118	--	204	4	218	--	304	--
105	--	119	--	205	--	219	--	305	--
106	--	120	--	206	3	220	--	306	--
107	--	121	--	207	--	221	--	307	--
108	--	122	--	208	--	222	--	308	--
109	--	123	1	209	--	223	--	309	--
110	--	124	--	210	--	224	--	310	--
111	--	125	--	211	--	225	1	311	--
112	--	126	--	212	--	226	--	312	--
113	--	127	1	213	6	227	1	313	--
114	--	128	1	214	--	228	--	314	--
315	--	319	--	323	--	327	--	27	--
316	--	320	--	324	--	328	--	28	--
317	--	321	--	325	--	21	7	159	8
318	--	322	--	326	--	23	--		

1. Equipment Room Inaccessible (Door Welded Shut or Stuck). 2. B-25 Box Stored. 3. Concrete Pad-Only.
4. Removed in 2002. 5. Not Surveyed. 6. Waste Storage (Partial Survey Only).
7. Only Large Room with Theater-Style Chairs (South-Facing Double Doors). 8. Restroom-Only (South Facing).

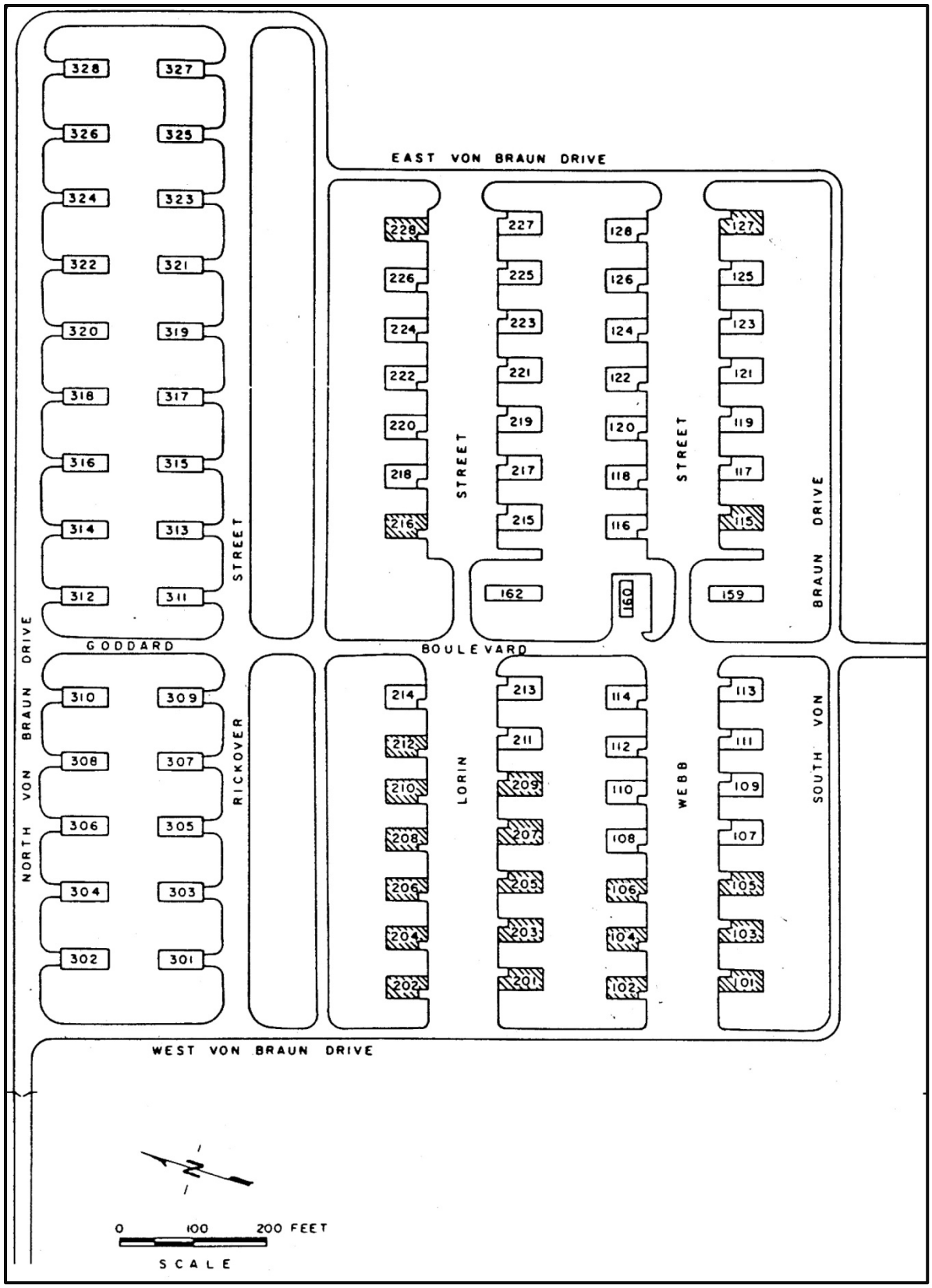

Figure D-5. Shelter Building Layout by Number [Adapted from Figure 3-19, Earth Tech (1992)].

