Radiological Closure of a Nuclear Weapon Accident Site with Plutonium Contamination - 9479

J. Hackett, PE, CHP, J.J. Weismann, CHP, M. Tepperman, RG
Cabrera Services, Inc.,
473 Silver Lane, E. Hartford, CT 06118

S.E. Rademacher, PhD, CHP
U.S. Air Force Safety Center
9700 Avenue G, SE, Kirtland AFB, NM 87117

ABSTRACT

An explosion and fire in a BOMARC-missile launching pad in June 1960 resulted in the direct release of weapons grade plutonium (WGP) within the confines of an Air Force site in central New Jersey. The site had undergone a large-scale remediation and final status survey (FSS) in 2002 to 2004 that resulted in over 20,000 cubic yards (yd^3) of plutonium-contaminated soil being excavated. However, it was later discovered that the prior investigation did not address all impacted areas of the site. Several years after the initial remediation project was completed, plutonium contamination in the form of discrete particles was discovered at the site in areas excluded from the previous investigation. Emergency response activities following the fire, while following standard practices of the day, resulted in the initial spread of contamination beyond the expected fate and transport pathways that were addressed during the initial project. Routine maintenance and site operational activities at the site also contributed to further spread of contamination beyond what was expected.

Cabrera Services, Inc. (CABRERA) completed several phases of site characterization, radiological remediation, and final status survey (FSS) at the site in accordance with the Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) [1] to address the discrete particle issues at the site. CABRERA also conducted a thorough plutonium particle speciation study in coordination with the University of Nevada at Las Vegas as part of the development of a radiological conceptual site model. Details of this study are being presented in a separate publication.

The WGP contamination throughout the site presented unique challenges in terms of site characterization and remediation. Specific technical challenges included the field detection of discrete high-activity plutonium particles over a 200-acre site and designing survey and sampling approaches to ensure compliance with the protocols outlined in the MARSSIM. CABRERA utilized innovative technologies and approaches to achieve these goals, including a large-area sodium-iodide (NaI) gamma scanning spectrometry system, *in situ* gamma spectroscopy with high-purity germanium detectors, and multiple-depth soil sampling methods to identify locations with contamination exceeding ROD criteria (8 picocuries per gram [pCi/g] plutonium-239/240 [Pu-239/240]). The large area scanning system was a driveover-based multi-channel analyzer system with integrated Global Positioning System units to quickly identify, locate, and map areas of concern. The driveover data was post-processed using regions of interest and background subtraction to improve detection sensitivity with ^{241}Am region of interest data correlated with soil concentration data obtained from an on site gamma spectroscopy laboratory. Remediation activities ranged from individual discrete particle removal to bulk soil excavation in several areas of the site. Over 60 yd^3 of additional contaminated soils were required to be excavated to ensure that all survey units would meet FSS requirements.

In 2007, CABRERA completed field characterization and remediation activities at the Site, and in 2008 issued the FSS report recommending that the site was suitable for closure in accordance with the

requirements of the published Record of Decision (ROD). [2] The results were subsequently approved by the US Air Force Safety Center and the State of New Jersey Department of Environmental Protection.

INTRODUCTION

Cabrera Services, Inc. (CABRERA), under contract to the U.S. Air Force, successfully completed the radiological release of a former Boeing Michigan Aeronautical Research Center (BOMARC) missile accident site. The eventual release was the culmination of a multi-phase investigation performed under the framework of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) and the MARSSIM. The BOMARC Site occupies approximately 218 acres (882,000 square meters [m^2]) on a military reservation in Central New Jersey. The facility is located on land permitted to the Air Force.

Completion of this FSS and Spot Remediation project was an integral part of the overall site closure strategy for achieving unrestricted radiological release of the overall Site impacted area from the United States Air Force Safety Center (AFSC), which has regulatory authority for the plutonium under Section 91(b) of the US Atomic Energy Act of 1954. To accomplish this objective, a comprehensive, adaptive site closure strategy was implemented that included characterization, remove of any discrete Pu particles or localized Pu particle concentrations found, and final status survey of all areas in order to meet the BOMARC RW-01 Accident Site ROD signed into effect in November, 1992. [2] The New Jersey Department of Environmental Protection (NJDEP) served in a consultation and advisory role throughout the CERCLA investigations performing reviews of site planning documents, field operations and reports.

SITE BACKGROUND

On June 7, 1960, at approximately 1500 hours, sensors in Shelter 204 at the BOMARC Site detected a fire caused by an explosion. The shelter was unattended at the time and the missile was in a “ready” state. Local firefighters responded to the alarm within 3 to 5 minutes. The fire continued to burn intensely, consuming most of the fuel, until approximately 1600 hours when Explosive Ordnance Disposal (EOD) personnel entered the area to check the status of the missile. The fire was brought under control by 1615, and continued to burn at a low intensity until approximately 1830 hours; the order to cease operations and leave lines charged was given at approximately 2000 hours. Water continued to be sprayed into the shelter for an additional 8 hours. The approximate 30,000 gallons of water used to extinguish the fire flowed out from under the door of the shelter, down the asphalt apron and west down the street, where it entered a drainage culvert [3].

