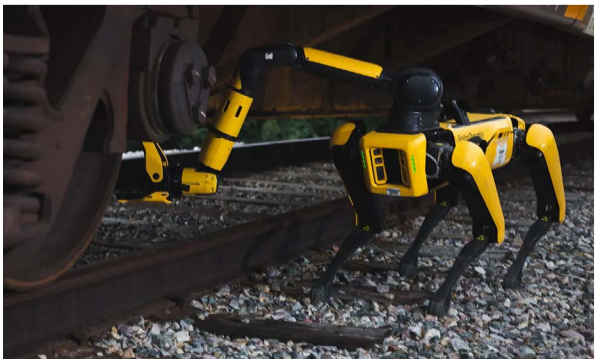
Research Report

ANGELA PUTNEY, CHRISTOPHER SCOTT ADAMS, IVAN LEPETIC, AUGUSTINE BRAVO

Use Cases for Collecting Radiation Measurements with Unmanned Systems



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About This Report

First responders have prepared and will need to prepare for and respond to radiation emergencies. Both preparedness and response activities require measuring radiation levels, often over large areas. Preparedness activities will largely focus on mapping low-level background radiation; however, responses could potentially expose personnel to elevated or dangerous levels of radiation and/or contamination. To reduce potential responder exposures and the resource burden of collecting measurements, first responders are interested in using unmanned systems (UxSs) for radiation detection. UxSs are useful for some aspects of a response, and some combinations of UxSs and radiation detectors are better suited than others for various missions and environments. This report and the use-case appendixes provide example missions and system types that first responders may encounter or choose to deploy for measuring radiation levels during preparedness and/or response activities.

This report is designed for use by state, local, tribal, and territorial first responders in determining appropriate uses of UxSs in planning for and responding to a radiation emergency and identifying basic system design configurations required for each use. Such advice will allow first responders to better leverage the advantages of UxSs to enhance the safety and efficiency of their emergency planning and response while controlling for technological risks and limitations.

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About the Homeland Security Operational Analysis Center

The Homeland Security Act of 2002 (Public Law 107-296, § 305, as codified at 6 U.S.C. § 185) authorizes the Secretary of Homeland Security, acting through the Under Secretary for Science and Technology, to establish one or more federally funded research and development centers (FFRDCs) to provide independent analysis of homeland security issues. RAND operates the Homeland Security Operational Analysis Center (HSOAC) as an FFRDC for the U.S. Department of Homeland Security (DHS) under contract 70RSAT22D00000001.

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Summary

Issue

By definition, first responders are among the first at the scene of an emergency or disaster. If the emergency or disaster involves or could involve radiation, the responders are in danger from something they cannot see or feel and need tools to measure the levels and types of radiation to ensure their own safety and properly respond to save others. Radiation detectors mounted on unmanned systems (UxSs) have the potential to aid first responders in such measurements and reduce their exposure to radiation. UxSs are relatively new tools that likely will improve responder safety and reduce the amount of time and equipment and the number of responders needed for a given situation.

Approach

We examined potential use cases and conditions for using UxSs for radiation detection by state, local, tribal, and territorial first responders. We reviewed policy documents, journal articles, news articles, after-action reports, and emergency exercise reports that the National Urban Security Technology Laboratory provided to us and those located through internet searches or following leads from other documents. Additionally, we engaged with subject-matter experts on radiation detection and UxSs. We elicited information from first responders on how radiation detection is currently done with or without UxSs and to identify any ways they use UxSs for other purposes. Additionally, to understand the possible, we conducted a brief survey of UxSs and radiation detectors that could be mounted on or used with UxSs.[1] Using this information, we developed concepts of operation for three radiation-detection use cases.

Key Findings

- UxSs can be used in various radiation-detection use cases to support emergency preparedness and response
- The 21 radiation-detection use cases we considered had six common characteristics: (1) pattern-based surveys of ambient radiation levels, (2) multiple radiation measurements in small areas, (3) directed measurements over larger areas, (4) repeated surveys over time, (5) radioisotope identification, and (6) physical sample collection.
- The main factors in deciding the types of UxSs and radiation detectors to consider are the details of the first responder organization's area of operations (dense urban environment, open desert, suburban towns, etc.).
- The advantages of first responders using UxSs for radiation detection include the potential for increased personal safety and more efficient use of resources.

[1] This was not a market survey and was in no way inclusive of all radiation detectors or UxSs on the market. The sole purpose was to provide a proof of concept for potential UxS and detector classes.

- The disadvantages of first responders using UxSs for radiation detection include usage being limited by weather conditions, regulations, potentially short sortie times (i.e., frequent need to refresh power),[1] connectivity problems between UxSs and operators, and insufficient integration of detectors and UxSs.
- The most straightforward path toward a responder organization procuring a UxS radiation survey capability will be to purchase a system or combination of components (UxS and radiation detector or instrument) that the manufacturers have preidentified as being compatible.
- Before expecting to use UxS systems to conduct radiation surveys during an emergency, it is essential that first responders
  - evaluate whether the UxS can accomplish the objectives of the survey and whether conducting the survey is the best use for the UxS capability during an emergency
  - conduct training and exercises with the desired UxS configurations in environments and with scenarios that reflect real-life conditions to be encountered during an emergency.

How to Use This Document

- First responder entities can use this document to inform UxS and detector acquisition and their organization's market research.
- First responder entities can use the appendixes to inform UxS procedures and exercise development.

[1] We define a *sortie* as a single trip made by a UxS to investigate radiation levels. Such a trip may be to take a measurement in one location or measurements at multiple locations.

Contents

Figures and Tables

Figures

Tables

CHAPTER 1

Introduction

Purpose

First responders frequently put their lives at risk to save people from multiple types of hazards. Many hazards pose threats to responders, such as fire, bullets, and collapsing buildings and the corresponding burns, wounds, and broken bones. Radioactive material, if present, complicates a response that requires careful risk management. Radiation hazards cannot be seen or felt but, nonetheless, can cause severe damage to the human body, although the harm may not appear for months, years, or even decades after exposure.

Because radiation is not readily noticeable without specialized detection equipment, first responders must develop clear protocols for responding to radiation emergencies. This report addresses this need by examining how unmanned systems (UxSs), including unmanned aerial vehicles (UAVs), unmanned ground vehicles (UGVs), and unmanned surface vehicles (USVs), could be used in planning for and responding to radiation emergencies.[1]

The report provides an overview of how these systems might be used and then presents three use cases that illustrate how first responders could use UxSs in planning for and responding to radiation emergencies. Included in the use cases are descriptions of the characteristics of UxSs and radiation detectors that could apply to each situation. Because the UxSs and radiation detectors are best acquired before an incident, the use-case appendixes also include guidance on what to consider when procuring such equipment.

Background

A Primer on Ionizing Radiation

Ionizing radiation is defined as a

> form of radiation, which includes alpha particles, beta particles, gamma rays, x-rays, neutrons, high-speed electrons, and high-speed protons. Compared to nonionizing radiation, such as found in ultraviolet light or microwaves, ionizing radiation is considerably more energetic. When ionizing radiation passes through material such as air, water, or living tissue, it deposits enough energy to break molecular bonds and displace (or remove) electrons. " (U.S. Nuclear Regulatory Commission [NRC], 2023)

Alpha particles consist of two protons and two neutrons (i.e., a helium nucleus) (NRC, 2021b). *Beta particles* are electrons or positrons, and *gamma rays* are high-energy photons; both are emitted from the nuclei of unstable atoms. *Neutrons* are emitted during nuclear or spontaneous fission or from a neutron source, for

[1] For clarity, we use *UxS* to refer to all types of unmanned systems of any domain. When referring to a specific domain, the unmanned platforms for that domain, such as *UAV* for air, *UGV* for ground, or *USV* for water surface, will be used. Note that *unmanned aerial system (UAS)* is now a common term essentially synonymous with UAV, similarly *drone* is often used as well. To avoid confusion with UxS, this document will use *UAV* with a few exceptions.

example, a source containing beryllium and an alpha emitter (Karam, 2021). This form of radiation is called *ionizing* because it has enough energy to break molecular bonds or ionize atoms, which also means that it can pose a health hazard. This health hazard is increased if the radioactive material is inhaled or ingested (NRC, 2020b) because the material may remain in the body for a long time and in very close proximity to human tissue.

Radiation and radioactivity are measured in various units, both in the International System of Units (SI) and British systems. The measure of radioactivity is defined by the number of atomic decays per unit of time (usually one second) and is measured in becquerel (Bq) or curie (Ci) units. *Radiation exposure* is the "amount of radiation traveling through the air" and is measured in roentgen (R) or coulombs per kilogram (C/kg) units. *Absorbed dose* is the "amount of radiation absorbed by an object or person" and is measured in radiation absorbed dose (rad) or gray (Gy) units. Finally, *dose equivalent* "combines the amount of radiation absorbed and the medical effects of that type of radiation" while *equivalent dose* takes into account the specific organ(s) exposed and their relative sensitivity to radiation to determine the equivalent risk to the whole body;[2] both are measured in roentgen equivalent man (rem) or sievert (Sv). Although a simple conversion from exposure (R) to absorbed dose (r) to effective dose is not possible, the rough conversion of 1 R = 1 rad = 1 rem for beta and gamma radiation is often used (NRC, 2020a).

What Is a Radiation Emergency?

Radiation emergency, as used in this document, refers to any release of radioactive material, or the unexpected presence of elevated levels of radiation, in which members of the public are at risk of adverse health outcomes, up to and including death, through exposure to radiation levels. A radioactive release could occur because of accidental leaks from legitimate uses of radioactive materials (e.g., radiation sources used in industry or to generate power), intentional misuse of radioactive material (e.g., stolen industrial sources positioned or distributed to cause harm to the public), or the use of nuclear weapons. During such emergencies, responders and affected state, local, tribal, and territorial (SLTT) agencies should take regular radiation measurements; these measurements will be used to inform decisions related to responder health and safety, public health and safety, and public messaging. SLTT officials, such as first responders or organizations responsible for environmental protection or public health, may also need to collect similar radiation measurements both before an incident (i.e., background radiation level measurements) and after the initial lifesaving response (for remediation and recovery confirmation).

How Might UxSs Be Used in a Radiation Emergency?

The central principle of radiation safety is to keep radiation exposures as low as reasonably achievable (ALARA). Using UxS to conduct radiation surveys in radiological areas is one example of ALARA in that it largely removes humans from this task, saving their radiation exposure for tasks that must be performed by people, such as lifesaving activities, extinguishing fires, and stabilizing the scene. Using a UxS for such routine activities as radiation surveys to identify hot spots and the areas with the highest radiation dose rates can further help with ALARA by providing responders with information to help them select the lowest dose

[2] *Dose equivalent* is "the product of the absorbed dose in tissue, the quality factor, and all other necessary modifying factors at the location of interest. The units of dose equivalent are the rem and the sievert (Sv)" (National Research Council, 1999, p. 272). *Equivalent dose* is used in "radiation protection, the absorbed dose averaged over a tissue or organ rather than a point, as is the case for dose equivalent) and weighted for the radiation quality that is of interest. For this quantity, the weighting factor is called the radiation weighting factor instead of the quality factor" (National Research Council, 1999, p. 272).

rate paths into and out of the hot zone and dangerous radiation zone.[3] In addition, if some tasks, such as methodical surveys of large outdoor areas, can be preprogrammed, such tasks might be performed autonomously at some point in the future, if regulations permit. Whether piloted or operating autonomously, using a UxS can also serve the principle of ALARA, for example, with a UAV flying over rubble, rough terrain, and other obstacles to take radiation measurements that might otherwise be difficult, time-consuming, and/or dangerous for a person on the ground.[4]

What Types of Radiation Emergencies Exist?

The responses to radiation emergencies can differ according to the severity of the incident, its location, ancillary damage, and other factors. The magnitude of injuries, damage, dose rate from radioactive fallout, and other risks following a nuclear detonation, for example, far exceeds those expected to be seen in the aftermath of an attack using a radiological dispersal device (RDD) or radiological exposure device (RED),[5] and the response to a nuclear detonation will be fundamentally different from the response to a radiological attack. Following a nuclear detonation, radiation dose rates from fallout will be dangerously high for the first day or so, limiting the ability of responders to operate in highly radioactive areas and possibly requiring initial surveys in these areas to be obtained using UxS.

The radiation detection and measurement responsibilities of responders also differ by the type of radiation emergency. Multiple factors can affect when, where, and how responders conduct radiation measurements, but the most important is, perhaps, the safety of responders, followed by the extent of the dispersion of radioactive material. For example, measurements to locate a single lost source can require a much more targeted operation over a narrower area than measurements to track the radioactive plume generated by a release from a nuclear facility. Table 1.1 summarizes these different categories of postincident measurement approaches.

The *Nuclear/Radiological Incident Annex to the Response and Recovery Federal Interagency Operational Plan* (DHS, 2023) defines different radiation emergencies, divided into unintentional hazards and intentional threats and covers a range of emergencies that could expose the public to elevated levels of radiation. These emergencies are summarized in Table 1.2. Note that each type of emergency can fall into multiple categories. Additional information can be found on the Radiation Emergency Medical Management program website (U.S. Department of Health and Human Services, 2024).

[3] A *hot zone* is "the zone immediately surrounding a HAZMAT [hazardous materials] incident that extends far enough to minimize deterministic effects and reduce the risk of stochastic effects from the HAZMAT to personnel outside the zone and is demarcated by the hot line area." For radiation emergencies, a *hot zone* is defined as an area where radiation levels exceed 10 mR/hr (0.1 mGy/hr) or 60,000 disintegrations per minute per unit area (dpm/cm^2) beta and gamma at 1.5 cm (~0.5 inch) and 6,000 dpm/cm^2 at 0.5 cm (~0.25 inch) with an alpha probe (National Council on Radiation Protection and Measurements, 2010). A *dangerous radiation zone* is the area within the hot zone that has "the potential to cause early health effects if doses to people are not controlled and thus actions taken within this area should be restricted to time-sensitive, mission-critical activities such as lifesaving." Specifically, this is an area in which radiation levels exceed 10 R/hr or ~0.1 Gy h–1 air-kerma rate (kinetic energy released per unit mass in air). See National Council on Radiation Protection and Measurements, 2010.

[4] Note, however, that UxSs entering high-radiation environments can interact with radioactive materials on surfaces or suspended in the air and become contaminated. These systems may then need to be decontaminated prior to safe handling by humans.

[5] An *RDD* is "[t]he combination of radioactive material and the means (whether active or passive) to disperse the material with malicious intent; fission reactions do not occur in the RDD or its dispersed material" (DHS, 2017). Nuclear weapons are excluded from this definition. An *RED* is "a device incorporating radioactive material designed to harm or injure people by passively exposing them to ionizing doses of radiation without their knowledge" (DHS, 2023).

TABLE 1.1
Categories of Radiation Emergency by Measurement Approaches

Category Name	Description
Localized source	A single radioactive source or a group of radioactive sources in close proximity causes deleterious health and environmental effects confined to those in a relatively small high radiation area.
Dispersed source	An incident spreads radioactive material, creating an extended high radiation area and wider dispersal through a plume of airborne material that will deposit detectable contamination across a large area.
Nuclear detonation	A nuclear explosion causes significant immediate physical damage and mass fires and widespread dispersal of dangerously radioactive material. Health and environmental effects occur over a large area.

For each of the emergencies in Table 1.2, federal and SLTT first responders need to ensure that saving lives, managing the scene, attending to both radiological and nonradiological hazards, measuring radiation levels, and safeguarding their own safety and health are all being addressed appropriately.

Scope of This Analysis

We analyzed different types of radiation emergencies, including both intentional threats and unintentional hazards. We included natural disasters and industrial accidents because they can cause widespread dispersal of radiological material. Within those groups, the focus was on emergencies happening in or near urban areas because population density can complicate response and recovery and because there is a larger potential loss of life and economic damage.

This report focuses on SLTT capabilities rather than federal ones. Although we studied federal roles, responsibilities, and capabilities as part of the analysis leading up to this report, we developed it to inform SLTT acquisitions and operational decisions. Additionally, it is assumed that the SLTT organizations reading this report have, or plan to have, some UxS capabilities and expertise. Therefore, we did not consider general UxS needs or issues, such as developing a UAV pilot training program or creating a maintenance and logistics capability to support the fielding of UxS, although an SLTT organization should consider these and similar factors when making acquisition decisions.

We considered all types of UxSs (aerial, ground, maritime surface, subsurface) but focused on UxSs that a typical first responder organization could likely acquire, such as smaller UAVs (i.e., less than approximately 55 lbs) and portable, commercially available UGVs. For detectors, we considered only those that detect radiation (gamma, alpha, and beta) and those that might be needed to support those measurements, such as altitude. The report mentions the need for cameras, location measurement, and communication devices to support operators in determining the location of the UxS and in sending and receiving data, but that is not the focus of this report. Similarly, we recognized other sensors or detectors can provide useful, non–radiation-related information, such as the presence of chemicals or biological threats, location of deposition (via the Global Positioning System [GPS]), height of the UAV above ground, or images of the contaminated surface during an emergency and that can be added to UxSs, but these are not the focus of this report.

Limitations

This report has some limitations. First, we did not conduct a full market survey for either the UxSs or radiation detectors; however, we do identify the key characteristics needed for the UxSs and radiation detectors to address the different use cases. The representative examples provided are solely illustrative, not exhaus-

TABLE 1.2
Radiation Emergency Types

Emergency Type	Description	Category
Unintentional Hazards		
Accidentally lost, found, or orphaned radioactive material sources[a]	A radioactive source is misplaced, uncontrolled, or unwanted and that risks exposure to the public.	Localized source[f]
U.S. nuclear facility accidents[b]	Accidental releases from U.S. nuclear facilities cause risks to the U.S. public.	Localized source Dispersed source
Accidental breaches of research and test reactors	Incidents similar to releases from other nuclear facilities involving nuclear reactors that can have nonstandard designs or radioactive fuel materials.	Localized source Dispersed source
Transportation accidents involving radioactive materials	Transportation vectors (e.g., trains, trucks, planes) carrying radiological cargo crash or otherwise malfunction such that there is a risk of exposing the public to their radioactive cargo.	Localized source Dispersed source
Domestic nuclear weapon accidents[c]	A U.S. nuclear weapon is accidently launched, detonated, or jettisoned on U.S. soil.	Localized source (lost or stolen weapon) Dispersed source (subcritical accident) Nuclear detonation (supercritical accident)[e]
Launch or reentry accidents involving spacecraft containing nuclear systems[d]	Spacecraft that use nuclear-powered reactors or other nuclear power sources are involved in accidents.	Dispersed source
Intentional threats		
Nuclear detonation	An adversary detonates a nuclear weapon in the United States, which could cause widespread dispersal of radioactive material and significant infrastructure damage and loss of life from the impact of the blast, depending on the size of the nuclear detonation in question and its proximity to human populations and infrastructure.	Nuclear detonation
RDD	An adversary detonates a conventional explosive that is designed to disperse significant quantities of radioactive material across a wide area.	Dispersed source
RED	An adversary places a strong radioactive source in a public place to expose individuals in a circumscribed area to radiation without needing a detonation to occur.	Localized source

[a] Orphaned sources, per the NRC, are radioactive sources that are unwanted and uncontrolled or controlled but causing an imminent radiological threat (NRC, 2024).