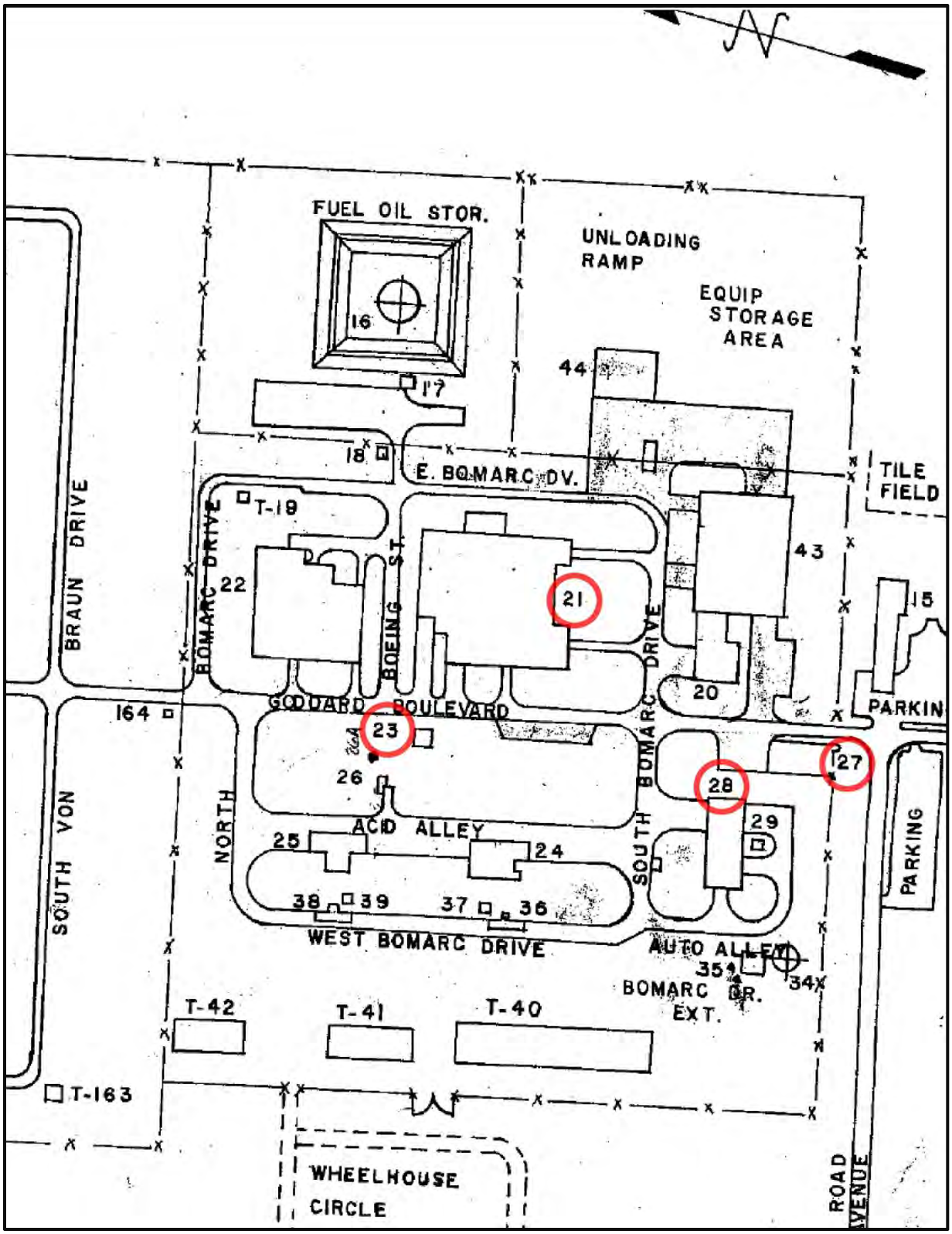

Figure D-6. Building Layout by Number of Non-Missile Area Buildings [Adapted from Figure 2-4, Cabrera (2008), Red Circles Denote Buildings Screened for Radiological Contamination].

TABLE D-6. FIDLER Screening Remarkable Findings (Rademacher *et al.* 2009).