The explosion and fire in Shelter 204 at the BOMARC missile installation resulted in the release of Weapons grade plutonium (WGP), along with small quantities of weapons grade uranium (WGU) and depleted uranium (DU), within the confines of the site. An initial cleanup of the remaining missile components was performed immediately following the incident. The USAF and U.S. Department of Energy (DOE) prepared an unclassified report that estimated the upper limit of Pu left on the BOMARC Site after the initial cleanup at 300 grams (g).

Throughout the 1960s, 1970s, and 1980s, numerous radiological surveys and investigations were performed to monitor residual levels of Pu-239, Americium-241 (Am-241), and other non-radioactive contaminants at the Site (Figure 2-3). In addition to scanning surveys, surface soil, subsurface soil, vegetation, groundwater, potable water, and surface runoff water samples were intermittently collected and analyzed along with smears (for removable radioactive contamination) and direct radiation measurements.

The BOMARC site was voluntarily investigated by the USAF using processes delineated by CERCLA. The site did not screen high enough during the Preliminary Assessment to warrant inclusion on the National Priorities List as a Superfund site. A Remedial Investigation (RI), Feasibility Study (FS) and Baseline Risk Assessment were performed between 1989 and 1992 to determine the extent of radioactive contamination at the Site, resulting risks to human health and the environment, and the need for and extent of remedial actions. [4] The RI included a geophysical investigation, field measurements, and collection and analysis of samples. Samples included groundwater, surface water, concrete and asphalt cores, surface soil, subsurface soil, wipe, and ambient air. The geophysical survey was performed using magnetic profiling and ground penetrating radar.

The USAF decided to pursue the 'Offsite Disposal' alternative from the FS with disposal of radioactive contaminated waste at an offsite radioactive waste disposal facility. The selected remedy for the Site addresses source control (remediation of on-site contaminant sources) of radioactive wastes in order to eliminate or reduce the risks posed by the site to levels that are protective of human health and the environment. The major components of the selected remedy included:

- Excavation of source soils containing greater than 8 pCi/g of Pu. This will limit maximum risk to any future resident of the site to a level on the order of one in 10,000 (10^{-4}) excess cancer risk, a level considered acceptable by the EPA;
- Excavation and sectioning of contaminated portions of the concrete apron, utility bunkers and the missile shelter;
- Excavation and removal (if found) of the missile launcher;
- Containerization, transport, and disposal of radioactive materials in an offsite facility designed for long-term management of radioactive materials;
- Restoration of the site by back filling with clean fill as needed, followed by grading and re-vegetation of the site with indigenous plant species. In addition, strict engineering controls will be applied during the excavation phase to prevent any possible exposures to workers or to offsite populations. These include dust suppression, and runoff/sedimentation control measures.

The Record of Decision (ROD) decision was based on information contained in the Environmental Impact Statement (EIS) filed with the U.S. Environmental Protection Agency (EPA) on May 22, 1992 [4], the RI/FS dated May 1992 [5], and the administrative record for the BOMARC Missile Accident Site.

Summary of Prior Investigations

Based on the 1992 RI/FS, 1992 ROD, and 1996 site characterization [6], a remedial action was from 2002 to 2004 to remove Pu contaminated soil and building materials from the area around Shelter 204 and along the drainage path to the southwest. Remedial activities began in March 2002 and were completed in June 2004. Over 20,000 cubic meters (m^3) of Pu contaminated soil and debris was excavated and shipped to an offsite disposal facility. It is believed that the 2002-2004 remediation effort removed over 99 percent of the radiological contamination left on site following the BOMARC missile accident. [7]

Following remedial activities, final status surveys (FSS) were performed in all remediated areas. The surveys included scanning 100 percent of the survey area with FIDLER detectors, systematic soil sampling, and biased surface soil sampling based on scan results. Some additional remediation was documented as being required based on results of the scan surveys and soil sample results.