[b] Per the *Nuclear/Radiological Incident Annex*, a nuclear facility includes "nuclear power plants, national laboratories, research facilities, spent fuel sites, nuclear fuel cycle facilities (production and decommissioning), and naval reactors (DHS, 2023).

[c] These incidents are often called *broken arrow* incidents, according to U.S. Department of Defense (DoD) terminology (Herbet, 2008; Department of Defense Manual 3150.08, 2020).

[d] The most notable example of this emergency type was the COSMOS 954 crash (Harvey, 2020).

[e] Subcritical means that the fission rate is decreasing, and supercritical means that the fission rate is increasing.

[f] Even in localized source emergencies, radioactive material can spread beyond the incident site, depending on such factors as weather, infrastructure, and response operations.

tive, and not an endorsement of any specific system or product. Second, there are few comparisons of radiation measurements by a UxS to those by humans to determine whether there is any loss of fidelity in UxS-collected measurements. Third, UxSs are complex, and their use is still relatively new, which leads to many potential configurations when combined with radiation detectors, and we have not included all possible combinations. Fourth, the report does not discuss licensing, permitting, or approvals, such as Federal Avia-

tion Administration (FAA) rules and regulations for UAVs, for using the different UxSs in detail. Fifth, we do not consider the cost of UxSs or detectors in this report, although we did scope the types of UxSs to those likely to be available to first responders. Therefore, we do not provide information about whether a given use case will be more cost-effective relative to the use of a manned alternative. Sixth, the use cases presented here are dependent on the availability and depth of guidance documents and subject-matter experts to identify and develop them. Finally, all use cases are for responding to serious emergencies that have, thankfully, been rare or nonexistent domestically. Although fortuitous for our country, this means that the use cases are based more on speculation than examples from actual events.

Organization of This Report

Chapter 2 describes the types of and general specifications for the radiation detectors and UxSs suggested for the use cases elaborated on in Appendixes A, B, and C. Chapters 3, 4, and 5 describe the approach taken to identify use cases and assess whether they are likely to be appropriate for UAS integration. Appendixes A, B, and C elaborate on how UxS may be applied to three use cases: the 10-point monitoring plan (a specific plume deposition monitoring case), locating a lost source, and conducting a critical infrastructure (CI) assessment.

CHAPTER 2

Unmanned Systems and Detectors

We did not conduct a full, formal market survey of UxSs, radiation detectors, or radiation instruments.[1] The UxS market is constantly changing and emergency response capability needs vary among SLTT jurisdictions and levels of government; therefore, this report does not provide recommendations for specific UxSs or detectors or combinations thereof. Rather, this report provides some overall descriptions of the types of radiation detectors and UxSs that would likely be appropriate for different use cases.

Decisions about which UxSs and detector or instrument to select should carefully consider whether the two systems can be integrated and operated together for the expected use case. Some companies sell systems that are already integrated, in which the UxS and radiation detector are part of a single platform and do not require any third-party integration or user do-it-yourself (DIY) approach. Other UxS companies offer flexible payload attachment modules or publish payload integration technical details online, enabling a range of options for a third-party integrator or DIY, so that responders may attach various components and sensors to meet their organization's specific needs.

Multiple tables in this chapter include representative examples of radiation-detection equipment. This report does not endorse or recommend any specific instrument or manufacturer, and selection will depend on the mission, the environment, and jurisdiction-specific needs.

General Advice for Choosing Radiation Detectors and Unmanned Systems

The most straight forward path toward procuring a UxS radiation survey capability will be to purchase a system or combination of components (UxS and radiation detector or instrument) that the manufacturer(s) have preidentified as being compatible. Table 2.1 lists some example pairs of UxSs and radiation detectors, noting that details of each are included in the later detector and UxS tables. These systems do not offer as much customization or tailoring of sensor or payload configuration options as if the separate detector and UxS were chosen, and may be more expensive, but will provide a convenient option for jurisdictions that are unable to verify UxS and instrument compatibility.

Responders should note that the market is rapidly changing, with both UxS and radiation-detection manufacturers developing new combined systems and UAV-tailored detector designs. So, the list provided in this document may not be representative of the market.

Using third-party integrators or DIY approaches, which may enable response organizations to use equipment already in their inventories or allow greater flexibility in complete system design, can range from being

[1] Although the terms are sometimes used interchangeably, *detector* and *instrument* are not synonyms. *Detector* refers to the probe, and it is part of an *instrument*. An instrument includes components other than the detector, such as the battery, screen, and wireless communications—and it is the instrument that communicates information to the user. However, for simplicity, the term *detector* is frequently used for both in this document.

TABLE 2.1
Examples of Combined Radiation Detector and Unmanned Systems

Detector Product (Company)	UxS Product (Company)	Integrator or Selling Company	Brief Type Description	Operational Time (min)
NuEM DRONES G (NuviaTech)	Explorian XLT (Airolit)	Nuvia Tech sells the system as NuDRONES-G COMBO	Gamma and neutron RIID on quadcopter	≤35
FPG (Artkis)	Unknown	Artkis sells the system as Radiation Detector Drone	Gamma detector on quadcopter	≤20
MUVETM R430 (Teledyne FLIR)	SkyRanger R70 (Teledyne FLIR)	Teledyne FLIR	Gamma and neutron RIID on quadcopter	<40
SPIR-Explorer (Mirion)	Hawker Q800X (Aeracess)	Aerborne sells Hawker for use with SPIR-Explorer	Gamma RIID on quadcopter	≤30
	Baron Hexacopter	Mirion and RADeCO each sell the RadKnight Baron Hex	Gamma RIID on hexacopter	≤25
Multiple options	Spot (Boston Dynamics)	RADeCO will integrate buyer's choice on Spot; also sell CERBERUS QUGV, which is Spot with full package for detection in hazardous areas	Radiation detector on doglike robot	≤90

SOURCE: Features information from manufacturers' and sellers' websites.
NOTE: RIID = radioisotope identification device.

a low to significant development effort. Table 2.2 summarizes some of the key radiation instrument and detector characteristics, whose trade-offs and capabilities will influence the overall system that a responder would want to deploy for the surveys they intend to conduct. This table provides more information about possible trade-offs to users that are considering a third-party integrator or DIY approach and going through the decisionmaking process to pair an instrument with a UxS platform, as opposed to selecting an existing integrated system. The following sections provide example detectors and UxSs to demonstrate various available characteristics.

General Radiation Detectors for Unmanned Systems

Radiation detectors can be categorized according to their capabilities, and first responders might employ detectors from one or several of these categories depending on what the responders need. Most detectors are sensitive to gamma radiation (photons), and most radionuclides emit gamma radiation, which can be detected more easily at a distance, so gamma detectors are useful for various use cases. Some radionuclides emit alphas, betas, or neutrons in addition to gammas. In these cases, the gamma detector will still work, but first responders might wish to have an alpha, beta, or neutron detector as well. A few radionuclides emit only alpha or beta particles,[2] and others emit neutrons in addition to other forms of radiation. Detectors for these particles exist but are not as versatile as gamma detectors. Detecting betas and, especially, alphas is more challenging than detecting gammas. Alphas travel only a few millimeters in air, so the detector must be held close to the source, and the probes are fragile; betas travel up to 6 or 7 m in air (Karam, 2021).

First responders should take several factors into account when deciding which radiation detectors and instruments to use: the type of radiation to be detected, the size and weight limitations of the UxS, the necessary detector sensitivity, whether radionuclide identification is necessary, and the capability to transmit read-

[2] Some radionuclides very rarely emit gammas but emit an alpha, beta, or neutron more readily.

TABLE 2.2
Radiation Instrument and Detector Characteristics

Instrument or Detector Characteristic	Impact on UxS Configuration and Survey Operation
Sensitivity	The sensitivity of the detector—the minimum detectable changes in radioactivity—can have a substantial impact on the altitude at which the detector can detect fluctuations in radioactivity in the surrounding environment. Small detectors, such as personal radiation detectors (PRDs), may not detect low levels of contamination if flown far above the ground or if passing over an area too quickly.
Weight	Detector payload weight is a substantially limiting factor when it comes to configuring a UxS, particularly UAS. If responders are not purchasing a fully integrated system and are instead selecting their own detector to match a UxS/UAS, this characteristic alone may determine the detector and UAS pairings that are feasible.
Shape and dimensions	The shape and dimensions of the radiation instrument may be another limiting factor, particularly for UASs because the shape can affect flight stability, balance, and wind resistance. Some UASs are designed to be highly configurable with different payloads and sensors and have various mounting options, but others may be more limited with respect to the payload shapes and sizes they can accommodate.
Type of radiation detected	The type of radiation—gamma, beta, alpha, and neutron—underpins the type of survey that responders expect to conduct during an emergency and can influence which detector, instrument, and/or UxS is appropriate for the task (UAS or UGV): • **Gamma radiation** can be detected over long distances, making detection from a UAS feasible. However, successful detection is influenced by detector sensitivity, which can be influenced by detector size for many use cases. • **Alpha and beta radiation** detection requires placing the meter very close to the radioactive material—millimeters for alpha, centimeters to meters for beta. However, most alpha- or beta-emitting radioactive materials also emit gamma, enabling detection by measuring gamma. • **Neutron radiatio**n is not typically encountered during radiation emergency response; if encountered, however, a gamma radiation survey is usually more important for health and safety
Data integration	Instruments and detectors can communicate data to the user in various ways, and many instruments have more than one method. This characteristic is probably one of the most varied: • **Stream data directly** to a centralized dashboard, either directly from the instrument (e.g., using an integrated cellular or Wi-Fi module) or to another device (e.g., a phone or the UxS itself) over a wired or wireless connection (e.g., Bluetooth). • **Save data locally** (on the detector) for manual retrieval for analysis by the user after the survey is complete. • **Display data live** on a screen.
Data output	Instruments and detectors can read-out in various data types and units, such as the following: • **Exposure rate (R/hr, Gy/hr, Sv/hr):** Radiological boundaries and zones are defined by exposure rates (e.g., the *hot zone* is the area in which exposure rates are 10 mR/hr and higher; the *dangerous radiation zone* has exposure rates of 10 R/hr and higher) • **Count rate (counts per minute or second):** In a contamination survey, count rates are used to identify the presence of contamination and the need to decontaminate a person, item, or area. • **Dose (cumulated exposure R, rem, Gy, or Sv):** This is a measure of the total amount of energy deposited by ionizing radiation; radiation dose limits are set by regulatory agencies, and controlling radiation dose is an effective way to manage risk • **Spectroscopic data:** Every gamma-emitting radionuclide has a characteristic "fingerprint" that can be used to identify the nuclide; this is the nuclide's energy spectrum and collecting spectroscopic data is used to identify the radionuclide(s) that are present • **SI or U.S. unit scales:** In the U.S. Customary units, R, r, rem, and Ci; in the SI system, Gy, Sv, and Bq. To all these can be added the standard multipliers (*micro*, *milli*, *kilo*, *mega*, etc.).
Instrument battery	• Most instruments contain a battery. Some also contain a power line in, including with flexible standards, such as USB-C. Batteries, especially disposable ones, can substantially add to the payload weight. • Detectors (e.g., Table 2.3) alone (in contrast to *instruments*) often do not include a battery. This means that power must be either drawn directly from the UxS or via an additional external battery. The additional battery will add weight and will need to be securely mounted and, potentially, weatherproofed.

ings in real time, among others. If the UxS has a limited payload capacity, a PRD may be preferable because PRDs have the advantages of being small and lightweight—but a PRD must be flown at a lower altitude than a larger, more sensitive detector. Some PRDs also have spectroscopic capabilities and so can determine whether the source of radiation is naturally occurring, from materials used in medicine or industry, or from special nuclear material (National Urban Security Technology Laboratory [NUSTL], 2017).[3] PRDs often use cesium iodide (CsI), sodium iodide (NaI); cadmium zinc telluride (CZT), and yttrium silicate (YSO) as detection mediums (NUSTL, 2017).[4]

If the UxS has the payload capacity, RIIDs may be more useful because they can identify specific radionuclides yet still provide the same exposure or count rate measurements that non-RIID detectors do. The RIID detectors themselves are typically made of thallium-doped sodium iodide (NaI(Tl)), high-purity germanium (HPGe),[5] lanthanum bromide (LaBr), cerium bromide (CeBr), and cadmium zinc telluride (CZT). These devices compare the energy spectrum of the gamma radiation with known values, which are different for each radionuclide. Information about the radionuclide may be useful in determining next steps or in identifying a lost source (see Appendix B). The disadvantages of these detectors are their size, weight, and cost. These factors may pose challenges when coupling with a UxS (NUSTL, 2015).

Table 2.3 describes radiation instruments of various sizes that have their own batteries and data-collection capabilities (albeit likely requiring pairing with another device, such as a phone or tablet, if real-time data

TABLE 2.3
Examples of Radiation Detectors for Unmanned Systems

Product (Company)	Radiation Detected	RIID	Dimensions (inches)	Weight (lbs)	Connection Type
MUVE R430 (Teledyne FLIR)	Gamma Neutron	Yes	4 × 4 × 4	≤2	USB-C "UAS interface port"[a]
TN15 (Kromek)	Neutron	No	5.1 × 1.2 × 0.9	0.24	USB
Sigma 25/50 (Kromek)	Gamma	No		0.47–0.69	USB
GR Family (Kromek)	Gamma	No		Various (under 1 lb)	USB
SPIR-Explorer (Mirion)	Gamma	Yes	9.8 × 5.2 × 3.2	≤2	USB
DroneRAD (Direct Scientific)	Gamma Neutron Alpha Beta	No	1.75 × 8.5	<6	USB
NuEM Drones G (NuviaTech)	Gamma Neutron	Yes	3 × 3 for crystal	<10	433 MHz 868 MHz
RS-530 UAV-mounted Spectrometer System (Radiation Solutions, Inc.)	Gamma	Yes	3 × 3 for crystal	6.6	Wi-Fi Ethernet USB

SOURCE: Features information from manufacturers' and sellers' websites.

NOTE: Blank cells represent unavailable data.

[a] Contact manufacturer for details, but the port allows simple connection to the Teledyne FLIR SkyRanger® R70 quadcopter.

[3] Spectroscopic PRDs are lighter and less expensive than handheld RIIDs but take longer to collect a spectrum.

[4] A full discussion of the different detection media and types of detectors is beyond the scope of this report. Such information may be found in Karam (2021).

[5] High-purity germanium (HPGe) systems generally require longer counting times than sodium iodide (NaI) detectors and are typically bulky, heavy, and expensive—all of which are characteristics that may not be suitable for integration with a UxS.

streaming is desired). Figuring out how to adequately attach these systems to the UxS selected will require additional work. Direct collaboration with the manufacturer of the UxS and/or detector or instrument may also be necessary.

There are also standalone radiation detectors—radiation-detection equipment that does not have onboard power or data-collection capabilities. Table 2.3 identifies several of these. The first five examples in Table 2.3 all weigh less than 2 lbs, and are relatively compact, making them more suitable for integration with a small UxS, such as a small UAV; the remaining examples may need slightly larger UxSs. Some of these detectors are designed to be compatible with certain UxSs (see Table 2.1 for some examples). Others will require careful alignment of hardware and software compatibility between the detector and the UxS. The UxS payload capacity, mounting mechanisms, power supply, data-sharing, and processing require careful consideration. For example, the instrument may be configured so that it is connected to the UxS power supply, which could potentially drain the UxS battery more quickly and decrease overall operating time, or the operator may need to add a separate battery for the instrument, which could increase the payload and affect stability, wind resistance, or other UxS operating functions. Selection of a radiation *detector*, as opposed to an *instrument,* may potentially result in a significant integration (DIY or third-party) effort for maximum customization.

As an alternative, jurisdictions may choose to attach a lightweight radiation instrument, such as a PRD or RIID meter that they already have in their equipment inventory, to a UxS to collect measurements. This approach may require additional configuration to mount the lightweight or handheld instrument onto the UxS, stream data to a wireless device for real-time processing, or store data for later upload and analysis. Table 2.4 includes a few examples of PRDs and RIIDs, but DHS also conducted some market surveys a few years ago that can provide a starting point for searching for other examples (NUSTL, 2015; NUSTL, 2017).

General Unmanned Systems for Radiation-Detection Uses

UxSs are configurable to some degree, but several factors should be considered when deciding which UxS best fits the situation at hand. UxSs can be broken into several categories, which we will define in detail and

TABLE 2.4
Examples of Handheld and Personal Radiation Instruments and Detectors

Product (Company)	Radiation Detected	RIID	Dimensions (inches)	Weight (lbs)	Connection Type
MiniRad-DX (D-tect Systems)	Gamma	No	2.44 × 1.22 × 4.21	0.38	USB D-tect SensorNet
RadEye PRD4 (ThermoScientific)	Gamma Neutron	No	4.1 × 2.6 × 1.6	0.42	Bluetooth
PM1703GNA-II/BT (Polimaster)	Gamma Neutron	No	3.43 × 2.83 × 1.26	0.44	Bluetooth
PM1401K-3P (Polimaster)	Gamma Neutron Alpha Beta	Yes	10.3 × 2.36 × 2.56	1.81	USB
identiFINDER R425 (Teledyne FLIR)	Gamma Neutron	Yes	1.77 × 1.77 × 1.77	≤2.6	USB-C Bluetooth
SPIR-Ace (Mirion Technologies)	Gamma Neutron	Yes	8.1 × 6.2 × 2.2	3.2	Cellular Wi-Fi MicroUSB

SOURCE: Features information from manufacturers' websites.