Shelter Number	Location (Cell/Other)	Finding	Later Actions (Disposition)
121	Cells 29/31	FIDLER slightly elevated, under center of He tank	Detailed survey of area, wipe and debris sample. No isolated particle.
123	Cell 30	FIDLER slightly elevated, near pipe depression area	Detailed survey of area, wipe and debris sample. No isolated particle.
124	Cell 29	FIDLER slightly elevated, under He tank	Detailed survey of area, wipe and debris sample. No isolated particle.
126	Cell 30	FIDLER ~ 6k, in pipe depression area of floor	Detailed survey of area. No isolated particle. FIDLER response unconfirmed.
201	Cells 3/4	FIDLER ~ 10k cpm on floor	Loose, readily removed.
	Cell 21	FIDLER ~ 10k cpm on floor	Loose, readily removed.
	Cell 4/5	FIDLER ~ 2.7k cpm on debris	Detailed survey of area, debris sampled. No isolated particle.
	Cell 37	FIDLER ~ 8k cpm on floor	Loose, readily removed.
203	Cell 2	FIDLER ~ 29k cpm on floor	Loose, readily removed.
205	Cell 29	FIDLER slightly elevated, under He tank	Detailed survey of area. No evidence of isolated particle.
	Cell 1	FIDLER ~ 18.5k cpm on floor location	Loose, readily removed. $^{239+240}$Pu estimated @ 290 nCi (field).
207	Cells 44/47	FIDLER ~ 10k cpm on floor location, 20 cpm α-radiation	Hand abrasive removed about 75% of contamination. Rotary hammer successful in removing remaining.
208	Border Cell 4 & Exterior Pad	FIDLER slightly elevated over joint between shelter and pad.	Loose, readily removed by removing material in joint.
210	Cells 4/8	FIDLER ~ 3.5k cpm on floor location	Hand abrasive successful in removal. $^{239+240}$Pu estimated @ 28 nCi (lab).
	Cells 6/7	FIDLER ~ 7k cpm along crack in floor, multiple locations	Four separate closely-spaced locations. Hand removal with chisel successful for one. Rotary hammer successful in removing remaining.
	Cell 16	FIDLER ~ 3k cpm on floor location	Hand removal with chisel partially successful. Rotary hammer successful in removing remaining.
211	Cell 48: Concrete & Metal Threshold	FIDLER ~ 25k cpm on floor location at interface between concrete floor slab and metal threshold	Loose, readily removed by removing material in joint.

TABLE D-7. Debris γ-Spectroscopy Sampling Results (Rademacher *et al.* 2009).

Shelter	Debris Mass (g)	^{241}Am* (pCi/g)	$^{239+240}$Pu**		Area @ 15 cm Depth Equivalent to 8 pCi/g***
			Concentration (pCi/g)	Activity (pCi)	
101 (Main, Partial)	1860	0.15 ± 0.02	0.84	NA	< Criterion
102 (Main, Partial)	1300	1.72 ± 0.14	9.6	NA	NA
104 (Main, Partial)	928	0.56 ± 0.06	3.1	NA	< Criterion
106 (Main, Partial)	953	0.09 ± 0.03	0.5	NA	< Criterion
201 (Main, Partial, 1st)	2680	1.1 ± 0.1	6.1	NA	< Criterion
201 (Equip, 1st)	2170	1.36 ± 0.10	7.6	1.6×10^4	< Criterion
201 (Main, 2nd)	391	0.53 ± 0.08	2.95	1.2×10^3	< Criterion
203 (Main, Partial)	2070	9.9 ± 0.6	55.1	NA	NA
203 (Equip)	1490	2.68 ± 0.18	14.9	2.2×10^4	0.012 m^2
205 (Main)	4770	7.98 ± 0.49	44.5	2.1×10^5	0.12 m^2
205 (Equip)	1830	0.44 ±0.05	2.5	4.5×10^3	< Criterion
207 (All)	6300	5.23 ± 0.33	29.1	1.8×10^5	0.10 m^2
208 (Main, 1st)	3830	20.2 ± 1.2	112.5	4.3×10^5	0.24 m^2
208 (Pit, Partial)	1170	3.12 ± 0.21	17.4	NA	NA
208 (Equip, 1st)	878	0.22 ± 0.04	1.23	1.1×10^3	< Criterion
208 (All, 2nd)	240	2.03 ± 0.20	11.3	2.7×10^3	0.002 m^2
209 (All, 1st)	3320	1.40 ± 0.85	78.0	2.6×10^5	0.14 m^2
209 (All, 2nd)	360	1.73 ± 0.18	9.64	3.5×10^3	0.002 m^2
210 (Main, 1st)	3570	5.92 ± 0.38	33.0	1.2×10^5	0.07 m^2
210 (Pit, Partial)	659	7.61 ± 0.49	42.4	NA	NA
210 (Equip, 1st)	2270	0.51 ± 0.05	2.8	6.4×10^3	< Criterion
210 (All, 2nd)	349	8.16 ± 0.61	45.5	1.6×10^4	0.009 m^2
211 (All)	4200	0.66 ± 0.07	3.7	1.5×10^4	< Criterion
212 (Main)	4740	0.38 ± 0.05	2.1	1.0×10^4	< Criterion
212 (Equip)	1700	0.06 ± 0.01	0.33	5.7×10^2	< Criterion
213 (Main, Partial)	775	< 0.09	< 0.5	NA	< Criterion
214 (All)	8020	1.12 ± 0.08	6.2	5.0×10^4	< Criterion
Bldg. 23 (Decon)	2461	< 0.06	< 0.33	NA	< Criterion
	$^{239+240}$Pu: 8 - 73 pCi/g				$^{239+240}$Pu > 73 pCi/g