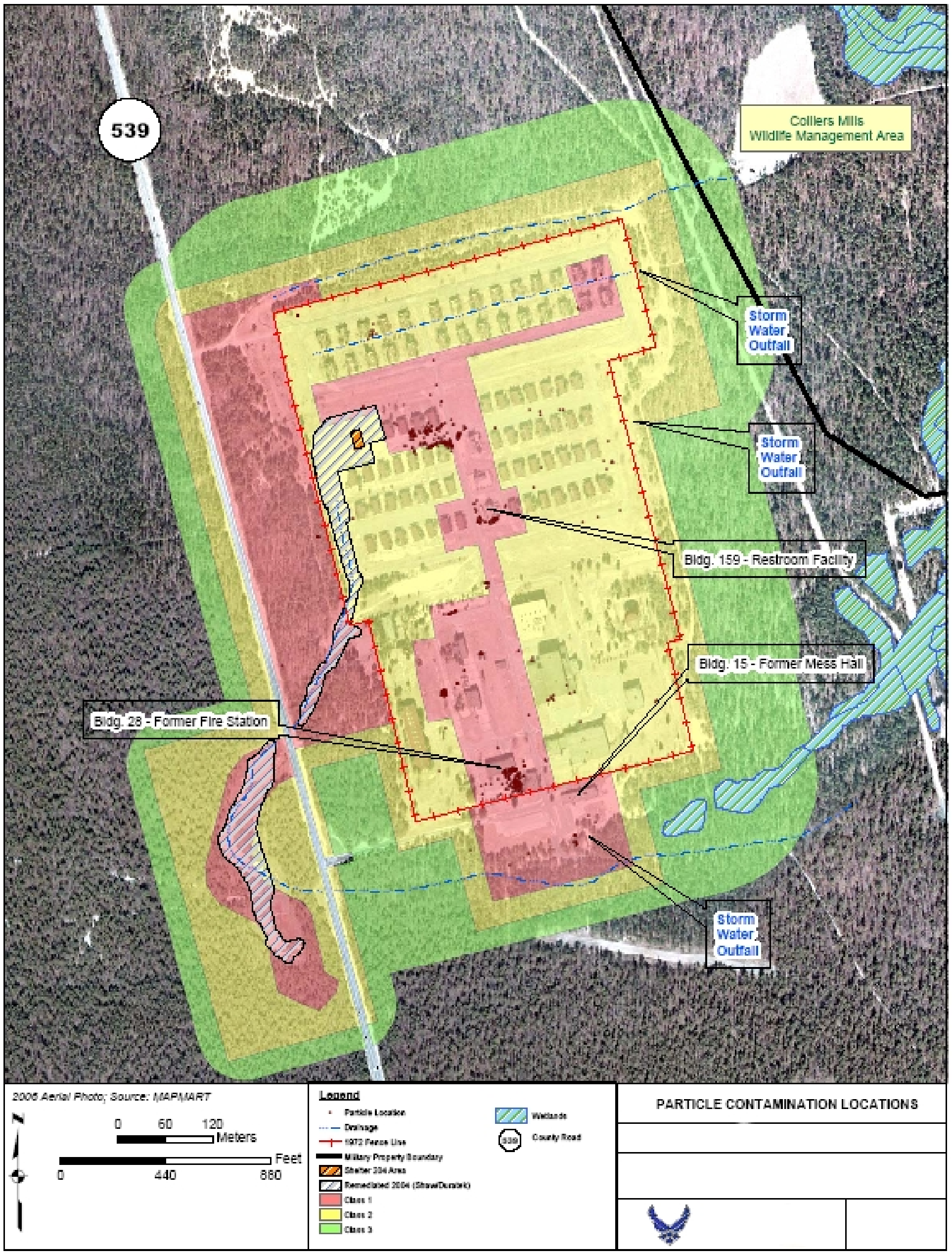
It was later discovered that the prior investigation did not address all impacted areas of the site. Several years after the initial remediation project was completed, plutonium contamination in the form of discrete particles was discovered at the site in areas excluded from the original remedial action. It is postulated that emergency response activities following the fire, while following standard practices of the day, resulted in the initial spread of contamination beyond the expected fate and transport pathways that were addressed during the initial project. Contamination was generally located at three following types of locations:

- Areas directly associated with the 1960 incident response activities
- Accumulation points from precipitation-related events since the 1960 incident
- Areas with contamination tracked in by other activities since the 1960 incident

The locations of the particle contamination found at the BOMARC site are shown in Fig. 1. The areas with the highest occurrence of particle contamination were those that were believed to be directly associated with the response to the 1960 release incident. These areas include the restroom facility at Building 159, the vehicle wash-down area near Building 28 (Maintenance Building/Fire Station), the refueling area near Building 36, and the guard station at the entrance to the Shelter area. Particle contamination was also found at collection points, such as road intersections, where runoff from asphalt areas would accumulate. The collection of particles discovered at the southern portion of the Site (notated near the storm water runoff label on Fig. 1) is also believed to be due in part from snow removal activities performed on the adjacent asphalt parking areas during winter months. Finally, areas of contamination were found at seemingly random locations. It is postulated that these areas are the result of contamination tracking from one of the primary areas, although the true mechanism for transport is not precisely known.

In 2005, CABRERA performed a Phase I Characterization Investigation on the discrete particles using surface and subsurface soil sampling, downhole gamma measurements, and *in situ* gamma spectroscopy. Included in this investigation was a particle speciation study at the University of Nevada Las Vegas (UNLV). This study was commissioned to study the chemical and physical forms of the Pu particles for use in environmental fate and transport modeling as well as human health risk assessment evaluations. A summary of their experimental results included:

- Electron microscopy showed that the discrete particles had relatively large physical dimensions (100 – 500 micrometers in diameter);
- The Pu particles are chemically and physically stable, and could remain in the environment in their current form without significant environmental weathering from normal conditions; and
- The large particle size and form make them non-respirable and highly insoluble, meaning that the potential dose consequence from either inhalation or ingestion was not significant.