TABLE 2.5

Air Platforms—Unmanned Aerial Vehicles

Product (Company)	Platform Type	Operational Weight (lbs)	Operational Temperature (°F)	Speed (mph)	Maximum Range (mi)	Maximum Altitude (ft)	Dimensions (inches)	Control Type	Operational Time (min)	Payload Capacity (lbs)[a]
eBee X Series (AgEagle)	Fixed wing	3.60		25–68	17.2	400	45.7 wingspan		90	
Skywalker Ready to Fly Drone (UAV Systems International)	Fixed wing	5.50		55	12.0			2.4 GHz	59	1.10
Spirit (Ascent AeroSystems)	*VTOL coaxial copter*	*10.60*	*–40 to 130*	*40–60*		*14,600*	*12 x 25.5*	*GPS*	*38–58*	*6.50*
Edge 130 Enterprise (Flightwave)	*VTOL Tri-copter*	*3.41*		*24–65*		*12,000*	*10 x 30 x 51*	*900 MHz telemetry* *2.4 GHz data*	*3–125*	*0.76*
Alta X (FreeFly)	*VTOL quadcopter*	*78.28*	*–4 to 122*	*60*			*89 x 15*	*900 MHz* *2.4 GHz* *5.8 GHz*	*10–50*	*35.00*
Aurelia X8 (UAV Systems International)	VTOL hexacopter	54.00	5 to 122	35	1.5	9,842		915 MHz 433 MHz 2.4 GHz	50	24.00
SkyRanger R70 (Teledyne FLIR)	VTOL quadcopter	11.00	–4 to 122	31	5.0		17.7 x 53 x 53	915 MHz 922 MHz 2.2 GHz	40–60	7.70
Explorian XLT (Airolit)	VTOL quadcopter	35.00	–4 to 104					2.4 GHz 5.8 GHz	60	11.00
Hawker Q800X (Aeraccess)	VTOL quadcopter	17.60	–4 to 122	37			44.5 diameter	2.4GHz	30	11.00
Baron Hexacopter	VTOL hexacopter	26.00					42.5 diameter	915 MHz 2.4 GHz 5.8 GHz	30	

SOURCE: Features information from manufacturer websites.

NOTE: VTOL = vertical takeoff and landing. Blank cells indicate unavailable data. The italicized systems are on the Defense Innovation Unit's (DIU's) Blue UAS cleared list as of April 30,2025, which means that it meets several DoD requirements for such factors as sources of parts and airworthiness and can be purchased via the General Services Administration Schedule. A UxS not being on the list may only mean that DIU has not yet assessed that system.

[a] Payload capacity may differ with the configuration of the UxS; thus, these advertised values may differ, and not all vendors provide values. In addition, some UxSs may operate with a greater payload capacity but with decreased performance.

with specific examples and values in Tables 2.5 to 2.7, for use in air, land, and maritime environments. UAVs and UGVs are most likely to be useful for first responders looking to take radiation surveys to prepare for or respond to a radiation emergency.

UAVs can be multirotor copters, fixed-wing systems, or coaxial-rotor systems; multirotor copers are the most common and available and the easiest to operate. These UAVs can serve as versatile, stable, and maneuverable platforms on which to mount and use detection equipment. In selecting a UAV or detection equipment, it is necessary to strike a balance between the payload capacity and flight capabilities. Table 2.5 contains a list of UAVs as example systems. The multicopters are frequently the most versatile for integrating sensors because the equipment can hang below it. The table includes fixed-wing aircraft, but detectors will need to be more closely integrated with the airframe to allow these to fly appropriately. These will most likely need to be integrated by the vendor or a third party to conform to the shape necessary.

UGVs can be treaded (often called crawlers), wheeled, or legged (called *doglike* in this document) systems; tread and wheel based are the most common, but leg-based systems are increasing in popularity. UGVs provide capabilities to access indoor spaces, confined spaces, and complex operational environments. UGVs have higher payload capacities, battery runtimes, and detector placement dexterity than UAVs. Table 2.6 contains a list of UGV as example systems.

Water-based UxSs vary in the requirements needed for operation. Maritime UxSs can be either above-water vessels, commonly called USVs, or an underwater remotely operated or unmanned underwater vehicles. Table 2.7 lists examples of unmanned subsurface and maritime vehicles. The UxS use cases elaborated on in this document do not discuss use of maritime systems for radiation survey because radioactive contamination that settles over water will be difficult to measure due to dilution and water shielding, limiting the utility of such systems during an emergency response.

Special Considerations

Height-of-Operation Considerations for UAV-Mounted Radiation Detectors

It is worth nothing that detection (or identification) of radioactive material becomes more difficult as distance from the radioactive material increases because of the need to be able to recognize a statistically significant increase in radiation levels (count rate or dose rate) above background from the extra radioactivity. The problem is that the dose, or count, rate from the radioactivity added to the background decreases with increasing distance (in this case, with increasing altitude). At the same time, the background radiation levels remain roughly the same, which mean searching for a smaller and smaller signal amidst a constant amount of background radiation at higher altitudes. For example, if the distance from a radioactive source is doubled, the dose rate from the source is reduced to one-fourth of the original level, and the background remains roughly the same. As a result, detectors operating at greater distances need to be larger than those at smaller distances to identify the same amount of radioactivity from contamination or a source.

Surveying an extended area (e.g., a football field) for distributed contamination is different from searching for a radioactive source. In particular, although radiation dose rate and count rate fall off with the inverse square of the distance from the source, radiation dose rate and count rate fall off more gradually from a distributed source because the radiation is reaching the detector from all directions and from many distances. Thus, the radiation count rate and dose rate from a distributed source fall off effectively linearly with increasing distance until the instrument is high enough (about one-third, or the square root of the area) for radiation measurements to begin to approximate a point source (for an area of 1 acre, this would be a height of about 20 m). Having said that, for our purposes, what matters most is that a UAV be able to carry a radiation instrument at an altitude of between 10 and 20 m long enough to accomplish a particular task.

TABLE 2.6

Unmanned Ground Vehicles and Surface Platforms

Product (Company)	Platform Type	Operational Weight (lbs)	Operational Temperature (°F)	Speed (mph)	Maximum Range (mi)	Dimensions (inches)	Control Type	Operational Time (min)	Payload Capacity (lbs)[a]
Unitree B2 (Unitree)	Dog	88–264	–4 to 130	13.4	9–12	43 × 17 × 25	1000M ethernet	240–300	88
ANYmal X (ANYbotics)	Dog	132.5	32 to 104	2.2	0.93–1.5	18.35 × 5.35 × 3.07	2.4–5 GHz Wi-Fi 4G LTE	60–120	
Vision 60 (Ghost Robotics)	Dog	134	–49 to 131	6	6.2	33 × 18 × 25	2.4–5.8 GHz Wi-Fi 4G LTE GigE switch	180	22
Spot (Boston Dynamics)	Dog	71.7	–4 to 113	3.6		43.3 × 19.7 × 33.1	Wi-Fi 2.4 GHz	90	30.9
EX-ROBOT (Nexxis)	Crawler	165–220	–4 to 122	1.5	0.93	37 × 27 × 21.8	4G LTE Wi-Fi		
MicroTraxx Robotic Crawler (The Machine Lab, Inc.)	Crawler	3		5.4	0.19	8 × 8 × 3	Tethered Optional 100 ft retrieval cord	30–45	

SOURCE: Features information from manufacturer websites.

NOTE: Blank entries are for unavailable data.

[a] Payload capacity may differ with the configuration of the UxS; thus, these advertised values may differ, and not all vendors provide values. In addition, some UxSs may operate with a greater payload capacity but with decreased performance.

TABLE 2.7

Pipe Crawler, Underwater, Maritime Unmanned Systems

Product (Company)	Platform Type	Operational Weight (lbs)	Operational Temperature (°F)	Speed (mph)	Maximum Range (mi)	Maximum Depth (ft)	Connection Type	Operational Time	Payload Capacity (lbs)[a]
PureRobotics® Condition Assessment Platform (Xylem)	Pipe crawler			1	2		Tethered line		
CRP90 (minicam)	Pipe crawler	10							
A-200 (Deep Trekker)	Pipe crawler	64.6	23 to 104	0.8	0.12–0.18	164	Tethered line 512 Hz sonde	300 min	
DT320 Mini Pipe Crawler (Deep Trekker)	Pipe crawler	25	23 to 104	0.44	0.03–0.24	124	Tethered	240–480 min	
PIVOT Remotely Operated Vehicle (Deep Trekker)	Underwater	37	14 to 122		0.18–0.62	1000			
Hydrus (Advanced Navigation)	Underwater	14.77	23 to 95	1.7–2.3	0.15–0.93	98–3280	Wi-Fi GNSS		
Voyager (Saildrone)	Maritime USV	1,201	N/A	2–9	10,000	N/A	N/A	~12 months	
Bluebottle (Ocius)	Maritime USV	1443	N/A	2–6	N/A	N/A	N/A	N/A	661
C-Worker 4 Autonomous Surface Vehicle (L3Harris)	Maritime USV	2271	N/A	4–6.9	N/A	N/A	1.25–10 MHz RF IP mesh radio 4G LTE Wi-Fi	48 hrs	88

SOURCE: Features information from manufacturer websites.

NOTE: GNSS = Global Navigation Satellite System; RF = radio frequency. Blank entries are for unavailable data.

[a] Payload capacity may differ with the configuration of the UxS, thus these advertised values may differ and not all vendors provide values. In addition, some UxS may operate with a greater payload capacity but with decreased performance.

The ability to detect contamination on the ground is a function of the amount of activity dispersed, the distance from the dispersal location, the isotope(s) present, the counting efficiency of the detector for the type of radiation emitted and its energy, and the altitude at which the survey is flown. Of these, once radioactivity has been dispersed, the only factors that are within the control of those performing the survey are the distance from the source and the altitude at which the survey is performed. In general, the amount of contamination per square meter is expected to be lower as the detector moves farther from the dispersal location, and the count rate from a given amount of radioactive contamination will drop with increasing altitude. Thus, flying higher and/or further downrange will lead to a reduced count rate. Surprisingly, the physical size of the detector does affect the count rate but does not affect the count rate very much because the background count rate for a larger detector is higher than for a smaller detector, making it more difficult to identify relatively low levels of contamination.

Table 2.8 shows this effect by calculating the greatest altitude at which three different detector sizes would be able to show the presence of contamination from 1,000 Ci of Cs-137 dispersed over an area of about 160 km^2 in a triangular pattern stretching over a distance of 10 km from the dispersal location (see Figure 2.1). Please note that these altitudes will be different for different radionuclides, different distribution patterns, and so forth. Using these (and other) calculations, UAV surveys can be done, and the UAV should be flown at the lowest altitude at which rotor wash will not resuspend small particles. If that altitude is not known, consider flying at an elevation of 10 to 20 m above ground level or the lowest altitude permitted by obstructions (e.g., trees, powerlines, buildings).

In addition, be aware of the following:

- Some manufacturers have developed detectors specifically designed to improve sensitivity and directionality for surveys conducted at altitude.
- Training and exercises should be conducted with the desired UxSs in environments and with scenarios that reflect real-life conditions to be encountered during an emergency, to the extent possible.
- Flying at too low an altitude risks contaminating a UAV, which can produce elevated radiation readings because of radiation emitted by the radioactive contamination.

Legal and Regulatory Limitations for UxS Operation

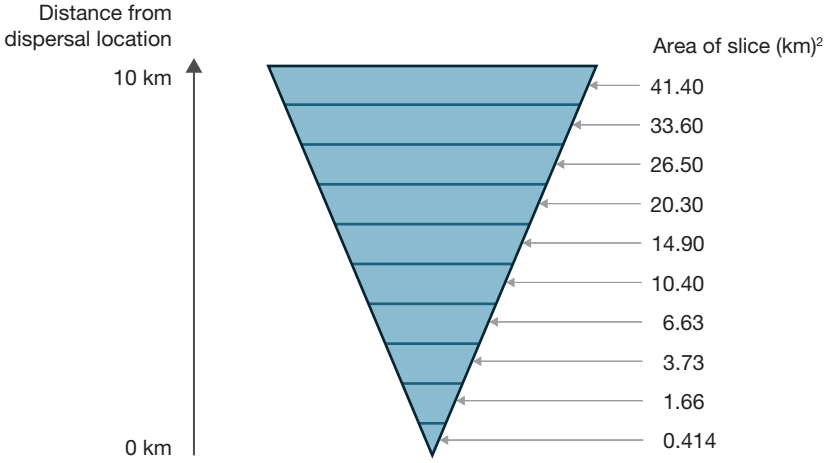
UGVs have far fewer regulations than UAVs, which may make UGVs a preferred option for some jurisdictions during emergencies. There is no single regulatory body for UGVs, and motor vehicle laws may only apply if the UGV is operated on roadways. In contrast, the FAA has many regulations for operating UAVs, as described in Code of Federal Regulations, Title 14, Aeronautics and Space (Part 107, Small Unmanned Aircraft Systems), including two different types of pilot certificates for small UAVs (i.e., less than 55 lbs maximum takeoff weight). Both certificates require the pilot to pass a knowledge-based test (no flight test needed),

TABLE 2.8
Maximum Altitude for Reliably Detecting Contamination from Various Levels of Contamination

Activity (Ci)	Contamination at 10 km		Detector size, inches (cross-sectional area, cm^2)		
	Ci/km^2	dpm/m^2	1 × 1 (6.25)	2 × 2 (25)	3 × 3 (56.25)
1,000	13	5.4 × 107	65 m	45 m	63 m
100	1.3	5.4 × 106	2.8 m	2.9 m	3.6 m
10	0.13	5.4 × 105	Undetectable	Undetectable	Undetectable

SOURCE: Features information supplied by NUSTL.

FIGURE 2.1
10-Point Survey Area, Extended to 10 km, with the Calculated Area of Each 1-km Slice



one intended for use by recreational pilots and one for commercial pilots. The FAA also requires that UAVs be registered and that users follow restrictions and limitations for operating a UAVs in the national airspace system. These include locations for flying, the altitude of flight, whether the pilot (or a spotter) can maintain visual line of sight (LOS), flying over people, flying during the day or night, and lighting requirements on the UAVs. These restrictions limit the utility of UAVs during emergencies because radiation measurements often need to occur beyond the LOS of the pilot.

First responders can obtain waivers from the FAA, which would allow a pilot to go beyond the standard rules for operating the UAVs. The waivers could include flying beyond visual LOS, over people, at night, and over 400 ft altitude. First responder groups (e.g., a fire department) can also apply for and receive an FAA Certificate of Authorization that allows more flexibility in their area of interest and can be tailored to the specific concept of operations that the responders require. Obtaining these waivers can take time, and each responder entity must procure them before they can effectively use UAVs. The nature of emergencies means that a first responder entity needs to be prepared with the appropriate registrations, authorities, and waivers in advance. During an emergency, the FAA can provide emergency waivers in a few hours or faster, but prior approvals can significantly help expedite operations (FAA, 2023). Additionally, there are airworthiness certifications for some operational conditions, particularly for 14 CFR §107.140 (Category 4 Operations), which can restrict any modifications (e.g., swapping one sensor for another).

Finally, operation beyond the LOS of the pilot, which would be beneficial to several radiation measurement use cases, are still limited, even with an emergency waiver and a Certificate of Authorization. The UAV must remain within 1,500 ft of the pilot at all times (even if beyond the pilot's LOS), must not fly 50 ft above or 400 ft around an obstacle blocking LOS, and must return to LOS as soon as possible (FAA, undated). This limits operations in urban or forested areas and where UAVs must travel a significant distance from the pilot to collect a measurement. However, there are ongoing pilot programs for using a drone as a first responder, in which even these restrictions are removed. Section 930 of the FAA Reauthorization Act of 2024 (Public Law 118-63) also requires the FAA to have a beyond visual LOS final rule for UAV operation by the end of 2026, so it is unclear how long these restrictions will remain in effect.

Radiation Exposure to UxS Platform

In addition to causing injury to humans and animals, radiation can damage electronics. The effects on electronics depend on the exposure, the type of damage, and whether the electronics are radiation hardened. This section provides a brief overview of radiation effects on electronics.

Radiation effects can be categorized as total ionizing dose, displacement damage, and dose-rate effects. *Total ionizing dose* leads to current leakages and soft breakdowns and has more of a long-term effect on the equipment (which may degrade post–radiation exposure or become more vulnerable with later exposures). In *displacement damage*, a particle collides with an atom in a semiconductor lattice. *Dose-rate effects* change the device state. For example, a bit may flip or may be stuck in a position. In some cases, the device can recover on its own or may need to be power cycled. In other cases, the radiation causes permanent damage (Reed et al., 2020).

Most consumer electronics are not radiation tolerant or radiation hardened yet are able to withstand 500–1,000 rads, much higher than the limit for radiation workers (2–5 rads) (Courtland, 2011) and higher than the doses a UxS is likely to receive, except in the aftermath of a nuclear surface burst or being close to a nuclear power plant's core after a major nuclear power disaster. A device's tolerance for radiation depends on the components of the device and the design of the device. Devices used in nuclear power plants and those launched into space are typically the most radiation hardened (Reed et al., 2020). Aside from a nuclear power plant accident or nuclear weapon detonation, most radiation detectors likely will not be exposed to damaging amounts of radiation.

A review of publicly available manufacturer information for UxS systems revealed that very few indicate a radiation tolerance for their devices and systems. Where this information *is* made available, insufficient additional information is provided to allow a comparison of multiple devices or systems that were tested under standardized conditions to high levels of radiation; this makes it difficult to evaluate the performance of UxS systems operating in a very high radiation field.

Contamination of UxS Equipment

Separate from radiation exposure,[6] responders should also consider and be prepared to manage potential risks of contamination of people, the UxS, and the environment, that may result from the use of UxS during a radiation emergency. The primary concern is that the use of a UxS in an area where there is removable radioactive contamination, such as the areas near the detonation of a dirty bomb or industrial accident, which could cause the settled material to be resuspended, potentially contaminating the UxS or nearby people and be redispersed into the local area. In addition, contamination will emit radiation, making it appear as though radiation levels are higher than they actually are. How much resuspension—if any—will depend on a combination of factors, including the type of system (aerial, ground, etc.), how far above the ground the system is operated, the amount of contamination in the environment, and whether the material is conducive to being disturbed by such forces as a UAV's rotor wash. The nature of the emergency will also matter. A sealed radioactive source, which is technically not contamination, presents the lowest risk for contamination because the radioactive material never leaves its container. Unsealed and dispersed radioactive material presents the highest risk.

