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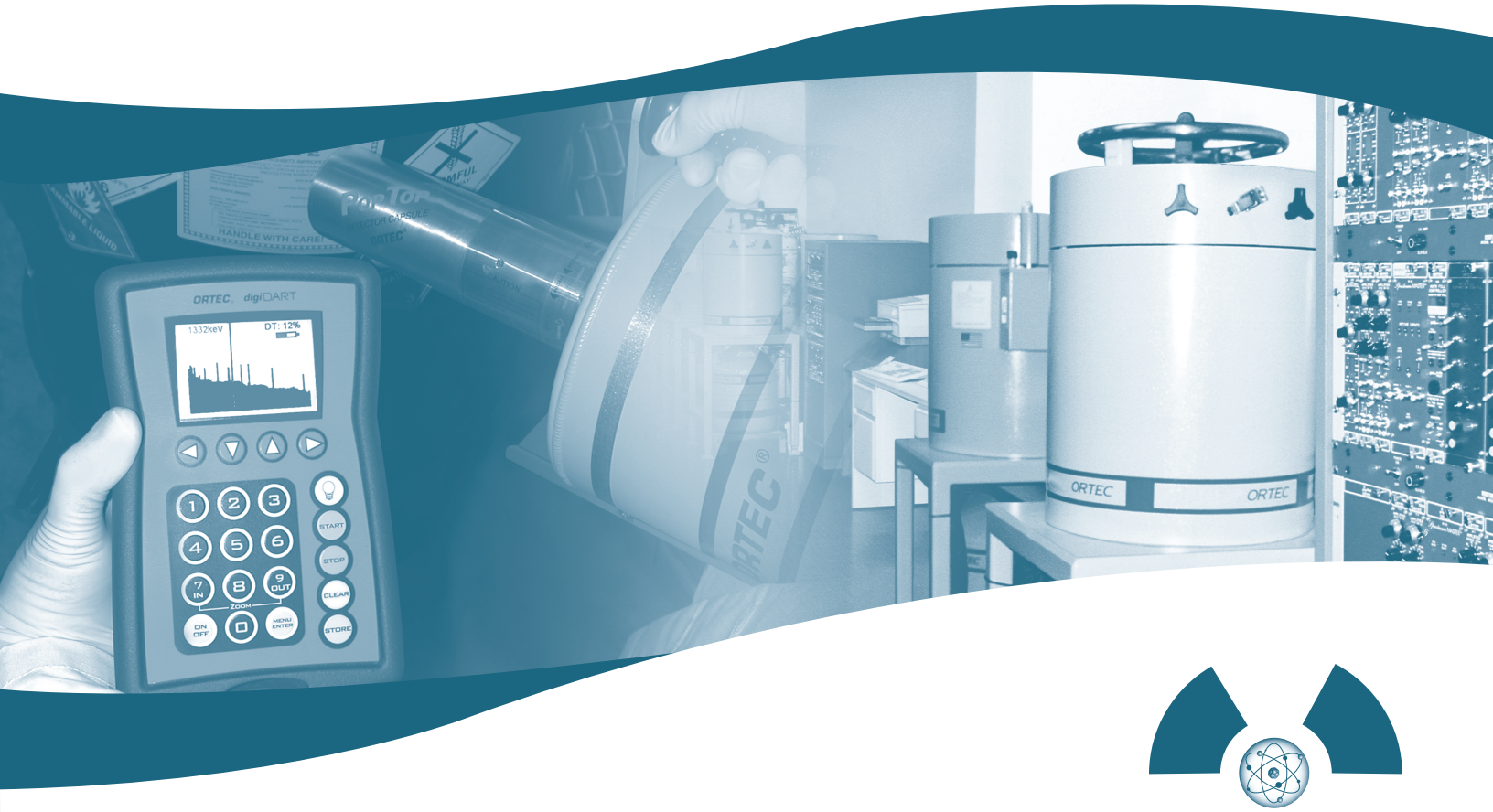
Uses of Field and Laboratory Measurements During a Radiological or Nuclear Incident



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U.S. Environmental Protection Agency
Office of Air and Radiation
Office of Radiation and Indoor Air
National Air and Radiation Environmental Laboratory
Montgomery, AL 36115

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This report was prepared for the National Air and Radiation Environmental Laboratory of the Office of Radiation and Indoor Air, United States Environmental Protection Agency. It was prepared by Environmental Management Support, Inc., of Silver Spring, Maryland, under contract 68-W-03-038, work assignment 35, and EP-W-07-037, work assignments B-33 and I-33, all managed by David Garman and Dan Askren. Mention of trade names or specific applications does not imply endorsement or acceptance by EPA.

PREFACE

In the aftermath of a major release of radioactivity to the environment, such as the detonation of multiple radiological dispersal devices ("RDDs" or "dirty bombs") or an improvised nuclear device (IND), hundreds of thousands of environmental samples will be collected and analyzed during the first year. In addition, a large number of field measurements will be made following a major radiological or nuclear incident. Immediately following the initial response, many of the cleanup and response decisions will be based on the results of measurements made with hand-held or field-portable equipment while others will require collection of individual samples from various media and surfaces for analysis at radiochemistry laboratories. This document describes the interrelationship among field and laboratory radiological analytical measurements, their respective advantages and disadvantages, and the planning and analytical considerations necessary to obtain data of known and defensible quality for use by decisionmakers, primarily during the recovery phase. Key to this understanding is the metrological concept of measurement uncertainty. Both field and laboratory measurements will play significant and complementary roles during the recovery operations and subsequent cleanup. This guide is intended to provide decisionmakers, response and remediation managers, and field and laboratory personnel with the necessary understanding to obtain technically adequate and defensible data in a timely and effective manner.

The need to ensure adequate laboratory infrastructure to support response and recovery actions following a major radiological or nuclear incident has been recognized by a number of federal agencies. The Integrated Consortium of Laboratory Networks (ICLN), created in 2005 by 10 federal agencies,[1] consists of existing laboratory networks across the federal government. The ICLN is designed to provide a national infrastructure with a coordinated and operational system of laboratory networks that provide timely, high-quality, and interpretable results for early detection and effective consequence management of acts of terrorism and other events requiring an integrated laboratory response. It also designates responsible federal agencies (RFAs) to provide laboratory support for chemical, biological, and radiological agents across all of the response phases. To meet its RFA responsibilities for environmental samples, the U.S. Environmental Protection Agency (EPA) has established the Environmental Response Laboratory Network (ERLN) to address chemical, biological, and radiological threats. For radiological agents, EPA is the RFA for monitoring, surveillance, and remediation, and will share responsibility for overall incident response with the U.S. Department of Energy (DOE). As part of the ERLN, EPA's Office of Radiation and Indoor Air is leading an initiative to develop tools and training to aide environmental radiological laboratories in the role of supporting cleanup and remediation activities following a major radiological or nuclear incident.

EPA's responsibilities following a major radiological or nuclear incident, such as a terrorist attack, include response and recovery actions to detect and identify radioactive substances and to coordinate federal radiological monitoring and assessment activities. This document was developed to provide guidance to those who will support EPA's response and recovery actions following a radiological or nuclear incident.

[1] Departments of Agriculture, Commerce, Defense, Energy, Health and Human Services, Homeland Security, Interior, Justice, and State, and the U.S. Environmental Protection Agency.

The use of procedures, developed in advance, for performing field and laboratory measurements to assess radioactivity levels of samples that contain significant quantities of radioactive materials will ensure that the radioanalytical data produced will be of known quality and appropriate for the intended incident response decisions. This guide will provide perspectives that may help field and laboratory personnel have confidence that their measurements of radiation and radioactivity will be of adequate quality to support cleanup decisionmaking.

As with any technical endeavor, a radiological or nuclear incident may necessitate use of particular methods or techniques to address specific data quality objectives and measurement quality objectives. This document does not catalog analytical methodologies or radionuclides, nor does it intend to prescribe or preclude the use of particular methodologies as long as protocols selected satisfy incident-specific data quality objectives and measurement quality objectives. A list of radionuclide-specific methods to support response and recovery actions following a radiological or nuclear incident can be found in *Standardized Analytical Methods for Environmental Restoration Following Homeland Security Events – SAM 2010* (EPA 2010).

Detailed guidance on recommended laboratory radioanalytical practices may be found in the *Multi-Agency Radiological Laboratory Analytical Protocols Manual* (MARLAP 2004), which provides detailed radioanalytical guidance for project planners, managers, and radioanalytical personnel based on project-specific requirements. Additional guidance may be found in the *Multi-Agency Radiation Survey and Assessment of Materials and Equipment Manual* (MARSAME 2009).

This document[2] is one in a planned series designed to present radioanalytical laboratory personnel, Incident Commanders, and other field response personnel with key laboratory operational considerations and likely radioanalytical requirements, decision paths, and default data quality and measurement quality objectives for samples taken after a radiological or nuclear incident, including incidents caused by a terrorist attack. Companion guides published or in preparation include:

- *Radiological Laboratory Sample Analysis Guide for Incidents of National Significance – Radionuclides in Water* (EPA 402-R-07-007, January 2008)
- *Radiological Laboratory Sample Analysis Guide for Incidents of National Significance – Radionuclides in Air* (EPA 402-R-09-007, June 2009)
- *Radiological Laboratory Sample Screening Analysis Guide for Incidents of National Significance* (EPA 402-R-09-008, June 2009)
- *Method Validation Guide for Qualifying Methods Used by Radiological Laboratories Participating in Incident Response Activities* (EPA 402-R-09-006, June 2009)
- *Guide for Laboratories – Identification, Preparation, and Implementation of Core Operations for Radiological or Nuclear Incident Response* (EPA 402-R-10-002, June 2010)
- *A Performance-Based Approach to the Use of Swipe Samples in Response to a Radiological or Nuclear Incident* (EPA 600/R-11/122, October 2011)

[2] All the documents in this series are available at www.epa.gov/erln/radiation.html and at www.epa.gov/narel/incident_guides.html.

- *Guide for Radiological Laboratories for the Control of Radioactive Contamination and Radiation Exposure* (EPA 402-R-12-005, August 2012)
- *Radiological Laboratory Sample Analysis Guide for Radiological or Nuclear Incidents – Radionuclides in Soil* (EPA 402-R-12-006, September 2012)

Comments on this document, or suggestions for future editions, should be addressed to:

Dr. John Griggs
U.S. Environmental Protection Agency
Office of Radiation and Indoor Air
National Air and Radiation Environmental Laboratory
540 South Morris Avenue
Montgomery, AL 36115-2601
(334) 270-3450
Griggs.John@epa.gov

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DEDICATION

This report is dedicated to the memory of our friend and colleague, David Garman. Dave administered nearly three dozen separate contracted radiochemistry projects for EPA dating back nearly 17 years, beginning with the *Multi-Agency Radiological Laboratory Analytical Protocols* (MARLAP) in 1994. Dave put up with countless changes of prime contractors, priorities, subcontractors, and budgets, all with good cheer, diligence, and all while keeping up with his "day job" as counting room lead for alpha-spectrometry analysis at NAREL.

Dave started with EPA's National Air and Radiation Laboratory in 1992. He left many friends throughout EPA and the radioanalytical community, and he will be greatly missed.

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Acronyms, Abbreviations, Units, and Symbols

(Excluding chemical symbols and formulas)

α .....alpha particle
α .....probability of a Type I decision error
AAL .....analytical action level
ADL .....analytical decision level
ANSI .....American National Standards Institute
ASTM .....American Society for Testing and Materials
β .....beta particle
β.....probability of a Type II decision error
BEGe.....broad energy germanium [detector]
Bq.....becquerel (1 dps)
CDC .....Centers for Disease Control and Prevention
CFR.....Code of Federal Regulations
Ci.....curie
cm.....centimeter
cpm.....counts per minute
CRCPD .....Conference of Radiation Control Program Directors
D&D.....decontamination and decommissioning
DHS.....United States Department of Homeland Security
DL .....discrimination level
DOD.....United States Department of Defense
DOE .....United States Department of Energy
DOECAP.....Department of Energy Consolidated Audit Program
DOT .....United States Department of Transportation
dpm .....disintegration per minute
dps.....disintegration per second (Bq)
DQO.....data quality objective
ε.....electron capture
EPA.....United States Environmental Protection Agency
ERLN .....Environmental Response Laboratory Network
FDA.....United States Food and Drug Administration
FIDLER.....Field Instrument for the Detection of Low-Energy Radiation
FSMO.....Field Sampling and Measurement Organization
γ.....gamma ray
g.....gram
GIS .....geographic information system
G-M.....Geiger-Műller [detector]
GUM .....*Guide to the Expression of Uncertainty in Measurement*
h.....hour
HPGe.....high purity germanium [detector]
HVAC .....heating, ventilation, air conditioning [system]
IC.....Incident Commander
ICLN .....Integrated Consortium of Laboratory Networks
ICRU .....International Commission on Radiation Units and Measurements

IEC .....International Electrotechnical Committee
IND .....improvised nuclear device (i.e., a nuclear bomb)
ISGS .....*in situ* gamma spectrometry
ISO .....International Organization for Standardization
ISOCS^{TM} .....In-Situ Object Counting System
k.....coverage factor
keV .....kiloelectronvolt (10^3 electronvolt)
L .....liter
LSC .....liquid scintillation counting/counter
m .....meter
MARLAP .....*Multi-Agency Radiological Laboratory Analytical Protocols [Manual]*
MARSAME .....*Multi-Agency Radiation Survey and Assessment of Materials and Equipment [Manual]*
MARSSIM .....*Multi-Agency Radiation Survey and Site Investigation Manual*
MDC .....minimum detectable concentration
MeV .....megaelectronvolt (10^6 electronvolt)
µCi.....microcurie (10^{-6} Ci)
µg .....microgram (10^{-9} kilogram)
min .....minute
MQO .....measurement quality objective
mrad .....millirad (10^{-3} rad)
mrem .....millirem (10^{-3} rem)
NaI(Tl) .....(thallium-activated) sodium iodide [detector]
NAREL .....National Air and Radiation Environmental Laboratory
nCi.....nanocurie (10^{-9} Ci)
NCRP .....National Council on Radiation Protection and Measurements
NELAC .....National Environmental Laboratory Accreditation Conference
NIST.....National Institute of Standards and Technology
NRC .....United States Nuclear Regulatory Commission
ORIA.....Office of Radiation and Indoor Air
PAG.....Protective Action Guide
pCi.....picocurie (10^{-12} Ci)
PT.....proficiency testing
QA.....quality assurance
QAPP .....quality assurance project plan
QC.....quality control
QSAS .....Quality Systems for Analytical Services
RCRA.....Resource Conservation and Recovery Act
RDD .....radiological dispersal device (i.e., “dirty bomb”)
rem .....roentgen equivalent: man
RFA.....responsible federal agency
RFETS .....Rocky Flats Environmental Technology Site
s.....second
SI.....International System of Units
SOP .....standard operating procedure
SRM .....standard reference material

Sv .....sievert
TNI.....The NELAC Institute
u_{MR} .....required method uncertainty
V&V .....verification and validation
ZnS.....[silver activated] zinc sulfide [detector]

Radiometric and General Unit Conversions

To Convert	To	Multiply by	To Convert	To	Multiply by
years (y)	seconds (s) minutes (min) hours (h) days (d)	3.16×10^{7} 5.26×10^{5} 8.77×10^{3} 3.65×10^{2}	s min h d	y	3.17×10^{-8} 1.90×10^{-6} 1.14×10^{-4} 2.74×10^{-3}
disintegrations per second (dps)	becquerels (Bq)	1	Bq	dps	1
Bq Bq/kg Bq/m^3 Bq/m^3	picocuries (pCi) pCi/g pCi/L Bq/L	27.0 2.70×10^{-2} 2.70×10^{-2} 10^{-3}	pCi pCi/g pCi/L Bq/L	Bq Bq/kg Bq/m^3 Bq/m^3	3.70×10^{-2} 37.0 37.0 10^{3}
microcuries per milliliter (µCi/mL)	pCi/L	10^{9}	pCi/L	µCi/mL	10^{-9}
disintegrations per minute (dpm)	µCi pCi	4.50×10^{-7} 4.50×10^{-1}	pCi µCi	dpm	2.22 2.22×10^{6}
cubic feet (ft^3)	cubic meters (m^3)	2.83×10^{-2}	m^3	ft^3	35.3
gallons (gal)	liters (L)	3.78	L	gal	0.264
Gray (Gy)	rad	10^{2}	rad	Gy	10^{-2}
roentgen equivalent man (rem)	sievert (Sv)	10^{-2}	Sv	rem	10^{2}

NOTE: Traditional units are used throughout this document instead of the International System of Units (SI). Protective Action Guides (PAGs) and their derived concentrations appear in official documents in the traditional units and are in common usage. Conversion to SI units will be aided by the unit conversions in this table.

1. Scope and Purpose

This document explains the importance and interrelationship of field and laboratory measurements following a radiological or nuclear incident. Understanding and delineating the purpose of each field or laboratory measurement process, and implementing the measurements in a controlled, well-documented manner, are critical to ensure that data generated in response to a radiological or nuclear incident in the field and in the laboratory are both technically and legally defensible.

Section 2 provides a foundation for subsequent discussion of the document by discussing the radionuclide(s) contaminants associated with a radiological or nuclear incident and the manner in which they are deposited. These are critical elements to consider when determining which field and lab measurement techniques (or combinations of the two) can most effectively be used to address measurement challenges associated with an incident.

Section 3 of the document addresses key considerations for project planning. Measurement quality objectives (MQOs) must be developed for the contaminant(s) of concern to ensure that the measurement methods selected will be able to reliably meet project data quality objectives (DQOs). Once the analytical requirements have been established and appropriate measurement technologies identified, measurements can be carried out.

Section 4 addresses the importance of the fundamental principles of metrology to ensure that measurements will be traceable to national standards and reported in association with defensible estimates of uncertainty. It also discusses the need for a quality systems approach to ensure that measurements are conducted in a controlled manner using validated methods, by trained, qualified personnel, and that all analytical operations are well-documented to preserve their defensibility over time.

Section 5 of the document identifies the respective capabilities and limitations of field and laboratory measurement techniques and attempts to demonstrate the complementary nature of the two during the days and months following an incident. Factors impacting calibrations and background corrections are addressed in this section.

Section 6 contains tables that summarize and compare the respective strengths and limitations of laboratory and field measurements for different types of radionuclides and measurement conditions. Section 7 provides conclusions and recommendations for field and laboratory measurements as well as an overall summary of this document.

Three appendices follow the main body of the document. Appendix I presents a case study of how *in situ g*amma spectrometry (ISGS) was used during the decontamination and decommissioning (D&D) of the Rocky Flats Environmental Technology Site. The tables in Appendix II show the applicability of a number of different instrument types for measurement of a list of radionuclides and activity levels. Finally, Appendix III uses several scenarios to explore how the DQO/MQO process can be applied to field and laboratory measurements, and demonstrates how field and laboratory measurements can be used in a complementary manner during a response to a radiological or nuclear incident.

While most of the material in this document applies to all phases of an incident, the primary focus of the document will be the recovery phase, because this phase is EPA's primary responsibility.

2. Introduction

Immediately following a radiological or nuclear incident, prompt feedback of real-time measurement results will be crucial in supporting decisions regarding the health and safety of the public. Field measurements used for this assessment will be invaluable because they provide real-time data to decisionmakers for determining the presence of a general hazard, and whether or not the radiation exposure poses an imminent danger.

During the initial phase of an incident, responsible agencies and first responders must determine the following as rapidly as possible:

- Radionuclide(s) in the source device;
- Levels of gross activity present on contaminated surfaces, and in the air, water, soil, and other potentially contaminated areas, items or media;
- Extent of the areas affected by contamination;
- Levels of radiation exposure; and
- What actions may be required based on Protective Action Guides (PAGs).

Estimates of the number of laboratory samples required and the expected time frame to respond to a radiological dispersal device (RDD or dirty bomb) incident have been developed based on White House Security Council Planning Scenario #11.[3] These assessments conclude that, following a single incident in one metropolitan area with only one radionuclide (regardless of the radiation emission type from this radionuclide), well over 350,000 measurements would be required within a one-year period. More information on this scenario can be found in EPA's *Assessment of Nationwide Laboratory Surge Capacity Required to Support Decontamination of Chemical, Biological and Radiochemical-nuclear Agents* (ICLN 2007) and *The Current Gap in Environmental Radioanalytical Laboratory Capacity.*[4]

The responsibilities of various federal, state, and local agencies to address the possible health and environmental consequences of a radiological or nuclear incident properly fall at different times in the recognized timeline of an incident. These agencies (e.g., the Department of Homeland Security (DHS), Food and Drug Administration (FDA), Centers for Disease Control and Prevention (CDC), Department of Energy (DOE), EPA, state and local government) must respond with technologies that are appropriate to their missions and responsibilities.

From the radioanalytical perspective, an RDD scenario involving a single gamma-emitting radionuclide is perhaps the simplest scenario possible. Measurements in the field and in the laboratory become more complicated when a mixture of alpha, beta, or gamma emitters, or pure

[3] http://cees.tamiu.edu/covertheborder/TOOLS/NationalPlanningSen.pdf

[4] *The Current Gap in Environmental Radioanalytical Laboratory Capacity*, prepared for EPA in March 2007, currently in draft.

alpha- or beta-emitting radionuclides are present. The destructive capability and radiological impact of an improvised nuclear device (IND) would be considerably greater than that from an RDD. Despite differences in the magnitude of the event, either of these scenarios would quickly overwhelm resources in the field and at laboratories, making optimal use of all available resources essential.

Samples resulting from any radiological or nuclear incident will consist of a variety of matrices and will originate from different geographic locations and environmental conditions. The data quality objectives and measurement quality objectives[5] for an incident will be tailored to the phase of the incident and will address issues specific to the radionuclides and matrices of concern, and the locations and environmental conditions in and beyond areas directly impacted by the event. For example, measurements of building surfaces in the early phase would be expected to focus primarily on detecting levels of radioactivity that could result in short-term exposures in excess of levels stipulated by protective action guides.

As the event progresses into the intermediate and recovery phases, efforts will shift toward identifying progressively lower levels of contamination. Large areas will need to be quickly characterized and cleared for longer-term use and habitation. Accordingly, the DQOs and MQOs needed to support decisionmaking will become increasingly more demanding of analytical measurements. A number of methods may be available for measuring radionuclides and their radioactive emissions. The methods selected must be capable of reliably meeting the established MQOs (i.e., a performance-based approach). This includes selecting and validating appropriate techniques for sampling and analysis.

Measurements using field instruments will likely predominate in the earlier stages of an incident when preliminary estimates of the type of radiation and activity levels present must be rapidly determined so that protective actions can be implemented effectively and without delay. Early measurements may not be radionuclide-specific or even capable of reliably detecting radionuclides with weakly penetrating radiations. Field crews also may need to gather samples and send them to radiochemistry laboratories for rapid, unambiguous confirmation of field measurements when these have high or unknown levels of uncertainty. Radiochemistry laboratories also may be called on to provide sensitive and accurate measurements of specific radionuclides in order to meet measurement quality objectives for detection capability and uncertainty needed to support decisionmaking by the Incident Commander (IC) or designee.

Following the initial response phase of the incident, EPA, at a minimum, will be responsible for:

- Delineating the ultimate extent of contamination;
- Assessing potential doses from various exposure pathways where low-level radioactive contamination persists;

[5]"Data quality objectives (DQOs) are qualitative and quantitative statements that clarify the study objectives, define the most appropriate type of data to collect, determine the most appropriate conditions from which to collect the data, and specify tolerable limits on decision error rates. … Measurement Quality Objectives (MQOs) can be viewed as the analytical portion of the DQOs and are therefore project-specific." [MARLAP (2004), Section 1.4.9] See also Section 4 of this document for further discussion of the directed planning process.

- Reassuring the public that facilities, property, or homes have been decontaminated effectively;
- Determining that the disposition of contaminated equipment, materials, environmental matrices, or facilities has been correctly and safely performed; and
- Conducting ongoing monitoring.

Field measurements are valuable as they will be used to guide the process of exposure control and remediation on a timely basis, especially in the earlier phases of an incident. As the response to the incident progresses through the intermediate and recovery phases, action levels will become progressively lower as decisions are based on longer-term goals. There will be a need for increasingly sensitive, accurate, and radionuclide-specific analyses, and expectations for stringent measurement quality will increase accordingly. Laboratory determinations will be needed to provide critically needed measurement capabilities and capacity.

Throughout the incident response, quality systems are needed to provide the framework for quality assurance and quality control (QA/QC) programs. Properly implemented quality systems will provide the basis for defensible and informed decisionmaking under the stressful conditions that will be encountered during an incident response. Integrated internal QC measures and external measurement intercomparisons will demonstrate and document that measurements meet established MQOs. Management structures and independent internal and external quality oversight will ensure that the quality system is being implemented consistently and adequately. All measurement techniques will be validated, and testing will be performed only by adequately qualified and trained analysts following documented procedures.

Quality systems for laboratories have been addressed in detail by consensus standards development organizations. Standards include documents such as ISO 17025 (International Organization for Standardization [ISO]/ International Electrotechnical Committee [IEC] 2005) and The National Environmental Laboratory Accreditation Conference (NELAC) Institute (TNI) Standard (NELAC, 2003). Although the TNI Standard theoretically applies to field sampling and measurement organizations, quality systems and associated certification and accreditation programs have just begun to be implemented on a limited scope for several field parameters (TNI 2007).

In March 2011, EPA's Forum on Environmental Measurements directed that "...organizations (e.g., laboratories, field sampling and measurement) generating environmental data through measurement under Agency-funded acquisitions must submit documentation of their competency, which may include participation in applicable certification and/or accreditation programs." At present, however, this directive has yet to be generally applied to measurements of radioactivity in the field. As such efforts proceed, however, similar levels of data quality may be expected of measurements from laboratory and field sampling and measurement organizations (EPA 2011a).[6]

[6]"Laboratories that perform field sample analysis are required to comply with rigorous quality systems standards. Compliance with such standards provides the basis for accreditation by state regulatory agencies. Yet similar standards do not exist for all field activities. Organizations conducting these activities are not required to meet a quality system standard, do not need an accreditation for the work being performed and rarely are subjected to routine oversight inspections. This inconsistency jeopardizes data usability and compromises the overall objective of

Finally, field and laboratory measurements need to be coordinated in a manner that will ensure that appropriate decisions can be made based on the phase of the incident and the action levels and concentrations of the radionuclides that need to be analyzed. The abilities and strengths of the various types of field measurements coupled with laboratory measurements are explored further in this document.

3. Impact of Source Term and Measurement Conditions on MQOs and Selection of Measurement Technologies

The source-term radionuclides for a nuclear or radiological incident will have a significant impact on the most effective measurement approaches used following an incident. For example, the RDD incident described in White House Security Council Planning Scenario #11 involves a single, medium-energy, beta-gamma-emitting radionuclide that emits gamma radiation readily amenable to non-destructive field radioassay techniques. Medium- to high-energy gamma rays penetrate through matrix materials to produce a characteristic gamma ray signature, thus largely eliminating the need for extensive laboratory work for the qualitative identification of gamma emitters that may be present. When gamma-emitting contamination is deposited on the surface of objects, field instrumentation techniques are capable of generating data that can be used for defensible incident response decisionmaking. Thus, ^{137}Cs represents a best-case radionuclide from the standpoint of rapid and reliable measurement and remediation since responders can most effectively utilize non-destructive field radioassay techniques. In the case of pure alpha, beta, or low-energy gamma emitters, the selection of viable field measurement alternatives is more limited, and laboratory analysis may be needed to provide data of sufficient quality for decisionmaking, especially for lower activity measurements in the later phases of an event.

3.1 The Impact of Source-Term Radionuclides on Measurement Approach

When planning measurement approaches that will be used to respond to an incident, it is important to consider that other less optimal, yet likely, scenarios are possible that are not conducive to rapid, accurate field measurements. By their very nature, *in situ* measurements can detect a radiation only after it is emitted from an object. The radiation may need to penetrate an unknown amount of matter before it reaches the surface of the object, is emitted, and can be detected. The type of radiation impacts its transmission through matter. This, together with the depth of penetration into the object, will significantly affect the detectability of radiation emitted from the object. Measurements of alpha and beta particles and low-energy photons that have very short ranges in matter will almost always be subject to significant self-absorption effects, whereas more highly penetrating, more energetic gamma rays will be less strongly attenuated and will be more reliably detectable until the radionuclides have penetrated deeper into the

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the data generation process. […] Regulatory agencies have become sensitive to the negative impact that the absence of an FSMO [Field Sampling and Measurement Organization] quality system standard may have on critical data. This includes acknowledging that the quality of samples and field data that go to the laboratory is as critical to the process as the quality of data generated by the laboratory. In response, such agencies have initiated steps to establish quality system requirements for field sampling and measurement organizations." From: David N. Speis, Guest Dialog: Improving Field Sampling Quality Control, Pollution Engineering; August 1, 2004; Available at: www.pollutionengineering.com/Articles/Column/63ead7de8fd68010VgnVCM100000f932a8c0.

surface being measured. When it is known that alpha- and beta-emitting contaminants are freshly deposited, or that they have been deposited on hard, relatively impermeable surfaces, accurate measurements in the field are practicable. If the radionuclides have penetrated into the surface, field measurements of alpha or beta emitters may not be possible, while accurate measurements of medium- to high-energy gamma-emitting radionuclides are possible even when the radionuclides of concern have penetrated 1–2 cm or more into the object being measured.