-

Fig. 1. Map of Residual Particle Locations Discovered at the BOMARC Site. The Footprint of the Former Remediation Effort is Shown as Crosshatch. The MARSSIM Classification Scheme of the New FSS is also Overlaid for Reference.

SCOPE OF ADAPTIVE CLOSURE PROJECT

Overview

Field activities conducted as part of this closure project involved the characterization, remediation, and FSS of all BOMARC Site in accordance with MARSSIM criteria. The objectives of the radiological characterization and remediation of the BOMARC Site were to:

- Determine the extent of Pu contamination in soil and asphalt with radioactive concentrations above the ROD remediation goal of 8 pCi/g;
- Remediate areas contaminated radiologically above the ROD clean-up level;
- Verify the adequacy of the remediation; and
- Demonstrate through the FSS process that the BOMARC Site is suitable for unrestricted radiological release, per the requirements of the ROD. [2]

Radionuclides of Concern

The radionuclides of concern (ROC) present in WGP are primarily Pu-238, Pu-239, Pu-240, and Am-241 from the decay of Pu-241 (half-life of 14.7 yr). The estimated alpha particle activity fractions for the WGP at the BOMARC Site in 2005 as provided by AFSC are: Pu-238: 0.014, Pu-239: 0.68, Pu-240: 0: 0.15: and Am-241: 0.16. AFSC estimated the total Pu to total U activity ratio at 469:1 based on previous characterization studies [6].

Table I. Radionuclides of Concern for BOMARC Site FSS Investigation

Radionuclide	Half-life (yr)	Principal Mode of Decay and approximate energies [in megaelectron volts (MeV)]
Pu-239	2.41E04	Alpha: 5.16, 5.14
Pu-240	6.56E03	Alpha: 5.17, 5.12
Am-241	4.32E02	Alpha: 5.49, 5.44 Gamma: 0.0595
U-234	2.44E05	Alpha: 4.78, 4.72

Of the radionuclides listed above, Am-241 has the most favorable photon emission characteristics with a 59.5 keV gamma-ray with an emission frequency of 36 percent. This photon is of sufficient energy to afford reasonable measurement sensitivity in high-resolution gamma spectrometry counting systems. Plutonium-239/240 has direct photon emissions, but the energy is very low (14 keV x-ray), making measurement difficult due to attenuation in the soil. A Pu-239/240 to Am-241 ratio of 5.4 to 1 was established based on the review of numerous environmental investigations performed over a 38-year period. The *Review of the $^{239/240}$Pu to ^{241}Am Activity Ratio Analysis for Work Related to Remediation of the BOMARC Missile Accident Site* [8] documents 5.4 to 1 as the best estimate of the Pu-239/240 to Am-241 ratio for soils at the BOMARC site For purposes of the FSS, a surrogate ratio derived concentration guideline level ($DCGL_{SR}$) of 1.5 pCi/g Am-241 was used to represent the clean-up level established in the ROD. The radionuclide ^{241}Am was used as a surrogate for Pu, specifically Pu-239/240, which comprises over 95% of the Pu activity.

Adaptive Survey Design

The BOMARC site survey was designed to be adaptive in the sense that all surveys were designed in accordance with the project data quality objectives (DQOs) and survey considerations given in MARSSIM such that the data could be used to support decisions regarding suitability for unrestricted radiological release of the Site. If the data collected in a particular area met the requirements for release in accordance with the MARSSIM FSS design, then it was considered released. Conversely, if discrete particles or a was discovered during either scan surveys or soil sampling, that area was investigated, remediated as required, then re-surveyed to verify compliance with the DQOs.

The entire Site investigation area was divided into either MARSSIM Class 1, 2, or 3 survey areas, depending on the locations of previously identified discrete particles and information uncovered during Historical Site Assessment research. The layout of the survey areas planned for the Site FSS are shown in Fig. 1. The classification scheme is color-coded for easy identification of each particular area.

Table II. Area Breakdown for Each MARSSIM FSS Classification Type

Survey Area Classification	Total Area (acres)	Total Area (m^2)
Class 1	45	182,109
Class 2	111	449,201
Class 3	62	250,905
Total	218	882,215

Survey Implementation

Surface scanning measurements, soil sampling at both and biased locations, and spot remediation with confirmatory surveys were all utilized to accomplish these stated survey objectives. Each of these survey actitivities are described in more detail below.