The most effective way to minimize resuspension and contamination is to fly the UAV high enough that the rotor wash cannot disturb the ground beneath it. However, the altitude of flight will depend on various

[6] *Exposure* means exposure to ionizing radiation. *Contamination* means the presence of radioactive materials in a location where it is neither expected nor desired. The presence of radioactivity in a laboratory test tube, for example, is an experiment. That same radioactivity that has splashed onto the researcher's hand is contamination.

factors (e.g., environmental obstacles and the sensitivity limitations of the radiation-detection equipment payload). UGVs may become contaminated if their wheels, treads, legs, etc., touch the radioactive material. Depending on the UGV, it may be possible to wrap the contact surfaces in a material appropriate for keeping contaminants from reaching the contact surface (e.g., plastic, Tyvec®), thereby reducing contamination of the UGV itself or facilitating decontamination of the equipment later on by removing the covering. When the UxS is contaminated by a radionuclide with a short (hours, days) half-life that decays into a stable isotope,[7] decontamination could be accomplished by simply isolating the UxS for a period of several half-lives.

Potential Unmanned System Listings

As stated at the beginning of this chapter, we are not endorsing or recommending particular systems or detectors. We do, however, suggest referring to the following three sources to assist with UxS procurement decisions. These are not the only sources, but they are well regarded:

1. DIU has been assessing UAVs for several years for DoD use. DIU has a list of systems, called the Blue UAS Cleared List (DIU, 2025), that entities in DoD can purchase from the General Services Administration schedule. DIU assesses a UAS to meet a specific capability need (the list addresses many different capabilities) and to meet several federal and defense laws and regulations, including such items as source countries of components and airworthiness. Because the Blue UAS Cleared List is published on the internet (at DIU, 2025) and regularly updated, SLTT entities can see which UASs DIU has tested and verified.
2. Several commercial entities review systems, publish articles, host conferences, and generally provide information about UxSs. The Association for Uncrewed Vehicle Systems International is one such nonprofit organization that has supported the uncrewed systems industry since 1972 (Association for Uncrewed Vehicle Systems International, undated). Aside from events, the association has a database of uncrewed systems and robotics, by subscription or with membership.
3. MITRE offers the Drone Selector™ Tool (MITRE, undated), which may be a helpful resource for first responders to view and compare basic specifications across a broad range of UAV platforms.

[7] The NRC defines *half-life* as the "time required for half the atoms of a particular radioisotope to decay into another isotope" (NRC, 2021c). As the NRC points out, half-lives range from fractions of a second to billions of years. The NRC defines *isotope* as "two or more forms (or atomic configurations) of a given element that have identical atomic numbers (the same number of protons in their nuclei) and the same or very similar chemical properties but different atomic masses (different numbers of neutrons in their nuclei) and distinct physical properties" (NRC, 2021d).

CHAPTER 3

Use-Case Development

In this report, we discuss three use cases for employing UxS for radiation measurement in the wake of a radiation emergency: following the 10-point monitoring plan, locating a lost source, and assessing CI. These use cases span different radiation emergencies, categories, and measurement techniques. In this chapter, we discuss how and why we selected these use cases and the operational concepts and requirements for each of them.

Use-Case Identification

We began by identifying different use cases for radiation measurement in response to a radiation emergency. To do so, we reviewed the recommended responses for different radiation emergencies, as given in written federal emergency response guidance and subject-matter expert discussions. From these, we identified discrete radiation measurement tasks occurring either before, during, or after the incident, when responders need to take radiation measurements at specified locations to achieve their mission. Frequently, these measurement tasks are recommended to support a zoned approach to response, in which responders categorize different areas as different zones (e.g., hot zones) according to levels of radioactivity and use these zones to guide the response protocols. Each measurement task corresponds with a phase of response, per the Response and Recovery Federal Interagency Operational Plan (Federal Emergency Management Agency [FEMA], 2023b) and the Nuclear/Radiological Incident Annex to that document (DHS, 2023). Figure 3.1 illustrates different phases and how they correspond with one another, noting that the length of time varies with the situation and that the phases can overlap in time (U.S. Environmental Protection Agency, 2017).

To build radiation measurement use cases, we consolidated response tasks for different radiation emergencies when possible. This process resulted in 21 discrete radiation measurement use cases in which UxS could potentially be employed. For each use case described in Table 3.1, we identify the goal for taking a measurement, the responsibilities for responders, and the relevant radiation emergency or emergencies to which the use case pertains.

FIGURE 3.1
Operational Phases and Protective Action Phases for Response and Recovery

SOURCE: Adapted from DHS, 2023.
NOTE: Operational phases are at top, with protective action phases below.

TABLE 3.1

Use Cases for Radiation Measurement

Measurement Use Case	Measurement Objective	Responder Responsibility	Relevant Emergency Categories	Assessment
Preincident Phase				
Background radiation monitoring[a, b]	Determine background radiation levels in a set survey area to be used as a reference during emergencies	Taking regular measurements across a wide area, typically at set distances between measurement locations	All emergencies	Potential candidate
Preevent survey[b]	Establish the background radiation levels of a building or location and clear that space of any potential radiation-emitting threats or hazards prior to an event[c]	Taking regular measurements across a defined, smaller area, often under time and manpower constraints and involving surveys of complex indoor and outdoor spaces	All intentional threat emergencies across the different categories (RDD, RED, nuclear detonation)	Potential candidate
Training[b]	Familiarize operators with systems and sensors	Varied, depending on operation being trained	All emergencies	Potential candidate
Prerelease monitoring[b, d]	Determine whether and when an anticipated release of a plume of radioactive material from a nuclear power plant actually occurs[e]	Taking regular measurements in a narrow area near the facility, but over an extended period	Dispersed source emergencies (specifically nuclear facility accidents)	Not good candidate
Early Phase				
Locate lost, stolen, or orphaned source[b, f]	Find a missing radioactive source	Searching for source over wide area	Localized source emergencies	Good candidate
Confirmation[f, g]	Confirm presence of radiation following the discovery of an incident	Taking two measurements proximate to the suspected contaminated area	Localized source emergencies, dispersed source emergencies	Not good candidate
Directionality[g]	Determine directionality of radiation movement	Taking multiple measurements in all directions near site of initial confirmation	Dispersed source emergencies	Not good candidate
Plume transect[d, g]	Determine whether radiation has dispersed, and possibly deposited, following the determination of directionality	Taking regular measurements in a straight line perpendicular to direction of radiation movement to understand the breadth of material deposited by the plume. For RDDs, this transect is recommended to be approximately 1 km from the incident site, can differ for nuclear facility incidents.	Dispersed source emergencies	Potential candidate
Near field survey[g]	Define hot zone boundary	Taking multiple measurements in the area between the site and the transect line	Dispersed source emergencies	Potential candidate

Table 3.1—Continued

Measurement Use Case	Measurement Objective	Responder Responsibility	Relevant Emergency Categories	Assessment
10-point monitoring plan[d, g]	Measure extent and magnitude of plume and material deposited from plume	Taking ten or more measurements in the direction of the plume, at set distances and angles relative to the site. Some measurements may be taken during other use cases, such as the near field survey, and reused for this use case.	Dispersed source emergencies	Good candidate
Outlying areas survey[d, g, h]	Confirm safety of unaffected areas for public reassurance	Taking multiple measurements in areas proximate to, but away from, the site, not in the direction of the plume	Dispersed source emergencies, nuclear detonations	Good candidate
Intermediate Phase				
Wide-area survey[i]	Define contaminated area boundary	Taking continuous measurement to understand the boundaries of the potentially hazardous area. For nuclear detonations, these measurements may be very far afield from the incident site.	Dispersed source emergencies	Good candidate
Field analysis[i]	Determine the nature of source	Analyzing the physical and chemical properties of the radiation source in the field	All emergencies	Potential candidate
Radiological risk assessment[i]	Locate and identify specific hazards within hot zone	Taking nonroutine measurements in areas of the hot zone with elevated radiation, based on elevated readings from prior surveys, following completion of lifesaving activities	All emergencies	Good candidate
Grid survey[i]	Gain granular understanding of contaminated area	Taking measurements at regular intervals (e.g., 50–100 m) within the contaminated area and covering the entire contaminated area	Dispersed source emergencies, nuclear detonations	Good candidate
Boundary resurveys[i]	Understand the spread and scope of contamination	Taking daily measurements outside the boundaries of the contaminated area	Dispersed source emergencies	Potential candidate
Critical Infrastructure (CI) assessment[b, i]	Determine safe areas in CI to support response and recovery actions	Exploring and documenting hazards and impacts on select CI sites	Dispersed source emergencies, nuclear detonations	Good candidate
Waterway monitoring[i]	Understand the extent of contamination into water supply	Taking daily measurements of waterways in and around contaminated areas	Dispersed source emergencies, nuclear detonations	Not good candidate

Table 3.1—Continued

Measurement Use Case	Measurement Objective	Responder Responsibility	Relevant Emergency Categories	Assessment
Late phase				
Deposition monitoring[b, i, j]	Understand the extent of contaminant deposition in soil	Surveying a wide area by air or ground and locating and identifying contaminants in soil via analysis of soil samples	Dispersed source emergencies, nuclear detonations	Potential candidate
Remediation sampling and analysis[b, i, j]	Determine the right remediation approach based on current hazard levels	Gathering measurements and samples before and during remediation process	All emergencies	Not good candidate
Verify Remediation[b, i]	Determine whether specified area is decontaminated to acceptable levels	Iteratively assessing radiation levels of area following remediation	All emergencies	Not good candidate

[a] DHS, 2023.

[b] Discussions with responder entities.

[c] *Event* here refers to a "planned, nonemergency activity occurring in a particular place during a particular interval of time, like a parade or a sporting contest," per the DHS Lexicon (DHS Management Directorate, 2017). National Security Special Events and Special Event Activity Rating events are both types of events where responders may conduct pre-event surveys for radioactive materials.

[d] FEMA, 2023d.

[e] A malfunctioning nuclear power plant may come to a point at which it is likely to release radioactive material imminently. Responders and on-site safety staff may preposition monitoring capabilities around the facility to track when or what the facility releases beyond its perimeter or even if there is a release at all.

[f] FEMA, 2010.

[g] DHS, 2017.

[h] FEMA, 2023a.

[i] FEMA, 2023c.

[j] Federal Radiological Monitoring and Assessment Center, 2019.

These 21 use cases are not equally amenable to the use of UxSs; we rated each using the applicability of integrating UxSs into a response operation. To do so, we separately identified and then weighed the advantages and disadvantages of using UxSs to accomplish each use case. This assessment (shown in the last column of Table 3.1) was based on several considerations: current manpower use for that case, competing manpower demands at that stage of the emergency response, compatibility of UxS capabilities with the operational needs of the use case, likely availability of the UxS during that stage of the emergency response, and risks to manned operations from likely radiation hazards for that case. We rated the use cases in which the advantages across these considerations most outweighed the disadvantages as being good candidates for employing UxSs to accomplish, at least in part, the radiation-detection tasks necessary to do for a given use case.[1] In general, we rated the use cases that either demanded measurements over a wide area under time constraints or involved radiation risks that pose significant risks to operators as good candidates for employing UxSs.[2]

Of the good candidate use cases for employing UxS, three were chosen for further elaboration in this document:

- 10-point monitoring plan
- locating lost, stolen, or orphaned sources
- CI assessment.

However, we also looked for opportunities to apply the recommendations from these use cases to other use cases for radiation measurement that were not explicitly discussed in this document and have listed those use cases in both Chapter 4 and the appendixes. Such information may be useful when making decisions about acquiring one or more UxSs and radiation detectors.

Use-Case Development

For each of the three use cases, we provide recommendations for how responders might employ UxSs to achieve the measurement objectives and a concept of operations (CONOPS). Technology needs and key performance parameters for the radiation detectors and the UxSs were included for each CONOPS. Key advantages and disadvantages to employing UxSs in these use cases were also highlighted to support first responders with determining whether it makes sense to employ UxSs.

[1] We rated the use cases that had identifiable advantages of using UxSs but also some complications that could limit the effectiveness of UxSs as potential candidates. We rated the use case where, on first assessment, the limitations of UxSs appear to outweigh the advantages as not good candidates.

[2] Of the use cases listed in Table 3.1, we identified the following as good use cases for employing UxS: locating lost, stolen, or orphaned sources; using the 10-point monitoring plan; conducting outlying area surveys, conducting wide-area surveys, assessing radiological risk, conducting grid surveys, and assessing CI. However, our assessments are preliminary and not based on significant experience using UxS during emergencies for these purposes. Additional research is required to identify opportunities or situations in which UxSs may have utility, especially for more marginal use cases.

CHAPTER 4

Organization of the Use-Case Discussions

Appendixes A, B, and C discuss the three use cases in detail: the 10-point monitoring plan; location of lost, stolen, or orphaned sources; and CI assessment, respectively. In this chapter, we discuss the basic organization and contents of the appendixes and offer suggestions for how to use the appendixes.

Organization of Appendixes

Each appendix has the same organizational layout:

- **Purpose** provides a brief explanation of the purpose of the appendix and use case.
- **Mission description** includes considerations for the mission.
- **CONOPS** discusses prerequisite tasks involved in preincident planning and response tactics and provides an example CONOPS.
- **Detector Capability Needs** explains which types of radiation detectors are most useful to achieve the mission described in the use case.
- **UxS Capability Needs** describes the key characteristics of the UxS platforms needed to achieve the mission described in the use case.
- **Key Performance Parameters** provides parameters for each of the detector and UxS needs described in the previous two sections.
- **Advantages and Disadvantages of Using UxS in This Use Case** summarizes the advantages and disadvantages of using UxS are summarized. Entities can use this information in acquisition decisions, along with their own factors, such as manpower, costs, and the ability to use the equipment for nonradiation emergencies.
- **Variations for Similar Use Cases** identifies some variations of the use case presented.

How to Leverage the Use Cases

The cases were designed for responders to use before a radiation emergency to support selection, acquisition, training, and exercising of radiation-detection–enabled UxS platforms.

Selecting a UxS to Meet Local Needs

The selection of appropriate UxSs and detectors depends on many factors, including local topography, anticipated distance to a radiation source or release, and on balancing the need for procuring and deploying UxSs for other kinds of emergencies or to address nonradiation aspects of a radiation emergency. Regional topography can vary widely: One jurisdiction may have many tall buildings and underground spaces (e.g., garages, subway systems) in a relatively small area, and another may cover a large geographic area and have only one-

to two-story buildings. Similarly, some jurisdictions may have a nuclear power plant or a large medical facility that uses radiation in detecting and treating diseases and, thus, may need equipment capable of detecting certain isotopes or collecting specific types of radiation measurements (e.g., contamination survey). Additionally, a jurisdiction might want to use UxSs for emergencies not involving radiation and would likely value the capability to swap payloads to respond to different types of emergencies.

Given their needs and current emergency equipment inventories, each jurisdiction needs to determine whether it makes sense to acquire a dedicated UxS for radiation detection or whether to attempt to integrate radiation detection into existing capabilities. In either case, decisionmakers should understand what systems might be needed for radiation detection to allow sufficient time for operational planning, acquisitions, and training prior to an incident. Whether the UxSs are used solely for radiation detection or also for other purposes, first responders need to be familiar with the UxSs, radiation detectors, and any other sensors used.

Training and Exercising Prior to an Emergency

The use cases provided in the appendixes can be a starting point for first responders to plan operational implementation of UxS capabilities for emergency response missions. However, before expecting to use UxSs to conduct radiation surveys during an emergency, it is essential that first responders train and exercise with the desired UxSs in environments and with scenarios that reflect real-life conditions to be encountered during an emergency.

An additional benefit of training or exercising with UxS capabilities prior to an emergency is that doing so may enable efficient collection of background radiation measurements. Having the data beforehand may provide an environmental baseline that is useful to both preventative radiological nuclear detection (e.g., search and interdiction of radioactive material) and consequence management operations and will allow more efficient adjudication of alarms and identification of atypical readings, which could potentially necessitate a response. In general, the techniques and methods used to collect data during a background survey should match those that responders would use in response operations and should use the same instrumentation, configurations, measurement times, heights, etc., when possible, which will benefit data quality assessment and improve the utility of the data.[1]

[1] See NUSTL (2025) for additional information on how to plan and conduct a background radiation survey.

CHAPTER 5

Similarities Across Use Cases

Although each radiation emergency and the response will be unique, different use cases might employ similar approaches to radiation detection. The use cases presented in the appendixes may be applied in other emergencies not described in detail. To assist responders in making these connections, this chapter lists use cases identified in Table 3.1 that have similarities and explains the rationale for the similarities.

Common Characteristics of Radiation Measurement Use Cases

This section describes six common characteristics that apply to different measurement use cases, including those executed in different phases of the response.

Pattern-Based Survey

Systematic radiation surveys are needed both before and after a radiation emergency. An efficient way to ensure complete coverage of a survey area is to use a pattern (e.g., grid, spiral, strip) to divide the area and then take measurements at regular intervals within that pattern to ensure appropriate measurement coverage and spacing.

Multiple Radiation Measurements in a Small Area

Following a radiation emergency, many measurement use cases need responders to take multiple measurements at different points in a small defined area over a short time. Measurements are frequently required in areas with elevated radiation hazards, such as the hot zone of the incident or specific enclosed spaces. The goal of these measurements may be to confirm the presence of radiation or to identify the boundaries of a hazardous area.

Directed Measurements over a Larger Area

For radiation emergencies that affect a wide area, responders may need to collect measurements well beyond the incident site. Because these measurements cover a large area, the specific location of the measurement is determined in advance and communicated to the measurement team to execute.

Repeated Surveys Over Time

Radiation hazards do not dissipate quickly, so responders may need to collect measurements repeatedly to understand how a radiation hazard has diminished or changed over time. These repeated measurements can occur daily, weekly, or on some other regular schedule, as appropriate.