* 95% Confidence Interval. ** $^{239+240}$Pu:^{241}Am = 5.57. NA = Not Applicable (Total Mass Unknown).

***1 m^2 @ 15 cm depth and ρ = 1.5 g/cm^3, contains 2.25×10^5 g.

TABLE D-8. Gridded Static α-Radiation and Scanning FIDLER Measurements, and Wipes Data Summary (Rademacher *et al.* 2009).

Analytical Method		Parameter	Shelter Number									
			201	203	205*		207	208	209	210	211	212	214
FIDLER Scanning (cpm, 1-minute integrated)		Mean	1932	1904	1236	1889	1217	1242	1219	1216	1225	1212	1243
		Median	1949	1924	1274	1913	1204	1251	1212	1191	1210	1214	1256
		St. Dev.	122	126	110	129	96	89	85	112	93	77	99
		Maximum	2145	2171	1418	2114	1470	1408	1412	1566	1436	1403	1418
		Minimum	1682	1646	984	1708	1089	1048	990	1027	1002	1073	1009
Static α-Radiation Measurements (cpm) Ludlum 43-89	Before Abrasion	Mean	4.0	6.5	4.8		3.6	6.0	9.2	19.8	3.9	3.4	2.8
		Median	4	4	4		4.0	4	6	17	4	2	2
		St. Dev.	3.2	7.8	4.2		3.9	6.6	12.6	14.0	3.5	3.5	2.5
		Maximum	14	44	18		22.0	32	82	65	16	16	8
		Minimum	0	0	0		0.0	0	0	3	0	0	0
	After Abrasion	Mean	4.4	7.9	6.0		3.6	5.9	7.4	19.1	4.1	2.8	3.3
		Median	4	4	4		2.0	4	6	15	4	2	2
		St. Dev.	3.9	11.7	8.5		3.5	7.2	7.7	15.8	3.1	2.5	2.1
		Maximum	16	72	52		16.0	46	48	66	16	8	8
		Minimum	0	0	0		0.0	0	0	3	0	0	0
	Difference: Before - After	Median	2	0	0		0	0	-2	-1	0	0	0
		Maximum	10	28	50		12	14	12	35	10	6	6
		Minimum	-8	-28	-14		-12	-8	-34	-30	-12	-16	-6
		# Positive	24	22	20		20	17	14	19	21	13	21
		# Negative	19	15	16		19	19	25	24	15	16	12
		# Zero	2	8	9		6	9	6	2	9	16	12
Removable (Wipes)	Gross α-radiation (dpm/100 cm^2)	Highest	1.8	3	< 1.5		1.9	< 1.5	4.7	29.2	1.7	< 1.5	1.7
		2nd Highest	1.3	1.7	< 1.5		1.4	< 1.5	2.7	12.5	< 1.5	< 1.5	1.2
		3rd Highest	< 1.5	1.5	< 1.5		< 1.5	< 1.5	2.1	2.1	< 1.5	< 1.5	< 1.5
		4th Highest	< 1.5	< 1.5	< 1.5		< 1.5	< 1.5	2.1	1.9	< 1.5	< 1.5	< 1.5
	Composites (Isotopic Pu)	$^{239+240}Pu$ (pCi)	1.46	9.87	6.7		4.92	14.2	45.7	92.5	7.22	2.25	1.59
		$^{239+240}Pu + {}^{241}Am$ (dpm/100 cm^2)	0.028	0.19	0.13		0.096	0.277	0.89	1.69	0.14	0.044	0.031

* 1st Column Main Shelter for FIDLER, 2nd Column for Equipment Room.