The physical and chemical form of each radionuclide, the matrix material, and the manner in which a radionuclide is distributed in the matrix material will impact measurements of radiation and radioactivity. An RDD may be constructed using radionuclides in a very insoluble, refractory form. Extreme temperatures, pressures, and chemical and physical interactions with surrounding materials also will affect the physical and chemical form of radionuclide(s) resulting from the detonation of an IND or RDD. Once contaminants are deposited in the environment, changes in the physical and chemical form of contaminants and the matrices with which they are associated occur as contaminants weather. The depth profile of radionuclides may change if they migrate into the matrix. Such effects will generally be more pronounced with porous matrices such as soil since water can readily transport contaminants into the material on which they were deposited. Field measurements may thus be complicated, especially if assumptions about self-absorption cannot be defended without performing secondary measurements, or if varying rates of adsorption and differential transport of source-term radionuclides limit the use of marker nuclides to model the distribution of source-term radionuclide mixtures.

3.2 Key Concepts: Surface Contamination vs. Volumetric Contamination

Attenuation effects may interfere with accurate, non-destructive measurements of radioactivity when contaminants are not deposited in a regular, thin layer on a smooth surface. Once radionuclides penetrate an object, the radiation emitted may be self-absorbed by the matrix material before it can escape the surface and be detected. When the degree of attenuation is high or not well-known, unbiased measurements of radioactivity and reasonable estimates of measurement uncertainty are generally not practicable, and the feasibility of field measurement techniques for generating definitive results for decisionmaking may be limited.

The concepts of surface versus volumetric contamination have been the topic of much discussion. A thorough understanding of these concepts and their impact on measurements of radioactivity is key to subsequent discussions. The *Multi-Agency Radiation Survey and Assessment of Materials and Equipment Manual* (MARSAME 2009) defines the two concepts as follows:

- *Surficial Radioactive Material* is radioactive material distributed on any of the surfaces of a solid object. Surficial radioactive material may be either removable by non-destructive means (such as casual contact, wiping, brushing, or washing) or fixed to the surface.
- *Volumetric Radioactive Material* is radioactive material that is distributed throughout or within the materials or equipment being measured, as opposed to a surficial distribution. Volumetric radioactive material may be homogeneously (e.g., uniformly activated metal) or heterogeneously (e.g., activated reinforced concrete) distributed throughout the materials and equipment (MARSAME 2009).

ANSI N13.12 defines *surface contamination* as "[r]adioactive contamination residing on or near the surface of an item," and *volume contamination* as "…contamination residing in or throughout the volume of an item." It further differentiates between the two, stating that "[v]olume contamination can result from neutron activation or from the penetration of radioactive contamination into cracks or interior surfaces within the interior matrix of an item" and that surface "…contamination can be adequately quantified in units of activity per unit area" (ANSI 1999).

In an attempt to address the issue in an operationally useful manner, this guide will address the concepts of *surficial contamination* or *surface contamination*, and that of *volumetric contamination*, pragmatically. The term "surface" is used in this document when reliable measurements of the radioactive contaminants deposited on an object are practicable. When a reference is made to a "surface," this refers to contamination deposited in a thickness of material near the surface of an object for which self-absorption effects are minimal enough that they do not impart uncorrectable bias or unknown amounts of uncertainty into the measurement of radioactivity in that surface. In contrast to this, measurements of radioactivity that are distributed throughout the volume of an object are considered to be volumetric contamination. Depending on the uniformity of their distribution, accurate measurements of radioactivity in that object may or may not be practicable.

Given strictly surficial or homogenously distributed volumetric contaminants, accurate measurements of radioactivity and estimations of measurement uncertainty are possible. Considering the realities of contamination in the environment, permeable and rough materials such as soil, concrete, asphalt, fabric, and wood are the rule and not the exception, and it is generally not known how deeply into the object the radioactive material has penetrated. This very significantly complicates accurate measurement of contamination. As time proceeds after an incident, processes such as weathering set in, and radionuclides further permeate the materials on which they were deposited. The depth of penetration may be such that levels of attenuation and self-absorption are poorly predictable and that they reach a point where radioactive emissions cannot reliably be detected at all by field measurements.

Even when corrections are made by assuming the depth of penetration, these assumptions may lack documented, defensible technical basis and may not lend themselves to realistic estimates of uncertainty. Lacking the key characteristics of a defensible measurement, such results, beyond limited applicability to scoping studies or the identification of obvious hot spots, are not of sufficient quality to support the decisionmaking process, and can be considered only qualitative in nature.

3.3 Impact of Ambient and Intrinsic Background on Measurements of Radioactivity

Levels of naturally occurring radioactivity intrinsic to the material being measured may be elevated or variable and may negatively impact the reliability or the ability of low-level field measurements to demonstrate that an area has not been impacted or that it has been adequately decontaminated to levels that will permit reoccupation. Similarly, ambient levels of background radiation from naturally occurring radioactivity or incident-related contaminants may interfere

with low-level measurements of radioactivity. For example, in one study of building materials from a single region, background dose rates from the natural radioactivity intrinsic to the building materials ranged from 2.5 to 14 μR/h (Abbady 2006). Significant local variations in gamma background due to non-homogeneous areal distribution of contaminants associated with the event itself may also interfere with reliable low-level *in situ* gamma measurements in locations adjacent to contaminants. In the presence of elevated background activity, extended count times (or even radiochemical processing at a laboratory) may be required to differentiate between background activity and signal from contaminant radionuclide(s), especially at many of the lower activity levels that likely will be applicable for recovery operations.

An incident involving pure alpha- or beta-emitting radionuclides such as ^{238}Pu or ^{90}Sr, or mixtures of pure alpha- or beta-emitting radionuclides with other radionuclides, would present significant challenges to field instrument measurements not envisioned by White House Security Council Planning Scenario #11. Earlier in the incident where higher-activity DQOs apply, field measurements may be used to guide remediation and, with laboratory confirmation of the underlying assumptions, field measurements often may be used effectively to address certain lower-activity late-phase DQOs. For pure alpha emitters, and less energetic beta emitters, or where significant weathering has occurred, however, laboratory measurements generally will be needed to obtain radionuclide measurements of sufficient sensitivity and accuracy to meet low-activity late-phase MQOs and final survey decisions.

In contrast to field measurements, there are fewer factors that interfere with laboratory analyses because the laboratory environment is so carefully controlled and measures are employed to address concerns that could adversely impact a field measurement. In the laboratory, for example, concerns about interference from ambient background are addressed by heavily shielding potentially affected instrumentation. Concerns about the intrinsic background activity of the matrix materials remain a common challenge to both to field and laboratory measurements. The activity and expected variability of radionuclides present in the background must be well-known in order to differentiate between signal from the background radioactivity and low activities of naturally occurring radionuclide contamination.

Concerns about non-uniform distribution of alpha- and beta-emitting contaminants can be addressed in the laboratory by homogenizing and careful subsampling to ensure the representativeness of results. Laboratories routinely employ digestion and fusion techniques to address intractable matrices. Chemical separation methods are used to purify and isolate elements of concern from substances or other radionuclides that interfere with sensitive and accurate measurements. Samples are measured in heavily shielded instrumentation with low and stable backgrounds, which minimizes the variations in background activity that are problematic in field measurements. When coupled with low backgrounds and spectrometric detection techniques, physical preparation and chemical separation steps permit sensitive radionuclide-specific measurements of individual alpha- and beta-emitting radionuclides in mixtures of radionuclides and complex matrices. As a result, laboratories can minimize and more accurately estimate uncertainties associated with single measurements than is generally possible in the field. Rigorous quality programs at laboratories require extensive validation of methods and quality control, and ensure consistent documentation of processes so that the quality of measurement results is highly defensible.

Laboratory measurements have their limitations as well. Although laboratory turnaround times have improved dramatically over the past decade and results often are available as quickly as several hours or days, samples must still be taken and shipped to the laboratory. Thus, a laboratory process can never provide real-time results, as is possible with field measurements. Time and effort are required in the field for collecting samples of surface or volumetric contamination to send to the laboratory. Because laboratories generally measure and report results in terms of the massic or volumetric activity of samples (i.e., pCi/g or pCi/L), accommodations must be made to relate these units on a "activity per sample" basis, or to the corresponding value in terms of areal activity (e.g., pCi/cm^2).

Perhaps the most significant limitation associated with laboratory analysis relates back to the number of *in situ* measurements and grab samples needed to characterize an area. While for alpha and beta emitters, there is no substantial difference between the number of *in situ* measurements or grab samples needed, when medium- to high-energy gamma emitters are concerned and when the areal distribution of the contaminant radionuclides may be non-homogeneous, more grab samples may be needed than *in situ* measurements to have a high degree of confidence that hot spots will not be overlooked. Similarly, the overall uncertainty associated with collecting multiple grab samples, as opposed to performing a single ISGS measurement of a larger area, may require that more samples be collected and measured. Even so, this may still result in higher overall combined measurement and sampling uncertainties, and in a higher risk of not detecting activity even though it may be present in detectable quantities.

3.4 Applying the Directed Planning Process to Radionuclide Measurements

As the event progresses into the intermediate and recovery phases, efforts will shift toward identifying progressively lower levels of contamination. Large areas will need to be quickly characterized and cleared for longer-term use and habitation. Incident-specific action levels will be set to support the tasks of:

- Reassuring the public that facilities, property, or homes have been decontaminated effectively; and
- Determining that the disposition of contaminated equipment, materials, environmental matrices, or facilities has been correctly and safely performed.

3.4.1 Action Levels for Incident Response

Undoubtedly a key factor will be public acceptability, which may in fact be more accurately characterized as intense public demands and expectations. In terms of reoccupancy or continued occupancy of impacted or possibly impacted areas, including places of work, schools, playgrounds, day care centers, hospitals, places of worship, etc., the public will very likely insist that these places be returned to the public's *perceived* "radiation free" status. This may effectively translate into public demand that action levels be set at a fraction of the ambient background for certain radionuclides, or at zero for source-term radionuclides not originally present in these locations. The public demand for extremely low action levels could result in

significant measurement challenges, ultimately requiring very low detection capability coupled with great precision (very small uncertainties).

While the Agency will certainly need to educate the public regarding the technical challenges involved with extremely low action levels, the public will still likely demand the most well-established, sensitive, and precise measurements possible. In addition, while the general public may not be familiar with the technical aspects of data verification and validation, quality assurance, and quality control, the public will almost certainly demand a high degree of *demonstrated* certainty for the data, as well as some type of rigorous technical review and evaluation of the data prior to Agency decisions. Given these likely public demands, as well as lessons learned from the World Trade Center recovery efforts, the Agency will need to employ well-established measurement processes capable of precisely measuring low levels of select radionuclides. These measurement processes will need to be supported by well-established and robust quality control procedures and practices that will provide sufficient information and documentation to allow for defensible data verification and validation.

3.4.2 Data Quality Objectives Process

The DQO process is used to define specific data requirements for field and laboratory measurement programs to ensure that the analytical measurements will be of sufficient quality to defensibly support the decisionmaking process. DQOs also are used to develop the performance and acceptance criteria for sampling and measurement criteria activities documented in the quality assurance project plan (QAPP). The output of the DQO process will specify the number of measurements needed, their locations, and any specific analytical requirements. The frequency of measurements and number of locations will depend on the degree of variability and amount of radioactivity compared with the established action level.

3.4.2.1 Decision Rules

One essential aspect of the DQO process is the specification of a decision rule. Decision rules may be qualitative or quantitative. They contain alternative actions to be taken depending on the decision about whether the result indicates there is sufficient probability that the analytical action level (AAL) has been exceeded or not. The decision that will be made is expressed in a hypothesis test.

A null hypothesis, H_0, is defined by initially assuming that the true concentration is either above or below the AAL. We assume that the null hypothesis is true unless the result of a measurement allows us to reject the null hypothesis. For most environmental measurements the consequences of exceeding an action level are greater than not exceeding it. Thus, the null hypothesis most frequently selected will protectively state that an AAL is exceeded unless data are available that demonstrate with high probability that the activity is less than the AAL.[7] By incorrectly deciding to reject the null hypothesis when it is indeed true we commit a Type I decision error.

[7] There are occasions where it would be appropriate to assume that a result is below an action level unless the contrary can be demonstrated. For a more complete discussion of decision rules, see MARLAP or Appendix VI in *Radiological Laboratory Sample Analysis Guide for Incidents of National Significance—Radionuclides in Water*, (EPA 2008).

By incorrectly *failing to reject* the null hypothesis when it is indeed false, we commit a Type II decision error.

There is uncertainty associated with every measurement. When the result of a measurement is used to make a decision, there is a probability that a decision error may occur. Given an example where the true concentration is equal to the AAL, by definition action should be taken. A single measurement is performed with the plan to compare that result to the AAL to decide whether the concentration is less than the action level. Since the result of each measurement varies according to its uncertainty, half of all possible measurements will fall below the AAL and half will be equal to or greater than it. Using this approach to making decisions, we commit a Type I decision error fifty percent of the time when the our measurement falsely indicates that the concentration is less than the AAL.

The DQO process places limits on the probability of making such decision errors. The limit for the probability of making a Type I error (denoted α) is specified at the AAL. The probability of making a Type II error (denoted β) is specified generally at a lower concentration called the discrimination level (DL). The discrimination level is a concentration at which the null hypothesis is false (i.e., a concentration below the AAL) and at the same time, a concentration which we need to be able to reliably distinguish from the AAL. For example, suppose the contaminant of concern is ^{226}Ra, and we know that ^{226}Ra is present in the background. Then by establishing the discrimination level equal to the background concentration of ^{226}Ra in the sample will minimize the probability that background concentrations of radium may be falsely identified as ^{226}Ra present at the AAL.

The AAL and the DL together bound the "*gray region*," an area in which decision error probabilities are not controlled as tightly as outside of it. When measurement results fall in the gray region, there is a higher risk that we will commit decision errors. The width of the gray region is defined as:

$$\Delta = | \text{AAL} - \text{DL} |.$$

3.4.2.2 Measurement Quality Objectives

MARSAME (2009) and the *Multi-Agency Radiological Laboratory Analytical Protocols Manual* (MARLAP 2004) contain guidance on developing MQOs from the applicable DQOs for measurements of radiation and radioactivity at laboratories and in the field. MQOs are generally quantitative data requirements that evaluate the quality of the measurement against the criteria upon which decisions will be based using those data.

By specifying the required method uncertainty (u_{MR}) at the AAL, it is possible to ensure that decision errors will not exceed the levels deemed appropriate by the DQOs for defensible project decisionmaking. Ensuring that measurements are of sufficient quality for decisionmaking also will minimize effort, time, and money spent on making measurements, all key driving factors in an incident response situation.

MARLAP considers the required method uncertainty at the AAL, u_{MR}, to be a fundamental MQO. For decisions about whether a single sample exceeds the AAL, u_{MR} can be calculated as

$$u_{MR} = \frac{\Delta}{z_{1-\alpha} + z_{1-\beta}}$$

where the null hypothesis (H_0) is "the true sample activity is greater than the AAL," Δ = [AAL–Discrimination Level] and $z_{1-\alpha}$ and $z_{1-\beta}$ are the respective quantiles of the standard normal distribution function.[8]

Details and refinements for the determination of the required method uncertainty are given in MARLAP Appendix C or Appendix VI of *Radiological Laboratory Sample Analysis Guide for Incidents of National Significance – Radionuclides in Water* (EPA 2008).

In order to implement the use of the required method uncertainty, the laboratory must have in place an acceptable method for estimating measurement uncertainty. MARLAP (2004) recommends the method presented in the *Guide to Expression of Uncertainty in Measurement*, also referred to as "the GUM" (ISO Guide 98, 1995). No measurement of radioactivity should ever be determined or reported without an associated uncertainty and its associated coverage factor, *k*. Simply reporting "counting uncertainty" is incomplete and for high-activity samples, may result in significantly underestimating the combined standard uncertainty of the measurement.

3.4.2.3 Controlling the Probability of Decision Errors with Analytical Decision Level

The AAL is the dividing point for a choice between two alternative actions. The quality of measurements of radioactivity should be driven by the need to make informed, defensible decisions about whether the AAL has been exceeded with acceptable limits on the probability of a decision error. Failure to take the variability of results and the magnitude of the measurement uncertainty into account will result in unacceptably high error rates for decisions, or in excessive time and effort invested in performing measurements with quality that exceeds levels needed for decisionmaking. High and uncontrolled probabilities of false decisions are not compatible with defensible decisionmaking, will result in less effective use of analytical resources during response, and will increase the time needed to complete recovery from the incident.

It is often important to correctly identify samples whose true activity exceeds an AAL. For example, when prioritizing samples to be sent to a laboratory, sending low-activity samples to a high-activity laboratory would be less problematic (for the laboratory at least) than risking contamination of a low-activity laboratory. By selecting the null hypothesis that *the true sample activity exceeds the AAL*, we protect against a Type I error of incorrectly deciding that true sample activity is below the AAL when it is actually above the AAL. We also want to be sure

[8] Values of $z_{1-\alpha}$ (or $z_{1-\beta}$) for some commonly used values of α (or β), taken from tables of the cumulative normal distribution (MARLAP 2004, Appendix G, Table G1), are:

α or β	$z_{1-\alpha}$ (or $z_{1-\beta}$)	α or β	$z_{1-\alpha}$ (or $z_{1-\beta}$)
0.001	3.090	0.10	1.282
0.01	2.326	0.20	0.842
0.025	1.960	0.30	0.524
0.05	1.645	0.50	0.000

that if the sample activity is significantly below the AAL, it is correctly identified, avoiding a Type II error of incorrectly deciding that the sample activity is above the AAL when it actually is below.[9]

Figure 1 is a graphical representation of a smoothed distribution from an infinite number of measurements of a sample or object where the true activity is equal to the established AAL. In the figure, the AAL is the mean of the distribution of measurements. Variability due to uncertainty in the measurement will cause one-half of all possible measurements to fall below the AAL, and one-half at or above the AAL. Based on a single measurement, a decision must be made about whether or not activity is present above the AAL.

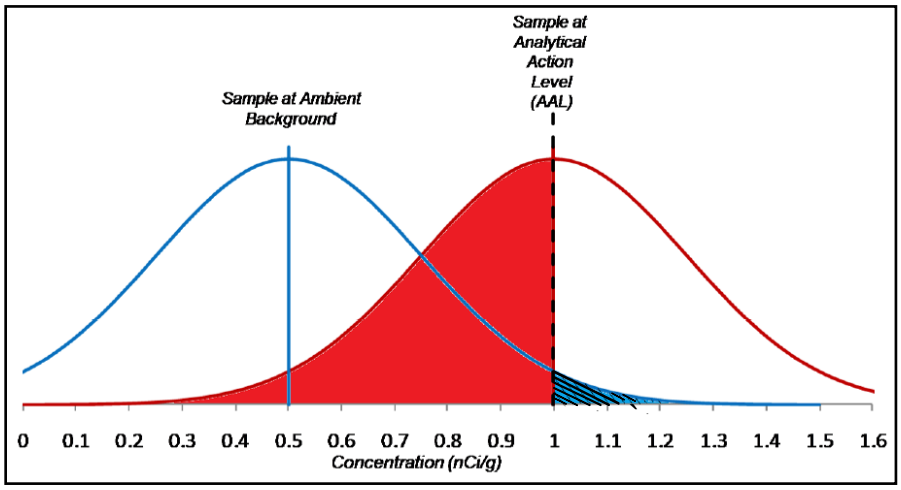

Figure 1 – Uncontrolled Decision Error at the AAL

If the measured result is compared directly to the AAL to decide whether the activity is equal to or above the AAL, there is a 50% probability that the measurement will result in an incorrect decision that the true activity is below the AAL (*this case corresponds to the solid area below the AAL*).

The magnitude of the measurement uncertainty affects the ability of a method to tell the difference between background activity and contaminant at the AAL. Without establishing a control on the measurement uncertainty, it may not be possible to discriminate ambient background activity from contaminant activity at or above the AAL (*this case corresponds to the cross-hatched area above the AAL*).

It is possible to control the probability of decision errors by comparing measured results with specified limits on uncertainty to an *analytical decision level* (ADL).

[9] In a case where there would be greater consequences associated with falsely concluding that activity is present when it indeed is not, the most appropriate null hypothesis would be, "*The measured activity is below the action level*." Because this case is less frequently applied for environmental analyses, it will not be presented here. For details, see Appendix VI of the *Radiological Laboratory Sample Analysis Guide for Incidents of National Significance – Radionuclides in Water* (EPA 2008).

Assume that the null hypothesis is that *the true activity of the sample exceeds the AAL*. We can calculate an analytical decision level as ADL= AAL – $z_{1-\alpha}\, u_{MR}$.

This means that before deciding that activity is not present at or above the AAL, the result of a measurement must fall below the AAL by a margin corresponding to the tolerable probability of falsely rejecting the null hypothesis that the true concentration is above the AAL.

The DL is the concentration for which the null hypothesis is considered to be false but at which it is important to be able to distinguish the concentration from that of a sample at the AAL. The AAL and DL together bound the "*gray region*" in which decision error probabilities are not controlled as tightly as outside of it.

Consider the hypothetical situation shown graphically in Figure 2. Assume that a DQO is established that stipulates that the null hypothesis is that *the true activity of the sample exceeds the AAL,* with tolerable Type I and Type II error rates of 5% and 10% respectively.[10]

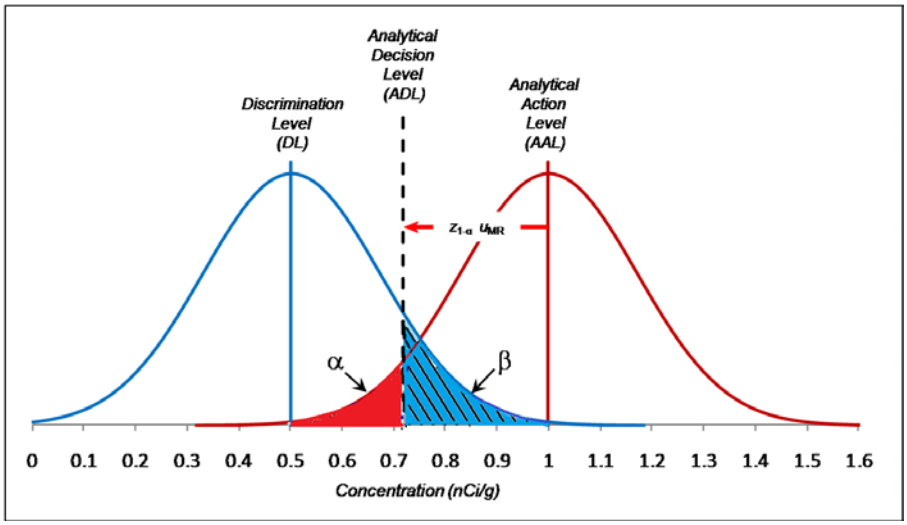

Figure 2 – Controlling the Probability of Decision Errors with the ADL and u_{MR}

The AAL for the screening process is 1.0 nCi/g. Samples with activity above 1.0 nCi/g may not be sent to the low-level laboratory.

A discrimination level of 0.5 nCi/g is selected since the matrix being measured contains naturally occurring background activity of 0.5 nCi/g, and there is concern that this activity will be mistaken for the contaminant of concern. The *gray region* (Δ) is the area between the AAL and the discrimination level. For a sample with true activity in the gray region, there is a high probability of a decision error. The width of the gray region, delta, is calculated as:

$$\Delta = |AAL - DL| = |1.0 - 0.5| \text{ nCi/g} = 0.5 \text{ nCi/g}.$$

[10]The probability of making Type I error is chosen to protect against the greater risk associated with incorrectly deciding that the sample activity is below the AAL when in fact it is greater than the AAL. The larger Type II decision error means that there are lower consequences—and thus greater tolerance—to falsely concluding that activity is present, even though it may be attributable to background activity.

The required method uncertainty ensures that the rate of Type I and Type II decision errors is maintained within the specified limits and is calculated as follows:

$$u_{MR} = \frac{\Delta}{z_{1-\alpha} + z_{1-\beta}} = \frac{0.5 \text{ nCi/g}}{1.645 + 1.282} = 0.17 \text{ nCi/g}$$

See footnote 5 for the values of $z_{1-\alpha}$ and $z_{1-\beta}$. The ADL, which is used as the decision criterion, is a function of the uncertainty of measurements of a sample at the AAL and is calculated as:

$$\text{ADL} = \text{AAL} - z_{1-\alpha}\, u_{MR} = 1.0 \text{ nCi/g} - [1.645 \times 0.17 \text{ nCi/g}] = 0.72 \text{ nCi/g}.$$

The curve centered about 1 nCi/g in Figure 1 represents the distribution of all possible measurements of a sample with a true activity equal to the AAL. In figure 2, consistent with established DQOs, *only 5% of this distribution (α) falls below the ADL*. The curve, centered about 0.5 nCi/g, represents the distribution of all possible measurements of a sample containing only naturally occurring background activity (equal to the discrimination level). Consistent with DQOs, *only 10% of this distribution (β) may exceed the ADL*.

Thus, only measurements that fall *significantly* below the AAL *(*i.e., *less than the ADL)* will lead to rejection of the null hypothesis, and thus reliably support the conclusion that the true activity of the sample has not exceeded the AAL. At the same time, the required method uncertainty, u_{MR}, is kept small enough to ensure that the AAL will be differentiated reliably from the naturally occurring background activity at the discrimination level. In contrast to decision error rates of 50% that may result from comparing measurements directly to the action level, comparing a measurement to the ADL will ensure that decision errors are maintained at the rates consistent with DQOs.

4. Metrology, Quality Systems, and QA/QC

An effective quality system is vital in assuring the quality of any radioanalytical measurement used for incident response decisionmaking. It ensures, among other things, that all measurements are traceable to national standards and provides defensibility against data challenges. The rigor and detail of one aspect of the quality system,[11] its QC requirements, will likely need to be increased from the initial response and final recovery phases and be the most stringent during final status surveys. A graded approach may be applied to reflect changing DQOs, MQOs, and needs for analytical quality. The QA/QC protocols used should always provide clear assurance that data is of sufficient quality to support the decisionmaking process. This section addresses some of the fundamental concepts of metrology, quality systems, and their importance in field and laboratory measurements for incident response.

4.1 Why is Metrology Important?

The *International Vocabulary of Metrology* (VIM; IBWM 2008) defines metrology as the "*…science of measurement and its application. […] Metrology includes all theoretical and*

[11]See section 4.3 for a more complete discussion of quality systems.

practical aspects of measurement, whatever the measurement uncertainty and field of application."

Radiation and radioactivity measurements can be complex, and establishing traceability for instrument calibrations for complex field measurements may pose technical challenges. Some practitioners may be uncomfortable in setting up equations for the various measurement models, or in developing them into expressions of uncertainty.

Failing to consider and apply the fundamentals of metrology, however, will result in measurements of unknown and very possibly substandard quality. Without meaningful estimates of measurement uncertainty, or traceability of measurements to national standards, it is not possible to demonstrate defensibly that a measurement possesses sufficient quality to reliably address DQOs applicable to incident response, or even to reasonably compare it to that taken by another analyst or organization. Since this could result in potentially serious consequences to the decisionmaking process, it is vital that the fundamental principles of metrology be understood and adequately incorporated into measurements of radiation and radioactivity.

4.2 The Principles of Metrology

The core approach to performing any measurement, whether it is a radiological measurement performed in a field or laboratory setting, rests on the basic principles of metrology. Every measurement is a comparison to a standard. The degree to which reference materials provide a universal reference depends on the quality of the link of those measurements to the applicable reference standards. ISO 1993a and MARLAP (2004) define traceability as a "*property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties*" (ISO 1993b).

Measurements of radiation and radioactivity must be traceable to national radiation or radioactivity standards (e.g., a *Standard Reference Material*™ from the National Institute of Standards and Technology). The definition of traceability also recognizes that the uncertainty of a measured value is an integral component of its traceability. This is because the uncertainty indicates the degree of confidence that can be placed in a measurement.

It is important that measurement results be reliable, and that results from different organizations be comparable, and objectively and confidently accepted as such among all those likely to use that data. Not only must instrumentation be calibrated, but measurements must also be performed, and quality control protocols that preserve, validate, and document the traceability of each measurement to the national standard must be available. This applies equally to measurements made in the field and to those performed in a laboratory setting.

Factors that may affect the quality of measurements include reference materials used, equipment calibration, and chemical treatment (e.g., extraction, digestion). These measurements can be strongly dependent on the source material or sample matrix, whose exact composition is almost never completely known. This limits the degree to which the measurement environment can be defined and controlled.

Some fundamental steps of metrology that should be followed in measurements of radioactivity are:

- Develop/define DQOs and MQOs;
- Choose or develop the appropriate measurement method to meet the MQOs;
- Understand a method and its strengths and limitations;
- Choose suitable National Institute of Standards and Technology (NIST)-traceable certified reference materials and use them properly;
- Validate the method to demonstrate that the method will meet the MQOs; demonstrate and confirm it;
- Identify the sources of uncertainty in the method;
- Derive a model or an equation for the measurement that allows the combined standard uncertainty to be determined;
- Evaluate the uncertainty of each measurement using a recognized approach;
- Clearly establish and document that results are traceable to a national standard; and
- Report the results, the associated combined standard uncertainty with the appropriate units, the number of significant digits, and the coverage factor.