Radionuclide Identification

Understanding the nature of the radiation hazard in an emergency presents will often require identifying the specific radionuclide. Therefore, some measurement use cases go beyond detection of the presence of radiation to identification of the source.

Physical Sample Collection

As part of the recovery process, physical samples may need to be collected and analyzed in a laboratory. Collection of soil, air, or water samples may be useful for identifying contaminated areas and verifying the effectiveness of remediation efforts.

Crosswalk of Use Cases and Radiation Measurement Characteristics

Table 5.1 provides a crosswalk of the radiation measurement characteristics and the use cases (Table 3.1) that share characteristics.[1]

TABLE 5.1
Radiation Measurement Characteristics and Use Cases Needing Such Characteristics

Radiation Measurement Characteristic	Use Cases with This Characteristic
Pattern-based survey	• Background radiation monitoring • Preevent survey • Prerelease monitoring • Locate lost, stolen, or orphaned source • Directionality • Wide-area survey • Grid survey • Waterway monitoring • Deposition monitoring • CI assessment • Remediation sampling and analysis • Verify remediation
Multiple radiation measurements in a small area	• Confirmation • Directionality • Near-field survey • Radiological risk assessment • CI assessment
Directed measurements over a larger area	• Plume transect • 10-point monitoring plan • Outlying areas survey • Boundary resurveys
Repeated surveys over time	• Background radiation monitoring • Prerelease monitoring • Boundary resurveys • Waterway monitoring • CI assessment • Remediation sampling and analysis • Verify remediation

[1] Note that the training use case defined in Table 3.1 is being left out of this because it cuts across all characteristics and is something that responders will need to do regardless of their responsibilities. On the other hand, the CI assessment use case shares all but one of the identified characteristics in common. This is because assessing CI for radiation hazards covers so many scenarios that many characteristics can describe that use case.

Table 5.1—Continued

Radiation Measurement Characteristic	Use Cases with This Characteristic
Radionuclide Identification	• Field analysis • Radiological risk assessment • Waterway monitoring • Deposition monitoring • CI assessment • Remediation sampling and analysis • Verify remediation
Physical sample collection	• Field analysis • Waterway monitoring • CI assessment • Remediation sampling and analysis • Verify remediation

Each of the appendixes details a specific radiation measurement use case. At the end of each appendix is a brief discussion of other use cases that have some of the same characteristics as listed in Table 5.1, along with some additional differences, as appropriate.

APPENDIX A

Use Case: 10-Point Monitoring Plan

This appendix describes the 10-point monitoring plan use case and provides the following information:

1. rationale for using UAVs
2. steps for using UAVs and timeline considerations
3. capability needs to aid decisions
4. advantages and disadvantages
5. similar use cases.

This appendix is intended to be a reference document for responders grappling with using UxS for the 10-point monitoring plan. The basic concept of operations for conducting this survey (with humans, not UxSs) is described in the RDD response guidance (FEMA, 2023c). As with all the use cases in this document, this section should be read during the preincident planning phase to help first responders determine what type of UxS configuration might be appropriate for this (or a similar) type of survey and to help them adapt existing CONOPS.

UAVs have a significant advantage over other types of UxSs for conducting this type of survey. The most apparent advantages are (1) that unlike UGVs, UAVs can cover a large outdoor area (several miles) that contains significant environmental obstacles (e.g., vehicles, people, buildings, lamp posts, trees) in a short time and (2) that UAVs can be launched from a location that is well outside the area to be surveyed. Because of these operational advantages, this use case will focus only on UAVs.

Purpose

The goal of the 10-point monitoring plan is to collect measurements to help refine dispersion models, characterize the extent of contamination, and inform early protective action decisionmaking.[1] During the early phase of an emergency involving a dispersed radioactive material (e.g., RDD) responders need to determine the contamination footprint and where individuals may need to either shelter in place or evacuate. Depending on weather conditions and the nature of the incident, airborne radioactive material can travel and deposit many miles from the incident site.

Mission Description

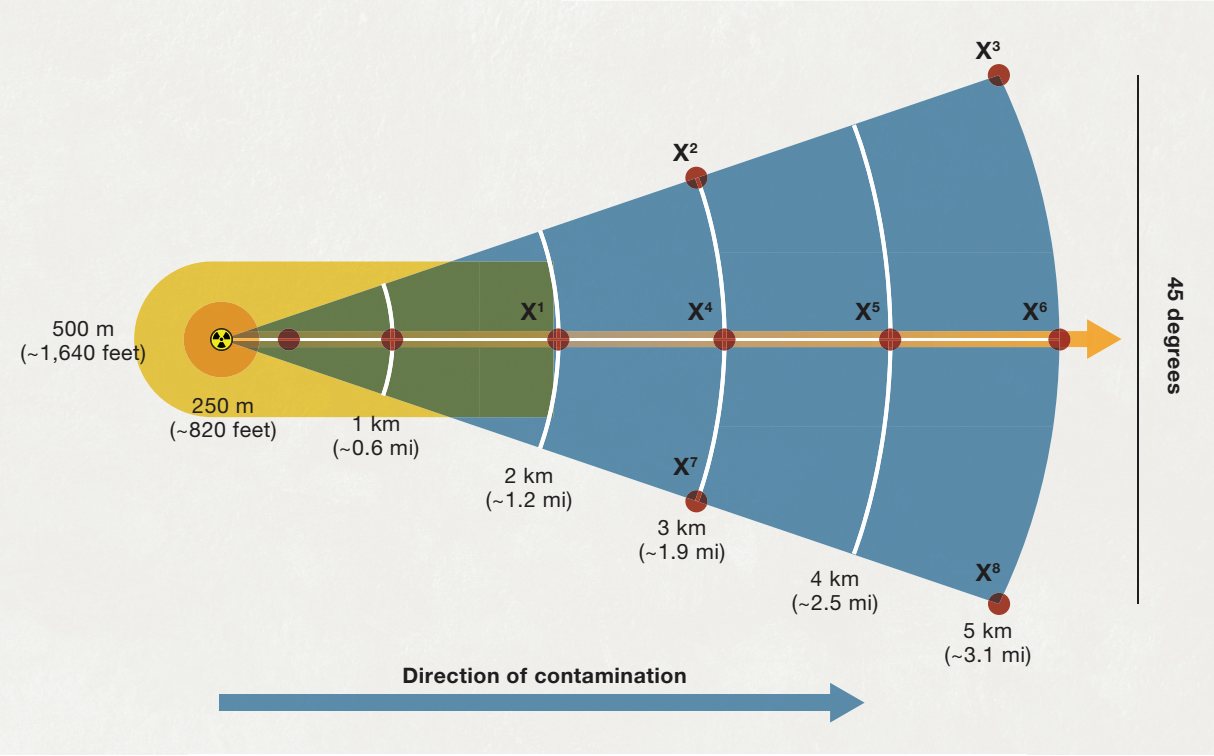
The 10-point monitoring plan involves taking ten measurements over a large area (approximately 10 km^2 or 4 mi^2) in the direction that contamination has spread. The measurements should be taken along the center-

[1] The *10-point monitoring plan* refers to a specific plan identified in the DHS RDD immediate response guidance (DHS, 2017). Not all responses will involve exactly ten points of measurement or follow the guidance for RDD response

line of the plume's deposition and at 22.5-degree angles left and right of the centerline. For RDDs, these measurements are recommended to be approximately 1 km apart, out to a distance of 5 km. However, if adapting this plan for other emergencies, where the plume might be higher and, thus travel further from the incident site (e.g., nuclear facility incidents), these measurements might make more sense to be further apart (DHS, 2017; FEMA, 2023d). Figure A.1 illustrates where the measurements could be taken for an RDD response, in relation to the incident site and plume centerline.

Because the 10-point monitoring survey is intended to inform initial public-safety decisions in the early phase (minutes, hours), this task should commence promptly once initial lifesaving rescue operations have begun and once the presence of radiation has been confirmed. On a notional ideal timeline, this could potentially initiate somewhere from 30 minutes to an hour after the incident is detected. This time frame might allow sufficient time for UAVs to arrive—depending on the jurisdiction or area it is arriving from. These ten measurements would be collected after responders took measurements at and near the incident site (the confirmation and near-field survey use cases), after the direction the plume traveled has been determined (the directionality use case) and after the centerline of the plume has been confirmed (the plume transect use case).[2] Responders should use these prior measurements to determine where to take the 10-point monitoring plan measurements. Some of these prior measurements could also be substituted for one or more of the ten needed measurements closer to the incident site, i.e., the unlabeled points in Figure A.1 (DHS, 2017).

FIGURE A.1
10-Point Monitoring Plan Overview



SOURCE: Adapted from DHS, 2017, Figure 8.

[2] For more information on these use cases, please refer to Table 3.1.

DHS guidance recommends ten measurements be taken, in no particular order, outside at approximately 1 m above the ground (DHS, 2017). If the UAS platform and sensor suite allow, measurements could be collected at higher altitudes.[3] See Chapter 2 for more information on height of survey considerations.

The distributed nature of the 10-point monitoring plan can present logistical challenges; however, all ten measurements do not need to be taken by the same individual or group and do not need to be taken by the responders who first arrive on scene. Using multiple teams of responders to collect the ten measurements can save time but requires coordination across groups and with incident command. Responders need to receive either geolocations or landmarks to orient where to collect each measurement. Data should be uploaded to a real-time incident map or shared with an emergency operations center. The upload does not need to happen immediately on collecting the measurement; responders in the field may not have access to a data link, so the upload can occur after the team returns to its base of operations (DHS, 2017).

Concept of Operations

The 10-point monitoring plan requires collection of multiple radiation measurements across a wide area in a relatively short time and during the early phase of the response when responder availability is at a premium. UAVs can serve as a force multiplier for responders, potentially replacing a measurement team with a single UAV operator, enabling some or all members of the measurement team to support other aspects of the emergency response or to take additional measurements, speeding up completion of the 10-point survey. As UAV regulations catch up to current technology, a single operator could supervise the autonomous operation of multiple UAVs rather than control each platform individually.

The CONOPS described in this section is not meant to be exhaustive or prescriptive, and different responder organizations may choose to integrate UAVs into their operations to best fit their situation and resources.

Prerequisite Tasks

Assess Current Incident Response CONOPS

Before making any decisions about UAV integration, all responder organizations should have a radiological emergency response plan and be familiar with best practices for conducting a 10-point monitoring survey. A radiological response plan should outline which organization(s) will respond to a radiation emergency in the responder organization's area of responsibility and the anticipated response timelines. Recognizing that each incident response is unique and dependent on the particulars of that situation, responder organizations should ensure that they know who within their organization may be responsible for carrying out the 10-point monitoring plan, what the CONOPS would be, and what resources responders would bring or need to request. DHS provides guidance on developing RDD response plans, particularly for the first 100 minutes of an incident (DHS, 2017).

[3] Responders will generally collect measurements at waist height, although any differences in height between responders or variations in detector carrying posture should not affect the comparability or fidelity of measurements. Comparing UAV measurements, which can be collected at higher altitudes, to measurements collected roughly ~1 m above the ground may require application of a correction factor to properly correlate, especially if the UAV sensor suite lacks the ability to measure altitude above ground level.

Inventory UAV and Detector Capabilities

Responder organizations should catalogue their UAV capabilities prior to any incident. This should include understanding what platforms and detectors they currently have access to, where these platforms and detectors are located, and what capabilities these platforms and detectors provide.

Gather Background Radiation Measurements

Ideally, responder organizations should have knowledge of the typical background radiation levels in their area of responsibility. Various organizations could have responsibilities or capabilities for taking measurements in specific areas, so responder organizations should coordinate with their partners.[4] If background levels cannot be obtained or are not available in an easily sharable format, it is possible to estimate background radiation levels by extrapolating from the background levels of adjacent locations.

Conduct Training and Obtain Permits, Licenses, etc.

Use of UAVs requires training, appropriate permits, and licenses. The FAA has many regulations for the use of UAVs. Some permissions to operate can be acquired prior to an incident, such as flying beyond visual LOS, and permissions may be expedited if the process, regulations, and waivers are understood prior to an incident.

Prepare for Local Weather and Terrain

The 10-point monitoring plan requires taking measurements over a large outdoor area, so local weather should be taken into consideration. Some weather conditions may not be conducive to using UAVs, such as heavy rain or snowfall, dense fog, and high winds. Outdoor operations can also involve complicated terrain or areas that have minimal roads, including steep elevations, dense vegetation, and coastal and riverine regions, so responders should be prepared to navigate the terrain in their area of responsibility and have backup survey capabilities prepared should environmental conditions prevent deployment of UAVs.

Mission Tasks

Following an RDD, responders need to act fast to secure the scene, start saving lives, and confirm the presence of radiation. Once those actions are underway, responders can begin planning for further measurements, including the 10-point monitoring plan. Responders can incorporate UAVs into the 10-point monitoring plan operations as follows:

Plan for Measurements

Depending on the affected area, available responders and UAVs and other competing operations, the incident command determines and communicates the locations for taking 10-point monitoring plan measurements. Ten measurement locations are selected according to the results of previously collected data to determine the direction of contamination (e.g., transect measurements, data from fixed sensors in the vicinity). Decision-makers also determine which groups of responders and UAVs are available to support which measurements. Factors to consider when making these decisions could include the following:

1. the number of responders and UAVs available to support measurements
2. the proximity of different groups of responders and UAVs to the measurement locations

[4] Background radiation surveys have been conducted at some level in every state, although the sizes of the areas covered and details vary. We recommend checking for state-level and local-level measurements. At a minimum, the U.S. Environmental Protection Agency monitors radiation through daily air sampling (in near real time) and periodic water sampling (Environmental Protection Agency, 2025). Additionally, DHS NUSTL has guidance on conducting background surveys (NUSTL, 2025).

3. the mobility needs for collection at a location
4. hazards for manned and unmanned operations in the vicinity
5. environmental limitations (weather, obstacles, etc.) that affect mobility, safety, and LOS of the UAVs
6. the maximum flight time and distance capabilities of the UAV platforms.

Communicate Measurement Locations to UAV Operators

After determining the measurement locations, incident command sends them to the responders who need to collect measurements, including to any UAV operators. This may be in the form of coordinates in CBRNResponder,[5] landmarks sent over the radio, or some other method. Incident command should also communicate which groups will collect radiation measurements at which points.

Travel to or Near Measurement Location, as Needed

Responders may not need to rely entirely on the UAV's mobility and power capabilities to maneuver the UAV and detector to the measurement location. Instead, these systems can be driven or carried to a location within range to launch and reach one or more points. Ideally, radiation levels at this location should be at or near background exposure levels to mitigate potential contamination of the responder and UAV and to keep the responder's exposure ALARA without jeopardizing the mission.

Deployed UAV Team Reassesses Environmental Conditions (e.g., weather, obstacles, other hazards)

Weather (e.g., rain, snow) will affect detectors, communications, and UAV operation; thus, knowledge and consideration of the conditions are necessary. Obstacles, such as high-rise buildings, smoke, trees, and vehicles, may obstruct LOS or present a hazard to safe operation of the UAV. Removeable radiological contamination, if present or suspected, may be resuspended off the ground if the UAV flies too low, presenting a hazard to people and buildings in the immediate area.

Check Detector Prior to Launching UAV

Measurement teams using UAVs need to check the detector prior to launching to ensure it is firmly positioned on the UAV, operating, and responding appropriately to radiation (e.g., testing against a radioactive source of known strength). Reaffirm the expected performance of the detector by taking a measurement with a check source of known radioactive quantity and, if in an area that is at background, take note of the background measurement.

Launch UAV and Travel to Measurement Location

The operator launches the UAV and ensures it travels to the measurement location. Under current standard operating procedures, this requires remote operation within LOS.[6] The UAV must launch, ascend to the desired flight path altitude, and travel to the measurement location while maneuvering around obstacles. Then, the UAV will either need to take a measurement at its current altitude or descend to take the measurement, such as to a few meters. Testing and evaluating the UAV system prior to an actual emergency will be

[5] CBRNResponder is a tool sponsored by FEMA for chemical, biological, radiological, and nuclear (CBRN) incident data-sharing and management. More information can be found at U.S. Fire Administration (2023), and both more information and the tool are accessible via the FEMA Office of Emerging Threats (FEMA, 2025).

[6] Current regulations, standard procedures, and available UAV technology pose significant barriers for establishing the capability to take measurements autonomously and/or beyond LOS. Should these barriers change—or drone programs develop procedures to resolve them—autonomous collection of measurements at preset locations may become desirable for collecting measurements to support the 10-point survey.

essential to understanding the limits of its capabilities and detection sensitivity, which are highly dependent on the detector being used. Considerations are as follows:

1. Extended hover, slow descent, or slow maneuver of a UAV can significantly increase power requirements, thus reducing flight time. However, smaller detectors (e.g., PRDs), may need to be closer to the ground to adequately detect lower levels of radiation. See Chapter 2 for additional information on how detector sensitivity is affected by height of measurement.
2. Flying low may also increase the risk that radioactive material beneath the UAS is disturbed by the rotor wash, resuspending contamination.

Collect Data

The UAV should slow down or stop at the measurement location to get an accurate measurement.[7] This measurement should include the gamma radiation measurement and units, longitude and latitude of current position, height, and time of collection. Note that the time for the 10-point monitoring plan is rapid, and all 10 points should ideally be collected in about 30 minutes, which may mean that multiple UAVs or combinations of UAV and human collection will be needed. UAVs may be able to collect multiple points per sortie, depending on distances, power reserve, and the speed of the loaded UAV.

Transmit Data

Responders should transmit the collected data to incident command for inclusion in a real-time incident map. If the UAV platform has connectivity and communication capabilities, data can be transmitted in real time. Although less ideal, data can also be transferred when the UAV returns to the operator if the detector cannot wirelessly communicate or if there is no other way to send data to the operator while in flight. In the latter case, survey and decontamination of the UAV may be necessary before data can be obtained. Transmitted or transferred data should include the radiation measurement value, units, instrument type (meter or probe), radiation type, height, location, date, and time.