Surface Scans

Surface scan measurements in all survey areas were performed using CABRERA's Large Area Scanning System (CLASS). CLASS is designed as a turn-key system to rapidly measure, spatially correlate, and GIS map radioactivity concentrations in support of environmental characterization, remediation, and site closure activities. The CLASS is designed to mount to a variety of mobile survey platforms and is ruggedized to operate in a variety of environmental conditions. The system was front-mounted on an all-terrain vehicle for the scan surveys at the BOMARC Site. A photograph of the mounted system is shown in Fig. 2.

Fig. 2. CABRERA Large Area Scanning System (CLASS) Front-Mounted on ATV

The CLASS consists of an RSI RS-701 integrated controller and data acquisition system, an digital gamma ray spectrometer/multi-channel analyzer (MCA), a data controller, one to four RSX-256 4-liter (256 cubic inch) sodium-iodide (thallium activated) (NaI(Tl)) gamma scintillation detectors, and internal GPS. An external high resolution Trimble Pro XH GPS receiver can also be incorporated for better spatial correlation of collection radiation data. Radiation and location information is collected by the system at a very high data transfer rate (nominally one data point every second), and stored in an uncorruptible data file for real-time feedback and data validation/post-processing. The system operator receives real-time feedback using waterfall plots of total and radioisotope specific response and geo-referenced mapping of relative radiation concentrations. The data can also be transferred through a wireless network back to our data management center for real-time processing, and for conversion into GIS maps and data presentation formats.

The digital interface enables the user to pre-set multiple regions of interest (ROIs) within the energy spectrum to identify and track specific gamma radiation emissions from gamma-emitting ROCs. Using an ROI for field scanning is advantageous as it greatly reduces the detector background, which in turn reduces the scan minimum detectable concentration (MDC). For the BOMARC Site, four independent ROIs were programmed into the RSI for data collection: Raw Am-241 peak (55 – 65 kiloelectron volts [keV]), Background subtracted Am-241 peak, Raw Total Counts (0 – 3000 keV), and Background-subtracted Total Counts (0-3000 keV). Background subtraction is accomplished in the RSI software through entry of counts (or count rates) measured in target ROIs at the established background reference areas. The discrete particle scan MDC was developed based on the most-limiting elevated measurement comparison (EMC) area (80 m^2). This area corresponded to the 'largest unsampled area' within the triangular systematic grid spacing pattern of a Class 1 survey unit. The CLASS system was shown to be able to detect an elevated area of discrete contamination that satisfied this $DCGL_{EMC}$.

The CLASS also utilizes internal energy gain stabilization to ensure the ROIs remain centered on the corresponding energy peaks. The CLASS can operate with one to four large volume (4L) NaI detectors and can be set up to collect data independently from each detector or in a serial collection mode. The independent data collection allows for better spatial sensitivity while the serial or summed collection mode allows for overall maximum detection sensitivity. The serial collection mode can operate effectively due to the digital gain stabilization which maintains consistent response over the survey interval.

Areas identified by gamma surface scan measurements with contours of z-scores (number of standard deviations from the mean) greater than 3.0 were investigated. Sample locations with results that exceeded the investigation levels were further surveyed to determine the extent of the elevated residual radioactivity. *In-situ* gamma scanning using field instrument for the detection of low-energy radiation (FIDLER) detectors was used to investigate areas suspected of elevated residual radioactivity and to identify discrete particles. Remediated areas of elevated residual radioactivity were resurveyed by collecting surface soil samples and performing surface scans over 100% of the accessible area.

Soil Sampling and Analysis

Soil samples were collected to a depth of approximately 6 inches using hand shovels to remove the sample of soil. Asphalt samples were dislodged from roadways and parking areas by using jackhammers. Samples from over 3,000 soil and asphalt locations were collected for analysis. The locations of the Class 1 and Class 2 MARSSIM-design FSS samples are shown in Fig. 3.

An onsite gamma spectroscopy laboratory, equipped with two high-purity germanium (HPGe) detectors, was used to provide near real time analytical results for soil and asphalt samples. This reduced turnaround time was especially useful to support the adaptive sampling protocols, specifically with regard to quickly determining lateral and vertical extent of elevated residual radioactivity in identified areas. The chosen sample geometry was a 400-gram cylindrical cup with a height of approximately 6.3 centimeters (2.5 in). This geometry was chosen to allow for tandem counting of both sides of the cylinder to reduce the impact of heterogeneity issues that could result from single particles of low-energy (i.e., 59.5 keV) ^{241}Am photons. [9] Each sample was counted for a total of 20 minutes, with the first 10 on the first side, followed by a sample flip and continuing the count for another 10 minutes. The resported result is thus the composite average of the container over the total 20 minute counting period. Radiological data were reported as pCi/g dry weight along with estimated counting uncertainty and peak MDC in pCi/g dry weight.