4.3 Quality Systems

A management system for quality must precede the design of any QA program. ISO/IEC 17025 provides guidance for developing an overall management system for quality, administrative, and technical operations. Similarly, the EPA has provided *Guidance for Developing Quality Systems for Environmental Programs* (EPA QA/G-1, 2002a). The scope and purpose statement for QA/G-1 describes a quality system as "…the means by which an organization manages its quality aspects in a systematic, organized manner. It provides a framework for planning, implementing, and assessing work performed by an organization and for carrying out required quality assurance (QA) and quality control (QC) activities. It encompasses a variety of technical and administrative elements, including policies and objectives; organizational authority; responsibilities; accountability; and procedures and practices." The document also stresses that a successfully implemented quality system will reduce vulnerabilities and improve an organization's ability to make reliable, cost-effective, and defensible decisions. The quality system approach will help ensure scientific data integrity and produce well-documented data of quality appropriate for the purposes intended. It also will reduce the risk of embarrassing surprises and data challenges while improving on-time delivery of data and reducing expenditures by reducing the need to repeat measurements unnecessarily.

4.4 Quality Systems Standards – Quality Assurance and Quality Control of Measurement Systems

Radioanalytical measurements will play a vital role in rapidly and reliably characterizing the type and extent of contamination following a radiological or nuclear incident. They are also key components needed to efficiently and effectively remediate any contamination identified. The production of data of known and sufficient quality to support long-term decisionmaking requires a well-implemented QA program containing elements stated in guidance documents from

various quality standards organizations. The elements defined in these programs address in detail every aspect of measurement operations, including:

- Effective, consistent, and well-documented oversight of the analytical process;
- Receipt, tracking, and management of samples;
- The procurement of supplies and equipment;
- The qualifications and training of personnel;
- The setup, maintenance, and calibration of instruments and support equipment;
- Quality control of all measurement processes;
- Selection, validation, and proceduralization of analytical methods;
- Results' traceability to national standards (e.g., NIST);
- Creation, maintenance, and archiving of records and documents;
- The reporting and review of results and independent QA oversight of all measurement processes; and
- Review of analytical output.

Any measurement program that will be used as the basis for key decisions also must be supported by a substantial and robust QC program if it is to generate reliable, verifiable, and defensible results and uncertainty estimates. An effective QC program will empirically measure, control, and document the precision, accuracy, representativeness, and comparability of results. Lacking a comprehensive QA/QC program, the quality of data generated may be inadequate to support the generation of large data sets that can be validated to levels that will withstand the scrutiny of public or legal inquiry.

4.4.1 Quality Systems Standards, QA and QC for Field Measurements

Traditionally, it has been recognized that there are limits to the detail and the quality of testing for radioactivity that is practicable in the field. This has included requirements for the traceability of measurements, formalized QA, maintenance of constant test conditions, and implementation of effective QC requirements and oversight to ensure that the quality of results will meet DQOs/MQOs. As a result, fixed laboratories have traditionally been called upon to perform many of the most critical, complicated, and sensitive measurements. Fixed laboratories also have been required to maintain sophisticated quality systems commensurate with the higher quality of measurements being performed.

Over time, innovative field measurement techniques have become increasingly more available, and increasingly more sophisticated measurements can now be performed in the field. Since these measurements support the same decisions that traditionally required the quality of fixed laboratory data, field programs need to consider the same quality concerns that have been applied at fixed laboratories for many years.

Field sampling program QA/QC has not focused on addressing the analytical process, since this role was so frequently relegated to the fixed laboratory. Rather, it tended to address areas such as the tracking, management, and receipt of samples; preservation of samples; sampling techniques for various matrices; and procurement of supplies and equipment. Guidance on the performance of field measurement parameters (e.g., conductance, pH, radiation dose rate) and the operation of

field instruments has been provided by instrument manufacturers. A limited number of standard practices are available from standards organizations that address field measurements and associated QA/QC in detail. Based on available guidance and best practices, standard operating procedures are designed for use by field analysts. Thorough guidance is needed for field programs to ensure that sufficiently detailed direction is given to designing and effectively implementing a quality system for field measurements. This can best be accomplished by providing detailed analytical protocol specifications in quality assurance project plans, and by allowing for time to focus and implement QA/QC measures in advance of deployment.

Broad ranging formalized quality system standards and certification/accreditation and oversight programs have yet to be implemented that effectively address field measurement programs. Although two volumes of The NELAC Institute Standard apply to field sampling and measurement organizations (TNI 2007), implementation of these quality system standards, adopted in 2007, and associated independent accreditation is limited to field determinations of non-radioactive lead (Pb). The scope and timing of additional implementation has not been determined at this time. The *Multi-Agency Radiation Survey and Site Investigation Manual* (MARSSIM 2000) provides only general direction on QA measures applicable to field instruments. For example, *in situ* measurements, particularly those performed using efficiency modeling techniques, generate results that are not traceable to national standards (e.g., to a NIST Standard Reference Material). This critical fact often is overlooked and represents a huge divide between the standards of analysis needed to create accurate and defensible data and those that are sometimes applied in the field.

Training of field personnel is a second area that is difficult to address, especially for an incident response. Due to the nature of an incident response, there is little if any time available to effectively train a large number of instrument analysts and operators prior to mobilizing for the field. Training classes would be short and provide only generalized mechanical instructions on operating an instrument. A thorough knowledge of how matrix and geometry affect the measurement process cannot be taught during the pressure of responding to an incident. Cursory instruction cannot substitute for the expertise that results from long-term experience and documented historical performance running an analytical technique or instrument. Once in the field, oversight of relatively inexperienced analysts would be difficult to perform and to document. Additionally, each incident will have specific matrix and field sample geometry issues.

A third area of concern surrounds the defensibility of the precision and accuracy of results. Given the variability in measurement conditions and the characteristics of the objects to be measured, innovative, empirical quality control measures are needed to provide assurance that the measurement process and individual measurements consistently meet MQOs. Quality control measures for field measurements are not generally as robust as those routinely used for laboratory measurements. This is due in part to the nature of the measurement, and the challenge of constructing QC protocols for *in situ* measurements that demonstrate empirical monitoring and quality control of field measurements. One or more measures could be implemented that are appropriate to specific concerns surrounding the type of measurement being performed. Such measures might include:

- Routinely analyzing independent confirmatory grab samples at a laboratory to measure and control the bias and precision of the process;
- Analyzing *in situ* blanks to control absolute bias in each area where measurements are conducted by repeating the measurement in the same location and rotating the instrument 180˚ in the horizontal plane;
- Performing redundant measurements that validate the process using modified analysis parameters, for example, by:
  - Measuring the same object from different angles and distances to show adequate implementation of efficiency modeling and to help validate estimates of uncertainty;
  - Having a different person repeat the measurement;
  - Using a different instrument and/or software to repeat the measurement; or
  - Repeating the measurement after breaking down the equipment, leaving the area, coming back, and setting up the equipment and instruments again.
- Analyzing known reference samples to measure and control the accuracy of the process;
- Participating in regular external proficiency testing programs that provide independent empirical evidence of the accuracy and intercomparability of measurements;[12] and
- Utilizing independent verification contractors to ensure that the cleanup has achieved its stated goals.

During conventional clean-up and remediation activities (for example Resource Conservation and Recovery Act [RCRA] sites), a final status report is written at the completion of decontamination/removal tasks that summarizes the measurement data and discusses how a decision is made that the data are adequate to satisfy the DQOs. In the case of structures and land areas, the database that supports this consists of *in situ* measurements supported by independent confirmatory lab analysis of random and judgmental (i.e., "biased") samples. For regulated activities (U.S. Nuclear Regulatory Commission [NRC], DOE, agreement states), confirmatory split sampling by regulators and independent inspection and oversight are performed by an independent verification contractor responsible to the applicable regulatory authority.

Validating the methods/procedures to be used to conduct field measurements is another important practice that empirically demonstrates the accuracy, precision, comparability, specificity, and robustness provided by a method. If a field measurement technique is used in support of the decisionmaking process, validating it will help ensure that measurement biases and uncertainties for various geometries are known and that its capabilities are empirically tested and well-documented prior to its use.

Techniques used for determining field measurements often rely on assumptions that are difficult or impossible to verify (e.g., self-absorption effects, the impact of background on low-level measurements, or the assessment of complex measurement situations). Efficiency modeling techniques rely considerably on the judgment of instrument operators and their ability to set up, calibrate, check performance of, and use instruments and procedures to perform processes such as scanning surveys.

[12] Small demonstration programs have been carried out in the past, but there are currently no ongoing external programs that are designed to empirically assure the intercomparability of results produced under conditions that approximate those encountered in the field.

During an incident, the level of oversight and number of personnel available to support operations will presumably be stretched to the limit. Conditions in the field may vary significantly from measurement to measurement. The level of experience available may not guarantee that the level of documentation and review is adequate to verify all the critical conditions and assess the impact of decisions made during the performance of an *in situ* measurement. Analyst judgment, for example, is crucial in complex *in situ* measurements, yet judgment is difficult to quantify and may vary depending on the knowledge, experience, and skill of instrument operators and the specific challenges of the measurement.

Careful and complete documentation, effective prompt review, and retention of sufficient records to assure unambiguous recreation of a result are critical elements provided under a quality systems approach. Lacking effective technical oversight and experienced independent reviewers, an individual may be asked to self-perform quality-related functions that should be completed independently, a situation that would not be allowed under laboratory QA programs where independent review and oversight are required prior to release or utilization of results.

A very effective external QC measure, confirmatory sampling, should be incorporated as a routine QC measure into field sampling and analysis plans. Comparing field measurement results to radiochemical analyses of samples using recognized, independent, quantitative laboratory techniques provides empirical evidence of the effectiveness of the field measurement process. Integrating such quality control measures into the field measurement process lends a large degree of defensibility to field measurements as long as it is performed at intervals frequent enough to provide meaningful statistical feedback on the adequacy and implementation of the measurement program in all of its unique measurement situations. When the scope of the QC program is relatively limited, or when results are received long after the field efforts are complete and the decisionmaking is complete, the program will do little to provide meaningful controls on measurements.

4.4.2 Quality Systems Standards, QA and QC for Laboratory Measurements

EPA's G-series QA documents provide extensive guidance on topics applicable to measurement projects, including the development (EPA QA/G-1, 2002a) and assessment (EPA QA/G-3, 2003) of quality systems; on systematic planning using the DQO process (EPA QA/G-4, 2006; EPA QA/G-5M, 2002c); the development of quality assurance project plans (EPA QA/G-5, 2002b) and standard operating procedures (EPA QA/G-6, 2007); and on audits and assessments (EPA QA/G-7, 2000).

Laboratories and their operational systems have a history of maintaining quality systems that allow them to comply with extensive and elaborate quality requirements. These quality systems prescribe in detailed fashion the elements needed to generate and document usable data from the initial procurement of an instrument, through setup and calibration to data evaluation, reporting, and interpretation. The laboratory must maintain management structures that ensure adequate resources and oversight are available to perform the testing required of them. The laboratory's ability to generate analytical results must be validated for all measurements. The laboratory must routinely perform reliable and defensible QC that demonstrates that all measurement systems are in control and thus capable of meeting and producing data that meet MQOs. The laboratory also

must completely and unambiguously document all activities associated with measurements such that all results can be recreated from available records. Such programs and standards cited are written with the laboratory process of QA/QC and instrument calibration in mind. No comparable or comprehensive nationally accepted and nationally implemented quality systems programs are currently available for field measurements.

Radiochemistry laboratories operate under comprehensive laboratory quality systems standards such as the *TNI Standard* (NELAC 2003), Department of Energy Consolidated Audit Program's *Quality Systems for Analytical Services* (DOE 2009), the Department of Defense *Quality Systems Manual* (DOD, 2009), *ANSI N42.23-1996* (ANSI, 2004a), and *ISO/IEC 17025* (2005). One key example of the many elements addressed by laboratory quality programs is the calibration of detectors. Excerpts from several consensus standards regarding standardization and calibration are cited here to provide an example of the detail and broad influence of such documents on the overall process and the quality and defensibility of measurement results.

For example, laboratories are accredited by any number of organizations to standards such as the *TNI Standard* (NELAC 2003). The TNI Standard is a comprehensive quality standard that addresses, among other things, issues of traceability for laboratories conducting definitive environmental measurements:

> "… [T]he essential elements that shall define the procedures and documentation for initial instrument calibration and continuing instrument calibration verification to ensure that the data must be of known quality and be appropriate for a given regulation or decision."
>
> "[A]ll initial instrument calibrations must be verified with a standard obtained from a second manufacturer or lot if the lot can be demonstrated from the manufacturer as prepared independently from other lots. Traceability shall be to a national standard, when commercially available."

The American Society for Quality Standard E4 (ASQ E4), *Quality Systems for Environmental Data and Technology Programs-Requirements with Guidance for Use* (ANSI 2004b), states, for example, that for measurement devices, "Traceability to nationally recognized performance standards should be maintained when they are used for critical or sensitive items and activities." American Society for Testing and Materials (ASTM D7282 2007), provides detailed guidance on the setup, calibration, and quality control of instruments used for radioactivity measurements. MARLAP (2004) Chapter 15, "Quantification of Radionuclides," provides guidance on the importance of standardized calibration techniques using sources of known and traceable activity. Specifically,

> "The goal of calibration- or test-source preparations is to maximize detection capability while minimizing the introduction of bias and uncertainty into the measurement process. To achieve this goal, calibration sources should be prepared in a manner that provides comparability to test sources with respect to geometry, composition, and distribution of the test-source material within a container or on a source mount."

Furthermore, it states that:

> "Proper instrument calibrations are essential for the proper identification and quantification of radionuclides in samples. It is important to initially calibrate the instruments with calibration sources that are traceable to a national standards body. Once calibrated, the continuing validity of calibrations should be checked on a periodic basis (Chapter 18, Laboratory Quality Control) as specified in a laboratory's quality manual."

The QC measures taken to verify proper instrument calibration and use are another required component of a defensible measurement process. These measures include instrument stability and background checks, as well as quality control sample analyses that empirically demonstrate the validity of measurements. These elements are addressed, for example, in the Nuclear Regulatory Commission's Regulatory Guide 4.15, *Quality Assurance for Radiological Monitoring Programs (Inception through Normal Operations to License Termination)—Effluent Streams and the Environment* (NRC 2007), and include routine analysis of control samples, duplicates, blanks, and matrix spikes. Such QC samples often are not performed in an equivalent, formalized manner when making field measurements as would be required under an accredited laboratory's quality system.

Unlike laboratory systems, field operations are more transitory and are not as readily amenable to formalized audits. Accrediting authorities routinely audit laboratories to ensure compliance with the requirements of quality systems standards. Laboratories participate in routine independent proficiency testing (PT) studies to demonstrate satisfactory performance of laboratory methods. These PT studies are quantifiable measures of assurance that analytical systems are working properly to produce reliable and defensible data and that offer opportunities to make improvements when they do not.

In contrast, a field measurement team for an incident response may be made up of personnel who have been pulled together for that specific project. They may not have been routinely audited, nor are they as likely to have a documented record of compliance with a quality standard or standard operating procedures (SOPs). The use of different instruments in varied settings, and the implementation of guidance that varies from what they are accustomed to may necessitate additional QA/QC measures to ensure that measurements are defensible.

Regular blind intercomparison programs generally are not viable options for field sampling and measurements organizations due to practical challenges such as the preparation of test plots or the need to transport field crews to a facility where such plots are available. The benefits of using field calibration facilities, such as the large area calibration pads at Walker Field Airport in Grand Junction, Colorado (Leino *et al*., 1994; Novak, 1998), could be substantial because they would allow validation of *in situ* measurement technologies and training of field personnel prior to mobilization.

Quality systems standards address another parameter key to performing quality measurements in any setting. Variability in ambient conditions such as temperature, humidity, and ambient background could affect analyses and challenge notions of consistency and repeatability that form the basis for setting up, maintaining, and operating analytical instrumentation in laboratory

settings. Careful storage and control of samples generally allow reanalysis of a sample, should problems arise that could impact the quality or integrity of analyses.

Finally, laboratories maintain detailed records and generate extensive data deliverables that allow each individual measured parameter to be recreated in detail and the measurement data to be independently verified and validated. Based on the documentation produced, analytical results can be independently verified, validated, and assessed from the deliverables and from archived records. Comparable documentation for field measurements is more challenging because of the fluid field conditions compared to those in the more controlled laboratory environment.

4.5 Quality Assurance Project Plan

A QAPP supplements the default quality system by providing a blueprint of where, when, why, and how a particular measurement project will achieve data of the type and quality needed and expected. A QAPP can form the basis of a QA program (EPA QA/G-5, 2002b). This document should address:

- Personnel training and qualifications;
- DQOs and MQOs;
- SOPs, or schedules for the implementation of the QA program;
- Acquisition and maintenance of materials and supplies;
- Calibration;
- QC of instrumentation (including traceability of calibration sources);
- QC of routine measurements;
- External intercomparison programs and internal audits;
- Training of measurement personnel;
- Verification and validation (V&V) of data;
- Audits, corrective actions;
- Control and documentation of procedure revisions;
- Field logs (describing environmental conditions);
- Records of measurements (e.g., the time, date, location, instruments, and procedure used; personnel, etc.) with sufficient detail to permit results to be unambiguously recreated from data retained; and
- QC records for radiation measurement instrumentation (including the results of instrument checks, calibrations, instrument background determinations, and maintenance activities that could affect equipment performance).

4.6 Uncertainty Estimates and the Measurement Process

MARSSIM recognizes the importance of minimizing the uncertainty of data used for decisionmaking and stresses that "[s]ite surveys should be performed in a manner that ensures results are accurate and sources of uncertainty are identified and controlled" (MARSSIM 2000, Section 4.9). *MARLAP* (2004, Appendix B) discusses the sources and impact of uncertainty in the measurement process:

> "The uncertainty of the measurement process involves not only an instrument and its reproducibility, but also the representativeness of the sampling. There will be sampling uncertainty, due to spatial and temporal variability in concentrations across the site and from one sample to the next. There will also be analytical measurement uncertainty due to the variability in the measurement process itself. Since it is impossible to eliminate uncertainty, basing decisions on measurement data opens the possibility of making a decision error. Recognizing that decision errors are possible because of uncertainty is the first step in controlling them."

It goes on to state that:

> "…sampling uncertainty can be reduced by collecting a larger number of samples. Measurement uncertainty can be reduced by analyzing individual samples several times or using more precise laboratory methods. Which uncertainty is more effective to control depends on their relative magnitude. For much environmental work, controlling [reducing] the sampling uncertainty error by increasing the number of field samples is usually more effective than controlling measurement uncertainty by repeated radiochemical analyses." (MARLAP 2004, Appendix B, B-11 and B-14)

4.6.1 Uncertainty Estimates and Field Measurements

When using field survey instruments to perform large-scale radioactivity measurements, there are several factors that affect representativeness of sampling. These factors include:

- Non-uniform dispersion of radioactive material in the area being measured;
- Variability of ambient background radiation in and adjacent to the area being measured;
- Lack of knowledge about depth penetration of the radionuclide contaminant;
- Resuspension of some of the surface contamination during the measurement process;
- Weather conditions during and immediately prior to the measurement; and
- Robustness of the sampling and analysis plan.

In the field, it can be difficult to control and estimate these uncertainties. Thus, field surveys of structures and materials to be left in place may provide measurements of contamination with poorly known uncertainties. Follow-up analyses using swipes (to assess lower yet significant levels of removable and air-suspendable material), and surface and sub-surface grab samples (to assess volumetric contamination) can be used to confirm field measurements.

Another factor affecting the uncertainty of reported field data is the correspondence between the calibration geometry of the instrument and the actual geometric configuration of the radioactivity in the field. Although uncertainty estimates based on sample density and shape can be mathematically computed, there is no uniform method established for doing so. Guidance from documents such as *Guidance on Systematic Planning Using the Data Quality Objectives Process* (EPA QA/G-4, 2006), and the *GUM* (ISO 1995) may be applied to field measurements. The application of these methods to field surveys of materials and equipment is treated in MARSAME (2000). The GUM procedures for calculating uncertainties do not always presume that definitive estimates of each component of uncertainty are available, but provide a framework

for assessing the magnitude of such contributions given professional judgment and knowledge of the measurement process. This allows planners to focus on those parameters that are most likely to impact the overall uncertainty and affect decisionmaking.

The concepts of MQOs and DQOs for field measurements of radioactivity are not as well-developed and implemented as they are for laboratory measurements. Similarly, uncertainty analysis and its implication for the planning and decisionmaking process are not nearly as advanced as for laboratories. While MARSAME addresses many such concerns, it has only recently been published, and there has been little training available in its use. Promulgating these ideas into the field setting will require significant time, validation of the methods, and training of the analysts who will perform these measurements.

4.6.2 Uncertainty Estimates and Laboratory Measurements

MARLAP provides guidance on calculating uncertainty and measures used to minimize uncertainty in sample measurement processes in the radioanalytical laboratory. The guidance provided in MARLAP supports the concepts for detailed measurement uncertainty estimates. By placing each sample in a reproducible geometry within a shielded detector, laboratories create a controlled and predictable environment in which measurements will be performed (including stable, low, and well-characterized backgrounds). Samples are prepared to ensure congruence between the sample test source and the calibration geometry. While this is clearly advantageous in terms of minimizing measurement bias, it also minimizes measurement uncertainties and makes it easy to assess the contribution to the uncertainty from the measurement process.

The treatment of measurement uncertainties and their relationship to MQOs and DQOs have been thoroughly addressed in MARLAP for radioanalytical chemistry measurements in the laboratory. The basic principles underlying these methods are outlined in *Guidance on Systematic Planning Using the Data Quality Objectives Process*, the *GUM*, and other guidance documents. The methods for estimating measurement uncertainties are not limited to the applications cited in these references but are equally appropriate for virtually any type of measurement.

Determination and reporting of uncertainty for radioanalytical laboratory measurements have been routine at laboratories for many years. There have been volumes of publications on uncertainty in radioanalytical measurements. ISO 17025 and NIST traceability requirements have increased the focus on determining and reporting measurement uncertainty and made uncertainty analyses very familiar in the laboratory setting. MARLAP Chapters 19 and 20 provide detailed guidance and examples of estimating uncertainty in radioanalytical measurements. Training in the use of these specific methods has been provided at numerous MARLAP training classes since 2005 and at nationally recognized radiochemistry conferences for substantially longer periods of time.[13]

When considering the relative merits of *in situ* versus laboratory measurements, it is important to keep in mind that the overall uncertainty of an ISGS measurement of surface activity may be less

[13] See program descriptions for the 52nd and 53rd Annual Radiobioassay and Radiochemical Measurements Conference www.lanl.gov/BAER-Conference/.

than the combined uncertainty of laboratory measurement due to the uncertainty associated with sampling. It is for this reason that ISGS measurements are attractive options.

Nonetheless, before a program can rely on any measurement, be it from the field or from a laboratory, the quality of the measurement must be assured. This would include a demonstration that its estimate of measurement uncertainty is reliable and defensible and that it can satisfy applicable MQOs. If experience, guidance, and programmatic support for this are weak or lacking, or conditions are variable such that inputs into the uncertainty model are poorly known, field measurements should be verified on a routine basis using confirmatory laboratory measurements to demonstrate that MQOs have been satisfied.

5. Considerations on the Capabilities and Limitations of Radioanalytical Measurement Techniques in the Field and Laboratory

Field and laboratory measurement techniques each have their strengths and weaknesses, but they may be used together in a complementary fashion during the days and months following an incident. This section addresses some of the key factors impacting the effectiveness of measurement techniques as they are used in the field and at the laboratory for measuring different types of radiation and radioactivity. Among the key factors are the ability to accurately calibrate equipment for a given purpose, and to measure and apply corrections for background such that the bias and uncertainty of the measurements are controlled at levels that are appropriate for decisionmaking. An understanding of these factors will help Incident Commanders identify appropriate measurement techniques and take optimal advantage of the respective strengths of the variety of field and laboratory measurement options available to them.

5.1 The Impact of Background Radiation on Radioanalytical Measurements

Ambient radiation can have a significant impact on analytical measurements of low levels of radioactivity. When low action levels are encountered, as would likely apply during the recovery phase of an incident and during final status surveys, background activity must be accurately measured and subtracted from measurements to ensure the quality and defensibility of results. Inaccurate measurements of background activity will result in biased measurements and underestimation of uncertainty, and may potentially lead to incorrect decisions. The following section addresses the impact of background radiation on radioanalytical measurements in the field and in the laboratory.

5.1.1 The Impact of Background Radiation on Field Measurements

Most radiation detection instrumentation responds to one type, or to a combination of several types, of radiation. Field instrumentation generally provides results as gross activity[14] (e.g., counts) or dose or exposure (e.g., mrad or roentgens) for the particular type(s) of radiation. Because field detectors are built to be portable, they may not be heavily shielded and respond to any source of radiation that impinges on the active volume of the detector. Significant

[14] The expressions “gross activity,” “gross alpha,” “gross beta,” and “gross gamma” will be used in this guide to refer to non-specific measurements of alpha, beta, or gamma radiation. These will be contrasted with measurements of radioactivity, spectrometric or otherwise, that are specific enough to be attributed to a specific radionuclide.

contributions from the ambient background radiation beyond the area of measurement may limit the accuracy of field measurements adjacent to other contaminated areas. According to the International Commission on Radiation Units and Measurements (ICRU) 53, "[a]t a detector height of 1 m, about 30% of the total fluence rate measured comes from beyond a 3-m radius for ^{137}Cs that is uniformly distributed with depth in the soil." For a surface source distribution, about half the fluence comes from "beyond 10 m" (Reginatto *et al.*, 1997). Light shielding (collimation) often is used to reduce (but not eliminate) shine from beyond the immediate area being measured. Unfortunately, cylindrical shielding also reduces the field of vision of the detector and increases the number of measurements needed to characterize an area. This impact of ambient sources of background has been reduced and the "field-of-vision" of the detector improved by using a downward-looking bell-shaped shield with a detector mounted in the "neck" of the bell mounted on a wheeled frame for ease of movement.[15]

Sources of ambient radiation, such as cosmic radiation and naturally occurring radioactivity, are ubiquitous in the environment. Naturally occurring radioactive materials such as uranium, thorium, their decay progeny, ^{40}K, and others, represent significant sources of background radiation in soil, air, water, and construction materials (e.g., concrete, stone, wood, shingles, etc). For example, the National Council on Radiation Protection and Measurements (NCRP) lists the mean specific activities for several key naturally occurring radionuclides in soil as: 0.67 pCi/g ^{238}U; 10 pCi/g ^{40}K; 0.8 pCi/g ^{226}Ra; and 0.65 pCi/g ^{232}Th (NCRP 1976). Uranium, radium, and thorium decay through radon (an inert gas) into a number of radioactive decay products. As a gas, radon and its shorter-lived progeny are transported through the air and may deposit on surfaces and impact measurements of radioactivity on and around those surfaces in an unpredictable manner.

In addition to naturally occurring radioactivity, anthropogenic sources of radionuclides, such as ^{137}Cs or ^{90}Sr, are widely present in the environment as a result of fallout from the atmospheric testing of nuclear weapons. Typical global concentrations of ^{137}Cs and ^{90}Sr in surface soil samples may range up to 0.4 pCi/g and 0.3 pCi/g, respectively.[16]

The observed magnitude of the ambient background varies significantly in amount from location to location and over time. For example, background dose levels due to gamma radiation (excluding ^{222}Rn) can vary substantially but commonly range between 40–100 mrem/y. Outdoors, the beta dose rate from soil one meter above the ground is about one-third of the gamma dose. Beta/gamma exposure rate measurements, using field instruments that have only minimal shielding, may be impacted by variations in terrestrial radionuclide concentrations and the various effects of cosmic radiation, depending upon altitude (NCRP 1992).

If *in situ* measurements of alpha, beta, or gamma activity are to be considered unbiased and of known uncertainty, they may require adjustment to correct for the contribution from the intrinsic detector background activity, and for ambient radioactivity. As levels of residual radioactivity and MQOs approach background levels, the impact of ambient background on the quality of

[15] Personal communication with Edward Walker, 2010.

[16] Based on population-weighted average cumulative deposition density values (world) for ^{137}Cs and ^{90}Sr for the year 1999; from UNSCEAR 2000, Annex C, Table 11. Conversion from cumulative areal deposition values assumes deposition in the top 5 cm of soil, and a soil density of 1.6 g/cm^3.

field measurements will become much more critical. Accurate and precise measurements of detector background activity and corrections for background activity are possible in well-controlled environments where the detector and ambient background can be determined separately from the object being measured.

If the ambient background radiation level cannot be characterized accurately, measurements of radioactivity may be biased and measurement uncertainties difficult to estimate, resulting in measurements of unknown quality. If decisions about reoccupying space are based on such results, the amount of contaminant present in an area could be underestimated and result in a negative impact to public health. Conversely, unreliable background measurements could result in the overestimation of contaminant present, and the duration and costs of recovery operations could be increased unnecessarily. No matter what approach is taken, the accuracy of background correction factors should be established for different measurement situations and confirmed as a periodic QC measure by periodic confirmatory sampling.

5.1.1.1 The Impact of Background Radiation on Gross Measurements of Alpha and Beta Radioactivity in the Field

Typical hand-held survey meters, such as thin-window Geiger-Muller detectors, respond to alpha and beta particles and gamma rays but may not be sensitive enough for reliable measurements of alpha and beta/gamma contamination at activities close to ambient background levels. Detectors specific to certain types of radiation, such as alpha scintillation detectors, often have backgrounds that are low enough to perform reliable surface measurements of pure alpha emitters at relatively low activity levels.[17] When levels of radiation being measured are clearly above ambient background levels, as may be the case during the earlier phases of an incident, the contribution of background to the measurement may be small to negligible. As lower and lower levels of radioactivity are measured, as will be the case as an incident response progresses, differentiating between background and signal from the analyte becomes increasingly challenging and techniques that played a role early in the response may no longer be effective. Thus, it is important to account for sources of background activity when performing field measurements of radioactivity.