Survey the UAV for Contamination on Return

Use a contamination probe to check the UAV for any significant contamination. If contamination is found, first responders should follow their organization's procedure for decontamination of their electronics equipment, as appropriate. Note that, for some short half-life isotopes (i.e., hours, days), isolating the UAVs for multiple half-lives until the radiation is undetectable might be possible.[8]

Example Scenario

RDD Response

An RDD (e.g., dirty bomb) can use explosive force to disperse radioactive material, potentially creating a plume of airborne radioactive particles. Although dependent on the particle sizes produced, most particles will settle to the ground about 10 to 15 minutes after detonation and by the time responders start collecting measurements for the 10-point monitoring plan. Radioactive material that precipitates over bodies of water

[7] The amount of time a detector needs to stay at the measurement location to get a good reading depends on several factors, including the detector itself, the amount of radioactive material, and the activity of the material. Distance from the detector to the material is also an important factor. First responders should be familiar with how their detectors operate and have an estimate of the measurement time (*dwell time*) that their detectors require.

[8] Discussion of decontamination techniques is beyond the scope of this report.

will be difficult to measure; if one or more of the ten points is over water, those points may need to be moved or skipped (DHS, 2017).

In the scenario illustrated in Figure A.2, an RDD explodes in downtown Chicago, a few blocks east of Millenium Park. Radioactive material quickly dispersed north-northwest across the Chicago River and throughout the Magnificent Mile. Some of the radioactive debris settled further north and into Lake Michigan.

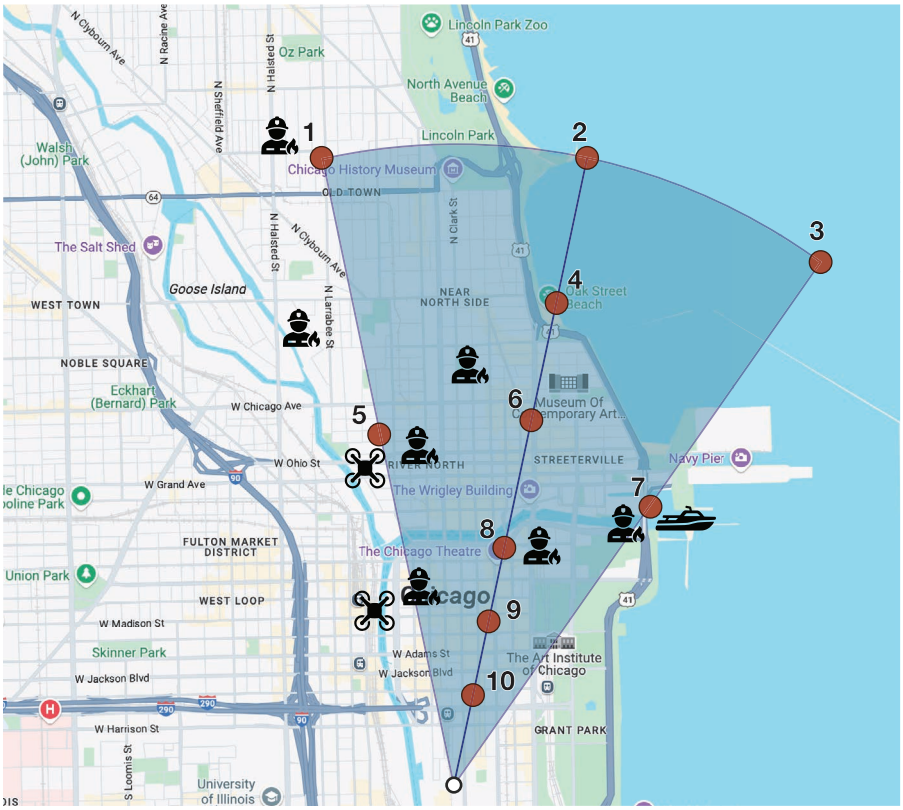
In responding to this emergency, incident command can take advantage of the existing footprint of Chicago Fire Department stations, personnel, and equipment. This includes manned surface vessels at the station near South Pier (A) and various UAVs in the area outfitted with radiation-detection capabilities (B).

Incident command would first establish the 10 points for measurement collection and assign them to appropriate teams according to proximity and capabilities. Measurements for points 1, 5, 7, and 8 can be collected at the nearby fire station and thus may not need to deploy any responders to gather data. Point 3 is sufficiently far over water that it can be skipped, as there would not likely be deposited material to meaningfully measure. The UAVs team south of the river can support measurements for points 9 and 10, as other responders in the immediate vicinity might be needed closer to the incident site. The UAVs team north of the river can support measurement in the dense urban environment around point 6 and near the waterfront for points 2 and 4.

This scenario presents several challenges. It involves collecting measurements in an urban area with multiple very tall buildings in close proximity, which not only poses a difficulty for aerial navigation and LOS,

FIGURE A.2

Chicago Radiological Dispersal Device 10-Point Monitoring Plan Response



SOURCES: Map data ©2025 Google and RAND analysis.

NOTE: Firefighter icons represent current fire stations in the affected area. Quadcopter icons represent assumed UAVs that can respond. Boat icons represent manned surface vessels that can support response.

but also can complicate communications between the UAVs and the operator. However, the Chicago River can inhibit north-south movement, especially for manned vehicles, that UAVs can more easily navigate. Finally, the expected plume would potentially deposit significant material into Lake Michigan, which would be difficult to measure but presents a minimal hazard to people. Wave action may also dilute readings taken too close to the waterfront. This makes measurements of deposition into the water a low priority during this phase of the emergency.

Detector Capability Needs

Gamma Detectors

Gamma detectors are the most useful for the scenario just discussed because most radionuclides—even ones that emit alpha and beta radiation—emit gamma radiation. Because the goal is to measure the exposure rate of radioactive material deposited by the plume onto the ground, a PRD or handheld survey meter would typically be used when humans are taking measurements. PRDs should adhere to American National Standards Institute (ANSI) standards (Institute of Electrical and Electronic Engineers Standards Association [IEEE-SA], 2016) for PRDs and measure exposure rate in units of microroentgens per hour (μR/h). These detectors can come in various form factors and sensitivities, provided they align with the UAV capability needs we discuss later. Although gamma spectrum analysis (via RIIDs) is not a focus of the 10-point monitoring plan, these measurements can allow responders to estimate alpha and beta radiation, which is important to determine the appropriate personal protective equipment (PPE) without needing to directly measure for these particles.

However, small detectors, such as PRDs, may require the UAV to reduce altitude to take a successful measurement. This may present significant operational limitations, depending on the environment to be surveyed, such as through the risk of the UAV dropping in between buildings (thus losing LOS and challenging control). If this is a possibility, response organizations may want to consider configuring a UAV that can carry a larger detector because larger detectors may be sensitive enough to take the required measurements many meters above the ground. See Chapter 2 for more discussion of detector size and height of measurement.

Alpha and Beta Probes

Most radionuclides that emit alpha or beta radiation also emit gamma radiation, which can often be detected at greater distances and altitudes. Therefore, the most feasible way to measure radiation levels is with a gamma detector. Using a RIID or a comparable instrument to identify the radioisotope can be a proxy method to rule the presence of alpha and beta radiation in or out without actually surveying for alpha and beta radiation directly.

In the rare case that the radionuclide emits only alpha or beta particles, an alpha or beta probe would be necessary to detect it. However, because of their limited range, these detectors must be close to the source or contaminated surface to be effective: Measuring alpha particles requires the probe to be no more than 0.5 cm from the surface, and measuring beta particles requires the probe to be no more than 7 to 8 cm from the surface. This level of proximity is not advised for a UAV, given hover and maneuverability capabilities and the potential for contaminating the UAV.

The technical limitations of taking alpha and beta radiation measurements pose a challenge to integrating UAVs into the 10-point monitoring survey. The procedure featured in the RDD response guidance asks responders to take these measurements to rule out the presence of alpha and beta radiation (FEMA, 2023c). Then, if alpha or beta radiation is detected, the guidance recommends that responders also take these mea-

surements as part of their 10-point survey. However, there are ways modify this procedure that would still allow integration of UAV capabilities into the 10-point survey, primarily through planning to

- Ensure that responders maintain the capability to rule out the presence of alpha and beta radiation through limited, manned collection by personnel
- In the unlikely circumstance that the material released emits only alpha or beta radiation, ensure that responders possess a capability to conduct the ten point monitoring survey with alpha and beta probes without support from UAVs and understand that the ten point survey may take longer to complete
- Recognize that most radioactive material that emit alpha or beta radiation also emit gamma radiation, so detection of the gamma radiation with UAVs may be sufficient for this early phase characterization of the extent and span of contamination spread—even if alpha or beta radiation is detected.

Non–Radiation-Detection Capabilities

The UAV sensor suite needs certain non–radiation-detection capabilities to support communication, geolocation, and altitude measurement. The sensor suite should be able to provide either the time or geolocation (including height) of any measurements taken. If the radiation instrument itself cannot measure altitude or geolocation, logging the time alone may be sufficient, provided another system or the UAV has the ability to track the platform's position over time. After the survey, the two data points—the measurement and time (from the detector) and the location data (from the UAV or other sensor suite)—can be combined after the survey. The sensor suite should also be able to communicate with the search team in real time and/or be able to record data for offline review. If data are recorded, the sensor suite should be able to offload data in a format that can be easily uploaded to the incident map (e.g., CBRNResponder).

Unmanned Aerial Vehicle Capability Needs

Given the mission needs for the 10-point monitoring plan, operations involving UAVs should incorporate platforms with the characteristics we describe in this section.

Carry and Effectively Employ Gamma Detectors

Gamma detectors are the most commonly needed instruments or detectors for 10-point monitoring plan measurements. Larger detectors give a greater sensitivity and can be flown at higher elevations but weigh more, which can limit performance and/or survey time. Detectors should be placed on the UAV such that the platform does not interfere with the ability of the detector to collect measurements—probably underneath the UAV with the sensor facing down. Power for the detector can come from its own battery, which may increase the payload weight for the UAV, or from the UAV itself, which may require additional reconfiguration and reduce flight time.

Receive Measurement Locations

The 10-point monitoring plan mission requires operators to maneuver to predetermined measurement locations. UAV operators need to know where these measurement locations are and be able to maneuver the UAV (or support autonomous maneuver of the UAV) to the locations. For manned operations, these locations may be based on landmarks, addresses, or intersections. For UAV operations, receiving locations in this format may not be as useful. Operators may prefer to receive this information instead as latitude or longitude points compatible with UAV GNSS systems.

Reach One or More Measurement Locations to Collect Data in a Timely Manner

The UAV must be able to measure radiation at multiple locations that are approximately 1 km or more apart. UAVs need to be able to travel quickly to and between these different measurement locations; however, the same UAV does not need to be used to collect a measurement from all ten points. Different UAVs starting from different locations can collect different points, and responders can collect measurements from certain points. UAVs that are not capable of traveling from a launch position to one or more measurement locations, taking a measurement, and returning within the estimated flight time, battery life, and payload conditions will likely not meet the mission need.

Collect Data on Ground Surface Contamination

The goal of the 10-point monitoring plan is to rapidly assess the extent of radioactive material deposited on the ground surface. For most RDD scenarios, the majority of a radioactive plume will likely settle 10 to 15 minutes after the detonation and by the time 10-point monitoring plan measurements are taking place.[9] This means that the UAV may need the ability to slowly descend and ascend to support gamma radiation measurements near the ground or to carry a gamma detector large enough to make an accurate measurement from the height of the flight path (see Chapter 2 for discussion on height of measurements). Radiation measurement is most accurate when the UAV is not moving or is moving very slowly (up to 0.8 m/s) because this allows the gamma detector time to collect more photons emanating from the source location. UAVs also need the ability to estimate their position above ground and record the height of the measurement (e.g., a laser-based altitude sensor).

Log and/or Communicate Radiological Data to Operator

The radiation-detection instrument must be able to log radiological data. Ideally, the data should also be communicated in real time to a dashboard accessible to the UAV operator or other emergency response personnel. The data can be fed from the detector or instrument either to a mobile device (phone, small tablet, etc.) that is also secured as a payload or directly to the UAV itself. Which option is available will depend on the specific capabilities of the detector or instrument and the UAV. The real-time data feed would enable responders to know that the UAV is successfully collecting radiological data and will speed up the availability of the data to public health officials and other emergency responders. If the data cannot be communicated live to a dashboard, they must be saved on the detection instrument itself for manual, hands-on retrieval after the UAV concludes its measurement and returns to the operator.

Remain Powered and Functional During Operation

The time it takes to complete the 10-point monitoring plan may vary depending on the emergency, the environment, and the availability of responders to support measurement. The flight path distance, launch location(s), speed, payload, presence of obstacles, LOS requirements, and desired time frame to complete measurements may strain UAV power limits. A UAV may need to have either sufficient energy storage to support its operations throughout the measurement collection process or the ability to return to the operator to swap or recharge batteries.

[9] In rare instances, collection of air samples of suspended radioactive material would be required (as opposed to collecting data on radiation emissions from that material). This collection would require specialized equipment (e.g., high-volume air samplers) and could not be done with a standard PRD or other portable gamma detector.

Key Performance Parameters

Each of the UAV and detector needs we have discussed is tied to key performance parameters, as shown in Table A.1.

Advantages and Disadvantages of Using Unmanned Aerial Vehicles

Using UAVs for the 10-point monitoring plan has both advantages and disadvantages. These should be considered along with such factors as cost, staffing, training, and maintenance in any decision to acquire and use UAVs. UAVs can allow personnel to maintain a safe distance when collecting measurements and free responders and resources for other important tasks, thus reducing workload and boosting effectiveness. UAVs can be used to collect measurements in places that may be inaccessible to people, such as rough terrain, heavily trafficked areas, or active transportation throughways (e.g., roads, highways, active train tracks).

UAVs also have disadvantages. For example, their time and place of operation can be limited by laws and regulations concerning privacy and air space. Operating a UAV beyond visual LOS without prior approvals may not be feasible in an emergency situation unless specific requirements have been met. UAVs may not be able to travel inside buildings because of the inability to get through doorways and concerns about resuspension of radioactive particles. They may also experience a loss of signal because of interference or a bad connection if there are obstacles, such as tall buildings, in the area. Inclement weather could prevent UAV operation or could cause flight times to be drastically reduced from exertion on the batteries, requiring that first responders rely on humans to take ground measurements. Finally, the UAV itself is not always designed with a specific detector in mind, so integration of new or multiple detectors could require response organizations to embark on a significant do-it-yourself effort accompanied by testing and evaluation prior to establishing a proven capability.

TABLE A.1
Key Performance Parameters

Capability Need	Key Performance Parameters
Carry and effectively employ gamma detectors	• UAV payload capacity • UAV configuration and detector mounting
Receive measurement location	• Effective communication distance • Communication frequency bands compatible with other systems being used • Communication protocol compatible with other systems being used
Reach one or more locations to collect data in a timely manner	• UAV speed • UAV maneuverability (e.g., around buildings, trees, rubble)
Collect data measuring ground surface contamination	• Detector operating to standards • UAV configuration and detector mounting • UAV ascent and descent capabilities • UAV altitude above ground level measurement ability • UAV payload capacity • UAV hover capability
Log and/or communicate radiological data to operator	• Detector or instrument data log and storage • Detector-UAV or detector-cellular integration
Remain powered and functional during operation	• UAV power capacity • UAV power consumption • UAV repowering capability (e.g., battery swapping, simple refueling) for additional sorties

Table A.2 summarizes the advantages and disadvantages of UAVs in the 10-point monitoring plan use case, which first responders can use to aid decisionmaking about acquiring and employing UAVs.

Variations for Similar Use Cases

The 10-point monitoring plan demonstrates a use case requiring multiple radiation measurements across a relatively wide area and in a short time. The following are other use cases that may be similar and rely on multiple radiation measurements:

- plume transect
- near field survey
- radiological risk assessment
- CI assessment (for some subsets of CI assessments).

TABLE A.2
Advantages and Disadvantages of Unmanned Aerial Vehicles in 10-Point Monitoring

Category	Issue
Advantages	
Responder safety	• UAV use can allow responders to take measurements with minimal exposure to radiation. • UAVs are more resilient to radiation than humans and can be operated at a safe distance in areas with otherwise dangerous radiation hazards. The advantage is greater for incidents involving radiation sources with high radiation levels.
Mobility	• UAVs can fly over terrain that manned vehicles or on-foot operations can struggle with, such as dense foliage, steep inclines, lack of roads, and cross-cutting waterways. • UAVs can potentially reach measurement points faster than humans can. • UGVs and USVs offer fewer mobility advantages in this use case.
Efficient use of resources	• UAVs can combine different operational roles in one platform (e.g., viewing scene with video while measuring radiation levels). • UAVs may allow some personnel to return to roles other than taking radiation measurements, especially if fewer people are required to operate the UAV-detector system than if only personnel took measurements.
Disadvantages	
Environmental limitations	• Operating in dense urban areas or areas with large amounts of RF traffic can limit communications between operators and UAVs. • Weather will affect different modalities differently (e.g., wind will limit UAVs), so UAVs may not be available at all times. • Precipitation will affect communications with all UxSs. This includes the ability to directly operate and receive data from systems. Using preplanned routes or autonomous control and collecting data after the sortie, if appropriate, can minimize this disadvantage.
Regulatory limitations	• Regulations limit UAV operations beyond visual LOS; thus, in some areas, the operators or others need to follow any UAVs. This limitation does not apply to UGVs, but these are not likely to be used for this use case.
Operational limitations	• UAVs may need to descend to take accurate readings at certain measurement locations, depending on the amount of radioactive material and the level of background radiation.
Technology limitations	• Power sources for UAVs and related operational time may be short. This can be a real challenge for this use case because it can require using UAVs over large areas, far from a power resupply (battery change, fuel, etc.). • Connectivity issues between operators and UAVs are not uncommon. Wi-Fi and cellular communications may not always be available in a location or in an emergency, and UAVs typically do not use first responder frequencies, which may be available. • UAVs and radiation detector integration may not be well developed. This is a consideration for system acquisition but can be overcome with time and effort.

Responders for a nuclear power plant emergency might also need to make multiple radiation measurements across a wide area quickly to characterize plume deposition, similar to the 10-point monitoring plan. Although there are various potential radiation emergencies at nuclear power plants, only some involve the formation of a plume of radioactive material that can be dispersed far from the premises over a long period. These include partial or complete reactor core meltdowns or fuel element failures. In these incidents, an explosion or fire proximate to the core and/or contamination of the reactor coolant steam with material from the core can release radioactive materials high in the air. In responding to these incidents, FEMA recommends that responders and plant licensees conduct measurements along the plume centerline and boundary early in the response to inform the accident assessment. This could include assessment of deposited radioactive material and air-based measurements (FEMA, 2023d). Plume deposition measurements may need to be collected five miles or more from the plant to support evacuation decisions (DHS, 2023). These measurements contrast to the closer-in measurements assumed for the 10-point monitoring plan for an RDD. They also may involve tracking an active plume that can cause dispersal of nuclear material far from the source, which is a more complex task than the one described as part of the 10-point monitoring plan for an RDD.