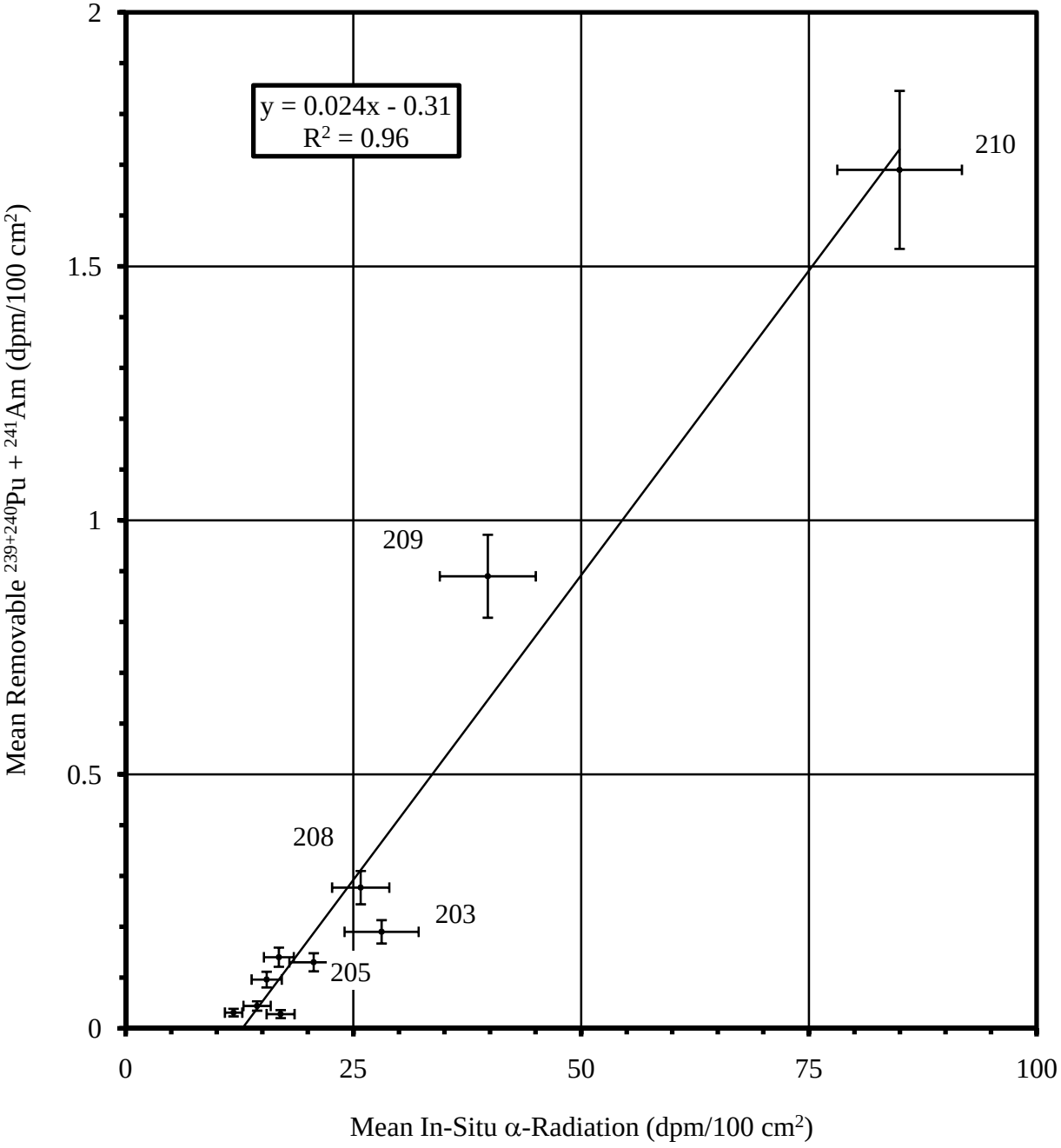

Figure D-7. Scatter plot of Mean Removable $^{239+240}$Pu + ^{241}Am Concentration to Mean In-Situ α-Radiation Concentration [Annotation of Select Shelters, 1-σ Uncertainty Bars] (Rademacher *et al.* 2009).

TABLE D-9. Summary Findings and Acceptable Levels for Surfaces (Rademacher *et al.* 2009).