Ambient background due to beta and gamma radiation will vary significantly by location and over time when using unshielded detectors in the field. The use of counting statistics as the basis for detection decisions may not adequately reflect this variability and could lead to an underestimation of the overall uncertainty of a measurement. Unreliable measurement results and underestimates of uncertainty may lead to incorrect detection decisions or a false sense of security about the quality of data obtained. Thus, it is critical to ensure that each measurement technique used is appropriate for conditions under which measurements will be performed. It should take into account variability in the background and demonstrate that a technique is still capable of meeting quantitative and qualitative MQOs.

[17]It should be emphasized that this statement is applicable only when the contamination is present directly on the surface of the object being measured such that self-absorption does not decrease the effective response of the detector and the magnitude of analyte signal relative to the background.

Matrix materials (soil, asphalt, building materials, etc.) may contain intrinsic background radioactivity from naturally occurring radionuclides present in the matrix prior to the incident. This intrinsic radioactivity contributes to gross activity measurements and, unless appropriate corrections are made, may be significant enough to result in incorrect decisions about whether contamination is present. Similar to ambient background, this effect becomes most significant as the incident response progresses toward later stages and the activities of concern approach background levels. The intrinsic radioactivity of a matrix material may be determined by analyzing a representative uncontaminated sample of the materials using the technique of interest. This information can be used to determine the expected distribution gross activity measurements of uncontaminated background samples and thus the levels at which one can identify, with confidence, situations that deviate from background. Depending on the natural background, the technique involved, and DQOs, it may or may not be possible to identify when contamination exceeds project DQOs. If action limits or corrections are derived without regard to the variability normally encountered under measurement conditions, systematic low or high bias may result and may lead to an unacceptably high rate of false decisions regarding the presence and the magnitude of contaminants.

While it may be possible to derive matrix-specific background corrections and estimates of associated uncertainty, sometimes it may be beneficial to seek out more robust detection techniques (e.g., when the analyte signal at the action level is less than five to 10 times the combined uncertainty of the sum of the ambient, intrinsic, and instrument backgrounds). For example, if a radionuclide is not present in significant concentrations in the environment, a spectrometric measurement technique such as high purity germanium (HPGe) gamma spectrometry might discriminate quite effectively against naturally occurring radionuclides that would interfere with the ability of a non-spectrometric technique (i.e., a gross activity measurement) to provide meaningful measurements at lower activity levels.

When gross activity results are corrected for contributions from ambient background activity, the accuracy and uncertainty of correction factors should be validated under differing measurement situations. It also is recommended that field survey measurements be verified on a periodic basis as a QC measure (e.g., grab sampling with confirmatory analysis at a fixed laboratory). Empirically validating measurement methods prior to use under real measurement conditions will allow defensible statements of applicability to be made about the measurement technique, and will demonstrate that the technique is capable of effectively meeting the DQOs and MQOs needed for incident response decisionmaking while minimizing vulnerability to future data challenges.

5.1.1.2 The Impact of Background Radiation on Field Measurements of Gamma Radiation

Gamma rays are the most penetrating form of radiation and have the longest range in materials compared to the other radiations (e.g., alpha and beta) commonly measured in the environment. Thus, concern about interference of gamma rays with the measurement is not limited just to the radioactive materials intrinsic to objects being measured. For example, a gamma measurement of a wall surface in a building interior will have some component contributed by sources in the area other than those in the expected field-of-vision of the detector. When detectors are only lightly

shielded or collimated, gamma rays from every part of the room and beyond can impinge on the detector and contribute to the measurement. Gamma ray sources outside the area being measured may significantly impact readings. For example, measurements taken inside a building in the vicinity of a nuclear facility show variations in "background" that correspond to the amount of radioactivity emitted from that facility.

When counting with a gamma spectrometer, background corrections may not be necessary if the radionuclide of concern is not present in the background of the area where the sample measurement is taken. While naturally occurring radioactivity is ubiquitous, most anthropogenic radionuclides are rarely encountered in significant concentrations in the environment. In the case of an incident response, however, radionuclides associated with the incident will be widely distributed in impacted areas, and may thus become a component of ambient backgrounds and interfere with measurements prior to remedial activities.

If background subtractions are applied to low-level *in situ* measurements, the background and especially its variability (i.e., uncertainty) need to be well-characterized and reflected in the measurement results or their evaluation. Where possible, the effect of background on sample measurements may be minimized (but not likely eliminated) by shielding the detector. The measurement process should include a careful consideration of whether variability in background activity is adequately reflected in the uncertainty of the background corrected result to ensure that measurements will be capable of meeting established MQOs. If non-specific gamma radiation (i.e., gross gamma) is being measured, local and temporal variations in background may make it difficult, or even impossible, to accurately and reliably determine the background activity (or its uncertainty). No matter what approach is taken, the accuracy of background correction factors should be established for different measurement situations and confirmed as a periodic QC measure by periodic confirmatory sampling.

5.1.2 The Impact of Background Radiation on Laboratory Measurements

By its nature, the laboratory provides an environment where factors affecting radioanalytical processing and measurements can be very carefully managed and controlled. Laboratory instruments are housed in permanent locations within a building with controlled operations, structure, temperature, and humidity. The detectors used for measurements are heavily shielded. The shielding not only reduces the levels of the ambient background radiation impinging on the detector surface, but it also helps to ensure that detectors are exposed to consistent and reproducible background radiation levels. As measurement requirements approach lower levels (as is the case in the recovery phase of a radiological or nuclear incident), the highly controlled background environment of the laboratory setting allows more sensitive and precise measurements and ensures quality and dependability of the data.

In instances where levels of contaminant radioactivity are very high, having a controlled background environment is less vital. In fact, analysis of large numbers of samples of very high radioactivity levels may create problems of cross-contamination and elevated or variable background in the laboratory (despite the available shielding). Thus, during the early phase of an incident, the number of samples of high activity sent to a laboratory to be analyzed should be minimized, and the purpose of the analysis focused on identifying the radionuclides that are

present, establishing an upper bound on their concentration, and verifying key field measurements.

Although there is generally a high degree of confidence that results measured in the laboratory accurately reflect concentrations in any given sample delivered to the laboratory, the size of the sample delivered to the laboratory is generally limited to the gram to kilogram range. This is a much smaller effective sample size than is possible with ISGS measurements and might require that more samples be taken and analyzed to obtain a similar level of confidence that an area is adequately characterized and hot spots have not gone undetected.

The determination of intrinsic background in the sample matrix is an issue common to both field and laboratory measurements. The activity of the matrix results from radionuclides present in the matrix prior to the incident. Similar to the case discussed previously for field measurements, intrinsic levels of radioactivity in the matrix may result in incorrect decisions that contamination is present unless appropriate corrections are made to the measurement. For example, background activity will confound attempts to identify alpha and beta emitters at activities similar to background when using gross activity measurement techniques. At the laboratory, in contrast, chemical separations can be used to determine levels of radionuclides present well below the native gross activity of the matrix.

Similar to field measurements, the intrinsic background of the matrix must be well-characterized to determine whether an area has been impacted. Unless the signal attributable to the analyte at the action level is less than five to 10 times the combined intrinsic backgrounds of the material being measured and can be shown to be *de minimis*, empirical matrix-specific background corrections and estimates of associated uncertainty must be established. At these lower activity levels, however, it is generally beneficial to seek out a more robust detection technique where such is available. For example, for radionuclides not present in significant concentrations in the environment, spectrometric techniques may permit effective discrimination against naturally occurring radionuclides and allow non-spectrometric techniques (i.e., gross activity measurements) to provide more accurate measurements at lower activity levels.

In contrast to many field measurements, ambient backgrounds in the laboratory are quite stable and can be well-characterized, thus minimizing bias and uncertainty in measurements. Measurements of detector background activity and corrections for background activity are possible in well-controlled environments where the detector and ambient background can be determined separately from the object being measured. The accuracy of background correction factors applied in the laboratory is established and confirmed on a routine basis as a condition of using an instrument.

5.2 Types of Measurements of Radioactivity

The subsequent discussion of instrumentation and measurements of radioactivity will address the strengths, weaknesses, and general considerations that affect the capabilities of field and laboratory measurements. In the most general sense, a field survey measurement is any measurement used to conduct a radiation survey in the field. For the sake of this discussion, however, a distinction will be made between field survey measurements and field spectrometry

measurements. Measurement techniques that measure *gross activity* will be classified as *field survey measurements*. These include measurements that measure gross alpha, beta, or gamma radiation, but which are not capable of determining the energy of the radiation or the isotope that emits the radiation. *Field spectrometry measurements*, on the other hand, refer to measurement techniques that are capable of analyzing the energy spectrum of radiation of concern, usually gamma radiation, and are thus capable of identifying the radionuclide(s) present.

For radiochemical analysis at laboratories, a similar distinction applies. Chemical separations followed by non-spectrometric measurements can achieve definitive, radionuclide-specific measurements at the lowest activity concentrations. Thus, a distinction will be made between *screening measurements* and *spectrometric measurements*. *Screening measurements* will refer to measurements of gross activity without determination of the specific radionuclide that led to the emission of the radiation, whereas *spectrometric measurements* will refer to those measurements capable of radionuclide-specific determinations.

5.2.1 General Considerations Regarding Field Measurements

Radioactive emissions from the surfaces of objects are measured using instrumentation sensitive to the radiation of concern (alpha, beta, or gamma). A large number of factors vary from material to material and impact the manner in which radiation is, or is not, emitted from the surface of an object. Variability in any one of these factors may significantly affect instrument response relative to the source of the radioactivity (for further discussion, see Section 5.3 below).

The accuracy and sensitivity of measurement are limited by knowledge about the measurement situation and the assumptions made about the parameters that play a role in the emission of radiation from the object being measured to the active volume of the detector. Field measurements are, by their very nature, measurements of radiation emitted from a surface. When contamination is deposited directly on a surface, its measurement is much easier than if it is deposited more or less volumetrically within an object. As discussed previously, *surface activity* is radioactivity deposited on or close enough to a surface that minimal self-absorption corrections are needed to effect a precise and unbiased measurement of that radioactivity. When the depth profile of the radioactivity is not known, or cannot be accurately accounted for during calibration of the instrument, accurate measurements of radioactivity are not possible. Due to alpha- and beta emitters' limited range in matter, their measurement will be significantly impacted even following minimal penetration of contaminants into an object. In contrast, reliable detection and quantification of medium- to high-energy gamma emitters are possible even if contaminants have penetrated several centimeters into an object.

While spectrometric measurements are sometimes considered to be of higher quality than gross activity measurements, depending on the specifics of the measurement situation (e.g., surface vs. volumetric contamination), the quality of either type of measurement may range from screening quality to an unbiased measurement of known uncertainty and may find differing levels of applicability depending on questions at hand.

5.2.1.1 Survey Measurements in the Field

First responders typically will use the latest technologies that rely on the detection of gamma rays, x-rays, and beta and alpha radiation. The applicable technologies include a variety of portable devices such as beta/gamma and alpha survey instruments in a variety of configurations.

Generally, gamma radiation above about 200 keV (medium- to high-energy gamma emissions) is the easiest to detect and accurately quantify with field measurements, because it is subject to significantly less attenuation than alpha, beta, and lower-energy photon emissions, and can thus penetrate several centimeters of material and arrive at the detector with enough energy to be registered. Field measurements frequently provide results as uncalibrated instrument response, such as counts per minute (cpm), or in terms of dose or exposure (e.g., μrad/h, μR/h) based on the particle flux at the meter.[18] For example, gamma survey meters, such as NaI(Tl) detectors and micro-R meters, are frequently calibrated using ^{137}Cs or ^{60}Co, perhaps due to the prevalence of these nuclides at many nuclear sites and their relatively low cost, but also since these detectors are optimally sensitive to radioactive emissions in this energy range. More recent generations of instruments, however, may report activity results referenced to various radionuclides. The user is strongly cautioned against interpreting such results as accurate measurements of absolute radioactivity (e.g., pCi or pCi/g) unless the instrument has been calibrated for the particular measurement situation since accurate quantitation is possible only after application of corrections for factors such as radionuclide(s) decay type and energy, matrix composition and density, geometric distribution of the contaminant, attenuation due to surface roughness or overlaying material, presence of multiple radionuclides, and variations in the contribution of activity from radionuclides in the background.

Like any other instrument, field survey instruments must be calibrated prior to use if they are to provide results that are traceable to national standards or intercomparable from instrument to instrument. Most field instrumentation used to measure the concentration of radionuclides (instead of dose rate) detects total particle fluence rate with minimal regard to the energy of the radiation. Conversion of measurements of count rate or dose (e.g., mrad per hour) to surface activity (pCi/100 cm^2) or volumetric/massic activity concentration (e.g., pCi/g) requires knowledge of how radiation has been attenuated within the volume of the source and scattered between the source and detector. Unless calibrations are performed that reproduce the radionuclides and geometries and take into account self-absorption effects caused by the matrix, the potential for bias and unknown level of uncertainty in absolute measurements of activity cannot be discounted without additional sampling and analysis.

For direct, static measurements of beta or alpha radiation on surfaces, the efficiency of a measurement can be viewed as a composite of two quantities:

1) Instrument efficiency, which is a function of:
   - Type of the radiation

[18] While measurements of particle flux at the meter can be used to produce accurate estimates of dose, the use of "uncalibrated instrument response," that is instrument net count rate, cannot be related to the activity of radionuclides present (e.g., pCi or dpm) without applying an empirically determined values for detection efficiency, i.e., cpm/dpm, of a specified radionuclide.

- Energy of the radiation
- Detector type
- Position of the detector relative to the surface being measured
- Window size and thickness

2) Source efficiency, which is a function of:
   - Type of the radiation
   - Energy of the radiation
   - Size and shape of the object
   - Density of the object
   - Physical composition of the object (i.e., average atomic number of constituents)
   - Depth profile of radionuclides in the object
   - Surface texture and roughness of the object
   - Density of the material
   - Current moisture content in the object

Establishing the instrument efficiency, that is, the response of a detector to radiation incident upon its active area, is a relatively straightforward process if radioactive sources are available with the appropriate radionuclides in the appropriate geometry.[19] Accurately measuring the source efficiency (i.e., the fraction of radiation emitted from a surface relative to the total number of decays taking place in that surface) for each type of object or surface to be measured, however, is a much more complicated task and may not be practicable without making simplifying assumptions. A number of factors determine the fraction of total radiation that will be emitted from a surface with enough energy to be detected.[20] Complex radiation transport models and considerable technical expertise may be needed to generate accurate corrections. Measurement geometries are usually much more complicated in reality than approximations based on point sources or radioactivity deposited homogenously on a plane surface. Detailed knowledge about the measurement conditions is required to derive corrections to the efficiency. While the density, physical composition, or even the surface texture can often be reasonably estimated for many objects encountered in the field, it is usually impossible to accurately gauge the depth profile of radionuclide penetration into the surface of objects encountered in the field. This single factor alone, if not properly accounted for, may seriously impact the accuracy of field measurements. This is particularly the case for weakly penetrating radiation such as alpha, low-to-mid-energy beta emissions, and low-energy gamma and x-ray radiation.

If radioactivity can be assumed to reside "on the surface" of an object and the depth of penetration of the radionuclide(s) is shallow enough that radiation is not significantly attenuated before it escapes from the object, accurate measurements with known uncertainty are possible in the field. As discussed earlier, this definition of *surface* is related to the range of the radiation in matter and the ability to make unbiased measurements of activity and associated estimates of uncertainty. Listed in order of increasing range, alpha emissions and beta emissions have the shortest range, followed by x-rays and then gamma rays. Gamma rays are clearly a best case in this regard assuming there is no contribution from sources adjacent to the surface being

[19] See ANSI standards N323A and N323B for calibration of portable instruments.
[20] See NUREG-1507 and ASTM standard E1893 for typical correction factors for source efficiency.

measured (e.g., a wall in another building or a storm drain beneath a sidewalk). Alpha particles, low-energy beta particles, and x-rays, in contrast, are worst cases because they are significantly attenuated while passing though small amounts of matter or even by the "roughness" of the surface from which they are emitted.

Sodium iodide or HPGe detectors, or arrays of such detectors, interfaced to a geographic information system (GIS) can be used quite effectively to produce radiation profile maps of gamma emitters for characterization and final status surveys. When combined with confirmatory random and judgmental grab sample analyses at a fixed laboratory, these maps may be presented in terms of pCi/g or pCi/unit area. Typical setups incorporate a 2×2-inch detector used manually to scan in "swing" mode, 2×2-inch shielded detector and electronics mounted on a wheeled frame for horizontal area coverage, and a large (5–8-inch diameter) NaI detectors mounted on a motorized vehicle or towed behind a vehicle for very large horizontal areas. This latter system usually includes a multichannel analyzer for *in situ* spectrum analysis, which may reduce or eliminate the need for lab analysis for gamma emitters. The limited resolution of NaI detectors, however, may limit the use of such techniques at lower activity levels because gamma emissions from many radionuclide(s) of concern overlap those in the background. Thus, the applicability of such techniques should be evaluated and validated on a case-by-case basis.

For scanning measurements of beta or alpha radiation (where the survey meter is moved above and across the surface), additional parameters such as the speed of the survey meter movement and the detector time constant must be considered to ensure correct results and detection capability. The geometric distribution of radioactivity and the efficiency with which the field instrument can detect its radiations must be known. At a minimum, the effective duration of the count must be estimated using assumptions about radionuclides present, source geometry, and detector efficiency to ensure that significant amounts of radioactivity are not missed. Finally, the technique used for scanning can be very operator-dependent, so this should be taken into account when setting up and validating the measurement method. NRC (1997) presents *Minimum Detectable Concentrations with Typical Radiation Survey Instruments for Various Contaminants and Field Conditions*. MARSSIM (2000, Section 6.7.2), suggests approaches that can be used for scanning surveys, and addresses the estimation of sensitivity (detection capability) of scanning survey measurements.

Given these concerns, it is vital that field measurement protocols be validated relative to MQOs prior to use to ensure that survey instrument methodologies will be capable of producing data of sufficient quality to support DQOs and decisions to protect public health and safety. Field measurement protocols should require correlated sampling and independent laboratory analysis to empirically derive factors that can be used to correlate raw instrument results with radionuclide concentrations in the matrix in question. Confirmatory sampling also should be performed as a routine quality control measure to provide evidence that field measurement techniques are being performed as expected and that correlation factors are accurate for the measurement situations to which they are being applied.

In the early phase of an incident, field teams may encounter higher levels of radioactive contamination that approach or exceed PAGs. By evaluating the impact of factors such as self-

absorption on detection efficiency in a manner that ensures that contaminants will be detected,[21] field teams may be able to use field survey instruments to rapidly provide protective results for highly contaminated areas and samples such as air, water, soil, contaminated surfaces of materials and buildings, and swipes. Such results may find great utility in providing prompt, conservative decisions regarding the health and safety of the public. At this point in an incident response, obtaining measurement results in real-time may outweigh the need to obtain accurate measurements of radioactivity and the potential dose it might cause.

During the intermediate and recovery phases of an incident, field survey instruments may be used to make dose measurements and identify areas with levels of contamination marginally above the ambient background. However, field survey measurement techniques may not be well-suited to detecting and quantifying contamination as instrument signal approaches low levels. Field survey measurements may not provide unequivocal results:

- Where analyte signal approaches the detection threshold of the detection technique, or
- Where complex physical monitoring geometries exist, or
- Where mixtures of radionuclides may be involved, or
- Where weathering or other processes have set in and led to volumetric contamination of materials.

Field survey instrument measurements can, in most cases, provide general radiation information, such as indications of the presence of radioactive contaminants, but lacking confirmatory analysis, they generally may not provide conclusive evidence of successful remediation during the intermediate and recovery phases of an incident.

5.2.1.2 Spectrometric Measurements in the Field

Field spectrometric measurements are capable of measuring energy spectra and using these characteristic spectra to provide for rapid identification of radionuclides that are present. One example of a field gamma spectrometer is a radionuclide identifier. This is generally a sodium iodide or high purity germanium gamma detector interfaced with a multi-channel analyzer with automated software that analyzes characteristic energy peaks of gamma emissions. The Conference of Radiation Control Program Directors (CRCPD) (2006) warns of the potential for misinterpretation of data:

> *[G]reat caution is advised, because no identifier is correct 100% of the time, and further analyses may be necessary for proper identification of a source. Several radioisotopes*

[21] Deliberately biased assumptions regarding self-absorption may help improve the reliability of field survey measurements. For example, by assuming a worst-case penetration profile for a known radionuclide contaminant, biased correction factors for self-absorption and associated estimates of uncertainty may be generated that ensure that concentrations of a radionuclide that exceed an action level will be identified. Alternatively, a deliberately biased ("judgmental") approach might be able to rapidly identify areas that likely exceed action levels, but which will require additional characterization to determine the actual concentration prior to taking action. When biased assumptions are applied, the technical basis for these assumptions must be clearly stated. The methods must also be validated under the conditions of measurement using samples containing known concentrations of contaminants (and interferences) prior to use. Once a method's limitations are well-characterized, it can be incorporated into standard operating procedures so that all measurements provide the required degree of protection.

emit gamma rays with energies that are similar or overlapping, or the radionuclide may not be available for comparison in the library. These are delicate instruments that are sensitive to abrupt changes in temperature and humidity. Additionally, radionuclide identifiers cannot identify a pure alpha or beta emitting radionuclide unless there is an associated gamma emitter from one of its decay products. Consequently, radionuclide identifiers may sometimes misidentify the radioisotope.

More sophisticated field spectrometry instruments have been developed for decommissioning nuclear power plants and radionuclide processing facilities at DOE sites. Much of the above discussion regarding the limitations of survey instrumentation also will apply to field spectrometry detectors. Field spectrometry measurements are by their very nature measurements of activity emitted from a surface and may be of limited benefit unless radiation is effectively resident on the surface of the object being measured.

Alpha, beta, and low-energy gamma rays and x-rays are much more rapidly attenuated than are gamma rays when they are emitted from material within an object's surface. Thus, alpha, beta, and low-energy gamma- and x-ray emitters do not lend themselves in the field to accurate spectrometric measurements of known uncertainty unless they are known to be deposited on the contaminated surface and thus are not subject to self-absorption effects. By contrast, the most penetrating radiation, medium- to high-energy gamma rays, is less subject to attenuation effects. Thus, unbiased field spectrometric measurements with known levels of uncertainty are possible as long as the deposition profile of the radionuclides of concern is predictable and can be accurately accounted for during calibration of the instrument.

5.2.1.3 *In Situ* Gamma Spectrometry Measurements

The most effective field spectrometry measurements are performed using collimated ISGS detectors operated with supporting software such as In-Situ Object Counting System [ISOCS™] or [ISOTOPICS™].[22] ISGS units are capable of greater specificity, and depending on measurement conditions and the analyte(s) of interest, of greater sensitivity than gamma survey measurements. Under the appropriate conditions, ISGS can provide significantly greater sensitivity than highly accurate laboratory gamma spectrometry measurements and decrease the overall number of measurements needed to characterize potentially contaminated areas. This is due to the large field-of-view and the much larger effective sample size that can be evaluated by a single measurement. Extended road surfaces, or large surface areas of walls, ceilings, or floors, or even entire rooms can be evaluated with a single measurement, reducing the need to collect samples for definitive or confirmative analysis at a laboratory.

When evaluating ISGS results, it is important to keep in mind that unless detailed information about the distribution of radionuclides in and around the objects being measured is well-known,

[22]ISGS should be differentiated from commercially available software packages such as ISOCS™ (Canberra Industries) and ISOTOPICS™ (AMETEK Ortec). In this guide, ISGS refers to the overall process of gamma spectrometry measurements performed *in situ*, or in other words, without the need to destructively sample or disturb the object or matrix in question. ISOCS™ and ISOTOPICS™, on the other hand, are proprietary techniques that facilitate one aspect of ISGS by estimating gamma spectrometry detection efficiencies using mathematical modeling of the counting geometries relative to a well-characterized detector.

measurements will be qualitative, or associated with high levels of uncertainty, such that only an identification of radionuclides may be possible.[23] *In situ* germanium spectrometers identify gamma-emitting radionuclides of any gamma radiation incident on the detector. Assumptions must be made about the geometric distribution of the radionuclide activity surrounding the detector even in cases where little knowledge about actual conditions may be available. The simplest approximation of geometric distribution, for example, would assume that all of the radioactivity in the field of view of the detector is concentrated at a single point source in the most distant point in the area of measurement, say in the furthest corner of a room five meters from the detector. The uncollided (unscattered, full energy) photon fluence rate at the detector position can then be calculated. Combining this fluence rate with that calculated based on a point source calibration for the detector efficiency, a screening-level approximation of activity may be obtained. It is important that assumptions regarding the distribution of activity lead to a result that conservatively overestimates the true amount of activity present.

In reality, more detailed analyses are required to accommodate the complex counting geometries that will be encountered in the field. These include models of volumetric sources of varying size, shape, and spatial distribution of the radioactivity within the source; knowledge of angular dependence of the photon fluence rate on detector response; and shielding effects resulting from materials between the source and the detector. While commercial products are available for doing such calculations, they require as input detailed models of the physical characteristics of the object being measured, including a geometric distribution of radioactivity in the object. Determining and documenting such information for each measurement situation, and performing the necessary modeling, are time-consuming and involve substantial technical understanding. Considerable professional judgment generally is needed to accurately and conservatively estimate input parameters. Thus, it is essential that these analyses be carried out by a skilled, knowledgeable, and experienced operator/analyst.

Absent a capable analyst, errors may be made that are unlikely to be detected in a review of the data or reflected in the reported uncertainty of the measurements. Lacking reliable estimates of uncertainty of measurements, critical decisions may be based on data with unknown and possibly substantial uncertainties. Decisions may not be adequately protective and could be called into question. Because of this fact, ISGS measurements are frequently limited to real-time applications such as guiding remediation or recovery operations where they can be used to very rapidly identify hot spots and gauge progress during cleanup. Final status measurements and periodic confirmatory samples are often analyzed at fixed laboratories at critical points in the process to provide independent assurance that the results obtained are both accurate and reasonable. It also is common for a significant proportion of final status measurements to be produced using definitive laboratory gamma spectrometry testing (see Appendix I for a discussion regarding the limitations and successful use of ISGS measurements at the Rocky Flats Environmental Technology Site).

Use of an *in situ* gamma spectrometer to collect reliable data requires that the instrument be set up in the area to be evaluated in a reproducible, consistent, and well-documented fashion. The

[23]Automated radionuclide identification routines such as those used in radionuclide identifiers can misidentify radionuclides present. Thus, even qualitative measurements should be evaluated by an expert gamma spectrometrist and, where necessary, confirmatory laboratory analysis performed before results are considered final.

instrument software requires input of observed geometry parameters. Once the setup is complete for an individual area, an instrument measurement (count) may begin. Typically when determining whether or not an area has contamination, a count time of one hour is reasonable, although depending on activity levels of concern, shorter or longer measurements may be required. Once the count is completed, the instrument may be moved to the next location and the process repeated. If the efficiency model is established prior to making the measurement, unreviewed results are available immediately upon completion of the measurement. If modeling is not complete prior to the measurement, the spectrum will require subsequent workup and reporting before unreviewed results are available.

Performing routine definitive field spectrometry measurements is a relatively newer development. In some cases, field measurements can in fact rapidly and effectively identify contamination at levels needed to support characterization and recovery efforts. If alpha or beta surface activity is accompanied by a unique gamma signature, it may be possible to quantify the alpha or beta activity using *in situ* spectrum analysis, minimizing the need for laboratory analysis of grab samples beyond periodic confirmatory samples. When the gamma signature is present and detection sensitivity permits, beta and alpha scans coupled with *in situ* gamma spectral measurements may allow for rapid clearance of surfaces at action levels that would be typical of the recovery phase.

There also is real concern about the size of the pool of capable, trained operators for field spectrometry instruments This underscores the importance of developing robust, formalized protocols for calibrating and operating instruments and performing QC for the field measurements.

Although ISGS units may be able to provide sensitive gamma isotopic measurements, ISGS may not always be a practical option for accurate evaluation of beta-gamma emitters on complex, contaminated areas or objects. Practical disadvantages and limitations of using ISGS during an incident response in a metropolitan area include:

- ISGS detectors must be operated in the field at cryogenic temperatures. This may require field use of liquid nitrogen, or modern electrically cooled portable detectors.
- Breakdown, relocation, and setup of heavily shielded collimated units can take time and effort and will practically limit the number of areas or surfaces that can be evaluated in a given period of time.[24]
- The units may have relatively long per-location acquisition times for low-level measurements, especially for lower-energy gamma-emitting radionuclides due to self-absorption effects when radionuclides are not deposited on the surface.
- Setup, implementation, and interpretation of data from an ISGS unit (e.g., ISOCS™ or ISOTOPICS™) require an experienced and technically adept operator (i.e., a specially trained spectrometrist), of which there are relatively few.[25]

[24]For certain applications, ISGS units have been very effectively implemented in a portable configuration.

[25]When performing an ISGS calibration (e.g., ISOCS™ or ISOTOPICS™), the operator must develop a mathematical model that describes or approximates the solid geometry of the object being measured. Other required input values are the elemental composition and density of the object, as well as the depth or penetration, distribution, and uniformity of contaminants in and on the object, all of which must be measured or estimated. Depending on the

- "False positive" (Type I error) and "false negative" (Type II error) measurements can result from radionuclides that are naturally present as ambient background since varying ambient backgrounds are often difficult to predict in field settings.
- Calibration methods for ISGS measurements may not meet the rigorous standards employed at fixed laboratories.[26] ISGS generally involves mathematically modeling the counting geometry. The skill and experience of the operator/spectrometrist, and the time and resources required to document the circumstances of the measurement, will be reflected in the reliability and accuracy of the calibration and the magnitude of the uncertainty.
- The level of QC measurements routinely performed for *in situ* measurements generally does not rise to the level of comparable practices used to perform QC at fixed laboratories.[27] (See discussion of quality control in Section 4 of this document.)
- Confirmatory laboratory analysis is needed to unequivocally verify the accuracy of efficiency models.
- Units must be checked based on documented QA/QC protocols to ensure that they are operating properly each time they are moved to evaluate a new area or surface.