APPENDIX B

Use Case: Locating Lost, Stolen, or Orphaned Source

This appendix describes the locating a lost, stolen, or orphaned source use case and provides the following information:

1. rationale for using UxS
2. steps for using UxS and timeline considerations
3. capability needs to aid decisions
4. advantages and disadvantages
5. similar use cases.

This appendix is intended to be a generalized reference document for responders grappling with using UxS for locating a lost, stolen, or orphaned radioactive source.[1] It should be read well before an incident so that first responders can gather information for their specific location and possible situations and determine whether and which kind of UxS is appropriate.

Purpose

Occasionally, radiological sources fall out of regulatory control. These sources can be unintentionally lost, stolen, or simply orphaned, which can pose a risk to the public if not recovered before being handled or manipulated by unauthorized people. UxSs can be used to efficiently search for the source, locate it, and bring it back into regulatory control.

Mission Description

If a radioactive source used in a regulated item is lost, stolen, or orphaned, it becomes a potential hazard and must be located through a search process, potentially over a large area. As part of this mission, operators search for such radioactive sources using a systematic approach to cover a search area completely and efficiently.

[1] For brevity, sources will be referred to as *lost*, but the information also applies to stolen and orphaned sources.

Concept of Operations

UxSs can support finding radioactive sources by systematically taking radiation measurements over a potentially wide area. UxSs can serve as a force multiplier for responders, potentially replacing a measurement team with a single UxS operator and a platform.

The following discussion demonstrates how UxSs might be integrated into radioactive source search operations. The CONOPS we describe is not meant to be exhaustive, and different responder organizations may choose to integrate UxSs into their operations to best fit their situation and resources.

Prerequisite Tasks

Determine the Area Where the Lost Source Is Likely to Be Found

Before a UxS is used to search for a lost source, some information should be obtained, including the boundaries of the area where the source is likely to be found. For a source known to have been lost during transit, a starting point for these bounds would be the path traveled by the courier.

Gather Background Radiation Levels for the Search Area

The background radiation levels in the search area will ideally be known ahead of time. This information will aid in determining whether an elevated reading is due to a source or simply background fluctuation. Responder organizations and partners should have knowledge of the background radiation levels for different locations in their area of responsibility. Various organizations could have responsibilities or capabilities for taking these measures in any specific area, so responder organizations should coordinate any measurements with partners.[2] If background levels cannot be obtained prior to the search, it is possible to estimate the background rate in one region by extrapolating the background rates of adjacent regions where the source is known not to be or highly unlikely to be present.

Obtain Information About the Lost Source

Information about the lost source should be obtained, if available. Such information may include the radionuclide, its emission types (alpha, beta, neutron, and/or gamma), the activity of the source, size of the source, its housing (if any), and the expected state of housing (e.g., intact, breached). If it is known or suspected that a source was breached, radioactive contamination could potentially have spread across a wide area. Some sources are transported in shielding material, which will diminish the amount of radiation that can be detected during the search.

Ensure That the UxS Used Has Needed Capabilities and That the Search Team Understands the Sensor Suite

The UxS used must be capable of covering the area where the lost source is believed to be. It should be capable of carrying the radiation detector and other sensors without impeding its operation. It must have sufficient power onboard to cover the search area or a method to rapidly repower, such as swappable batteries.

[2] Background radiation surveys have been conducted at some level in every state, although the sizes of the areas covered and details vary. We recommend checking for state-level and local-level measurements. At a minimum, the U.S. Environmental Protection Agency conducts monitoring of radiation through daily air monitors (operating in near real time) and periodic water sampling (U.S. Environmental Protection Agency, 2025). Additionally, DHS NUSTL has guidance on conducting background surveys (NUSTL, 2025).

Conduct Training and Obtain Permits, Licenses, etc.

Use of UxSs requires training, appropriate permits and licenses. The FAA has many regulations for the use of UAVs. Some permissions to operate can be acquired prior to an incident, such as flying beyond visual LOS, and permissions may be expedited if the process, regulations, and waivers are understood prior to an incident.

Understand Weather Conditions

Weather will affect detectors, communications, and vehicle usage, whether unmanned or manned; thus, knowledge of the conditions is necessary. If LOS is needed to operate UxSs, poor weather may mean they cannot safely be used. Heavy rain and wind can affect RF communications, thus hampering the sending of commands and receipt of data. If waypoints are used and if data are recorded for later viewing, the system could become usable.

Mission Tasks

Searching for a lost source involves five key tasks.

Select a Pattern-Based—e.g., Grid, Zigzag, or Parallel Line—Survey to Locate the Source

The boundary of the survey area is the region where the lost source is most likely to be. The optimal altitude and spacing of survey points or lines will be highly dependent on the expected activity of the radioactive source and the sensitivity of the detector, so it is not feasible to provide generalized guidance that applies to all scenarios and equipment. The detector should dwell for a minute in areas where more data are needed. Prior to employing UxSs for this survey, responders will need to understand the detection capabilities of their equipment, particularly its sensitivity at various distances from a point source of radioactive material. Some UxS manufacturers of integrated radiation-detection equipment provide benchmark data that can inform the ideal survey pattern.[3] In general, if the nuclide(s) and activity(s) are not known, the altitude and spacing can be adjusted as appropriate for higher-activity sources or sources that emit more penetrating radiation. For example, a 10-Ci source of Co-60, which emits dual high-energy gammas, will be detectable with a PRD at a distance of about 300 m, but the lower-energy gamma from a 10-Ci Americium-241(Am-241) source is only detectable at a distance of up to 100 m with the same instrument. Thus, the search pattern when searching for a Co-60 source can be flown with more widely spaced lines and/or grid locations than for an Am-241 source of the same activity. Depending on the situation, experts may be needed to analyze the data and report results. For most cases, any areas where a reading is two or more standard deviations above typical background radiation levels are candidates for further investigation and surveys.

Check Detector Prior to Initiating Search

A measurement team using a UxS needs to check the detector prior to launching to ensure that it is firmly positioned on the UxS, operating, and responding appropriately to radiation (e.g., testing against a radioactive source of known strength). Reaffirm the expected performance of the detector by taking a measurement with a check source of known radioactive quantity and, if in an area that is at background, take note of the background measurement.

Examine Candidate Areas Thoroughly, Including Visually

Candidate areas with elevated radiation measurements should be examined thoroughly by the UxSs or by humans. Examination should include a visual inspection of the area.

[3] For additional information on spacing and coverage concepts, see NUSTL (2025).

Identify and Characterize the Source of Radiation

Once the presence of a radioactive material has been confirmed, the search team should try to identify the precise location by conducting a visual inspection.[4] This visual inspection should also collect photos or video that technical personnel can use in combination with radiation measurements to assess whether the radioactive source's containment has been damaged. A detector capable of identifying radionuclides, such as a RIID, could also be used to identify the isotope(s), to help adjudicate whether or not elevated levels of radiation are the result of the lost source.

Inform the Source Recovery Team

The source's location, information about its condition, and radiation exposure measurements should be communicated to the recovery entity, which will put the source back under regulatory control.

Survey the UxS for Contamination on Return

Use a contamination probe to check the UxS for any significant contamination. If contamination is found, follow your organization's procedure for decontamination of first responder electronics equipment, as appropriate. Note that, for some short-half-life isotopes (i.e., hours, days), isolating the UxS for multiple half-lives until the radiation is undetectable might be possible.[5]

Example Scenario

Three pieces of background information should be obtained before starting the search for a lost source: boundaries of the area where the source is likely to be found, background radiation levels, and information about the source. Such information may include the radionuclide, radiation types (i.e., alpha, beta, neutron, and/or gamma), the activity of the source, the size of the source and its housing (if any), and the expected state of the housing. Figure B.1 shows an example search area.

The search is performed by conducting a grid or parallel line survey; Figure B.2 illustrates the latter. The size of the grid will be determined by the capabilities of the detector, as will the speed of the survey. In some cases, for example when the source may be along a slope, the UxS will need to travel vertically. The detector should stay in or return to areas where more data are needed. Areas with radiation levels two or more standard deviations above typical background radiation levels are candidates for the location of the source. These areas may be determined in real time or once data are obtained from the detector on its return to the operator. Radiation safety technical experts may be needed to interpret the data. Other sensors, such as a camera, are essential for navigation and to inspect the source. Once the source is located and identified as the lost source, it should be turned over to the recovery entity. This report does not discuss recovery techniques, including use the potential use of UxSs for recovery. Recovery should be managed by a specially trained hazmat or source recovery team.

Detector Capability Needs

Gamma Detectors

Gamma detectors are useful in this scenario as most radionuclides emit gammas. These detectors should adhere to ANSI standards for PRDs (IEEE-SA, 2016) and DHS standards for RIIDs (DHS, 2019). The expo-

[4] Some sources have a label, engraving, or tag attached to them identifying the source.

[5] Discussion of decontamination techniques is beyond the scope of this report.

FIGURE B.1
Search Area

SOURCES: Dmytro/stock.adobe.com (photo) and RAND analysis.

NOTE: If a source is lost during transport, the search area should include the road the source was transported on and the area adjacent to the road, as indicated by the yellow shading. A grid or parallel line survey should be performed inside the search area with the spacing between measurement points or lines being approximately 3 ft. It may be necessary to search underneath the road, e.g., if it is on a bridge.

sure rate meter should read in units of μR/h, per the ANSI standard. These detectors can come in various form factors and sensitivities, provided they align with the UxS requirements we discuss later. In general, a PRD would be sufficient for locating the source; however, a RIID is useful in identifying isotope(s) and confirming that the lost source in question was located.

Alpha and Beta Probes

Most radionuclides that emit alpha or beta radiation also emit gamma radiation, which can often be detected at greater distances and altitudes. Therefore, it will be most feasible to measure radiation levels with a gamma detector. Using a RIID or a comparable instrument to identify the radioisotope can be a proxy method to rule the presence of alpha and beta radiation in or out without actually surveying for alpha and beta radiation directly.

In the rare case that the radionuclide only emits alpha or beta particles, an alpha or beta probe would be necessary to detect it. However, because of their limited range, these detectors must be close to the source or contaminated surface to be effective: Measuring alpha particles requires the probe to be no more than 0.5 cm from the surface, and measuring beta particles requires the probe to be no more than 7 to 8 cm from the surface. This level of proximity is not advised for a UAV, given hover and maneuverability capabilities and the potential for contaminating the UAV. A UGV with a robotic arm capable of holding the alpha or beta probe in close proximity to the ground or surface could potentially be used here, although this could lead to contamination of both the UGV and the radiation detector. But, in all cases, it would be extremely difficult

FIGURE B.2
Illustrative Parallel Line Search Pattern

SOURCES: Lost_in_the_Midwest/stock.adobe.com (photo) and RAND analysis.
NOTE: An example of a parallel line search in a field. The bounds of the search area (i.e., the area in which the source is most likely to be found) are denoted by the red lines. The path of the search is denoted by the yellow arrows. The spacing of the lines is increased for clarity; in practice, the spacing should be approximately 3 ft. The lines will need to follow the contours of the terrain. The figure shows a two-dimensional projection.

to find a source that emits only alpha or beta radiation using any UxS and similarly tedious for a person to conduct such a search.

Non–Radiation-Detection Capabilities

The sensor suite needs to be able to communicate with the search team in real time or have the ability to record radiation measurements and GPS coordinates for offline review. If the data are being recorded, the sensor suite should be able to offload data in a format that can be easily uploaded to the incident map (e.g., CBRNResponder). If a RIID is used, the detector and UxS pair should be able to alert the operator when a spectrum is successfully taken, so that they can adjudicate the information and/or move the UxS to the next measurement location. Once located, identifying the source visually is often easy because many sources have tags attached with information about the source and its activity. If such a tag is not present, a RIID would be necessary to confirm that the source is the lost source in question.

UxS Capability Needs

Given the mission needs for locating a lost source, operations involving UxSs should incorporate platforms with the characteristics we describe in this section.

Provide Sufficient Operating Time

Depending on the size of the search area, the UxS run time can be critical for the operation. A UxS may need to have either sufficient energy storage to support its operations throughout the measurement collection process or the ability to return to the operator to have an energy solution swap or recharge. Some ground-based systems can run up to five hours on a single charge with limited payload capacity; although not common as of time of writing, some fixed-wing air-based systems can run for two or more hours with continuous use (Wilson et al., 2020).

Ensure Connectivity to the UxS Operator

The operator needs to be able to control the UxS. Although typical radiation detectors passively measure and log measurements, some RIIDs may require operator input to trigger a radioisotope identification. Many UxSs are connected to the operator by cellular or other wireless connection, which can be supported by a personal hot spot or other signal repeaters if the area has an unreliable network. If tethers are used for the UxS, operators should carefully consider any potential limit to maneuverability if the UxS needs to cover a geographically large area or an area with obstacles. Tethers may be beneficial if the search must be conducted in a dense RF environment or underground.

Are Appropriate for the Environment in Which They Will Be Used

The type of UxS depends on the environment. For example, indoor searches could be limiting for UAVs, given maneuverability and navigation complexities, so ground systems, such as a crawler with wheels or treads or a walking (doglike) robot with legs or wheels, would be more appropriate. For rough, steep, or otherwise inaccessible terrain, a UAV is likely preferable. Similarly, if the search area covers a very large unpaved outdoor area, a UAV will probably be faster and more efficient than a UGV. The UxS must also be able to conduct maneuvers the operator is familiar with at specific speeds and heights that will facilitate collection of radiation measurements.

Carry and Effectively Employ Gamma Detectors

The payload configuration of the UxS system depends on the lost source that needs to be found and the needs of first responders. A PRD is sufficient for most cases because most radionuclides emit gammas, and PRDs are typically small and lightweight, so many UxSs can carry them. However, using a larger, more sensitive detector allows wider gaps between survey lines or points and higher UAV flights while maintaining detection capability—at the cost of a heavier payload and potentially shorter battery life.

Key Performance Parameters

The UxS should meet the key performance parameters shown in Table B.1 to successfully conduct a lost source search.

Advantages and Disadvantages of Using Unmanned Systems

Table B.2 summarizes the advantages and disadvantages of using UxSs to search for and locate a lost source. First responder entities can use this table to aid decisionmaking about acquiring and employing UxSs for missions. These should be considered along with such factors as cost, staffing, training, and maintenance in any decision to acquire and use UxSs.

TABLE B.1
Key Performance Parameters

Capability Need	Key Performance Parameter
Provide sufficient operating time	• UxS power capacity • UxS power consumption • UxS repower capability (e.g., battery swapping, simple refueling) for additional sorties
Ensure connectivity to the UxS operator	• Effective communication distance • Communication frequency bands compatible with other systems being used • Communication protocol compatible with other systems being used
Be appropriate for the environment where they will be used	• UxS maneuverability (e.g., around buildings, trees, rubble) • UxS speed and detector response time – Travel over the terrain at a speed of about 1 m/s (3 ft/s) – Dwell up to a minute when needed – Any PRD alarm within 2 seconds – Readings in μR/h
Carry and effectively employ gamma detectors	• UxS payload capacity • UxS configuration and detector mounting • ANSI N42.32-2016 (IEEE, 2016) • Meets *Technical Capability Standard for Handheld Instruments Used for the Detection and Identification of Radionuclides—2019* (CWMD, 2019)

TABLE B.2
Advantages and Disadvantages of Unmanned Systems to Search for and Locate a Lost Source

Category	Issue
Advantages	
Responder safety	• UxS use can allow responders to take measurements with minimal exposure to radiation. • UxSs are more resilient to radiation than humans and can be operated at a safe distance in areas with dangerous radiation hazards. The advantage is greater for incidents involving radiation sources with high radiation levels. • UxSs, especially UGVs, may be able to be configured to recover lost, stolen, or orphaned sources once located, further limiting human exposure.
Mobility	• UAVs can fly over terrain that manned vehicles or on-foot operations can struggle with, such as dense foliage, steep inclines, lack of roads, and cross-cutting waterways. • UAVs can survey areas too high for human operators. • UGVs can reach confined spaces too tight for human operators, such as culverts or underneath rubble.
Efficient use of resources	• UxSs can combine different operational roles in one platform (e.g., viewing scene with video while measuring radiation levels). • Use of UxSs may allow some personnel to return to roles other than taking radiation measurements, especially if fewer people are required to operate the UxS-detector system than if only personnel conducted measurements.
Disadvantages	
Environmental limitations	• Operating in dense urban areas or areas with large amounts of RF traffic can limit communications between operators and UxSs. • Weather will affect different modalities differently (e.g., wind will limit UAVs), so the UxSs may not be available at all times. • Precipitation will affect communications with all UxSs. This includes the ability to directly operate and receive data from the systems. If preplanned routes or autonomous control is used and postsortie data are appropriate, this disadvantage can be minimized.
Regulatory limitations	• Regulations limit UAV operations beyond visual LOS; thus, in some areas the operators or others need to follow any UAVs. This limitation does not apply to UGVs.

Table B.2—Continued

Category	Issue
Technology limitations	• Power sources for UxSs and related operational time may be short. This can be a real challenge for this use case because it can require using UxSs over large areas far from a power resupply (battery change, additional fuel, etc.). • Connectivity issues between operator and UxSs are not uncommon. Wi-Fi and cellular communications may not always be available in a location or in an emergency, and UxSs do not typically use first responder frequencies, which might be available. • UxS and radiation detector integration may not be well developed. This is a consideration for system acquisition but can be overcome with time and effort.

Variations for Similar Use Cases

The lost source use case covers many different scenarios, sizes, and shapes of pattern search areas. Similar use cases that need a search pattern include the following:

- background radiation monitoring
- preevent survey
- prerelease monitoring
- directionality
- outlying areas survey
- wide-area survey
- grid survey
- boundary resurveys
- waterway monitoring
- deposition monitoring
- CI assessment
- remediation sampling and analysis
- verify remediation.