Category		Conditions/Measurement	α-Activity (dpm/100 cm^2) Removable Fraction	
			10 % (Default)	2.4 % (Measured)
Acceptable Surface α-Activity Concentration	AFI 48-148 (Occupational Use Scenario)	100 mrem in a year dose-equivalent (10% occupancy)	12,700	52,920
		100 mrem in a year dose-equivalent (50% occupancy)	2,540	10,580
		100 mrem in a year dose-equivalent (100% occupancy)	1,270	5,290
	ROD Dose Criteria (Occupational Use Scenario)	4 mrem in a year dose-equivalent (10% occupancy)	510	2,125
		4 mrem in a year dose-equivalent (50% occupancy)	100	425
		4 mrem in a year dose-equivalent (100% occupancy)	50	215
		4 mrem in a year dose-equivalent (30 year average, 10% occupancy)	1,010	4,210
		4 mrem in a year dose-equivalent (30 year average, 50% occupancy)	200	840
		4 mrem in a year dose-equivalent (30 year average, 100% occupancy)	100	420
	NJAC 7:29	15 mrem in a year dose-equivalent (100 % occupancy for resident)	44	181
	NRC Reg Guide 1.86	Average total (limited to 1 m^2 averaging area)	100	
		Maximum total (limited to 100 cm^2 averaging area)	300	
		Removable (limited to 100 cm^2 averaging area)	20	
Removable α-Activity (wipes)		Highest (3), gross α-radiation (among 693 shelters grid samples)	29.2, 12.5, 6.4	
		Highest (2) biased gross α-radiation	39 (shelter 203)	7.0 (shelter 209 pit)
		Highest shelter average $^{239+240}Pu$ + ^{241}Am (among 45 grid composite)	1.7	
Static α-Radiation (Grid Surveys)		Average (Net), Shelter 210 [highest shelter, Table D-8]	85 (72, 90 % CI: 66 – 77)	
		Average (Net), Shelter 209 [2nd highest shelter, Table D-8]	40 (26, 90 % CI: 21 – 32)	
		Highest measurement (shelter 209, Table D-8)	353	
Scanning α-Radiation (Grid Surveys)		Shelter 210, highest average shelter, Table D-8 (Net)	45 (31, 90 % CI: 25 – 37)	
		Shelter 203 (2nd highest average shelter, Table 7-6)	19 (5.5, 90 % CI: 1.7 – 7.7)	
		Highest measured location (shelter 210, pit)	1904	
		Highest measured residual (shelter 210, concrete ledge)	804	
α-Radiation (FIDLER)*		Partial remedial action, cell 44/47, shelter 207	6,770	

* FIDLER identified contamination Remediated

Appendix E

Launcher Pits and Bunkers Data and Photographs

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Figure E-1. Fluid Pumping from Pits.

Figure E-2. Filtering and Storage of Pumped Fluids.

TABLE E-1.Summary of Pit Conditions from 2009 Hydraulic Fluid Removal Activity [Summarized from Cabrera (2009)].

Shelter	Pit Condition		Radiological Measurements			Volume (gallons)		
	Equipment	Launcher	Water ^{241}Am [$^{239+240}$Pu] (pCi/L)	Sediment $*^{239+240}$Pu (pCi/g)	Final Removable α-Contamination (dpm/100 cm^2)	Pit Liquid Pumped	Hydraulic Fluid	Citrus / H_2O Flush
201	6 in. H_2O	Dry, Loose Dirt	ND (E)	6.2 (L)	(-0.8) – 0.5	None	15	25
202	Water Filled		ND (L) [-0.04 (L)]	6.2 (L)	N/A	4,200	25	NR
203	Dry	Dry, Dirt	N/A	N/A	0 – 1.9	None	NR	NR
205	Dry	Dry	N/A	5.9 (L) 1.7 (E)	(-0.8) – 0.5	None	55	35
206	Water Filled		ND (L) [0.05 (L)]	0.5 (L)	N/A	5,000	25	NR
207	2 in. H_2O	6 in H_2O, w/ Hydraulic Fluid	ND (E)	2.3 (E)	(-1.1) – 2.9	900	40	15
208	Dry	Dry	N/A	5.4 (L)	(-2.9) – 0	None	60	10
209	2 in. H_2O	Dry	1.3 (L)	N/A	(-1.1) – 1.6	None	35	55
210	Dry	Dry	N/A	2.7 (L)	(-0.5) – 6.2	None	25	NR
211	6 in. H_2O	2 in. H_2O, w/ Hydraulic Fluid	ND (L) [0.33 (L)] [0.10 (C)]	0.2 (L)	(-0.8) – 3.2	250	80	55
212	N/A	6 in. H_2O, w/ Hydraulic Fluid Spots	N/A	0.9 (L)	(-0.5) – 3.5	NR	50	25
213	1 in. H_2O	Dry, Dirt	< 19 (E) [0.07 (E)]	0.5 (L)	(-0.8) – 0.5	None	NR	NR
214	6 in. H_2O	12 in. H_2O, w/ Hydraulic Fluid	ND (L)&(E)	N/A	(-0.5) – 0.8	3500	20	NR
201-214 Composite	--		--	1.4, (-0.17), 2.2, (-0.11), 0.2, 1.2, (-0.07)	--	--	--	--

ND = Non Detect by γ-Spectroscopy, $*^{239+240}$Pu = ^{241}Am x 5.57, N/A = Not Accomplished, NR = Not Recorded, (E) – Equipment Pit, (L) – Launcher Pit

TABLE E-2. Data Summary for Gridded Fixed α-Radiation and Wipes on Launcher Pit Concrete Surfaces [TABLE 7-7, Rademacher *et al.* (2009)].