5.2.2 General Considerations Regarding Laboratory Measurements

A wide variety of instruments is used for sample measurements at laboratories. This discussion of laboratory instrumentation will address some of the strengths, weaknesses, and general considerations that affect laboratory instrument capabilities.

Laboratories maintain instruments that, similar to field survey equipment, measure alpha and beta emissions from samples without regard to the energy of the respective radiations. These include low-background gas proportional (alpha-beta) counters. Laboratories also maintain spectrometric instrumentation that performs a range of radionuclide-specific measurements. Examples include gamma spectrometers, alpha spectrometers, and liquid scintillation counters (LSCs).

The initial contamination resulting from a radiological or nuclear incident is expected to be largely removable or resuspendable as opposed to fixed, surficial contamination of structures, objects, roadways, etc. Although they cannot readily discern between fixed and removable contamination unless a sample is removed and analyzed separately, field measurements are capable of rapid and sensitive measurements of total surface radiation in an area. Laboratory measurements of removable contamination may be used to complement field measurements and

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complexity of the measurement, models may need to be developed specific to each measurement. While certain of these components are based on measured values that can be documented, others must be based on estimates that may be less well-documented.

[26] At fixed laboratories, all measurements are traceable to a national standard (e.g., a NIST standard reference material [SRM™]). Calibrations are performed by direct comparison of carefully prepared sample test sources to controlled calibration sources traceable to the appropriate national standard. Prior to first use, calibrations for each counting configuration are verified by comparison to a second independent traceable verification standard identical to the sample test source.

[27] Quality controls for *in situ* measurements include review of documentation about the measurement and the analysis.

to free field personnel to perform critical measurements of total surface contamination and grab and confirmatory sampling. The laboratory offers the advantage of high levels of sample throughput while maintaining accurate, sensitive, and radionuclide-specific results. The laboratory also is clearly best suited to the analysis of bulk samples for volumetric contamination.

Careful consideration of the complementary nature of field and laboratory measurements can thus ensure that data will meet DQOs/MQOs while meeting operational requirements for rapid turnaround and high throughput.

5.2.2.1 Survey Measurements at the Laboratory

At a radiochemistry laboratory, survey instrumentation is differentiated from more specialized instrumentation used to conduct accurate and sensitive radioanalytical measurements. At a radiochemistry laboratory, survey instruments are portable pieces of equipment used to support laboratory operations, most frequently in the area of health physics and contamination control. These instruments are rarely, if ever, used to perform sensitive analytical measurements of sample activity. Instead, they find relatively limited application for such applications as Department of Transportation (DOT) radioactive material receipt surveys, or health physics and contamination control surveys. Survey instruments can rapidly identify the presence of significantly elevated activities of gamma emitters. They provide results of high or poorly estimated uncertainty and are not able to reliably and accurately quantify concentrations of radionuclides in samples, particularly at the low activity levels that are of interest in the recovery phase.

During an incident response, vast numbers of samples or measurements will need to be taken and analyzed at radiochemistry laboratories. Samples must be rapidly, effectively, and accurately prioritized for subsequent handling and radionuclide analysis based on gross activity levels. Gross activity measurements of samples in the field or immediately upon receipt, using similar survey instrumentation, will identify and allow prioritization of samples containing the highest levels of gamma-emitting radionuclides. The majority of the samples, however, will contain relatively lower levels of activity that are not effectively measured with an unshielded instrument.

5.2.2.2 Non-Spectrometric Measurements at the Laboratory

Depending on the event, the source term may be pure alpha- or beta-emitting radionuclides, which cannot be detected by hand-held instrument surveys of the sample containers (in the field or in the laboratory). Alpha and beta emitters, or even lower levels of gamma activity that cannot be detected with survey meters, are of great concern in a low-level radiochemistry laboratory where contamination control concerns in working with open samples are much greater than in the field due to the very low levels of activity being handled and measured at the laboratory.

Radiochemistry laboratories maintain instrumentation such as low-background gas flow proportional detectors that perform non-specific measurements of alpha and beta radiation analogous to those that might be performed in the field. Although the instruments in the field bear similarity to those in the laboratory, laboratory instruments are generally heavily shielded

with lead and actively shielded using guard detectors to minimize ambient background radiation. The sensitive instrumentation available at a laboratory would allow the laboratory to achieve significantly better detection capabilities relative to most field measurements with relatively shorter count times. Since the laboratory can have many instruments, and since it can simultaneously process many samples in parallel using batch processes, laboratories can achieve very high levels of throughput with lower personnel demands than is generally possible in the field.

Environmental conditions within a laboratory are designed to be optimal for measuring radioactivity. Background radiation levels are stable, low, well-characterized, and not subject to variation from changes in measurement locale or to significant fluctuations from changes in environmental conditions. Power conditioners and line-voltage regulators are commonly used at laboratories to minimize electrical supply disturbances to the detection systems. These measures all ensure that measurements of backgrounds and samples will be optimally sensitive and that associated uncertainties and detection levels will be accurate and reliably determined. All of these parameters play key roles in ensuring the quality of low-level radioactivity measurements.

Laboratories also employ chemical separations to enhance the capability of various instrument measurement techniques. Chemical separations remove interfering matrices and radionuclides and minimize self-absorption effects that degrade instrument response and resolution. Laboratories can isolate a single radionuclide from a mixture of radionuclides or from the background soup of naturally occurring radionuclides present in nearly any sample. When combined with the appropriate chemical separations, even relatively simple gas-flow proportional alpha-beta counters are capable of a high throughput of sensitive and accurate radionuclide-specific measurements for a broad range of radionuclides.

5.2.2.3 Spectrometric Measurements at the Laboratory

Laboratories responding to radiological incidents will have gamma spectrometers, alpha spectrometers, and liquid scintillation detectors. Rapid screening measurements can be made with laboratory instruments such as liquid scintillation counters and gamma spectrometers. These measurements can help control widespread contamination interfering with measurements, and quick evaluation of an energy spectrum may provide a first qualitative hint of the identity of the radionuclide contaminant. While these instruments can be used for gross activity measurements, their full benefit is gained in using them to conduct spectrometric measurements of specific radionuclides.

In contrast to the majority of field measurement techniques, spectrometric measurement techniques available at the laboratory are capable of unequivocal, unbiased, and low uncertainty determinations of specific radionuclides. In fact, these techniques are sometimes the only viable option for determining low or medium activities of certain radionuclides. Spectrometric instrument measurements are more accurate and generally more sensitive than determinations that are possible with corresponding field measurements. This capability stems from these instruments' ability to measure energy spectra, and to discriminate between mixtures of

radionuclides based on their characteristic decay energies.[28] Laboratory spectrometers are operated in a very stable environment and can obtain low and reliable detection limits because of low and stable backgrounds, and because they can discriminate against background signal that does not exhibit the characteristic energy signature of the radionuclides of concern.

When laboratories perform measurements using alpha spectrometers, they can address the whole range of issues that prevent accurate measurement of alpha emitters in the field. Alpha particles are significantly attenuated by sub-milligram amounts of matter (e.g., microscopic roughness of surfaces). Most samples contain mixtures of radionuclides that emit alpha particles with overlapping decay energies. Many alpha emitters cannot be resolved unambiguously by an alpha spectrometer due to their overlapping energies. However, at the laboratory, chemical separations can be used to eliminate interfering matrix constituents and radionuclides and thereby obtain clean and well-resolved spectra for accurate determinations of alpha-emitting radionuclides[29] at very low detection levels.

Although the liquid scintillation counter is capable of performing a wide range of spectrometric measurements of alpha and beta emitters, its most common use in the radiochemistry laboratory outside of screening samples is for measurements of radionuclides that decay via low-energy emissions, particularly beta emissions such as ^{99}Tc, ^{241}Pu, or ^{3}H or low-energy gamma or x-ray emitters such as ^{125}I or ^{103}Pd. This application is possible because the radionuclide is dissolved in a liquid that serves as a detector, effectively eliminating the self-absorption effects that interfere with detection of radioactivity in any solid form. Similar to alpha spectrometry, chemical separations are used to isolate the element of concern prior to measurement to ensure the specificity of the measurement. When combined with chemical separations, liquid scintillation is often the only viable option for determining a number of beta emitters.

The most versatile spectrometric instrument in the laboratory is the gamma spectrometer in that it can be used for the determination of a very large number of radionuclides. Many of the same attributes of gamma emissions that make ISGS a powerful technique in the field are reflected in the simplicity and efficiency of gamma measurements at the laboratory. Similar to field measurements, the penetrating nature of gamma rays allows non-destructive measurements to be made. This allows very rapid and accurate determinations to be made in the laboratory with a minimum of effort but under much more controlled conditions than are possible in the field.

Although ISGS is probably the most attractive option for quickly characterizing large areas for gamma emitting contaminants due to its ability to cover large areas with a single measurement, the discussion of field measurements in Section 5.2 points out several concerns that should be addressed to ensure that the quality of data is defensible. The first is the impact of potentially high or spatially variable backgrounds on measurements that may interfere with effective operations in the immediate vicinity of areas significantly contaminated by the incident. It is

[28]One notable exception is *in situ* gamma spectrometry measurements which, due to the large effective size of samples, can obtain high sensitivity and minimize the likelihood of not detecting radionuclides that actually are present at levels of concern. The downside of ISGS is that it tends to deliver semi-quantitative results that, ideally, should bias "conservatively" high.

[29]Even amounts of residual matter as small as 25–50 $\mu g/cm^2$ can degrade the resolution of the energy spectrum to a point where differentiation between radioisotopes of an alpha-emitting element is not possible.

notable, however, that this will be of less concern in later phases once remedial activities have removed larger, contiguous sources of contaminants, and thus the background associated with them.

For freshly deposited gamma-emitting contaminants deposited over a large area, ISGS is a very powerful technique. One significant concern with *in situ* measurements involves limited traceability of ISGS measurements to national standards. Although instruments are checked with NIST-traceable sources to demonstrate their continued performance prior to use, they are not necessarily calibrated using reliable reference sources that match the area being measured. Thus, the accuracy of the analysis is largely dependent on assumptions about conditions encountered in the field. These assumptions are used to derive factors that relate the gamma-ray flux at the detector to the activity concentration of the specific radionuclide being measured. They include corrections for self-absorption effects related to the depth profile of contaminants in the solid matrix and variable distribution of radionuclides. Assumptions also could also needed to address the degree to which gamma-emitting marker nuclides are representative of pure alpha- or beta-emitting radionuclides in the source-term mixture, especially where weathering has occurred after deposition. Such assumptions may be readily confirmed by analyzing select random and judgmental grab samples at the laboratory as a regular, ongoing QC measure.

At the laboratory, high backgrounds are not of concern since instruments are heavily shielded (4"-thick lead shielding is routine). Similarly, variability of the background is a minor concern since instruments are maintained in the same configuration used for the sample measurements, and backgrounds are relatively constant and can be accurately measured and subtracted from sample measurements. As an additional control, the stability of backgrounds is tracked and trended using control charts. The second significant concern about field gamma measurements involved concerns about the traceability of the field measurements to national standards and the impact of assumptions that are made regarding the geometry of the source being measured. These assumptions include the spatial distribution of gamma emitters relative to the detector and corrections for self-absorption within the material being measured (affected by penetration within the object and the density and average atomic mass or “Z” of the material). These issues are routinely addressed at the laboratory by calibrating detectors for specific counting geometries using certified radionuclide standards traceable to NIST. Prior to counting, samples received from the field are homogenized and transferred into counting containers so that the geometry of the sample closely matches that of the calibration standard. Since the shape, volume, density, and radionuclide distribution in the standard can be closely matched to that of the sample, very accurate and precise calibration of the instrument and very accurate and precise sample measurements are possible. Once the detector is calibrated, it is common practice to verify calibration by counting a second standard obtained from a source independent of the one used for the calibration.

In practice, there are also disadvantages to laboratory gamma spectrometry as opposed to field gamma spectrometry. The first has to do with the relative detection capability of field versus lab measurements. Field gamma spectrometry measurements have to rely on assumptions about the measurement geometry and background. They may be associated with high or unknown levels of uncertainty, and depending upon MQOs, the energy of the radiation and deposition patterns, it may be possible to make conservative assumptions so that the results err protectively toward

reliable identification of the presence of contaminants above an action level.[30] If ISGS measurements are conservatively biased (or unbiased and of known uncertainty such that they can be used for reliable measurements), the sensitivity and effectiveness of ISGS measurements may exceed that obtainable by measurement in the laboratory of grab samples taken from the same area. In cases where deposition is non-uniform, ISGS can identify hot spots that would be very difficult to find without a large number of grab samples. This is primarily a function of the effective size of the sample because in field measurements, the sample size is effectively very large, whereas grab samples generally represent an area of ~100 cm^2. For example, effective coverage of a plane has been obtained with measurements performed one meter above the ground using a five-meter grid (Reginatto *et al*. 1997). As stated above, although many laboratory samples may be spared by using ISGS, it is generally important that the integrity of ISGS measurements and the assumptions underlying them be confirmed using correlated laboratory measurements.[31]

Another disadvantage of laboratory gamma spectrometry measurements is less technical and more practical in nature. Since samples must be taken and shipped to the laboratory, laboratory analysis cannot offer real-time results. Laboratories do, however, offer very rapid turnaround times for gamma spectrometric measurements, when needed, often providing results within hours of receiving a sample (depending on MQOs). In compensation for this, laboratories can perform large numbers of measurements in a relatively short amount of time.

Measurements made in a laboratory will determine unequivocally which radionuclides are present in a particular sample and can be used to address concerns that widespread contamination could have compromised field ISGS measurements.

5.3 The Effect of Measurement Geometry on Detector Calibration

When using field survey instruments for any type of measurement, the detector is generally positioned relative to a potentially contaminated object or surface to optimize coverage of the area. In some cases, larger areas may be measured in a single measurement, thus minimizing the number of measurements and lowering the overall time and effort required to characterize an area. One of the challenges that must be addressed for field measurements is ensuring that instruments are adequately calibrated. Once an instrument is calibrated, several questions should be addressed. Does the calibration reflect the object or surface being measured? What are the bounds of the measurement? Given those bounds, what is the potential for bias in the

[30]Unless there is empirical evidence to support them, *in situ* gamma spectrometry measurements are generally qualitative or associated with elevated levels of uncertainty. Nonetheless, they may be configured and effectively used in a manner that is protective of health and environment. In this case, it is assumed that background corrections will introduce no bias or that any bias introduced will be "conservative" (i.e., too little background will be subtracted yielding a final result with a high bias). It is also assumed that any bias associated with assumptions made during efficiency calibration or modeling will be "conservative" and thus produce results that always bias high. Since these measurements should be biased, confirmatory sampling and analysis are needed to determine the extent of bias introduced and to minimize unnecessary expenditures of resources and efforts in the recovery process.

[31]As discussed above, there is a downside to the higher sensitivity of *in situ* measurements that also must be taken into account. Given the large field of vision of the detector, the presence of a hot spot within the field of view of the instrument (even if it is beyond the direct area of measurement) may bias measurements. Thus, confirming measurements are often needed to isolate a hot spot. Nonetheless, ISGS would still outperform grab sampling followed by laboratory analysis, which would be more likely to fail to identify a hot spot.

measurement? Are personnel adequately experienced and trained to know how to perform the measurements and recognize when conditions are inconsistent with assumptions underlying the calibration? Can a reasonable yet conservative bound on the measurement uncertainty be established that will provide needed assurance that MQOs will be met using this technique?

5.3.1 Measurement Geometry and Field Survey Instrument Calibrations

Field measurements of gamma radiation are perhaps the most powerful and useful of field techniques available during incident response. The instruments are portable and setup is relatively rapid. Consistent with this, minimal shielding is generally used, often limited to a thin collimator around the detector itself. Although a portion of the detector is shielded, the detector will respond in varying degrees to radiation from all directions. Thus, there is no way to completely avoid, or to account and correct for, contributions from materials beyond the intended focus of the measurement. The calibration of field survey instruments is generally performed using single radionuclide sources in fixed geometries or by using Monte Carlo modeling. Although both of these approaches have been frequently used, lacking the ability to restrict the field-of-view of the instrument or to perfectly and accurately model the area within the field of view of the detector means that there may not be a one-to-one correspondence between the assumed calibration geometry and the area being measured. Significant measurement bias may result, and it may be difficult to accurately assign realistic estimates of uncertainty to the measurements.

ASTM D1893-08 (2008) speaks of challenges involved with calibration of detection systems used for *in situ* measurements of contamination.

> "The *in situ* measurement of the residual activity distributed within a volumetric medium of interest shall be based on the photon emission rate from that medium. The results of the evaluations of this photon emission rate are normally expressed in units of picocuries per gram (pCi/gm) or becquerels per gram (Bq/gm). This evaluation will be dependent on the background response of the detector and on a conversion factor established for the medium of interest. Non-uniform distributed source geometries can result in large interpretation errors of *in situ* measurements; therefore, caution should be used with these evaluations."

NCRP Report 112 (1991) also points out shortcomings of direct measurement techniques, among which is a "limited ability to relate the reading of a survey meter to that of an alternative dose-measuring instrument or device." It stresses that "…proper calibration of the instrument and a thorough understanding of its response characteristics can reduce such discrepancies" and that "[t]he selection and use of radiation detectors and instruments require detailed knowledge of their response characteristics as well as judgment in their application." The report also frames the context of many *in situ* measurements:

> "For purposes of common radiation control, routine measurements of surface contamination are made to fulfill regulatory requirements and to provide semi quantitative information on which to base further action (e.g., decontamination). Under such circumstances, a sophisticated and time-consuming calibration of a monitoring instrument is not justified. In some situations, e.g., the release of a previously

> contaminated building for unrestricted use, measurements must provide sufficient accuracy that regulators and others can make the proper decisions. In the latter instances, it is desirable, and perhaps necessary, that inaccuracies in measurements yield conservative results. It is, therefore, important that the variables that affect instrument response be understood well enough to ensure that errors are in the conservative direction."

Calibrating detectors for direct surface measurements of alpha- and beta-emitting radionuclides in the field can be a greater challenge than for gamma. In order to physically calibrate a detector, a calibration source is needed that is representative of the surface or object being measured. The reality of field measurements is that there is considerable variability in surfaces being measured, including the composition of materials comprising the surface, and their shape, roughness, and position relative to the detector. Given the short range of alpha and beta particles, and their susceptibility to attenuation within the surfaces being measured, the depth profile of radionuclides within the surface will have a profound effect on attenuation of the radioactive emissions, and thus on the general validity of the calibration and its applicability to the measurement situation. When measuring radionuclides present on a surface, it is often assumed that radionuclides are present at the surface of an object and that self-absorption is either negligible or constant. The most accurate results for alpha- and beta-emitting radionuclides can be obtained when measuring freshly deposited contamination on a smooth, non-permeable surface. It is extraordinarily difficult to predict the penetration of alpha- and beta-emitting radionuclides within a surface. Thus, field measurements of alpha- and beta-emitting nuclides should be restricted to measurements of surface contamination on relatively smooth, clean, impermeable surfaces where the activity may be assumed to be uniformly distributed and effectively resident on the surface.[32] Even in cases that approach the ideal, surface texture can impact instrument response. It may not be possible to obtain representative, traceable calibration sources that conservatively match conditions expected in the field. This may necessitate application of additional correction factors, which must be determined empirically or by best judgment. If a detector cannot be reproducibly positioned relative to the surface being measured, calibrations might also be affected.

MARSSIM (2000) addresses this concern:

> "In many facilities, surface contamination is assessed by converting the instrument response (in counts per minute) to surface activity using one overall total efficiency. The total efficiency may be considered to represent the product of two factors, the instrument (detector) efficiency, and the source efficiency. Use of the total efficiency is not a problem provided that the calibration source exhibits characteristics similar to the surface contamination (i.e., radiation energy, backscatter effects, source geometry, self-absorption). In practice, this is hardly the case; more likely, instrument efficiencies are determined with a clean, stainless steel source, and then those efficiencies are used to determine the level of contamination on a dust-covered concrete surface."

[32]In the sense used here, "surface" refers to a thickness of material that will not significantly attenuate the radioactive emissions. This varies according to the material in question and the type and energy of radioactive emissions being measured. Clean refers to the surface being free of dust, debris, or other material that would requiring attenuation corrections. Quantitative measurements are not possible if the penetration profile is unknown.

MARSSIM also points to methods that can be used to minimize these effects. For example, it refers to NRC (1997) for typical source efficiencies for common surface materials and overlaying material. The text also lists factors that impact efficiency:

> "Instrument efficiency may also be affected by detector-related factors such as detector size (probe surface area), window density thickness, geotropism, instrument response time, counting time (in static mode), scan rate (in scan mode), and ambient conditions such as temperature, pressure, and humidity. Instrument efficiency also depends on solid angle effects, which include source-to-detector distance and source geometry. Source efficiency may be affected by source-related factors such as the type of radiation and its energy, source uniformity, surface roughness and coverings, and surface composition (e.g., wood, metal, concrete)" (ISO 1988).

It is critical that measurement geometries be well-characterized and well-defined. Measurement procedures should consistently define the conditions that must apply for a calibration to be valid and also ensure that all calibrations and measurements proceed according to these considerations. Prior to use in the field, empirical validation should be conducted to demonstrate that a measurement technique, as implemented in the field, will be capable of meeting pre-defined MQOs. Periodic QC measures, such as confirmatory sampling, should then be used on an ongoing basis to demonstrate that the measurement system is operating as planned.

Unless the bounds on such measurements are well-defined, and the methods validated and carefully implemented, bias may result and the uncertainty of the measurement may be underestimated or worse, not taken into account when evaluating the applicability of a technique for the required measurements. This could provide a false sense of security regarding the quality of the measurements being performed.

5.3.2 Measurement Geometry and Field Spectrometry Measurements

Several different types of field spectrometry instruments are commercially available. The most powerful and commonly used instruments are high-purity gamma spectrometers similar to those found in analytical laboratories. These instruments are ruggedly constructed to be used in harsh environments. They do have certain disadvantages because they are used directly in the environment they are monitoring. One such disadvantage is the concern about the introduction of bias by ambient background from gamma emitters adjacent to areas being characterized.

A detailed discussion of one example of the use and limitations in the use of field spectrometry measurements during the cleanup of Rocky Flats Environmental Technology Site can be found in Appendix I. See also Tables 3, 4, and Table 5 in Section 6, which summarize the applicability of several field instrumentation techniques for the determination of a select group of radionuclides important to incident response.

Assuming that the absolute geometry of the measurement is known, accurate, precise, and very sensitive, *in situ* measurements of gamma emitters are possible in the field. Specifically, this requires knowledge of the areal distribution and the depth profile of radionuclide contaminants, the elemental composition and physical makeup (e.g., density) of the matrix material, and the ambient contribution from the contaminant of concern in the vicinity of the measurement. When all of these factors are well-known, *in situ* measurements of gamma emitters are clearly the

fastest and most sensitive techniques available for the characterization of gamma-emitting contaminants. The long range of gamma rays and the resultant wider field of vision for gamma detectors allow measurement of relatively large areas. Not only does this increase the effective size of the "sample" measured and the sensitivity of the measurement as compared with grab sampling techniques, but ISGS techniques also are able to measure larger areas in a single measurement. This dramatically reduces the number of measurements needed to characterize an impacted area with confidence that hot spots will not be overlooked.

It is necessary that the limitations of ISGS measurements be carefully considered and addressed. Questions about the geometry, the composition of matrix materials, or the impact of ambient background on the field measurement almost always exist.[33] Without regular periodic confirmation of the assumptions that underlie the measurement, the accuracy and especially the estimates of measurement uncertainty of the *in situ* measurement should be called into question. Even when the technique is used for qualitative or approximate measurements, such as clearing hot spots in an area, it is vital that confirmatory measures be routinely employed that demonstrate the adequacy of the model and the competency of the operator used for the measurement. The most effective QC measure that can be used involves routine, periodic confirmatory measurements of grab samples under very controlled conditions in a laboratory.

5.3.3 Measurement Geometry and Laboratory Survey and Gross Activity Measurements

Laboratories utilize survey instruments that in many cases are similar or identical to those used for field survey measurements. These portable instruments are used almost exclusively for the least formalized laboratory measurements, such as those performed during sample receipt. The calibration and measurement protocols for such laboratory survey instrumentation do not vary substantially from those used for field survey measurements and do not result in substantially different measurement quality than what is available for similar instrumentation in the field.

More elaborate screening instrumentation available at radiochemistry laboratories can be used to perform rapid screening measurements of gross activity. Examples of screening instrumentation used at laboratories include low-background gas proportional counters, liquid scintillation counters, and sodium iodide gamma counters operated in gross activity mode. As used here, screening refers to measurements of "gross" activity in a sample that are potentially biased and have high levels of uncertainty. In other words, this measurement is not specific to a radionuclide and cannot differentiate between a mixture of radionuclides that emit the same radiation type (i.e., alpha, beta, or gamma). These laboratory instruments tend to be heavily shielded and can provide much more sensitive and reliable results than do survey measurements performed with hand-held field or laboratory instruments, especially at lower activity levels such as those that typically would be experienced in the later phases of an event. Often these laboratory screening measurements are preceded by a simple preparation step, such as drying, grinding, digestion, and a source preparation step to create a sample test source geometry that very closely matches that

[33]Assuming mean specific activities as quoted in NCRP Report No. 50, Table 2-6 (i.e., 0.67 pCi/g ^{238}U with seven alpha-emitting progeny in equilibrium, and 0.65 pCi/g ^{232}Th with five alpha-emitting progeny in equilibrium), the mean alpha activity of geological materials would approach 10 pCi/g with higher levels routinely encountered in a number of natural construction materials. Unless the background matrix has been very precisely characterized, it would be inadvisable to attempt to detect contaminants using gross activity measurements until the activity significantly exceeds these values.

of the applicable calibration source. Stable, low, and well-quantified backgrounds, and extended count times facilitate more sensitive measurements at lower activity levels than can be achieved with field or laboratory survey instruments. When combined with more stringent quality assurance and quality control measures routinely practiced in the laboratory, these techniques reliably provide very reproducible and defensible determinations of gross alpha, beta, or gamma radioactivity in samples received from the field. If a single radionuclide is involved, especially at levels well above background, screening information can often provide very accurate and reproducible estimates of the activity of the contaminant in the sample. Thus, within minutes to hours of receiving a sample, information of high quality not otherwise available in the field can be made available to an Incident Commander.

5.3.4 Measurement Geometry and Laboratory Spectrometry Measurements

As time progresses during the intermediate and recovery phases, an increasing proportion of samples will require radionuclide-specific analysis at successively lower levels. This will be necessary to satisfy DQOs and MQOs for cleanup criteria and to reassure the public that facilities, private property, public spaces, and personal residences have not been contaminated or that they have been successfully decontaminated.

In the laboratory, environmental conditions such as temperature, humidity, background, electrical line voltage, and contamination are very carefully managed to ensure reliable measurements of radioactivity, especially at the lowest activity levels. The combination of low, stable, and well-characterized backgrounds; extended count times; robust chemical separation methods (incorporating chemical yield carriers and tracers to substantially reduce or eliminate measurement biases relative to direct measurements); careful source preparation; and spectrometric detection methods all allow these techniques to unambiguously differentiate and accurately measure very low activities of contaminant radionuclides.

For example, alpha spectrometers can, using chemical separations, routinely and very accurately determine the activity of alpha emitters present at 0.1 pCi level and below. Liquid scintillation and gas-flow proportional counters can accurately determine beta-only emitters following chemical separation at concentrations commensurate with 10^{-6} risk levels and below.[34] Given progress in practical chemical separation techniques over the last five to 10 years, processing times that were previously measured in weeks have decreased to days or even hours. While there are no real analogs to laboratory capabilities for radionuclide-specific determinations of pure alpha and beta emitters in the field, sensitive spectroscopic measurements of gamma emitters using high resolution gamma spectrometers are possible without chemical separations, both in the field and in the laboratory.

While gamma ray analysis at the laboratory may not match the effectiveness and availability of real-time results possible with *in situ* measurements, the more controlled conditions in the laboratory are conducive to producing highly accurate measurements of known uncertainty. At the laboratory, samples are carefully homogenized and sample-to-detector geometries closely reproduced to ensure that measurements are traceable to national radionuclide standards.

[34]Although gas-proportional counters possess limited energy discrimination capabilities, they are not spectrometers. They are mentioned in this section, however, since when combined with element-specific chemical separations, they can be used to perform very accurate and reliable low-level measurements of pure beta-emitting radionuclides.

Measurement uncertainties associated with calibration, moisture, density, and sample homogeneity can be more accurately estimated. The laboratory also can very accurately determine and correct measurements for ambient background, thereby ensuring unambiguous determinations of radioisotopes even in the presence of contaminant or naturally occurring radioactivity present in the background.

Thus, with relatively limited exceptions (such as ISGS measurements in well-characterized areas), field measurements do not provide the sensitivity, specificity, and reliability of radionuclide-specific measurements performed at a laboratory. Significant questions regarding the intercomparability of field data may arise, whereas the controlled environment, standardization of radioanalytical methods and practices at radioanalytical laboratories, and regular participation in laboratory intercomparisons and proficiency testing programs ensure the intercomparability of results between laboratories.