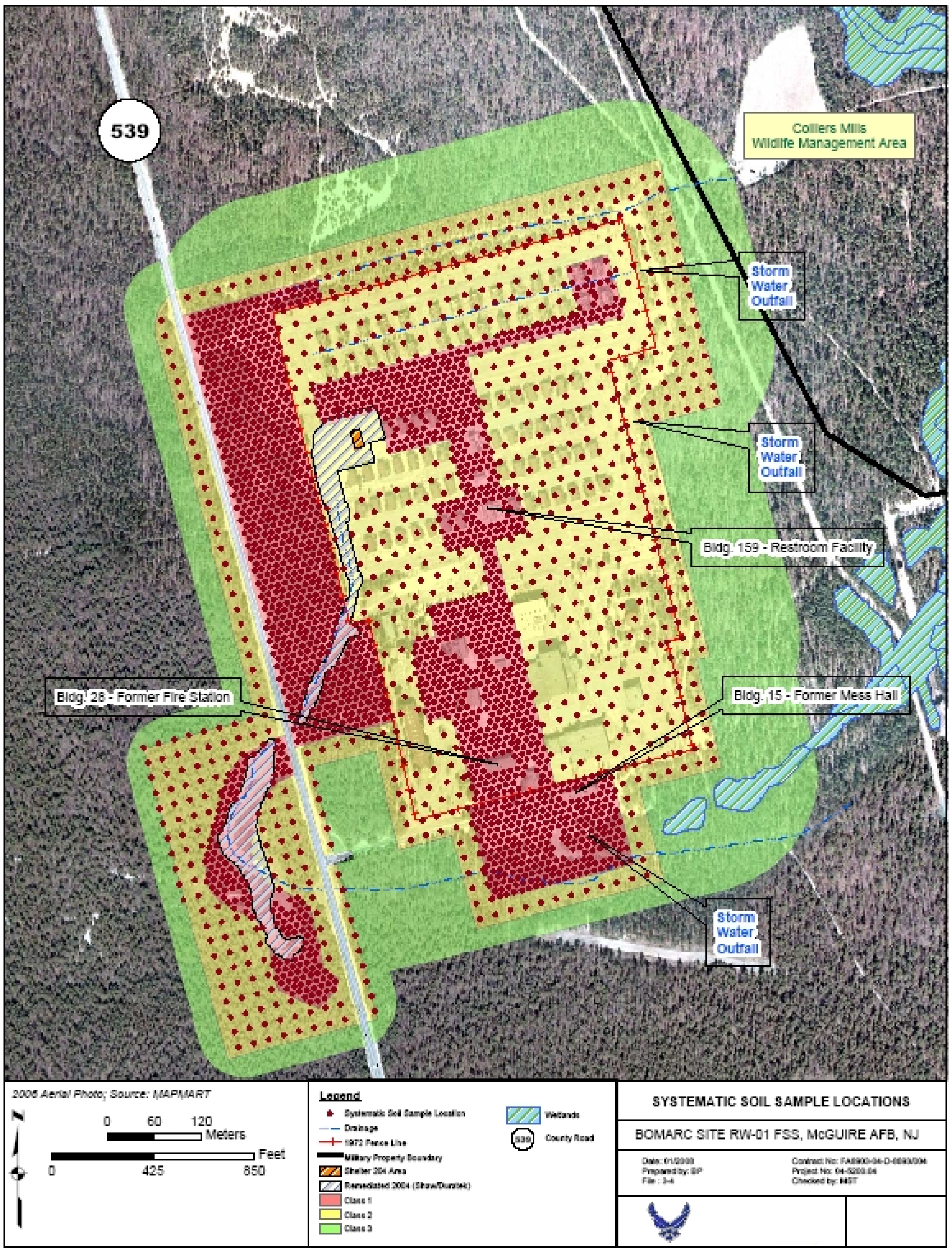


Fig. 3. Map of Class 1 and Class Systematic FSS Soil Samples. Random Samples within the Class 3 Survey Area Are Not Shown.

Spot Remediation and Waste Management

Remediation activities consisted of either manual removal of small, localized areas with particle contamination, or mechanical removal of larger areas of particle contamination. Removals continued until measurements with FIDLER detectors indicated that radioactivity levels were at or close to ambient background levels. However, post-removal soil sampling provided the confirmation that the location met the ROD requirements.

Remediated particle contamination and surrounding matrices (sand and asphalt) from small area footprints were loaded into lined, 1-cubic yard (CY) soft-sided containers for temporary storage until final loading for offsite disposal occurred. Local restrictions precluded the use of these soft-sided containers as the final shipping containers. Therefore, they had to trans-loaded into 20 CY intermodal containers and shipped via rail. All LLRW from the BOMARC Site was shipped to and disposed at the Energy Solutions, Inc. facility in Clive, Utah. A total of 65 CY of LLRW materials from the BOMARC Site were placed in four intemodal containers and shipped via CSX Railroad to the Energy Solutions facility.