Analytical Method		Shelter Number					
		201	203	205	208	209	210
*Fixed α-Radiation Measurements (cpm) Ludlum 43-89	Mean	0.5	0.17	0.9	0.9	1.4	12.5
	Median	0	0	0	0	0	0
	Standard Deviation	1.1	0.6	1.3	1.8	2.2	40
	Maximum	4.0	2.0	4.0	6.0	8.0	188
	Minimum	0	0	0	0	0	0
Removable (Wipes)	Highest Gross α-radiation (dpm/100 cm^2)	< 1.5	< 1.5	< 1.5	< 1.5	6.4	2.3
	Minor Remedial Action Accomplished in Area, Value Not Representative of Final Status						
* For estimated α-emission concentration in dpm/100 cm^2, multiply count rate by 4.35							

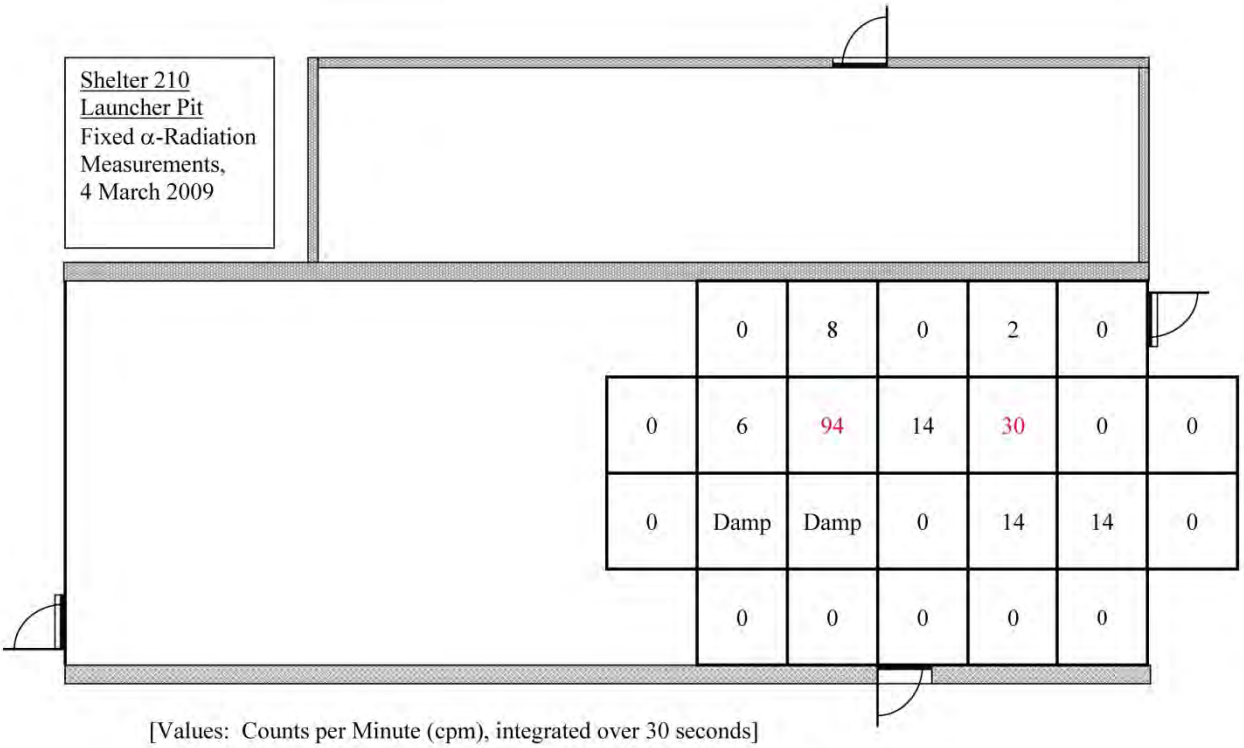

Figure E-3. Fixed α-Radiation Measurements in Launcher Pit of Shelter 210 [Appendix F, Rademacher *et al.* (2009)].

Figure E-4. Pumping and Filtering Water from Shelter 208 Power Bunker.

Figure E-5. Photo of Interior of Shelter 208 Power Bunker.

TABLE E-3. Radiological Data from Bunker Surveys.