Section 5 of this document compares and contrasts various aspects of field and laboratory measurements and addresses their relative strengths and weaknesses. Section 6 contains four tables that compare performance characteristics of several field and laboratory measurement techniques.

6. Comparison and Applicability of Field and Laboratory Measurements

Table 1 compares performance characteristics of non-spectrometric techniques for field and laboratory measurements of surficial contamination. Table 2 compares performance characteristics of non-spectrometric techniques for field and laboratory measurements of volumetrically contaminated objects. Analogous to Tables 1 and 2, Tables 3 and 4 consider performance characteristics for spectrometric measurements of surficially and volumetrically contaminated objects. These performance characteristics are differentiated according to the type of radiation being measured (alpha, beta, low-energy gamma ray, medium- to high-energy gamma rays) and the activity relative to background.

Tables 1 and 3 address surficial contamination and assume that the contaminant radionuclides are deposited homogeneously on a surface in such a manner that self-absorption corrections are not needed to perform unbiased measurements with well-defined and defensible estimates of uncertainty. Tables 2 and 4 address volumetric contamination and assume that contaminant radionuclides are deposited within the volume of an object or matrix material such that corrections for measurement geometry and self-absorption can be effectively applied and that the resulting measurement does not exhibit significant bias and reasonable estimates of uncertainty can be performed.

In the case of some field measurements, it may not be practicable to perform unbiased measurements, although measurements may be configured in such a manner that allows measurement quality objectives to be met defensibly. This specifically includes “judgmental” (i.e., strategically biased) measurements as long as the combined bias and uncertainty provides defensible and conclusive evidence that MQOs have been met.

These tables also presuppose that ambient sources of background radioactivity beyond the surface being measured (e.g., activity associated with volumetric contamination or inherent radioactivity of the object in question) can be accurately determined and subtracted from the

measurements in a manner that results in minimal absolute bias and permits reasonable and accurate estimates of measurement uncertainty.

For field measurements, the tables further differentiate between *in situ* measurements of surface contamination and *in situ* measurements of volumetric contamination. There is only a single table addressing laboratory measurement (Table 7 in Appendix II) because at the laboratory there is no significant difference in how surface or volumetric measurements are conducted beyond the units used to report results.

Note that when compared to field measurements, there are fewer permutations for laboratory measurements. Thus, there is minimal need to differentiate between emitter types, and there is only a single description to address lab measurements at each activity level. This is because laboratories, by design, can homogenize samples, perform chemical separations to address interferences, and carefully match calibration geometries to samples. By taking control of measurement conditions, there is no need to differentiate between many situations that pose different challenges to field measurements.

Given the variability of conditions in the field, independent confirmatory measurements of grab samples at a laboratory should always be performed, in parallel with *in situ* measurements, on a routine basis as a quality control measure to demonstrate the integrity of the measurement systems and to validate the accuracy of assumptions underlying the measurements.

Incident-specific circumstances, such as radionuclides of concern, matrix, interfering radioactivity, random circumstances surrounding the measurement, and DQOs and MQOs may influence the viability of a specific technique for a given situation. Tables 1 through 4 of this section are complemented by three tables in Appendix II, Tables 5, 6, and 7. These tables show the applicability of specific field and laboratory measurement techniques for determinations of different radionuclides of concern at low, medium, and high activity levels. Tables 5, 6, and 7 do not attempt to address every possible measurement technology; rather, they serve as a comparative tool and a starting point for selecting appropriate field and laboratory techniques for measurements of a variety of radionuclides at different activity levels.

Finally, Appendix III presents four simple example scenarios that synthesize information presented in this guide. They provide a simple demonstration of how the DQO/MQO process combined with a quality systems approach could be employed during response to a radiological or nuclear incident in an urban field setting. Several permutations are explored, ranging from the simplest scenario of a single medium- to high-energy gamma emitter, to more challenging scenarios with pure alpha and beta emitters, and mixtures of radionuclides. These simple examples are not meant for specific use in the field; rather, they identify how DQOs/MQOs, validated measurement techniques, and a quality systems approach could be applied in a field setting, and how field and lab measurements can be used in complementary fashion to most expeditiously characterize areas potentially impacted by a radiological event. These scenarios should serve as starting points for developing an approach to DQO/MQO-focused field measurements that are technically and legally defensible and as well-documented as measurements performed in a fixed laboratory.

Table 1 – Comparison of Non-Spectrometric Field and Laboratory Measurements of Surficially Deposited Activity

Activity Level	Emitter Type	Field Survey Measurements*	Laboratory Screening Measurements**
Gross activity at the action level significantly greater than background levels	*Single gamma emitter of medium- to high-energy* *Identity known*	Ideally suited for rapid, real-time location of hot spots, and qualitative or approximate measurements of single, surface-deposited radionuclide of known identity. Risk of false non-detection is low to moderate. Large field-of-vision may reduce sampling uncertainty and total number of required measurements relative to grab sampling techniques. Measurement bias and problems estimating measurement uncertainty increase with depth of penetration of contaminant in the surface. Confidence in measurements is significantly improved by a routine program of confirmatory sampling and independent laboratory analysis that validates assumptions about deposition profiles of contamination on and in the object being measured.	Ideally suited for rapid, high throughput screening, or unbiased, low-uncertainty measurements of a single radionuclide of known identity. Also well-suited for confirmatory measurements. Additional effort is needed in the field for grab sampling. Laboratory measurements are not completed in real-time since measurements follow sampling, shipping and preparation of test sources at the laboratory. Results reported by laboratories in terms of activity concentration (i.e., pCi/g or pCi/mL) may not be directly comparable to field measurements prior to conversion to areal concentration (i.e., pCi/m^2). Analyses are performed on prepared, homogenous aliquants representative of the sample provided to the laboratory, minimizing the degree of concern about false detection and non-detection. Low and stable backgrounds, good control of calibrations, and measurement geometries minimize introduction of bias during preparation and analysis and allow minimization and accurate estimation of measurement uncertainty. Well-defined, rigorous QC protocols provide documented evidence supporting the quality of results. In the case of medium- to high-energy gamma emitters, higher levels of uncertainty and increased likelihood of false non-detection accompany the need to take multiple samples to characterize an area, whereas *in situ* measurements of gamma emitters may
	Gamma or x-ray emitters of low to medium energy *Identity known*	Similar attributes as for medium- to high-energy gamma- and x-ray-emitters except: Measurements are less rapid; risk of false non-detection is moderate to high; rapid increase in measurement bias and problems estimating measurement uncertainty with decreasing energy of the radiation and increasing penetration of contaminant into the surface. Confidence in measurements is significantly improved by a routine program of confirmatory sampling and independent laboratory analysis that confirms assumptions about deposition profiles of contamination on and in the object.	
	Single high-energy beta emitter *Identity known*	Well-suited for rapid, real-time identification of hot spots and qualitative or approximate measurements of a single surface-deposited radionuclide. Risk of false non-detection and data quality depends on the adequacy of assumptions about self-absorption, surface roughness, efficiency corrections, and estimates of measurement uncertainty. Confidence in measurements is significantly improved by a routine program of confirmatory sampling and independent laboratory analysis that confirms assumptions about deposition profiles of contamination on and in the object.	

Activity Level	Emitter Type	Field Survey Measurements*	Laboratory Screening Measurements**
	Single low- to mid-energy beta or alpha emitter *Identity known*	Very limited applicability. Can play a supporting role in real-time identification of hot spots and approximate measurements of surface-deposited radionuclides. Risk of false non-detection is very significant for alpha and low- to mid-energy beta emitters. Total number of required measurements is similar to grab measurement techniques. Problems with bias and uncertainty estimates increase rapidly with surface roughness and when the contaminant may have penetrated below the surface of the object. Data quality depends on the accuracy of assumptions about self-absorption and surface roughness and estimates of measurement uncertainty. Confidence in measurements may be weak unless a routine program of confirmatory sampling and independent laboratory analysis confirms that contamination is present only on the surface of objects measured.	be able to characterize larger areas (e.g., up to 25 m^2) in a single measurement. As a result, more laboratory gamma measurements may be needed to characterize an area than would be required using ISGS. In contrast to gamma emitters, due to the short range of the radiations in matter, the number of measurements required to characterize alpha-, beta-, and low- to mid-energy photon-emitting contaminants will be similar in the field and in the laboratory. Given significantly better detection capabilities for short-range radiations, overall higher throughput of measurements may be possible at laboratories, allowing more effective used of field personnel to streamline recovery operations.
	Radionuclide mixtures *Identity unknown*	Well-suited for rapid, real-time identification of hot spots. Applicability is highly dependent on specific mixes; measurement conditions; ability to make accurate assumptions about the mixture, distribution, and depth profile of radionuclides; and ability to accurately calibrate survey instrumentation. High levels of alpha emitters increase probability of false detection and non-detection. Confidence in measurements may be weak unless a routine program of confirmatory sampling and independent laboratory analysis confirms that assumptions used during calibration match the conditions of analysis.	
Gross activity at action level similar to background levels	*Alpha, beta, gamma, or x-ray emitters* *Identity known or unknown*	Limited applicability. Low-level survey measurements with unshielded instrumentation do not reliably or accurately detect or quantify contaminants due to inability to distinguish signal from background. High risk of false detection/false non-detection due to temporal and spatial variability in background. Significant risk of false non-detection of alpha and beta emitters with rough or porous surfaces due to assumptions about geometry and variable deposition profiles. Confidence in measurements may be weak unless a routine program of confirmatory sampling and independent laboratory analysis confirms that assumptions used during calibration match the conditions of analysis.	Limited applicability but more sensitive, well-controlled measurements of gross activity are possible than in the field. Requires grab sampling, shipping and preparation of sample prior to measurement. Matrix is homogenized prior to measurement. Interpretation of results is limited when instrumentation cannot distinguish between analyte signal from background. The accuracy with which the "background activity" of the matrix is known determines usability of measurements.

* Unshielded beta/gamma and alpha survey meters.

** Laboratory Screening Measurements column applies to multiple emitter types. Laboratory screening includes gross alpha, beta, and gamma analyses for a variety of sample geometries. Instruments include shielded gas-proportional counters, gamma ray detectors, and liquid scintillation counters.

Table 2 – Comparison of Non-Spectrometric Field and Laboratory Measurements for Volumetrically Deposited Activity

Activity Level	*Emitter Type*	*Field Survey Measurements**	*Laboratory Screening Measurements***
Gross activity at action level significantly greater than background levels	*Gamma and x-ray emitters*	Suitability ranges significantly depending upon measurement conditions. Rapid, real-time measurements of a known single radionuclide are possible. Can be used qualitatively in scanning mode to quickly localize hot spots. Relating surface activity to volumetric activity requires that assumptions about the spatial distribution of contaminant in samples relative to the detector be taken into account during calibration of the instrument. Large field-of-vision may reduce sampling uncertainty and the total number of required measurements relative to grab sampling techniques. Risk of false non-detection, negative bias, and problems estimating measurement uncertainty are high. Non-homogenous distribution of contaminants within an object will impact the accuracy of instrument calibrations. When this technique is used to characterize volumetric contamination, a routine program for confirmatory sampling and independent laboratory analysis is needed to provide confidence in the field measurements by confirming the accuracy of assumptions used during calibration.	Ideally suited for rapid, high throughput screening, and unbiased measurements of known uncertainty of a single radionuclide of known identity. Well-suited for confirmatory measurements at the laboratory. Additional effort is needed in the field for grab sampling. Laboratory measurements are not completed in real-time since measurements follow sampling, shipping, and preparation of test sources. Low and stable backgrounds, good control of calibration and sample measurement geometries, and rigorous, well-defined QC protocols minimize concerns about false detection and non-detection, measurement bias, and inaccurate estimates of measurement uncertainty. Higher uncertainty and increased likelihood of false non-detection are associated with grab sampling. The number of samples needed to address this concern is higher than what would be required for *in situ* measurements of mid- to-high-energy gamma emitters. In contrast to gamma, the overall number of measurements required to quantify alpha-, beta-, and low- to mid-energy photon-emitting contaminants is similar to the number of field measurements required, but processing time in the laboratory may be more rapid.
	Alpha and Beta emitters, low-energy photon emitters	Poorly suited for any volumetric measurement with the exception of qualitative identification of hot spots. Risk of false non-detection, negative bias, and problems estimating measurement uncertainty are extremely high due to short range of alpha and beta particles in solids.	

Activity Level	*Emitter Type*	*Field Survey Measurements**	*Laboratory Screening Measurements***
Gross activity at action level similar to background levels	*Gamma and x-ray emitters*	Limited applicability. In most cases, low-level survey measurements with unshielded instrumentation do not reliably or accurately detect or quantify contaminants due to inability to distinguish signal from background. High risk of false non-detection and false detection due to variability in background radioactivity. Significant risk of false non-detection of alpha, beta, and low-energy-photon emitters when measuring rough or porous surfaces due to assumptions about geometry and variable depth of contamination that underlie calibrations. When this technique is used to characterize volumetric contamination, a routine program for confirmatory sampling and independent laboratory analysis is needed to provide confidence in the field measurements by confirming the accuracy of assumptions used during calibration.	Limited applicability but more sensitive and controlled measurements of gross activity are possible than in the field. Interpretation of results is limited when instrumentation cannot distinguish signal from background. The accuracy with which the "background activity" of the matrix is known determines usability of measurements. Requires grab sampling, shipping, and preparation of sample prior to measurement.
	Alpha and Beta emitters, low-energy photon emitters	Field techniques are generally poorly suited for any volumetric measurement of alpha and beta emitters with the exception of the qualitative identification of hot spots. Risk of false non-detection, negative bias, and problems estimating measurement uncertainty are extremely high due to short range of alpha and beta particles in solids.	

* Unshielded beta/gamma and alpha survey meters.

** Laboratory Screening Measurements column applies to multiple emitter types. Laboratory screening includes gross alpha, beta, and gamma analyses for a variety of sample geometries. Instruments include shielded gas-proportional counters, gamma ray detectors, and liquid scintillation counters.

Table 3 – Comparison of Spectrometric Field and Laboratory Measurements for Surficially Deposited Activity

Activity Level	Emitter Type	Field Spectrometry Measurements *	Laboratory Spectrometry Measurements**
Activity of the radionuclide(s) of concern at the action level significantly greater than background levels	Gamma emitter of medium- to high-energy	Ideally suited for rapid, real-time determination of radionuclide identity and for approximate measurements of surface-deposited gamma-emitting radionuclides. Can be used qualitatively in scanning mode to quickly localize hot spots. Risk of false non-detection is low-to-moderate. Large field-of-vision may reduce sampling uncertainty and the total number of measurements required relative to grab sampling techniques. Measurement bias and problems estimating measurement uncertainty increase with depth of penetration of contaminant into the surface. Confidence in measurements is significantly improved when a routine program of confirmatory sampling and independent laboratory analysis is used to confirm that contamination is homogenously distributed and only present on the surface of the object.	Laboratory analysis of alpha, beta, and gamma emitters is ideally suited for rapid, high throughput, low-bias, low-uncertainty measurements of radionuclides present alone or in mixtures. Also well-suited for confirmatory measurements at the laboratory. Laboratory measurements are not completed in real-time since the measurements follow sampling, shipping, and preparation of test sources. Additional effort is needed in the field for grab sampling. Results reported by laboratories in terms of activity concentration (i.e., pCi/g or pCi/mL) may not be directly comparable to field measurements prior to conversion to areal concentration (i.e., pCi/m^2). Analyses are performed on prepared, homogenous aliquants representative of the sample provided to the laboratory to minimize concerns about false detection and non-detection. Use of tracers/carriers during chemical separation and analysis, low and stable back-grounds, good control of calibrations, and measure-ment geometries minimize introduction of bias during preparation and analysis and allow minimization and accurate estimation of measurement uncertainty. Well-defined and rigorous QC provides evidence attesting to the quality of results.
	Gamma or x-ray emitters of low to medium energy	Similar attributes as for medium- to high-energy gamma and x-ray emitters except: Measurements are less rapid; risk of false non-detection is moderate to high; rapid increase in measurement bias and problems estimating measurement uncertainty with penetration of contaminant into the surface and decreasing energy of the radiation. Confidence in measurements is significantly improved when a routine program of confirmatory sampling and independent laboratory analysis are used to demonstrate that contamination is homogenously distributed and present only on the surface of the object.	
	Alpha and beta emitters	There is very limited application to spectrometric determinations of alpha and beta emitters in the field. Similar information can be obtained using gross activity measurements.	

Activity Level	Emitter Type	Field Spectrometry Measurements *	Laboratory Spectrometry Measurements**
Activity of the radionuclide(s) of concern at the action level significantly greater than background levels	Radionuclide mixtures	Gamma emitters are effectively determined in the presence of alpha and beta emitters. There is limited application to spectrometric determinations of alpha and beta emitters in the field (see above for respective discussions). If the activity of gamma emitters relative to alpha and beta emitters has been characterized, it may be possible to assume that the ratio holds, allowing mixtures of radionuclides to be characterized with field measurements of gamma marker nuclides. Confidence in measurements is significantly improved when a routine program for confirmatory sampling and independent laboratory analysis is used to demonstrate that contamination is homogenously distributed and present only on the surface of the object, and to verify assumptions about ratios for radionuclide mixtures that have been subjected to chemical processes such as weathering.	In the case of gamma spectrometry, there is higher uncertainty and increased likelihood of false non-detection associated with sampling than in field measurements of gamma, which can characterize larger areas. As a result, a larger number of samples may be analyzed for gamma emitters at the laboratory and more complex statistical analysis might be required than would be the case for *in situ* measurements of mid- to high-energy gamma emitters. In contrast to gamma, the overall number of measurements required to quantify alpha-, beta-, and low- to mid-energy-photon-emitter contamination will be similar to the number of field measurements required to do the same.
Activity of the radionuclide(s) of concern at action level similar to background levels	Gamma emitters of medium to high energy	Similar attributes to measurements of gamma emitters in medium- to high-activity settings, especially for non-natural radionuclides. The power of the technique diminishes when measuring radionuclides present in the matrix prior to the incident, or in areas where there is significant target analyte shine from collocated contamination.	Similar attributes to laboratory measurements above. Detection capability for medium- to high-energy gamma emitters may be less than that possible using ISGS.
	Alpha, beta, or low-energy photon emitters	There is limited application to spectrometric determinations of alpha and beta emitters in the field, especially for lower level determinations (see above for respective discussions).	Similar attributes to laboratory measurements above.

* Field spectrometry equipment includes gamma spectrometers, Field Instrument for the Detection of Low-Energy Radiation (FIDLERs$^{TM)}$, and radionuclide identifiers.

** Laboratory spectrometry measurements column applies to multiple emitter types. Laboratory spectrometry instrumentation includes alpha and gamma spectrometers and liquid scintillation counters, and non-spectrometric techniques that provide radionuclide-specific results when combined with chemical separations.

Table 4 – Comparison of Attributes of Spectrometric Field and Laboratory Measurements for Volumetrically Deposited Activity

Activity Level	Emitter Type	Field Spectrometry Measurements *	Laboratory Spectrometry Measurements**
Activity of the radionuclide(s) of concern at the action level significantly greater than background levels	Medium- to high-energy gamma emitters	Suitability ranges significantly depending upon conditions of the measurement. Rapid, real-time identification of hot spots or approximate measurements of a single radionuclide of known identity are possible. Levels of uncertainty may vary significantly. Relationship of surface activity to volumetric activity assumes that spatial distribution of contaminant in samples relative to the detector is well-known and accounted for during calibration. Large field-of-vision may reduce sampling uncertainty and the total number of required measurements relative to grab sampling techniques. Risk of false non-detection, negative bias, and problems estimating measurement uncertainty are high. Contaminants may be non-homogenously distributed within objects, leading to a mismatch between calibration and sample geometries. When this approach is used, a routine program for confirmatory sampling and independent laboratory analysis is needed to provide confidence in the field measurements by verifying assumptions used during calibration and analysis.	Similar attributes to laboratory measurements listed in the tables above except that measurements need not be converted to volumetric units. Detection capability for medium- to high-energy gamma emitters may be poorer than that possible using ISGS. In contrast to gamma, spectrometric analysis at the laboratory may be the only viable option for measurements of pure alpha and beta emitters.
	Alpha and beta emitters, low-energy photon emitters	Surface activity measurements are poorly suited for volumetric measurement of alpha and beta emitters. There is limited application for spectrometric determinations of alpha and beta emitters in the field beyond qualitative hot spot identification. In many cases, similar information can be obtained using gross activity measurements.	
Activity of the radionuclide(s) of concern at action level similar to background levels	Gamma and x-ray emitters	Similar attributes to measurements of gamma emitters in medium- to high-activity settings, especially for non-natural radionuclides. The power of the technique diminishes when measuring radionuclides present in the matrix prior to the incident, or in areas where there is significant target analyte shine from collocated contamination.	Similar attributes to laboratory measurements above except that measurements are generally reported in units of volumetric or massic activity. Approach is well-suited for sensitive, accurate, and precise radionuclide-specific determinations. In contrast to gamma, spectrometric analysis at the laboratory may be the only viable option for measurements of pure alpha and beta emitters.
	Alpha and beta emitters, low-energy photon emitters	Surface activity measurements are poorly suited for volumetric measurement of alpha and beta emitters. There is limited application for spectrometric determinations of alpha and beta emitters in the field beyond qualitative hot spot identification. Similar information often may be obtained using gross activity measurements.	

* Field spectrometry equipment includes gamma spectrometers, FIDLERs™, and radionuclide identifiers.

** Laboratory Spectrometry Measurements column applies to multiple emitter types. Laboratory spectrometry instrumentation includes alpha and gamma spectrometers and liquid scintillation counters, and non-spectrometric techniques that provide radionuclide-specific results when combined with chemical separations.

7. Conclusions

7.1 Conclusions and Recommendations Generally Applicable to Field and Laboratory Measurements

- There will be an unprecedented demand for radioanalytical capabilities following a radiological or nuclear incident. The Agency's decisions regarding re-occupancy of places of work, schools, playgrounds, day care centers, hospitals, places of worship, etc., must be based on defensible data of *demonstrated* accuracy and quality.
- Much attention has been focused on planning based on the White House Security Council Planning Scenario #11 involving a single gamma-emitting radionuclide. It is important to recognize that a Scenario #11-type event is one of the simplest possible scenarios in terms of radioanalytical measurement. Planning exclusively for the simplest case runs a significant risk of not being prepared to address more challenging scenarios, including mixtures of radionuclides, especially those involving pure alpha- or beta-emitting radionuclides. Such scenarios would place extensive demands on available resources in the field and at laboratories, and would more quickly overwhelm available resources than would Scenario #11.
- Both field and laboratory radionuclide measurements will play critical roles following a radiological or nuclear incident. There are inherent tradeoffs between laboratory and field measurements in terms of reliability, repeatability, uncertainty, turnaround time, cost, and throughput. If Incident Commanders, planners, and decisionmakers understand the respective benefits and limitations of the two approaches, they will be able to decide under which circumstances one approach is favored over another, and where and how the two approaches may be used synergetically to increase the effectiveness of the response while ensuring the reliability and defensibility of measurements used for decisionmaking.
- In the intermediate and the recovery phases, a gradual transition to progressively lower action levels and more demanding analytical requirements will likely require increased reliance on field spectrometry measurements and increased demand for laboratory measurements.
- DQOs and MQOs must be established to provide a defensible foundation for planning and for defending the types and quality of measurements used to support decisionmaking. They can control the levels of uncertainty and minimize decision error rates for decisionmaking.
- All radioanalytical measurements rest on the basic principles of metrology. Every result used for critical decisionmaking should be traceable to national radionuclide standards.
    - Instrumentation must be calibrated, and measurements performed to preserve traceability.
    - Reasonable and defensible estimates of measurement uncertainty must be determined and reported with each result to indicate the degree of confidence that can be placed in that result.

- The credibility, and ultimately the defensibility, of data depend on data being generated under a quality system framework.
    - Quality systems, such as those envisioned by ISO 17025, or the TNI Standard, are critical in providing a solid framework for ensuring that all measurements used to support the decisionmaking process are accurate and of known uncertainty, well-documented, traceable to national standards, and generally technically and legally defensible. Several important components of a quality system include:
        - Accreditation by independent authorities.
        - Validation of measurement methods and procedures prior to use to demonstrate that they are capable of reliably meeting MQOs.
        - All measurements performed by qualified and trained analysts.
        - Routine blind performance evaluations against traceable standards in various matrices.
        - Internal quality control measures to demonstrate the ongoing quality of measurements.
        - Rigorously documented programs to ensure that data can be recreated and independently validated and thus withstand possible data challenges.
    - Although the concept of quality systems for field measurements has been considered, implementation has yet to occur. The transitory nature of many field operations may be partially responsible for this.
    - Creative, more formalized, and effective quality controls could be implemented to support field measurements. These might range from implementing additional QC measurements in the field, to periodic independent confirmatory analyses at the laboratory.
- Emissions from naturally occurring radionuclides in the background may interfere with measurements of contaminant using gross activity techniques. This challenge may be overcome by increased use of spectrometric measurement techniques for gamma emitters that can most effectively be performed in the field.

7.2 Conclusions and Recommendations Specific to Field Measurements

- Field measurements will play a predominant role in the early phase. They:
    - Are ideally suited for generating real-time data for short-term protective action decisions involving medium- to high-activity levels.
    - Can provide real-time results for rapid and effective decisionmaking.
    - Can provide the best estimate of average activities of gamma-emitting radioactivity.
    - Can minimize the risk of not identifying hot spots of gamma emitters.
- The value of using field calibration facilities cannot be underestimated. The availability of such a facility, if used prior to deployment for an incident, would allow field sampling and measurement organizations to address potential weak points in their measurement systems to ensure that:
    - Measurement technologies could be validated against reliable reference sources.
    - Instruments could be calibrated against reliable reference sources.

  - Analysts could be trained and qualified in a real-world environment prior to deployment in the field.
- A number of technical and practical considerations impact the viability of field measurements in providing rapid, unbiased, low-uncertainty measurements of radioactivity. Several of these include:
  - Control of measurement geometry to ensure defensible *in situ* measurements.
  - The impact on calibrations and measurements of deposition patterns and mechanisms and self-absorption effects resulting from penetration of contaminants into solid surfaces. Gamma-emitting contaminants are the most amenable to field measurement. Alpha- and beta-emitting contaminants may present more challenges to field measurements and require confirmatory or primary laboratory analysis for their determination.
  - If an incident involves pure alpha and beta emitters, or mixtures containing pure alpha and beta emitters, field measurements may be much more limited in their ability to meet MQOs, especially in the later stages of an incident.
- The effectiveness and quality of field measurements may be limited by the availability of equipment and experienced and trained operator/analysts.
- Confidence in the field data is significantly increased by grab sampling with confirmatory analysis at a laboratory.

7.3 Conclusions and Recommendations Specific to Laboratory Measurements

- Laboratory measurements will play a limited role in the early phase. They:
  - Identify the complete list of contaminants.
  - Perform defensible confirmatory analyses for field measurements and measurements in media such as water.
  - Can be used to delineate the extent of impacted areas for lower activity air particulate and soil measurements.
- A number of technical and practical considerations impact the viability of laboratory measurements in providing, rapid, unbiased, low-uncertainty measurements of radioactivity. Several of these include:
  - Real-time measurements are not possible with laboratory measurements.
  - Grab samples must be collected and shipped to the laboratory for preparation and analysis, which leads to a delay in obtaining analysis results relative to real-time measurements in the field.
  - Laboratories can perform independent final status measurements to meet the highest data quality requirements.
  - Laboratories provide low-bias, low-uncertainty, and low-level measurements of alpha- and beta-emitting contaminants. Measurement geometries and calibrations are carefully matched, controlled environments provide low and stable backgrounds, and chemical separations may be combined with non-spectrometric and spectrometric measurement techniques to produce reliable measurements at the lowest activity levels.
  - In spite of longer turnaround times of one to several days, laboratories provide high throughput for less time-critical, quality-assured measurements of alpha, beta, and gamma emitters.

- If sufficient resources and expertise are available in the field to collect grab samples, combining laboratory and field capacity will result in an overall increase in analytical throughput and more rapid completion of recovery operations.
- Naturally occurring radionuclides in the matrix may interfere with measurements of contaminant using gross activity techniques. This challenge may be overcome by increased use of spectrometric measurement techniques for alpha, beta, and gamma emitters, which are readily available at the laboratory. (*Note that this challenge is shared with field measurements.*)
- For gamma spectrometry measurements, larger numbers of grab samples may have to be collected and analyzed in the laboratory to obtain the same level of confidence obtained using *in situ* gamma spectral measurements.

7.4 Summary

Ultimately, both laboratory and field measurements will be used in all phases of an event as part of the recovery and remediation process. The results of all measurements from these sources should not only support the DQOs and MQOs, but also should be complementary to each other. This is an extremely important part of the data assessment process that will provide the basis for a defensible decision. Whether measurements are performed in the field or the laboratory, the data generated need to be technically defensible. Data need to be obtained using rigorous and well-documented analytical protocols within the context of a robust and well-implemented quality management program. Ultimately, it is the responsibility of the Incident Commanders and their designees to ensure that all analytical data produced will be of sufficient quality to support decisionmaking.