FSS RESULTS

Driveover gamma radiation scanning was used initially to identify potential areas with contamination, which then underwent secondary investigation, sampling, and if necessary, remediation. As discussed previously, post-removal driveover scanning was performed at locations where contamination was identified and then manually and/or mechanically removed. The success of these incremental activities was shown using “before and after” figures that depict the integrated pre-removal and post-removal driveover scanning data, systematic soil sampling results, and particle contamination locations. An example of a “before and after” plot is provided in Fig. 4.

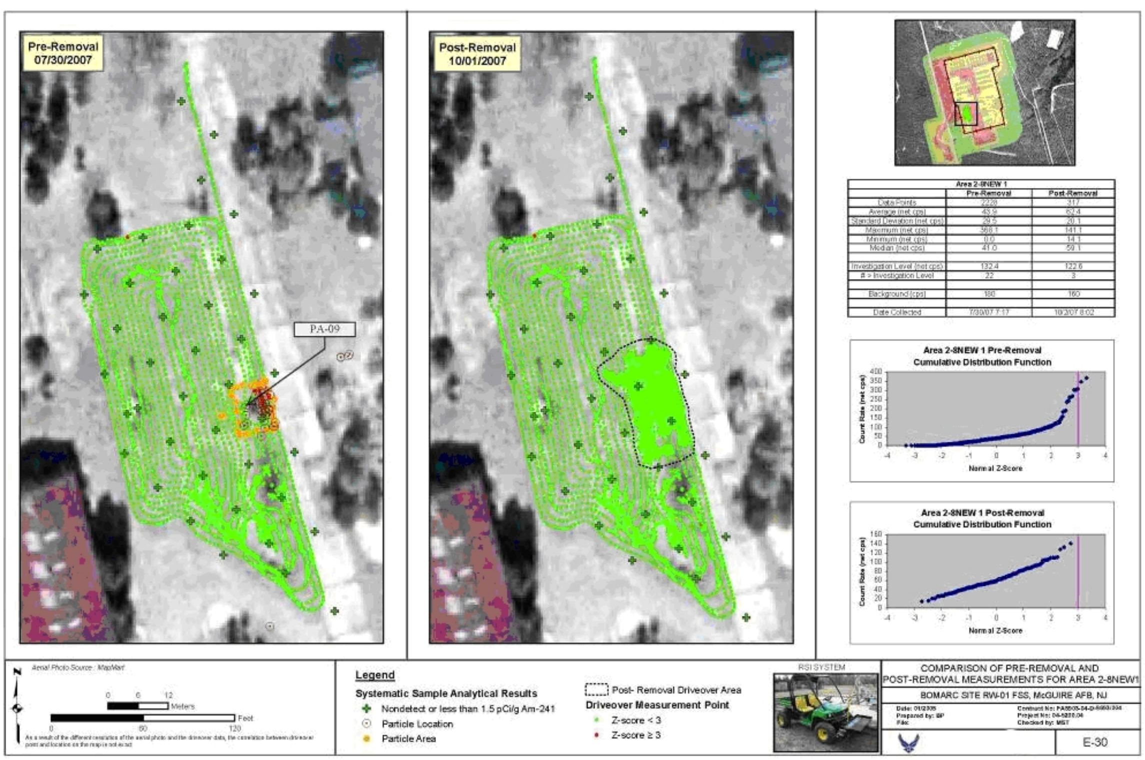


Fig. 4. CLASS Survey Output Map Showing Pre-and Post-Removal of Pu Particle Contamination. The Data Shown in Both Plots Represents the Am-241 ROI (Approximately 55 – 65 keV)

A summary of the pre-removal sampling results (i.e., systematic, biased, and subsurface samples) is presented in Table III. A total of 2,779 systematic surface soil samples were collected in the Class 1 and Class 2 areas. Of the 1,956 Class 1 systematic surface soil samples, 144 samples had detections of Am-241 – i.e., the result exceeded the analytical minimum detectable activity. Only 14 of 823 Class 2 systematic surface soil samples had detections of Am-241 over the Onsite Lab minimum detectable concentration.

Table III. Summary Table of Soil Sample Results Collected As Part of BOMARC Site FSS.

Sample Type	**Number of Samples**	**Number of Detections (1)**	**Minimum Concentration (pCi/g) (2)**	**Average Concentration (pCi/g)**	**Maximum Concentration (pCi/g)**
Class 1 Systematic	1956	144	-0.52	0.08	179.77
Class 2 Systematic	823	14	-0.51	-0.10	0.92
Biased	117	18	-0.43	1.57	65.76
Subsurface	274	3	-0.35	-0.08	3.17
Totals	**3170**	**179**			

[a] Analyte considered detected if analytical result exceeded the reported minimum detectable activity.
[b] pCi/g = picocuries per gram. Minimum, average, and maximum include all results, including those below the minimum detectable activity.

The results summarized in Table III were tested on a survey unit basis using the Sign statistical test and elevated measurement criteria as defined in the MARSSIM. All Class 1 and Class 2 survey units were shown to pass all MARSSIM FSS criteria developed for the Site.