Bunker	Gross α-Radiation in Water (pCi/L)	$^{239+240}$Pu in Sediment (pCi/g)		FIDLER Scan	α-Radiation on Surfaces (dpm/100 cm^2)		Reference
					Fixed Range [Mean] {n}	Wipe* (Range) [Mean] {n}	
208C	2.4 ± 1.4	< 1.4		1 spot metal flange, 7 kcpm	N/A	N/A	Rademacher *et al.* 2009
208P	3.6 ± 1.5	34.2		3 spots metal flange, 4 – 5.5 kcpm	N/A	N/A	Rademacher *et al.* 2009
	1.6 ± 1.4	N/A		Unremarkable	0–107.0 [31.3] {11}	16.3–20.9 [18.6] {2}	Cape 2009
210C	N/A	N/A		Unremarkable	2.3–109.3 [32.8] {10}	2.3–7.0 [4.7] {2}	
210P	1.0 ± 1.0	Composite	18.4	Unremarkable	2.3–39.5 [22.0] {9}	(-2.3)–4.7 [4.7] {2}	
212C	1.3 ± 1.4			Particle in debris, removed (45 kcpm)	2.3–20.9 [14.8] {10}	14.0-16.3 [15.2] {2}	
212P	1.2 ± 1.5			Unremarkable	0-32.6 [14.4] {10}	4.7-20.9 [12.8] {2}	
N/A = Not Accomplished, * Large Area Wipes (one per bunker was wipe of floor sludge							

Figure E-6. Select Portion of Figure C-14.

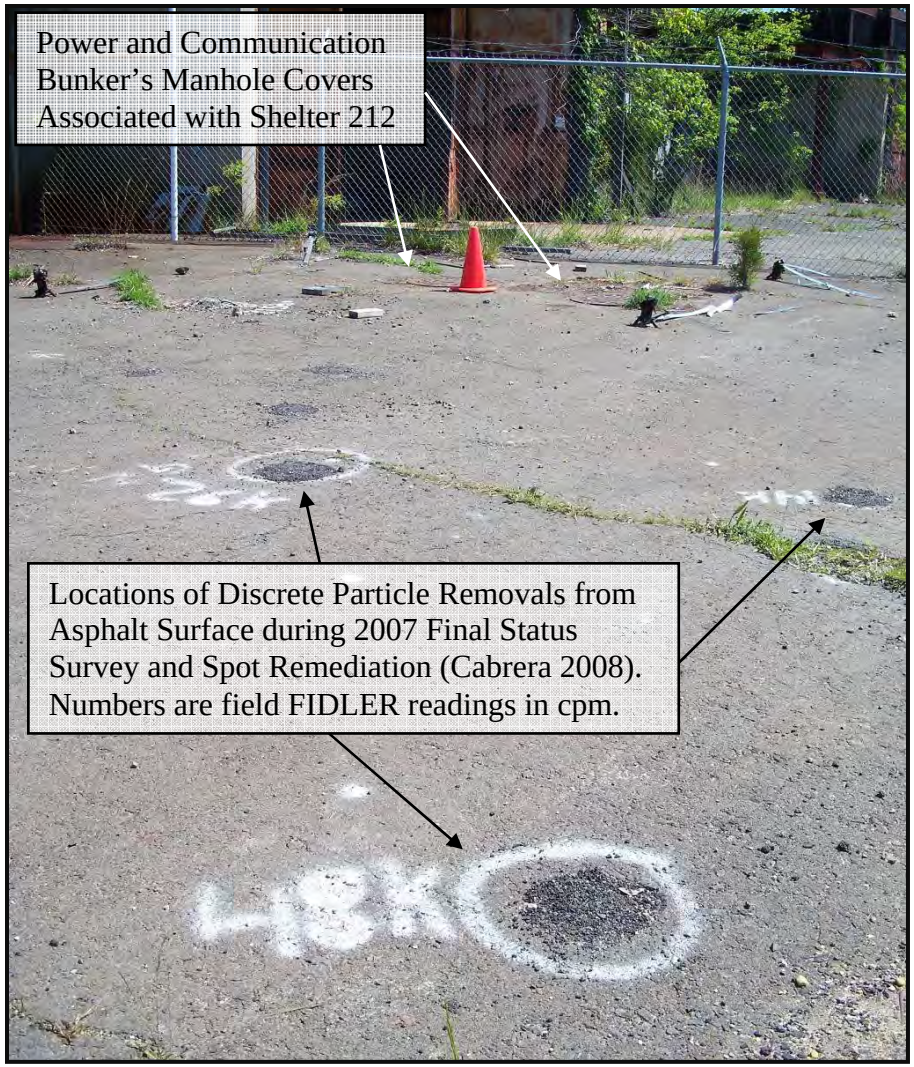

Figure E-7. Asphalt Area in Vicinity of Manhole Covers to Shelter 212 Communication and Power Bunkers (White Paint Identifies. FIDLER Reading and Location of Discrete Particle Removals).

Figure E-8. Soil Contamination Removal Area Near Shelter 213 (Area 1 on Figure E-6).

Figure E-9. Soil Contamination Removal Area Near Building 162 (Area 2 as Annotated on Figure E-7).

Figure E-10. Bulkhead to Shelter 216 Power Bunker (Arrows Indicate Location of α-Radiation Contamination on Grout).

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