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Appendix I: Case Study on the Use of Field Spectrometry Instruments for Remediation at Rocky Flats Environmental Technology Site (RFETS)

At Rocky Flats Environmental Technology Site, *in situ* gamma spectrometry (ISGS) was one of several radioanalytical techniques used to support the decontamination and decommissioning (D&D) process. Given RFETS' historical mission, the majority of contamination at the site resulted from plutonium processing and involved isotopes of americium and plutonium with lesser amounts of uranium. Experience during the D&D at RFETS showed that ISGS was a valuable tool at the radiologically contaminated site. Given the right environmental conditions and the resources for physically characterizing objects being measured and performing data reduction via established procedures, it was able to play vital and complementary roles in assessment and remediation activities. At the same time, experience showed that ISGS applications have clear limitations and that these limitations may run counter to expectations that large amounts of definitive radioanalytical data can be quickly and easily generated in the field, especially if more complex mixtures of pure alpha and beta emitting radionuclides are present in the source term.

ISGS found primary application at RFETS in situations where grab sampling was impractical (e.g., large objects or areas) and results were needed in real-time. Specific applications included:

- Support of excavations of contaminated areas and landfills (e.g., 903 Pad[35]);
- Identifying the extent of heavily contaminated areas;
- Safeguarding measurements of special nuclear materials in glove-boxes (i.e., "hold up");
- Tracking progress during cleanup and excavation to provide "go" and "no-go" determinations;
- Surveys of outdoor areas (soil, pads, or other potentially contaminated surfaces); and
- Characterization and final status surveys in buildings and outdoor areas during assessment.

Most critically, in order for ISGS to provide usable results, the isotope of interest must be a gamma-emitting radionuclide. Alpha and beta emitters cannot be detected unless they also possess a secondary gamma ray emission. At RFETS, this was nearly an insurmountable challenge because the primary contaminant at the site, plutonium, is an alpha emitter that emits only very weak gamma and x-rays. Thus, plutonium is not readily detectable using gamma spectrometry unless very large amounts are present.[36] ISGS would not have played a significant

[35] ISOCS™ was used at Rocky Flats in the remediation of the 903 Pad to help guide the progress of excavation in real-time. It might be misleading, however, to say that the measurements made at the 903 Pad using ISGS were definitive since quantitative *in situ* measurements of contaminants often are impossible in the presence of confounding contaminants and the background activity associated with them. In such cases, samples must be taken "destructively" and transported to an area where the background activity has been quantitatively determined. At the 903 Pad, for example, a fixed geometry approach was used for many of the measurements. Although ISOCS™ was used, it was most frequently not applied *in situ* but rather in a manner more reminiscent of conventional gamma spectrometry measurements with the exception that ISOCS™ measurement efficiencies were modeled and results generated without direct comparison to a NIST standard. Although the results generated may have been reasonable, they were not traceable to a NIST standard as would be required of quantitative measurements.

[36] While absolute detection thresholds for ^{239}Pu were typically at the nanocurie level, exact detection thresholds depend on ambient background, composition of the material being measured, depth and profile of deposition, areal

role in the D&D effort at RFETS except for the fortuitous availability of accurate data on the isotopic makeup of plutonium used at the plant. This, together with the latest date of plutonium separation (beginning when production operations at the plant ceased), made it possible to inferentially relate the ^{241}Am present to the ^{241}Pu. Despite this information about the source term, extensive pre-survey and post-survey confirmatory sampling and radiochemical analysis at fixed laboratories were needed to verify that the americium to plutonium ratios presumed from process knowledge were still valid and had not been changed due to chemical processes and transport mechanisms following deposition of the contaminants in the environment.[37]

Although *in situ* techniques played an indispensable role in the rapid pace and ultimate success of D&D at RFETS, it would be misleading to overlook the fact that ISGS results were qualitative in nature, or associated with unknown levels of bias and uncertainty. To perform an accurate "calibration" for this technique, the following conditions must be met:

- Ambient background must be accurately determined, particularly for environmental and low-level measurements where incident-related contaminants may be present adjacent to the location of the measurement.
- The physical characteristics of the material or materials comprising the object being measured must be accurately known, including their elemental composition and density.
- The shape of the contaminated objects and materials of which they are composed and their spatial relationship to the detector must be well known.
- The areal and volumetric distribution of the contaminants on and in the objects being measured must be very well known.
- All of these factors must be synthesized into a mathematical model that is representative of the measurement, which must be done by a gamma spectrometrist specially trained and experienced in the technique.

Given the number of critical factors underlying the application of ISGS in the real world (and the assumptions generally necessary to estimate these factors), it is not surprising that in many cases it is extremely difficult to realistically assign uncertainty to ISGS measurements. Similarly, it should not be overly surprising when realistic assessments of measurement uncertainty exceed those obtained through fixed laboratory measurements.

Thus, for critical measurements requiring reliable and defensible data (as opposed to "go" and "no-go" measurements, such as those used to guide remedial excavations), samples were taken and radiochemical analysis performed under the carefully controlled conditions available in radioanalytical laboratories. Fixed laboratory analysis was crucial in situations where *in situ* measurements were technically or practically infeasible. This analysis also was used to develop

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distribution of the contaminant, and location of the detector. ^{241}Am, which has a reasonably abundant gamma ray emission, for example, would not meet the criteria specified in 10 CFR 835 Appendix D for removable surface contamination with MDCs of ~30-50 dpm/cm^2 for an ideal geometry, a flat plane surface, and extended count times between eight and 24 hours (based on personal experience and unreleased MDC data).

[37] According to informal communications with several individuals, attempts to apply similar assumptions at other DOE sites have met with limited success.

correlation factors used to guide *in situ* measurements, and as a reliable and defensible confirmatory technique (i.e., "ground truth").

Additionally, accurate measurements with ISGS are possible only when extensive and detailed information regarding the distribution and deposition characteristics of the contaminant is available. Even minor variations in the characteristics (e.g., variations in depth and profiles of contaminant penetration due to porosity, or even due to surface roughness) could introduce significant errors into measurements. The most accurate results are obtained in cases where surface contamination was "fixed" on a flat surface by stabilizing the contaminant with paint. In practice, though, confirmatory sampling followed by chemical separation and laboratory analysis is necessary to validate the assumptions made during calibration of the instruments. On a number of occasions, traditional sampling and analysis indicated that the original assumptions made to calibrate the ISGS were inaccurate and that the inaccuracy of measurements was not covered by the reported uncertainty.

In the field (e.g., with soils or rough or porous surfaces), it became increasingly difficult to make defensible assumptions and more frequent, extensive, and specialized analysis of grab samples (e.g., radionuclide penetration analysis in cored or scabbled samples) was necessary to ensure that ISGS measurements were accurate. Given the time, effort, and cost for the fixed laboratory analysis, the need to synthesize this information gained, and the delay in time needed to do this, much of the perceived rapidity of analysis was lost.

Even if only ^{241}Am is present and conditions are otherwise reasonably ideal (e.g., ^{241}Am-free background, with the detector ~30 cm from a plane surface), the sensitivity of the technique may not be able to reliably measure ^{241}Am at the levels needed to detect surface contamination at the limits established under 10 CFR 835 Appendix D (20 dpm/100 cm^2). For example, one representative minimum detectable concentration (MDC) study performed at RFETS indicated detection capabilities ranging from 30-50 dpm/100 cm^2 for areal deposition of ^{241}Am using a broad energy germanium (BEGe) detector even with extended count times of eight to 24 hours.

Another limitation of ISGS encountered at RFETS involved measurements in contaminated areas. Because the detector is only lightly shielded (using a collimator), ambient radiation in an area cannot be reliably differentiated from analyte signal. As a result, when contamination was present in an area of concern at RFETS, often it was not possible to determine the background activity. This necessitated collecting grab samples for measurement under adequately controlled conditions. For example, although many ISOCS™ measurements were made during the 903 Pad excavation, a large number of these samples were removed from the area and counted away from the main source of contamination (in a quasi fixed-geometry situation very similar to the traditional laboratory setting).

Finally, the experience at RFETS showed that while there are distinct advantages given the right conditions, there are just as distinct limits to sample throughput for ISGS (specifically ISOCS™) measurements. Gamma spectrometrists specially trained and experienced in ISGS techniques are needed to produce defensible data. Based on interviews with personnel intimately involved in performing ISOCS™ measurements onsite at RFETS, 15 to 60 minutes are needed to set up a gamma "shot." A highly experienced operator is required who can very carefully document

conditions of analysis, prepare accurately dimensioned sketches of the area, determine and document the composition of the object being analyzed, and identify conditions that could impact very subtle (and subjective) factors in the analysis such as depth of penetration of contaminants. Count times vary depending on the sensitivity of the measurement needed, but even assuming a short count of 45 minutes, a single operator with a single instrument could be expected to perform a maximum of eight measurements in a day. If extended counts (8- to 24-hours) are needed, throughput drops precipitously. Once the spectrum and associated data have been acquired, data reduction and analytical results are performed by an experienced spectrometrist. At RFETS, this required approximately 20 minutes per gamma spectrum in routine cases. Thus, optimistically, four people would be required to produce about 25 measurements per day. This does not make any allowance for confirmatory sampling or integration of feedback from confirmatory sampling.

In summary, ISGS would not have been capable of detecting levels of plutonium low enough to support environmental and free-release criteria at RFETS without making assumptions regarding ratios of plutonium relative to the marker isotope, ^{241}Am. That it was used at all is due to the fortuitous availability of historical isotopic characterization data for the site's plutonium. Calibrating ISGS detection systems requires extensive knowledge that was not always available to operators in the field. Varying and unknown levels of self-absorption in weathered settings complicated the development of ISGS calibration models. As a result, extensive pre- and post-survey fixed-laboratory radiochemical measurements were needed to confirm and support the assumptions used to generate the ISGS data. The ambient background activity of ^{241}Am from site contaminants often precluded use of *in situ* techniques for measurements of ^{241}Am. Instead, where defensible analyses were required (i.e., results traceable to NIST standards that would be used to make decisions of record), ISGS results were not generally used; rather, grab samples were routinely taken and sent to fixed laboratories for alpha isotopic analysis.

In the case of a radiological or nuclear incident, it is foreseeable that even if a large amount of ISGS equipment is procured, similar circumstances could apply. Large numbers of expert, experienced operators and spectrometrists would be needed to perform ISGS measurements, a requirement that would very likely cause staffing shortfalls. The limitations of assumptions needed to develop models for calibration and elevated background from co-located contaminants or natural background would require the coordination of field and lab resources to balance the need for large numbers of measurements with the data quality needed to support critical decisionmaking.

Appendix II: Applicability of Selected Field and Laboratory Measurement Techniques

Tables 5, 6, and 7 provide a comparative overview of the applicability of various detection techniques for determining radionuclides at low, medium, and high activity levels in the field and at the laboratory. The tables may help to provide perspective on the relative applicability of specific techniques for measurements of radionuclides conducted at different activity levels. Incident-specific parameters, such as those listed below, will all affect the viability of a specific technique for measurement of the radionuclides of interest:

- DQOs;
- MQOs;
- Matrices to be sampled;
- Deposition profiles of radionuclides in matrices;
- Interfering radionuclides or radiation;
- Non-radiological interferences;
- Need for rapid or even real-time measurements; and
- Relative availability of needed instrumentation, skilled and experienced analyst/operators or samplers, and laboratory capacity.

Clearly, incident-specific circumstances such as DQOs, MQOs, matrix, interfering radiation, circumstances of the measurement, etc., will influence the viability of a technique to a given situation. Thus, these tables should be viewed only as a comparative tool and as a starting point for comparing field and laboratory techniques for measurements of various radionuclides.

In the tables below, cases where a technique is generally well-suited to unbiased, low-uncertainty determinations of a radionuclide contaminant at the respective activity level are marked with a solid dot (●). Cases in which the test is deemed to be of marginal applicability, or cases where the technique is by its nature non-definitive, or where applicability is limited over a significant portion of the range noted are marked with an open circle (○). Where a technique is deemed to be unsuitable for determining the radionuclide at the activity level in question, the slot is left blank.

For field measurements, the tables further differentiate between *in situ* measurements of surface contamination and *in situ* measurements of volumetric contamination. There is only a single table addressing laboratory measurements because there is no significant difference in how surface or volumetric measurements are conducted beyond the units used to report results.

In general, instruments that have high or variable backgrounds, such as unshielded instrumentation, will find limited applicability unless the levels of radioactivity of concern are high enough that analyte signal can be unambiguously differentiated from ambient radiation levels. This clearly limits the applicability of many field techniques at the lowest activity levels.

When an uncontaminated sample matrix contains elevated levels of background radioactivity intrinsic to the uncontaminated matrix material, these will compete with or mask signal from the analyte. This is commonly the case in measurements of radionuclides at low-to-medium activity levels. Thus, techniques based on the measurement of gross activity are viable only when the activity of the contaminant significantly exceeds the gross activity in the uncontaminated sample

matrix. In the field, and in some cases at the laboratory, this will limit the applicability of most non-spectrometric techniques to medium- to higher-activity levels.

In some cases, the analyte of concern itself is a radionuclide encountered in the ambient background or in the uncontaminated matrix material, such as isotopes of radium, uranium, lead, and polonium. In such cases, the intrinsic activity and associated uncertainty of the analyte in uncontaminated matrix material must be determined by separately analyzing representative uncontaminated matrix material. The uncertainty with which competing background activity is known will define the threshold for determining the presence or absence of contaminant.

Spectrometric techniques, especially gamma spectrometry, can discriminate against interfering radiation while specifically measuring the contaminant even when significant levels of background activity are present. Gross gamma measurements may not provide unambiguous results at the low and medium activity levels, while gamma spectrometric measurements may detect very low levels of radionuclides even in the presence of the ambient levels of interfering radioactivity.

Radionuclide-specific measurements in the laboratory will nearly always produce more accurate results and reliable estimates of uncertainty at lower levels of activity than is possible for field measurements. Field measurements using lightly shielded or unshielded alpha, beta, or dose rate meters, especially at low-to-medium activities, will not be able to discriminate against the intrinsic background signal of the matrix. This concern can be addressed at the laboratory by combining chemical separations with heavily shielded alpha and beta measurement techniques to provide radionuclide-specific data with lower detection levels and smaller measurement uncertainties. Controlled counting geometries, longer count times, and tighter QA/QC controls also allow lower uncertainties and a higher degree of defensibility.

Field techniques can provide defensible results that meet MQOs given the proper conditions. Most optimally, when radionuclide(s) of known identity are freshly deposited on smooth and relatively impermeable surfaces, bias due to inaccurate self-absorption corrections is significantly minimized to a point where it is non-problematic. In most cases, however, radionuclides are deposited on permeable and irregularly shaped surfaces, where weathering may have occurred requiring more information about measurement conditions to generate accurate estimates of the detection efficiency and its associated uncertainty. Such information could include the size and shape of the active source, information about the spatial distribution (including depth of penetration for self-absorption corrections), the degree of homogeneity of contaminants within the source, the elemental composition of the object, and the ambient background activity in the area of the measurement.

There is one notable exception where field measurement sensitivity may be significantly greater than the corresponding measurements at a laboratory. ISGS is a very powerful tool for real-time field measurement of medium- to high-energy gamma emitting radionuclides. If the measurement geometry is reproducible and well-controlled, accurate results and low measurement uncertainties may be possible at detection limits that are much lower than may be routinely available at the laboratory. ISGS measurements, however, often are subject to interference from ambient background, which may introduce bias into results and increase the

uncertainty of the measurement. Laboratory gamma spectrometry measurements, on the other hand, are made in an environment where background from ambient sources of radiation has been effectively eliminated but tends to be limited by the size of the sample that can be measured.

Even when factors impacting instrument calibrations and background corrections are less well-known, a conservative set of assumptions may be applied to allow ISGS measurements to be used protectively for rapid characterization of large areas and detecting hot spots in the field with a minimum of effort. Given the potential for mismatch between measurement conditions and the assumptions underlying the gamma spectrometer calibrations, however, assumptions should be carefully applied and operational controls established to ensure that measurements will consistently err on the side of protecting human health and the environment (i.e., always have a positive bias).

Since *in situ* measurements may be biased or have high or unknown levels of uncertainty, they should be clearly qualified as such and used only very judiciously for decisionmaking. Positive measurements that could be the result of bias in the measurement system, or for which estimates of uncertainty may be unrealistically low, should be verified prior to taking significant action. The validity of all field measurements also should be routinely confirmed by independent measurement of samples at laboratories since measurement conditions and bias are much more carefully controlled in the laboratory setting than is generally possible in the field. These confirmatory data provide the program with high quality, traceable results and documented evidence, thus providing solid support for decisionmaking during incident response.

Assuming there are further limiting technical issues, decisions about whether field or laboratory measurement techniques (or both) should be used will be influenced by operational considerations such as: Is there a need for rapid or real-time results? Are trained and experienced sampling personnel and fixed laboratory capacity available? Are trained, experienced operator/analysts and field instrumentation available for field analysis?

Table 5 – Applicability of Selected Field Measurement Techniques for *In Situ* Measurements of Surface Activity / Concentrations of Radionuclides

	^{241}Am	^{244}Cm	^{238}Pu	$^{239/40}$Pu	^{238}U#	^{235}U	^{232}Th#	^{210}Po	^{226}Ra#	^{90}Sr	^{89}Sr	^{32}P	^{99}Tc	^{3}H	^{241}Pu	^{125}I	^{129}I	^{137}Cs	^{60}Co	^{103}Pd
1° Radiation	α	α	α	α	α	α	α	α	α	β	β	β	β	β (LE)	β (LE)	ε (LE)	β (LE)	β	β	ε (LE)
2° Radiation	γ x	x (ω)	x	x (ω)	x (ω)	γ x	x γ (ω)	n/a	γ (ω) x(ω)	n/a	n/a	n/a	n/a	n/a	n/a	γ (LE)	γ (LE)	γ x(ω)	γ (ω)	x(ω) (LE)
HPGe (ISGS – energy greater than 0.06 MeV)																				
Low Activity	○					○			I									●	●	
Medium Activity	●				○	●	○		○									●	●	
High Activity	●				●	●	○		●									●	●	
Unshielded Geiger-Műller (G-M) (thin window non-specific ionizing radiation – gross alpha/gross beta)																				
Low Activity																				
Medium Activity	○	○	○	○	○	○	○	○	○	○	○	○	○					○	○	○
High Activity	●	●	●	●	●	●	●	●	●	●	●	●	●					●	●	●
Unshielded NaI(Tl) (Gross Gamma)																				
Low Activity																				
Medium Activity	○				○	○	○		○							○	○	●	●	○
High Activity	●				●	●	●		●							●	●	●	●	●
Alpha Scintillator (large-area in situ zinc sulfide (ZnS) detector – gross alpha)‡																				
Low Activity	○	○	○	○	○	○	○	○	○											
Medium Activity	○	○	○	○	○	○	○	○	○											
High Activity	●	●	●	●	●	●	●	●	●											
Unshielded Beta Scintillator (large-area in situ organic scintillator detector – gross beta, average energy greater than 500 keV)‡																				
Low Activity										○	○	○						○	○	
Medium Activity										●	●	●	○					○	○	
High Activity										●	●	●	●					●	●	
Gas Proportional Counter (large-area in situ detector – discriminated gross alpha/beta)‡																				
Low Activity	○	○	○	○	○	○	○	○	○	○	○	○						○	○	
Medium Activity	○	○	○	○	○	○	○	○	○	○	○	○	○					●	●	○
High Activity	●	●	●	●	●	●	●	●	●	●	●	●	○					●	●	○
Gas Proportional Counter (segmented large-area in situ detector – discriminated gross alpha/beta)‡																				
Low Activity	○	○	○	○	○	○	○	○	○	○	○	○						○	○	
Medium Activity	○	○	○	○	○	○	○	○	○	●	●	●	○					○	○	○
High Activity	●	●	●	●	●	●	●	●	●	●	●	●	●					●	●	○
Thin NaI(Tl) Low-energy Photon Detector (e.g., FIDLER – x-ray spectrometry specificity is limited, self-absorption prevents unbiased, low-uncertainty determinations unless surface deposited)																				
Low Activity	○	○	○	○	○	○	○													
Medium Activity	○	○	○	○	○	○	○									●	●	○	○	●
High Activity	●	●	●	●	●	●	●									●	●	○	○	●

● – suitable for definitive (unbiased, low-uncertainty) determination; ○ – capable of screening quality measurements only;

Low activity refers to levels between ~0.1- 10 pCi/g alpha or ~1-100 pCi/g beta-gamma; **Medium activity** refers to levels between ~10-500 pCi/g alpha or ~100-5000 pCi/g beta-gamma; **High activity** refers to levels greater than ~500 pCi/g alpha and ~5000 pCi/g beta-gamma (determinations with low uncertainty are possible at levels significantly above background); # determination based on decay progeny if in equilibrium; α - alpha emission; β - beta emission; γ - gamma ray emission, x - x-ray emission; ε - electron capture decay; LE - emission less than 100 keV; ω - low intensity emission (between 0.1% and 5%); I - poorly resolvable gamma-ray interference.

‡ **Interference from crosstalk may limit the effectiveness of beta measurement techniques when high activities of alpha activity are present, and vice versa.**

Table 6 – Applicability of Selected Field Measurement Techniques for In Situ Measurements of Volumetric Activity / Concentrations of Radionuclides

	^{241}Am	^{244}Cm	^{238}Pu	$^{239/40}$Pu	^{238}U#	^{235}U	^{232}Th#	^{210}Po	^{226}Ra#	^{90}Sr	^{89}Sr	^{32}P	^{99}Tc	^{3}H	^{241}Pu	^{125}I	^{129}I	^{137}Cs	^{60}Co	^{103}Pd
1° Radiation	*α*	*α*	*α*	*α*	*α*	*α*	*α*	*α*	*α*	*β*	*β*	*β*	*β*	*β (LE)*	*β (LE)*	*ε (LE)*	*β (LE)*	*β*	*β*	*ε (LE)*
2° Radiation	*γ x*	*x (ω)*	*x*	*x (ω)*	*x (ω)*	*γ x*	*x γ (ω)*	*n/a*	*γ (ω) x(ω)*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*γ (LE)*	*γ (LE)*	*γ x(ω)*	*γ (ω)*	*x(ω) (LE)*
HPGe (ISGS – energy greater than 0.06 MeV)																				
Low Activity	○					○			I									●	●	
Medium Activity	○				○	●			●									●	●	
High Activity	●				○	●			●							○	○	●	●	○
Unshielded G-M (thin window non-specific ionizing radiation – gross alpha/gross beta)‡																				
Low Activity																				
Medium Activity	○	○	○	○	○	○	○	○	○	○	○	○	○					○	○	
High Activity	○	○	○	○	○	○	○	○	○	○	○	○	○					○	○	
Unshielded NaI(Tl) (Gross Gamma)																				
Low Activity																				
Medium Activity	○				○	○	○		○									●	●	
High Activity	○				○	○	○		○							○	○	●	●	○
Alpha Scintillator (large-area in situ ZnS detector – gross alpha)																				
Low Activity																				
Medium Activity	○	○	○	○	○	○	○	○	○											
High Activity	○	○	○	○	○	○	○	○	○											
Unshielded Beta Scintillator (large-area in situ organic scintillator detector – gross beta, energy greater than 500 keV)‡																				
Low Activity																		○	○	
Medium Activity										○	○	○	○					○	○	
High Activity										○	○	○	○					○	○	
Gas Proportional Counter (large-area in situ detector – discriminated gross alpha/gross beta)‡																				
Low Activity																		○	○	
Medium Activity										○	○	○						○	○	
High Activity	○	○	○	○	○	○	○	○	○	○	○	○						○	○	
Gas Proportional Counter (segmented large-area in situ detector – discriminated gross alpha/gross beta)‡																				
Low Activity																		○	○	
Medium Activity	○	○	○	○	○	○	○	○	○	○	○	○						○	○	
High Activity	○	○	○	○	○	○	○	○	○	○	○	○						○	○	
Thin NaI(Tl) Low-energy Photon Detector (e.g., FIDLER – x-ray spectrometry specificity is limited, self-absorption prevents unbiased, low-uncertainty determinations unless surface deposited)																				
Low Activity																				
Medium Activity	○	○	○	○	○	○	○									○	○	○	○	○
High Activity	○	○	○	○	○	○	○									○	○	○	○	○

● – suitable for definitive (unbiased, low-uncertainty) determination; ○ – capable of screening quality measurements only;

Low activity refers to levels between ~0.1- 10 pCi/g alpha or ~1-100 pCi/g beta-gamma; **Medium activity** refers to levels between ~10-500 pCi/g alpha or ~100-5000 pCi/g beta-gamma; **High activity** refers to levels greater than ~500 pCi/g alpha and ~5000 pCi/g beta-gamma (determinations with low uncertainty are possible at levels significantly above background); # determination based on decay progeny if in equilibrium; α - alpha emission; β - beta emission; γ - gamma ray emission, x - x-ray emission; ε - electron capture decay; LE - emission less than 100 keV; *ω* - low intensity emission (between 0.1% and 5%); I - poorly resolvable gamma-ray interference.

‡ **Interference from crosstalk may limit the effectiveness of beta measurement techniques when high activities of alpha activity are present, and vice versa.**

Table 7 – Applicability of Selected Laboratory Measurement Techniques for Determining Activity / Concentrations of Radionuclides

	^{241}Am	^{244}Cm	^{238}Pu	$^{239/40}$Pu	^{238}U#	^{235}U	^{232}Th#	^{210}Po	^{226}Ra#	^{90}Sr	^{89}Sr	^{32}P	^{99}Tc	^{3}H	^{241}Pu	^{125}I	^{129}I	^{137}Cs	^{60}Co	^{103}Pd
1° Radiation	α	α	α	α	α	α	α	α	α	β	β	β	β	β (LE)	β (LE)	ε (LE)	β (LE)	β	β	ε (LE)
2° Radiation	γ x	x (ω)	x	x (ω)	x (ω)	γ x	x γ (ω)	n/a	γ (ω) x(ω)	n/a	n/a	n/a	n/a	n/a	n/a	γ x	γ x	γ x(ω)	γ (ω)	x(ω)
Unshielded G-M (thin window)																				
Low Activity																		○	○	
Medium Activity	○	○	○	○	○	○	○	○	○	○	○	○	○					○	○	
High Activity	○	○	○	○	○	○	○	○	○	○	○	○	○			○	○	○	○	○
Unshielded NaI(Tl) (Gross Gamma)																				
Low Activity																				
Medium Activity	○				○	○	○		○									○	○	
High Activity	○				○	○	○		○							○	○	○	○	○
Shielded NaI(Tl) (Gross gamma)																				
Low Activity	○	○			○	○	○		○									○	○	
Medium Activity	○	○			○	○	○		○							○	○	○	○	○
High Activity	○	○	○	○	○	○	○	○	○							○	○	○	○	○
Shielded HPGe Gamma Spectrometry – *energy greater than 0.06 MeV*)																				
Low Activity	○				○	○	○		○									●	●	
Medium Activity	●				○	●	○		○									●	●	
High Activity	●				●	●	●		●									●	●	
Low Background Gas Proportional Counting (gross alpha/gross beta screen)																				
Low Activity	○	○	○	○	○	○	○	○	○	○	○	○	○					○	○	
Medium Activity	○	○	○	○	○	○	○	○	○	○	○	○	○			○	○	○	○	○
High Activity	○	○	○	○	○	○	○	○	○	○	○	○	○			○	○	○	○	○
Low Background Gas Proportional Counting (chemical separation – element or radionuclide specific)																				
Low Activity	●	●	●	●	●	●	●	●	●	●	●	●	●				○	●	●	
Medium Activity	●	●	●	●	●	●	●	●	●	●	●	●	●			○	●	●	●	○
High Activity	●	●	●	●	●	●	●	●	●	●	●	●	●			○	●	●	●	●
Liquid Scintillation Counting (α/β screen – direct analysis)																				
Low Activity	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Medium Activity	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
High Activity	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○

	^{241}Am	^{244}Cm	^{238}Pu	$^{239/40}$Pu	^{238}U#	^{235}U	^{232}Th#	^{210}Po	^{226}Ra#	^{90}Sr	^{89}Sr	^{32}P	^{99}Tc	^{3}H	^{241}Pu	^{125}I	^{129}I	^{137}Cs	^{60}Co	^{103}Pd
1° Radiation	α	α	α	α	α	α	α	α	α	β	β	β	β	β (LE)	β (LE)	ε (LE)	β (LE)	β	β	ε (LE)
2° Radiation	γ x	x (ω)	x	x (ω)	x (ω)	γ x	x γ (ω)	n/a	γ (ω) x(ω)	n/a	n/a	n/a	n/a	n/a	n/a	γ x	γ x	γ x(ω)	γ (ω)	x(ω)
Liquid Scintillation Counting (chemical separation – element or radionuclide specific)																				
Low Activity	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Medium Activity	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
High Activity	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Alpha Spectrometry(following separations)																				
Low Activity	●	●	●	●	●	●	●	●	●											
Medium Activity	●	●	●	●	●	●	●	●	●											
High Activity	●	●	●	●	●	●	●	●	●											

● – suitable for definitive (unbiased, low-uncertainty) determination; ○ – capable of screening quality measurements only;

Low activity refers to levels between ~0.1- 10 pCi/g alpha or ~1-100 pCi/g beta-gamma; **Medium activity** refers to levels between ~10-500 pCi/g alpha or ~100-5000 pCi/g beta-gamma; **High activity** refers to levels greater than ~500 pCi/g alpha and ~5000 pCi/g beta-gamma (determinations with low uncertainty are possible at levels significantly above background); # determination based on decay progeny if in equilibrium; α - alpha emission; β - beta emission; γ - gamma ray emission, x - x-ray emission; ε - electron capture decay; LE - emission less than 100 keV; ω - low intensity emission (between 0.1% and 5%); I - poorly resolvable gamma-ray interference.