CONCLUSIONS

CABRERA, under contract to the US Air Force, completed field characterization and remediation activities at a former BOMARC missile accident site with residual plutonium discrete particle contamination.. In 2008, the Site was approved for radiological closure by in accordance with the requirements of the published ROD [2] by the US Air Force Safety Center and the State of New Jersey Department of Environmental Protection. The final release was the culmination of a multi-phase investigation performed under the framework of CERCLA and the MARSSIM.

The WGP contamination throughout the site presented unique challenges in terms of site characterization and remediation. Specific technical challenges included the field detection of discrete high-activity plutonium particles over a 218-acre site and designing survey and sampling approaches to ensure compliance with the protocols outlined in the MARSSIM. CABRERA utilized innovative technologies and approaches to achieve these goals, including a large-area NaI gamma scanning spectrometry system, *in situ* gamma spectroscopy with high-purity germanium detectors, and multiple-depth soil sampling methods to identify locations with contamination exceeding ROD criteria (8 pCi/g Pu-239).

Scan surveys over 200 acres were completed and over 3,000 surface and subsurface samples were collected to accomplish this objective of final Site closure. The FSS was designed using a comprehensive, adaptive site closure strategy was implemented that included characterization, remove of any discrete plutonium (Pu) particles or localized Pu particle concentrations found, and final status survey of all areas.

REFERENCES

Environmental Protection Agency (EPA). 2000. *Multi Agency Radiation Survey and Site Investigation Manual (MARSSIM)*. EPA-402-R-97-016, Rev. 1. United States Environmental Protection Agency. August.

Labat-Anderson, Inc. 1992. *Record of Decision for the BOMARC Missile Accident Site, McGuire Air Force Base, New Jersey*. Omaha, Nebraska. November.

CABRERA. 2006a. *Final Historical Site Assessment for BOMARC Missile Site, McGuire Air Force Base, New Egypt, New Jersey*. Cabrera Services, Inc. April.

Earth Technology Company. 1992. *Final Environmental Impact Statement, RW-01*. Volumes 1-3, April.

Earth Technology Company, 1992. *Remedial Investigation/Feasibility Study, Stage 2: BOMARC Missile Accident Site Report*. May.

OHM Remediation Services, Corp. 1998. *Final Report, BOMARC Missile Accident Site, RW-01, McGuire AFB, BOMARC Facility, Plumsted Township, Ocean County, New Jersey.* Linden, New Jersey. June.

Duratek, Inc. and Shaw E & I. 2005. *Final Status Survey Report for the Release of the BOMARC Missile Site, McGuire AFB, New Jersey*. Revision 0. Oak Ridge, Tennessee. March.

Air Force Safety Center (AFSC). 1999. *Review of the Pu-239/240 to Am-241 Activity Ratio Analysis for Work Related to Remediation of the BOMARC Missile Accident Site*. Weapons, Space, and Nuclear Safety Division, Kirtland Air Force Base, New Mexico. December.

Rademacher, S.E. 2001. *The Influence of Heterogeneity in Gamma Spectroscopy Analysis of Soil Contaminated with Weapons Grade Plutonium.* Air Force Institute for Environment, Safety and Occupational Health Risk Analysis, Brooks AFB TX. IERA-SD-BR-SR-2001-0006. October.

AUTHOR BIOGRAPHICAL SKETCHES

John R. Hackett is a Health Physicist for Cabrera Services. John has over 10 years experience in operational Health Physics and Environmental Engineering. He received Environmental Engineering degrees from Northwestern University (BS, 1996) and Clemson University (MS, 1999). He has a Professional Engineer license in Colorado and is a Certified Health Physicist.

Joseph J. Weismann is Health Physics Program Manager for Cabrera Services, Inc. He received his Bachelor of Nuclear Engineering from the Georgia Institute of Technology. He has 17 years experience in applied and environmental health physics, specializing in environmental restoration and facility decommissioning. He has a comprehensive certification by the American Board of Health Physics.

Mark Tepperman, PG. is an Operations Manager for Cabrera Services, Inc. in San Antonio, TX. He holds a BA in Earth Science from Washington University and MS in Geology from West Virginia University. Mr. Tepperman served as the Project Manager for the BOMARC Particle Removal and Final Status Survey. He has over 30 years experience in project management and the application of earth sciences for mineral extraction, contamination evaluation, and environmental remediation involving petroleum, organic compounds, metals, and radioactive materials. Mr. Tepperman is a member of SAME and AAPG.

Steven Rademacher is Chief, Radioactive Materials Licensing and Safety, USAF Safety Center. He received a Bachelor of Biomedical Engineering from Marquette University, Master of Science in Health Physics from Texas A&M University, and a PhD is Radiological Health Sciences from Colorado State University. He has 23 years of experience in general industrial hygiene and broad-based health physics in the US Air Force. He is a certified health physicist.