‡ **Interference from crosstalk may limit the effectiveness of beta measurement techniques when high activities of alpha activity are present, and vice versa.**

Appendix III: Example Scenarios: Approaches to Integrating Field and Laboratory Measurements During Response to a Radiological or Nuclear Incident

This section presents several scenarios that illustrate some of the challenges that may be encountered, and some of the benefits that may be gained, during an incident response by coordinating field and laboratory measurements to rapidly and accurately characterize the situation while making optimal use of limited resources at the field and laboratory.

This section presents several simple scenarios to help show how radioactive emission type and energy, DQOs / MQOs, and the use of non-spectrometric versus spectrometric measurement techniques all have an impact on possible approaches to characterizing an area. They also provide a taste of how field and laboratory measurements can be used in complementary fashion for more effective and efficient characterization of indoor spaces such as those in potentially contaminated buildings.

These examples should not be viewed as limiting. For example, scenarios involving complex mixtures of alpha- and beta-emitting radionuclides are possible and would require more extensive use of spectrometric techniques in the field and heavier reliance on laboratory measurements following chemical separations.

Scenarios #1 and #2 demonstrate the capabilities of ISGS measurements. When compared to grab sampling followed by laboratory analysis, using ISGS for the determination of gamma emitters can significantly decrease the number of measurements needed to characterize an area while significantly increasing the probability that contamination, if present, will be detected. Using ISGS, where possible, may free up laboratory capacity to perform more sensitive and unbiased gamma spectral measurements of known uncertainty such as periodic, routine confirmation of ISGS measurements. ISGS is not without drawbacks, however. The scenario demonstrates that an unshielded *in situ* detector will respond to all incident radiation, even if it originates from beyond the presumptive confines of the intended measurement.

Scenarios #3 and #4 involve pure alpha and beta emitters. These underscore the limitations of alpha and beta measurements in the field. Given the very short range of this radiation, a much larger number of samples is needed to demonstrate that an area has not been contaminated. In these scenarios, not only are the testing techniques not sensitive enough to address the lowest action limits for removable contamination, but pending empirical evidence of their efficacy, they also should be recognized for what they are: screening tests. Although results are calculated using conservatively assigned attenuation factors to address potential geometry concerns (surface penetration and texture), a certain fraction of results will be subjected to confirmatory analysis using a technique at the laboratory that is capable of delivering unbiased results of known uncertainty.

Scenario #1: Following an RDD event, Building #1 is to be assessed for ^{60}Co contamination. The building was downwind from the incident, and there is potential for contamination since the heating, ventilation, and air conditioning (HVAC) was running during and after the incident as the plume passed. As is the case throughout the city, there is also the potential that people have tracked contamination from other areas into the building. AALs have been established by the

IC[38] at 7100 dpm/100 cm^2 and 710 dpm/100 cm^2 for total and removable ^{60}Co contamination, respectively. The MQO for required relative method uncertainty for screening measurements of gross gamma or gross beta activity is 34% of the respective AALs of 7100 dpm/100 cm^2 and 710 dpm/100 cm^2. The corresponding analytical decision levels (ADLs)[39] are 3100 and 310 dpm/100 cm^2 respectively.

Cobalt 60 contamination will be assessed by *in situ* gamma counting (non-spectrometric screen) on each floor of the building. Given the long range of gamma rays, a single gamma measurement can characterize a relatively large area, minimize the risk of false non-detection, and minimize the total number of measurements required relative to measurements of alpha or beta radiation. This could minimize the need to take multiple grab samples for analysis at the laboratory. Given the better detection capabilities for beta radiation at the laboratory and the relative ease of taking swipes, it may be more effective to screen for higher levels of gamma and to assess removable contamination by taking swipes and counting beta at a radiochemistry laboratory. This optimizes limited field staff and equipment resources and significantly streamlines characterization efforts in the field.

An unshielded *in situ* NaI(Tl) gamma detector is set up in an elevated position in the center of the room and a 1-hour count is performed. The ISGS gamma measurement is evaluated using conservative assumptions about the geometry (i.e., all contamination is assumed to be concentrated at a distant point within the room but no more than 3 m from the detector, and that the radiations from ^{60}Co are attenuated by no more than 2 cm of intervening solid material). There is no concern about "shine" from outside the building since it is known that ambient ^{60}Co levels outside the building are low. Therefore, no background correction will be applied, minimizing the risk of negative bias.

[38] Actual AALs established for a specific incident would vary by incident. The AALs presented are provided here for demonstration purposes only. These values are roughly equivalent to values shown in NRC (2006) Appendix B, Table B.1 *(Acceptable License Termination Screening Values of Common Radionuclides for Building-Surface Contamination)*. Per note a) of NUREG-1757, "[s]creening levels are based on the assumption that the fraction of removable surface contamination is equal to 0.1. For cases when the fraction of removable contamination is undetermined or higher than 0.1, users may assume, for screening purposes, that 100 percent of surface contamination is removable, and therefore the screening levels should be decreased by a factor of 10." Both total and removable limits must be met separately to satisfy criteria for free release. A single measurement of total activity less than the ADL for removable activity can be used to demonstrate compliance with the AAL for removable activity. See Section 3.4.2 for a more detailed discussion of MQOs, AALs, required method uncertainty and ADLs.

[39] The approach for determining MQOs is described in detail in Section VI of *A Performance-Based Approach to the Use of Swipe Samples in Response to a Radiological or Nuclear Incident* (EPA 2011b). MQOs are derived from DQOs consistent with MARLAP principles and ensure that decisions are based on measurements of sufficient quality to address the question at hand. The analytical decision level is the level below which the measurement provides sufficient confidence to reject the null hypothesis that "*activity present on the surface is greater than the action level.*" In this case, the AAL for total ^{60}Co contamination is established at 7100 dpm/100 cm^2. For the gross activity measurements, the DL is 0, the Type I tolerable error, alpha, 5%, and the Type II tolerable error, beta, 10%. Thus, the required method uncertainty, u_{MR}, is 2400 dpm/100 cm^2 at the AAL and the ADL is 3,100 dpm/100 cm^2. Thus, any result greater than the ADL of 3,100 dpm/100 cm^2 would trigger appropriate corrective actions (e.g., a more precise measurement, destructive sampling followed by lab analysis, or remediation). The values for the u_{MR} and ADL for removable contamination using gross activity screens are proportional to the AAL (1/10 the level for total contamination).

If ^{60}Co is detected in the gamma screening survey above the ADL for total contamination, a confirmatory survey will be conducted at a new location in the room to verify the initial reading. If ^{60}Co is detected, gross beta surface measurements will be conducted in the room in question with a large area beta scintillation detector and a portable 1×1" NaI(Tl) gamma survey. Swipes also will be taken in the room and analyzed at the laboratory for removable beta contamination to provide evidence to support achievement of removable AALs and to confirm survey results. If ^{60}Co is detected in the gamma survey, even at levels below the AALs, the default sampling frequency of one room per floor will be expanded as appropriate to minimize the risk of missing contaminated rooms. Finally, swipes and a portable NaI(Tl) survey will be taken in two rooms and two locations in the hallway of each affected floor.

As the gamma screening measurement proceeds, and after the technician has completed assembling survey documentation (including maps and QC), three random swipe samples are taken from judgmentally biased locations in the room (e.g., dusty areas, air intakes, door knobs), one each from two additional rooms on the floor, and one each in opposing halves of the hallway. The gamma measurement meets all MQOs for sensitivity and uncertainty and activity results are below the critical level. This supports the conclusion that ^{60}Co is not present in those locations at levels that exceed the AAL. The swipes will be sent to a laboratory for sensitive confirmatory counting for gross beta referenced to ^{60}Co. The swipes are quick, low-cost, and sensitive, and provide confirming evidence that there is no indication of removable contamination above the AAL. The technician tags the room and floor with a "survey results pending" notice and moves on to continue the process on the next floor of the building. The survey will be finalized in two days after all of the data from the building, including the swipe results, have been received back from the laboratory and independently assessed and approval is granted.

Table 8 – Summary of Measurements for Scenario #1

Location	Radiation Type	Primary Measurement	Secondary Measurement	Comment
Bldg #1 Rm 101	^{60}Co Beta-gamma	1 ISGS for total; 3 swipes for removable beta.	n/a	Clear pending laboratory analysis, data V&V, and assessment.
Bldg #1 Rm 111	^{60}Co Beta-gamma	1 swipe for removable beta.	n/a	Clear pending laboratory analysis, data V&V, and assessment.
Bldg #1 Rm 134	^{60}Co Beta-gamma	1 swipe for removable beta.	n/a	Clear pending laboratory analysis, data V&V, and assessment.
Bldg #1 1st floor hallway north	^{60}Co Beta-gamma	1 swipe for removable beta.	Area survey with 1×1" NaI(Tl)	Clear pending laboratory analysis, data V&V, and assessment.
Bldg #1 1st floor hallway south	^{60}Co Beta-gamma	1 swipe for removable beta.	Area survey with 1×1" NaI(Tl)	Clear pending laboratory analysis data V&V, and assessment.

Scenario #2: This scenario is essentially the same as Scenario 1 except the analysis will be made using ISGS instead of *in situ* gamma *counting*. Following an RDD event, Building #2 is to be assessed for ^{60}Co contamination. The building was downwind from the incident, and there is a

potential for contamination since the HVAC was running during and after the incident as the plume passed. As is the case throughout the city, there is also the potential that people have tracked contamination from other areas into the building. The MQO specifies that a relative method uncertainty of 30% is required at the respective AALs for total and removable contamination of 7100 dpm/100 cm^2 and 710 dpm/100 cm^2. The ADL is 3600 dpm/100 cm^2. The MQO for removable contamination is proportional to the AAL, i.e., $1/10^{th}$ those for total contamination.[40]

^{60}Co contamination will be assessed by ISGS in one room on each floor of the building. Given the long range of gamma rays, a single ISGS measurement can characterize a relatively large area and minimize the risk of false non-detection and the total number of measurements required relative to measurements of alpha or beta radiation. This could minimize the need to take multiple grab samples for analysis at the laboratory. On the other hand, due to the long range of gamma rays and the wide distribution of ^{60}Co contamination following the incident, gamma ray activity for ^{60}Co is present in the background, and there is concern that ^{60}Co detected in low-level *in situ* measurements may come from a source beyond the object being measured. Given better detection capabilities for beta radiation at the laboratory, and the relative ease of taking swipes, it will be more effective to screen for higher levels of total ^{60}Co using ISGS and to assess removable contamination by beta counting swipes at a radiochemistry laboratory. This optimizes limited field staff and equipment resources and significantly streamlines characterization efforts in the field.

An unshielded ISGS unit is set up in an elevated position above the center of the room, and a spectrum is recorded for 3,600 seconds. The ISGS gamma measurement is evaluated using conservative assumptions about the geometry: i.e., all contamination is assumed to be concentrated at a distant point within the room from the detector, which can be no more than 3 meters from the detector, and ^{60}Co is attenuated by no more than 2 cm of intervening solid material. In this case, there is no concern about "shine" from outside the building since it is known that ambient ^{60}Co levels outside the building are low. Therefore, no background correction will be applied minimizing the risk of negative bias.

If ^{60}Co is detected in the ISGS survey above the AAL for total contamination, a second survey will be conducted at a new location in the room to verify the reading and to ensure that detector placement did not bias the measurement (e.g., due to shielding by furniture, etc.). If ^{60}Co is detected, gross beta surface measurements with a large area beta scintillation detector and a gamma survey will be conducted in the room in question using a 1×1" NaI(Tl) detector. Swipes also will be taken in the room and analyzed at the laboratory for removable beta contamination to provide further support and confirmation of survey results. Finally, swipes and a 1×1" NaI(Tl) survey will be taken in two rooms and two locations in the hallway of each affected floor. If ^{60}Co is detected in the ISGS survey, even at levels below the AAL, the default sampling frequency of

[40] The incident command recognizes that the spectrometric measurement technique is of higher quality and evaluates u_{MR} and the ADL for total contamination using the following parameters: the DL is 0, the Type I tolerable error, alpha, is 5%, and the Type II tolerable error, beta, is 5%. The required method uncertainty, u_{MR}, is 220 dpm/100 cm^2 at the AAL and the ADL is 360 dpm/100 cm^2. Any result greater than 360 dpm/100 cm^2 will trigger appropriate corrective actions (e.g., a more precise measurement, destructive sampling followed by lab analysis, or remediation).

one room per floor will be expanded as appropriate to minimize the risk of missing significant levels of contamination.

Note: The building ventilation system was in operation during the incident, and contamination was spread throughout the system. A hot spot exists in the HVAC system but has not yet been identified. The building has been unoccupied since the incident so there is less concern that routine building cleaning operations have moved contamination or that it has become fixed.

An *in situ* gamma spectrometer is set up in the center of the first room to be surveyed. After performing QC checks to ensure that the instrument is operating properly, the technician starts the count and a spectrum is recorded over the space of an hour. The ISGS gamma measurement will be evaluated using conservative assumptions about the geometry (i.e., all contamination is concentrated at a single point in the room, 3 m from the detector, with less than 2 cm of intervening solid material).

As the ISGS measurement proceeds, and after the technician has completed survey documentation (including maps and QC), three random swipe samples are taken from judgmentally biased locations in this room (e.g., dusty areas, air intakes, door knobs), one each from two additional rooms on the floor, and one each in opposing halves of the hallway.

The measurement indicates that ^{60}Co levels are high enough that they do not permit rejection of the null hypothesis that "levels of total ^{60}Co in the room exceed the action limit." ^{60}Co is somewhere within the field of view of the detector, which given the high energy of the gamma rays in question, may extend beyond the four walls of the room. As soon as the first gamma ray measurement has been completed and initial results indicate potentially elevated levels of ^{60}Co, the technician moves the instrument and prepares to conduct a confirmatory count. After QC checking the instrument, the technician initiates a second one-hour ISGS count.

As the second gamma count proceeds, the technician performs additional surveys of the room. Based on the identification of ^{60}Co, static counts with a 600 cm^2 beta-scintillating detector are initiated at two random locations in the room. A scanning survey for gamma radiation is also performed with a portable 1×1" NaI(Tl) detector. Although the gamma scanning measurements are not of sufficient sensitivity to "clear" the room, they often are useful for hot spot identification. It is important to keep in mind that large area measurements may effectively "average" and thus fail to identify hotspot activity. The technician notes slightly elevated readings toward the center of the building in front of air conditioning ductwork. A note is made in the paperwork that the floor of the room is ceramic tile and that elevated gamma activity is observed over the tile. Based on the elevated readings in the NaI(Tl) survey in the vicinity of the air conditioning duct, one additional static count for gross beta is taken adjacent to the AC vent but no supporting beta activity is found. Based on available evidence, it appears that the source of the activity may be outside the room. The technician will note this in the report and bring it to the attention of the team leader.

The results of the second *in situ* gamma count support those of the first and indicate that detectable ^{60}Co is present. Since the field of view for the detector extends beyond the room, however, the detector may be responding to some source of contamination outside the room. The

static beta measurement in front of the air conditioning duct shows slightly elevated levels that exceed action limits for removable contamination. The results of the gas proportional beta counts in all non-ceramic locations meet specifications for sensitivity and measurement uncertainty, and the results are low enough to support the conclusion that ^{60}Co is not present at those locations at levels that exceed the AAL for removable contamination. The beta survey on the tile is predictably very elevated, but the technician has seen this problem before and notes the concerns about ^{40}K in the log. Following procedure, the technician takes four random swipes from the tiled area, and one swipe from a judgmental (i.e., worst case) location on the wood floor and queues these to be sent to the laboratory for confirmatory gross beta counting. The room is tagged with a note stating "survey results pending" and the process is repeated in the next room.

Table 9 – Summary of Measurements for Scenario #2

Location	Radiation Type	Primary Measurement	Secondary Measurement	Comment
Bldg #2 Rm 101	^{60}Co Beta-Gamma	2 ISGS for total; 3 swipes for removable beta.	3 static counts for gross beta surface activity; NaI(Tl) gamma survey	^{60}Co results above ADL; source not localized; laboratory swipe data, V&V, and assessment pending.
Bldg #2 Rm 111	^{60}Co Beta-Gamma	1 swipe for removable beta.	n/a	Laboratory analysis pending.
Bldg #2 Rm 134	^{60}Co Beta-Gamma	1 ISGS for total; 3 swipes for removable beta	n/a	^{60}Co below ADL; laboratory analysis, V&V, and assessment pending.
Bldg #2 North end of 1st floor hallway	^{60}Co Beta-Gamma	1 swipe for removable beta.	Area survey with 1×1" NaI(Tl)	Laboratory swipe analysis, V&V, and assessment pending.
Bldg #2 South end of 1st floor hallway	^{60}Co Beta-Gamma	1 swipe for removable beta.	Area survey with 1×1" NaI(Tl)	Laboratory analysis, V&V, and assessment pending.

Scenario #3: This is essentially the same scenario as Scenarios #1 and #2 with the exception that the RDD source term has been identified as pure alpha-emitting $^{239/240}$Pu. The building was downwind from the incident, and there is reasonable potential for contamination since the HVAC was running during and after the incident as the plume passed. As is the case throughout the city, there is also the potential that people have tracked contamination from other areas into the building. AALs have been established at 50 dpm/100 cm^2 and 5 dpm/100 cm^2 for total and removable contamination respectively. The MQOs specify that a required method uncertainty of 24% is required at the AAL. ADLs of 30 and 3.0 dpm/100 cm^2 are specified for total and removable contamination respectively.[41]

[41] Incident Command has established MQOs for u_{MR} using the following parameters. The AAL for total alpha is 50 dpm/100 cm^2. The DL is 10 dpm/100 cm^2, (set at an assumed native gross alpha of 10 dpm/100 cm^2), the Type I tolerable error, alpha = 5%, and the Type II tolerable error, beta = 5%. The required method uncertainty, u_{MR}, is thus 12 dpm/100 cm^2 at the AAL and the ADL is 30 dpm/100 cm^2. Thus, relative low uncertainty measurements are needed, and any result greater than 30 dpm/100 cm^2 will trigger appropriate corrective actions (e.g., a more precise measurement, destructive sampling followed by lab analysis, or remediation).

This scenario presents special challenges since field surveys for low levels of alpha-emitting contaminants are of limited effectiveness. Ambient levels of naturally occurring alpha emitters in building materials and interference from radon and decay progeny, for example, will prevent MQOs for removable contamination from being determined using *in situ* measurements. Wipe samples will be analyzed at the laboratory by gross alpha and, when needed, isotopically (after chemical separation from other alpha emitters) to determine the specific concentration of $^{239/240}$Pu. Even if field measurements, such as those conducted with a large area ZnS counter (600 cm^2), are able to provide sufficient sensitivity to differentiate between the gross alpha natural background (assumed to be 10 dpm/100 cm^2) from the 50 dpm/100 cm^2 AAL for total $^{239/240}$Pu contamination, it is important that the technician be able to identify situations where self-absorption may be a confounding factor that undermines the defensibility of the measurements. Laboratory analysis of grab samples will provide superior detection limits and lower measurement uncertainties for gross alpha, and thus minimize the risk of false non-detection.

Lacking techniques with similar detection range to ISGS, incident-specific protocols for alpha and beta detection specify that an increased number of surveys will be conducted in multiple rooms on each floor of the building. Large-area ZnS alpha detectors have been shown to be capable of rapidly identifying elevated levels of beta-gamma emitters, and alpha- and gamma-emitting contamination from ^{226}Ra (and progeny) on impermeable and relatively smooth surfaces.[42] It is important, however, to carefully evaluate the applicability of direct measurement techniques for each surface. When rough, dirty, or porous surfaces are involved, direct alpha measurements using a large-area ZnS detector may be "non-conservative" and thus may be suitable only for identifying hot spots and triggering more aggressive follow-up surveys. Similarly, porous or rough materials, and materials known to contain elevated levels of intrinsic naturally occurring alpha emitters (such as granites and some concretes), may not be amenable to gross alpha screening.

Where problematic surfaces predominate, or where direct measurements indicate possible contamination, field instruments such as FIDLERs may be used to improve the reliability of measurements, and certainly to perform real-time qualitative identification of hot spots, but they cannot defensibly "clear" an area, at least without confirming measurements that verify the assumptions upon which the clearance measurements are based. Instead, accurate determinations of $^{239/240}$Pu are most effectively and defensibly determined by grab sampling (e.g., scabbling or coring) followed by isotopic analysis for $^{239/240}$Pu at a radiochemistry laboratory. Wipe samples of removable contamination also can be sent to a radiochemistry laboratory for gross alpha screening, with potential alpha isotopic determinations of $^{239/240}$Pu, as indicated. Finally, confirmatory grab sampling at a direct measurement location will be performed as a recurring QC measure to confirm the accuracy of the direct measurements. Since AALs are provided in units of areal contamination, sample volumes must be recorded in terms convertible to equivalent surface area and the laboratory instructed to calculate results in terms of activity per unit surface area. If any of the laboratory results are positive for $^{239/240}$Pu, data will be assessed and additional action taken as deemed appropriate.

The technician enters the first room specified for surveying and sets up two large area ZnS detectors for a 30-minute static count of the tile floor and the welcome mat. As the counters

[42] Personal communication with Dick Dubiel of Millennium Shonka, 2010.

acquire data, the technician proceeds to collect swipes from five locations in room 101, and one swipe each from the north and south ends of the hallway. When acquisition is complete, the technician notes that uncertainty requirements have been met, but that the count on the welcome mat exceeds the action limit for total alpha. In keeping with protocol, he surveys the area, cuts a 100 cm^2 coupon from the area showing the highest survey results, and packages and labels this to be sent to the laboratory for confirmatory analysis. Once the work is complete, the technician marks the room as "potentially contaminated pending confirmatory laboratory analysis" and continues to room 111, where he initiates two more static counts for total alpha activity. As these data are being acquired, he collects five wipe samples each from rooms 111 and 134. When the static counts are finished, the technician verifies that the uncertainties will meet the MQOs and determines that both results are low enough to conclude that the activity will not exceed the AAL. He places a sign on the door indicating that laboratory analysis is pending and moves on to the next floor.

Table 10 – Summary of Measurements for Scenario #3

Location	Radiation Type	Primary Measurement	Secondary Measurement	Comment
Bldg #3 Rm 101	$^{239/240}$Pu Alpha	2 static counts for gross alpha total surface activity; 1 sample taken – "welcome mat coupon"	5 swipes for removable alpha activity	Gross alpha above action limit; sample taken for analysis. Laboratory analysis, V&V, and assessment pending.
Bldg #3 Rm 111	$^{239/240}$Pu Alpha	2 static counts for gross alpha total surface activity	5 swipes for removable alpha	Laboratory analysis, V&V, and assessment pending.
Bldg #3 Rm 134	$^{239/240}$Pu Alpha	n/a	5 swipes for removable alpha	Laboratory analysis, V&V, and assessment pending.
Bldg #3 North end of 1st floor hallway	$^{239/240}$Pu Alpha	n/a	1 swipe for removable alpha	Laboratory analysis, V&V, and assessment pending.
Bldg #3 South end of 1st floor hallway	$^{239/240}$Pu Alpha	n/a	1 swipe for removable alpha	Laboratory analysis, V&V, and assessment pending.

Scenario #4: This is the same scenario as Scenario #2 except in this case, the RDD source term is identified as ^{90}Sr. AALs have been established at 87 dpm/100 cm^2 and 8.7 dpm/100 cm^2 for total and removable contamination respectively. The MQO specifies that a required method uncertainty of 15% at the AAL. The ADLs are 65 and 6.5 dpm/100 cm^2 for total and removable contamination respectively.[43]

[43] Incident Command has established AALs, u_{MR} and ADLs using the following parameters to evaluate u_{MR} and the ADL. The AALs for gross beta screening are 87 dpm/100 cm^2 and 8.7 dpm/100 cm^2, for total and removable activity. The DL = is ½ the respective AAL, the Type I tolerable error, alpha = 5%, and the Type II tolerable error, beta = 5%. The required relative method uncertainty, u_{MR}, is 15% of the AAL, and the ADLs are 65 dpm/100 cm^2 and 6.5 dpm/100 cm^2 for total and removable contamination respectively. Given the low levels that would be required to demonstrate meeting levels for removable activity, they will be analyzed by taking swipes that will be sent to a radiochemistry laboratory for analysis on a low background proportional counter, and where necessary, verification of radioisotopic activity following chemical separations.

Given the limitations of field surveys for very low levels of beta contamination, the superior detection capability at laboratories for gross beta, and accuracy and reliability of laboratory analysis for ^{90}Sr, the approach will rely more heavily on laboratory analysis of swipes for non-permeable surfaces and on grab samples for porous or other rough surfaces. Because ^{90}Sr does not emit any gamma rays, ISGS is not a viable alternative. Lacking the detection range of ISGS, protocols specify that surveys will be conducted in two rooms on each floor of the building. If surfaces are impermeable and relatively smooth (and significant levels of naturally occurring radionuclides are not present), large area beta scintillation detectors have been validated to determine compliance with action limits for total ^{90}Sr contamination on smooth and impermeable surfaces. Due to the potential for self-absorption of beta emissions, surface measurements on porous or rough surfaces are considered non-conservative screens and are suitable only for identifying hot spots and triggering more aggressive follow-up surveys. Porous or rough materials, or materials known to contain elevated levels of naturally occurring beta emitters (such as ceramic tile, granites, and concretes), will produce high rates of false positive determinations. Where such surfaces are predominant, or where direct measurement has indicated possible contamination, grab sampling (e.g., coring or scabbling) is required followed by analysis for ^{90}Sr at a radiochemistry laboratory. Confirmatory grab sampling also is required at one direct measurement location at a frequency of one sample per building. Since AALs are provided in units of areal contamination, sample volumes must be recorded in equivalent surface area and the laboratory instructed to calculate results in terms of activity per unit surface area. If any of the laboratory results are positive for ^{90}Sr, data will be assessed and additional action taken as deemed appropriate.

The technician enters the first room specified for surveying and sets up both large area beta scintillation detectors for 10-minute static counts. As the counters acquire data, the technician proceeds to collect swipes from five locations in room 101, and one swipe each from the north and south ends of the hallway. When acquisition is complete, the technician notes that uncertainty requirements have been met and that both counts are low enough to conclude that the action limit for total beta has not been exceeded. The technician marks the room as “pending laboratory analysis” and continues to room 111 to initiate two additional static counts for total beta activity. As these data acquire, the technician collects five wipe samples each from rooms 111 and 134. When the static counts are finished, the technician verifies that the uncertainties will meet the MQOs and determines that both results are low enough to conclude that the activity is not high enough to exceed the action limit and trigger laboratory confirmation. The technician places a sign on the door indicating “laboratory analysis pending” and moves on to the next floor.

Table 11 – Summary of Measurements for Scenario #4

Location	Radiation Type	Primary Measurement	Secondary Measurement	Comment
Bldg #4 Rm 101	^{90}Sr Beta	2 static counts for gross alpha total surface activity	5 swipes for removable alpha activity	Laboratory analysis and V&V pending
Bldg #4 Rm 111	^{90}Sr Beta	2 static counts for gross alpha total surface activity	5 swipes for removable alpha	Laboratory analysis and V&V pending
Bldg #4 Rm 134	^{90}Sr Beta	n/a	5 swipes for removable alpha	Laboratory analysis and V&V pending
Bldg #4 North end of 1st floor hallway	^{90}Sr Beta	n/a	1 swipe for removable alpha	Laboratory analysis and V&V pending
Bldg #4 South end of 1st floor hallway	^{90}Sr Beta	n/a	1 swipe for removable alpha	Laboratory analysis and V&V pending

Observations on the Four Scenarios: Table 12 summarizes the number of samples needed for each of the above scenarios. Several general observations are noted:

- Gross measurements in the field may not be capable of reliably detecting radionuclide contamination at levels approaching background.
- Instrument detection capability does not guarantee that a technique will be useful for measuring contamination.
  - Bias due to self-absorption may not permit MQOs to be met and may require sampling and laboratory analysis.
  - High background activity may interfere with measurements, or may lead to such long measurements being required that grab sampling and laboratory analysis may be a more effective and efficient option.
- Alpha and Beta Emitters
  - The risk of false non-detection of alpha or beta emitters is higher than for gamma emitters.
  - Minimizing the risk of false non-detection for alpha and beta emitters must be accomplished using a robust sampling plan (e.g., MARSSIM). A similar number of measurements are needed in the field and at laboratories.
- Gamma Emitters
  - Gross gamma measurements may not be able to effectively or efficiently detect or measure radionuclides at levels approaching the ambient background.
  - Field measurements for gamma contaminants can significantly minimize the overall number of samples needed to characterize an area.
  - Fewer measurements are needed to characterize gamma-emitting contamination than alpha- and beta-emitting contamination.
  - ISGS can detect contamination at levels below ambient background as long as the radionuclide of concern is not present in the background.
- Strategic use of laboratory and field measurements may speed up the overall recovery process by optimally using laboratory and field resources.

Table 12 – Summary of Number of Scenario Measurements by Nuclide, Measurement Status, and Detection Status and Test

Radionuclide Radiation Type	Contam. present?	ISGS	Gross Gamma	Gross Alpha	Gross Beta	Alpha Swipes for Laboratory analysis	Beta Swipe for Laboratory analysis	Laboratory Nuclide Specific	Comment
^{60}Co Beta-gamma	N	1	1	0	0	0	7	0	ISGS decreases sample load
^{60}Co Beta-gamma	Y	2	2	n/a	3	n/a	7	0	Survey detects ^{60}Co but cannot localize source
$^{239/240}$Pu Pure alpha	Y	n/a	n/a	4	n/a	17	n/a	1	Survey detects alpha – sample to laboratory
^{90}Sr Pure beta	Y	n/a	n/a	n/a	4	n/a	17	1	Survey detects beta – sample to laboratory