When considering the acquisition and use of UxSs, an entity may wish to include these use cases in their decision process.

APPENDIX C

Use Case: Critical Infrastructure Assessment

This appendix describes a CI assessment use case and provides the following information:

1. rationale for using UxSs
2. steps for using UxSs and timeline considerations
3. capability needs to aid decisions
4. advantages and disadvantages
5. similar use cases.

This appendix is intended to be a generalized reference document for responders grappling with using UxS for assessing CI after a radiation emergency. It should be read well before an incident so that first responders can gather information for their specific location and possible situations and determine whether and which kind of UxS is appropriate.

CI covers many different areas and types of locations. Cybersecurity and Infrastructure Security Agency (undated) defines 16 CI sectors

> whose assets, systems, and networks, whether physical or virtual, are considered so vital to the United States that their incapacitation or destruction would have a debilitating effect on security, national economic security, national public health or safety, or any combination thereof.

Various types of locations would need measurements taken in an emergency, such as waterways (e.g., rivers, reservoirs), buildings (e.g., offices, factories, hospitals), bridges, vehicles (e.g., planes, trains, trucks, pipelines), and fields (including farms).

This use case focuses primarily on urban situations but can be applied more generally and adjusted for a jurisdiction's details, such as geographic size, number and variety of man-made structures, and types of CI (e.g., bridges, reservoirs, critical manufacturing plants, stadiums, malls, hospitals). It contains three parts: inside a building, outside one or more structures, and both inside and outside a large structure.

Purpose

Following a radiological emergency, such as a nuclear detonation or incident involving radioactive contamination, responders will need to understand

- the extent of damage to and around CI
- where it is safe for manned operations in and around CI
- safe route(s) to a location around or within CI (referred to as the *location of interest*).[1]

[1] Although UxSs may be helpful tools that first responders can use to identify a safe route for evacuation or access to CI or to look for people in need of assistance, the risk of radiation exposure to first responders is rarely a sufficient reason to delay prompt evacuation and medical treatment to people whose lives are in imminent danger.

For a response to a radiological incident, access or evacuation route(s) would need to be identified to clear debris, avoid fires and other hazards, and minimize radiation exposure (Centers for Disease Control and Prevention, 2024; NRC, 2021a). Areas with elevated or dangerous radiation levels may be encountered along the route, but, by limiting the time in the area or increasing the distance from the highest radiation areas, exposures can be ALARA. The route or location of interest might be inside or outside buildings or both, but radiation measurements are needed to determine where to go and what precautions are needed for first responders to remain as safe as possible. There may or may not be a need to identify the type of radiation source material and characterize contamination during the CI assessment process.

Mission Description

The overall mission is to determine the safest route to a location of interest. There may be a need to access the location of interest to turn on, turn off, or otherwise operate vital equipment for the CI. Nonradiological hazards (e.g., structural, chemical) may also be present, which can be investigated concurrently with radiation measurements, if the UxS can accommodate the necessary equipment. These nonradiological needs will not be explicitly stated in this appendix, but the approaches could include them.

Concept of Operations

UxSs can be used to support radiation measurements for CI assessment following a radiation emergency. Federal guidance already recommends using UxSs to safely explore and restore CI independent of the radiation measurement mission (FEMA, 2023c). This mission requires systematically taking radiation measurements in a facility and, possibly, within a short period to access and operate important systems within the facility. UxSs can also serve as a force multiplier for responders, potentially replacing a measurement team with a single UxS operator and platform.

The CONOPS described here is not meant to be exhaustive, and different responder organizations may may choose to integrate UxSs into their operations to best fit their situation and resources.

Prerequisite Tasks

Understand the Details of the CI to Prepare for Incidents

This includes, when possible, contact information; layouts of the site; knowing where important control locations for the CI might be; and, for sites that regularly have radiation sources, knowing the sources, activities, and expected radiation types. Building floorplans are useful because walls can interfere with LOS and affect UxS operation.

Gather Background Radiation Levels in and Around the CI

Background radiation measurements may be collected by first responders or another entity (e.g., a state or county health department).[2] That entity should make the values available prior to or during an emergency so that typical background readings can be used for comparison.

[2] Background radiation surveys have been conducted at some level in every state, although the size of areas covered and details vary. We recommend checking for state-level and local-level measurements. At a minimum, the U.S. Environmental Protection Agency conducts monitoring of radiation through daily air monitors (operating in near real time) and periodic

Develop Knowledge of Typical Isotopes, if Any, in Area

There may be entities in the area that typically use radiation sources (e.g., hospitals, nuclear power plants, or laboratories). Knowledge of the isotopes commonly encountered is useful for understanding what radiation sources are likely to be involved in an incident. This information may be available from a state or county environmental or health department prior to or during an emergency.

Ensure That an Appropriately Configured UxS Is Available, That Training Has Been Conducted, and That Permits, Licenses, etc., Have Been Obtained

Ensure that the UxS and radiation detectors appropriate for this use case have been acquired and they have been included in training. The FAA has many regulations for the use of UAVs. Some permissions to operate can be acquired prior to an incident, such as flying beyond visual LOS, and permissions may be expedited if the process, regulations, and waivers are understood prior to an incident.

Identify Operational Radiation Exposure Decision Points Prior to the Emergency

Similar to knowing the background radiation, knowing what levels of radiation are acceptable for first responders to use prior to an emergency will reduce confusion and delays. Responders should know how to define radiation zones (e.g., dangerous radiation zone, hot zone), turnback levels, and what levels should be used in the process of determining safe routes for evacuation or access.

Understand Weather Conditions

Weather will affect detectors, communications, and UxS operation; thus, knowledge of the conditions is necessary. If LOS is needed to operate UxSs, poor weather may mean the UxSs cannot safely be used. Heavy rain and wind can affect RF communications, thus hampering the sending of commands and receipt of data. If waypoints are used and if the data are recorded for later viewing, the system could become usable.

Mission Tasks

CI assessment involves four key tasks.

Determine Radiation Types Present to Aid Understanding of Dangers and Potential PPE

This is important because, if alpha and beta radiation is present, responders may require additional PPE (e.g., respiratory protection). Knowledge of isotope(s) present can help rule out some types of radiation. The entity reporting the situation, such as a nuclear power plant or hospital, might be able to provide this information. If this information is not available, a UxS-mounted RIID can be used to determine the radioisotope. Alpha and beta probes, which directly detect alpha and beta radiation, require close proximity for detection, so they are not likely to be suitable for a UAV and might be difficult to mount on a UGV.

Conduct a Survey of CI to Determine Where Safe Routes and Locations of Interest Might Be

Use a survey pattern appropriate for the indoor or outdoor space and radiation type(s) in question. The combination of UxS and radiation detectors should be appropriate for the space (e.g., UAVs measuring up the side of a building, UGVs in a low ceiling hallway).

Essential equipment should be included in the survey. For example, surveys inside and around buildings should check whether contamination has entered intake and outflow for heating, ventilation, and air conditioning systems and water systems, thus further dispersing radioactive material if operated.

water sampling (U.S. Environmental Protection Agency, 2025). Additionally, DHS NUSTL has guidance on conducting background surveys (NUSTL, 2025).

The survey pattern should fit the area and be familiar to the UxS operator. Search-and-rescue operations and crime scene investigations use multiple types of patterns that could also be used for collecting radiation measurements. Some examples are

- mowing the lawn, also known as strip or parallel search
- grid search
- spiral or expanding (or shrinking) square
- sector or zonal.

Create a Map of Safe Areas and Routes, as Needed

Using the data collected, provide information to those who need access to the location of interest about which routes to take, which areas they can access, and which areas to stay away from. Depending on how the emergency is being coordinated, this information is likely to be sent to the real-time mapping system in use, such as CBRNResponder, and the incident command.[3]

Survey the UAS for Contamination on Return

Use a contamination probe to check the UAS for any significant contamination. If contamination is found, follow your organization's procedure for decontamination of first responder electronics equipment, as appropriate. Note that for some short half-life isotopes (i.e., hours, days), isolating the UAS for multiple half-lives until the radiation is undetectable might be possible.[4]

Example Scenario

CI may be a building, an exterior space, or may be a combination of both; therefore, we discuss three potential scenarios in this section. Although the basic tasks are the same, the details differ, including the likely UxS-detector combinations.

For all cases, the initial search pattern would be to follow the basic route or path one would expect to take to the location of interest if there were no radiation and collect measurements on either side of the path to understand how wide a safe path might be. If there are physical blockages or very high radiation measurements, alternative paths will need to be found. This would expand the survey area, either to known alternative routes or to search for entirely new routes. For each CONOPS, if a lifesaving situation arises (e.g., an injured person is located during the search), lifesaving operations should take precedence over radiation measurements (DHS, 2017).

CI with All Interior Space

This scenario assumes the response is taking place in a building with hallways, rooms, stairs, and possibly some larger spaces, such as a cafeteria or small atrium. The mission is to find a safe route to one or more locations of interest inside the building.

Given the walls and possible need to open doors, a crawling or walking (doglike) robot might be the better choice for a UxS, perhaps one with a robotic arm or gripping attachment. If there are multiple floors and stairs, the walking robot might be better than a wheeled or crawling UxS at navigating between floors, but if

[3] CBRNResponder is a tool sponsored by FEMA for chemical, biological, radiological, and nuclear (CBRN) incident data-sharing and management. More information can be found at U.S. Fire Administration (2023), and both more information and the tool are accessible via the FEMA Office of Emerging Threats (FEMA, 2025).

[4] Discussion of decontamination techniques is beyond the scope of this report.

space and conditions allow, a multirotor UAV might also be possible. However, operators should consider the potential contamination risk to people, the UAV, or the environment when operating a UAV indoors because low flight can disturb nearby dust and dirt through rotor wash.

Given the likely mix of shapes and sizes of the spaces, such as hallways, offices, and large spaces, the survey pattern will likely need to be tailored to the space. Each type of space could be its own zonal survey, with some being more like a grid or strip survey for large or regular shapes.

Initially, the UxS could follow the expected path to the location of interest (e.g., through a lobby, into office spaces, down a hallway, entering the room of interest), taking radiation measurements approximately every 3 ft, at a speed appropriate to the detector. If the hallway is significantly wide, the UxS can zigzag down the hallway rather than conduct a grid or parallel survey, which will provide more information about the radiation levels, possibly in less time. If blockages are found or if radiation levels are too high, the UxS could try another route. Figure C.1 provides a notional situation inside a building with two locations of interest, to which people need access to operate important systems.

Depending on the types of walls and communication capabilities of the UxS, data could be sent back to the UxS operator. If communication inside the building is difficult and if there is a tether connected to the UxS, it can travel beyond LOS from the operator. If radiation measurements are being sent back to the operator and if those are showing low-enough levels to allow the operator to enter, the operator could follow behind the UxS—still close enough to communicate but at a safe distance from high radiation.

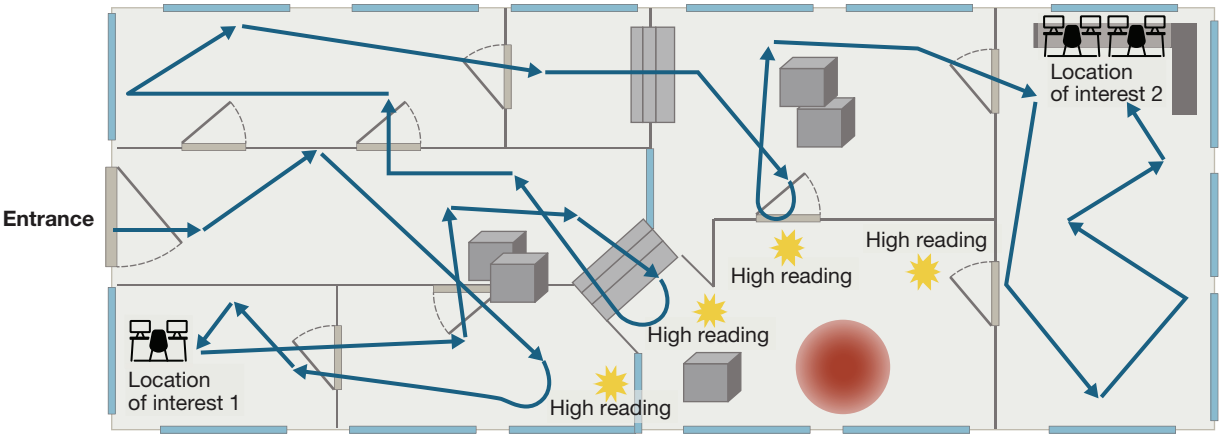
If, at any point, people in harm's way are discovered, lifesaving operations should begin. The risk of radiation exposure to first responders is rarely a sufficient reason to delay prompt evacuation and medical treatment to people whose lives are in imminent danger.

CI with All Exterior Space

This scenario of an exterior space might be applicable to the field of a football stadium (no roof), locating floors of a tall building with and without radiation as measured from outside, the campus of a large manu-

FIGURE C.1

Notional Illustration of Interior Unmanned System Radiation Measurement



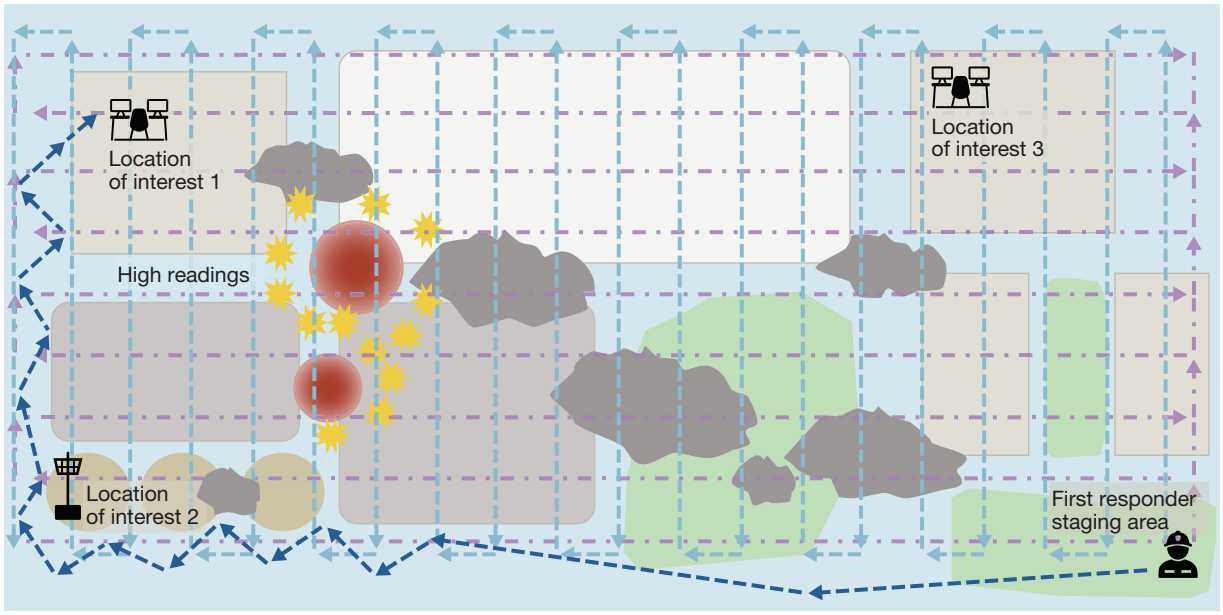
NOTE: The figure depicts a split-level building with two locations of interest, one near the entrance and one on the opposite end of the building. The red circle is the radiation source. Cubes represent physical blockages. Sets of horizontal rectangles are stairs. The solid dark blue line is route the UxS takes to locations of interest while mapping radiation levels. Yellow stars indicate locations of very high radiation readings, causing UxS to turn around because the route is not viable.

facturer or power plant, or the entertainment section of a city. The purpose of this scenario is to find a safe route to one or more locations of interest.

Initially, the UxS could follow the expected path to the location of interest (e.g., along a structure, up the sides of a structure, along the roof), taking radiation measurements approximately every 3 ft, at speed appropriate to the detector. If the space along the structure is wide enough, the UxS could zigzag along the path, taking measurements across the width to provide additional information for mapping the region. If blockages are found or if radiation levels are too high, the UxS could try another route. The UxS may need special treads to help navigate over rough terrain, debris or stairs. Figure C.2 provides a notional illustration of an outside situation containing three locations of interest, two inside buildings (e.g., control systems to be accessed) and one outdoors (e.g., a communications tower).

Depending on the distances and communication capabilities of the UxS, data could be sent back to the UxS operator during the process. If radiation measurements are being sent back to the operator and if those are showing low-enough levels to allow the operator to enter, the operator could follow behind the UxS—still close enough to communicate, but at a safe distance from high radiation. This can allow rapid refueling (e.g., battery swap) of the UxS in addition to possibly improved communications. Measurements up the side of a structure could help responders determine whether there is a radioactive source or contamination on a particular floor.

FIGURE C.2
Notional Illustration of Exterior Unmanned System Radiation Measurement



NOTE: The figure represents an exterior location that could be a manufacturing campus, power-generation location, or section of a city. Gray and brown rectangles and circles are buildings and structures. Green areas are nonbuilding spaces, such as parks. Irregular gray shapes are blockages, such as building debris. Red circles are radiation sources. There are three locations of interest to be reached. The staging area for first responders has been marked. The vertical teal dashed lines and horizontal purple dash-dot lines indicate a UAV route for basic mapping of both the physical situation and the radiation levels. An area of high readings is marked with yellow stars. The dashed dark blue line is a second UxS sortie, which could be UAV or UGV, to measure radiation levels more finely along potential routes to two locations of interest.

CI with Mixed Interior and Exterior Space

This scenario assumes there is both indoor and outdoor space or very large indoor space that has characteristics of an outdoor space, such as a warehouse or large manufacturing space (i.e., no hallways and rooms, but a mostly open floor plan). The purpose is to find a safe route to one or more spaces in and around the building.

Initially, the UxS could follow the expected path to the location of interest (e.g., through a lobby, onto the factory floor, along the path to the control room), taking radiation measurements approximately every three feet and at speeds appropriate for the detector. If possible, the UxS could zigzag along the route, taking measurements across the width of the potential path to increase the number of measurement points. If blockages are found or if radiation levels are too high, the UxS could try another route. Figure C.3 provides a notional illustration of a building with an open courtyard or field and interior building space.

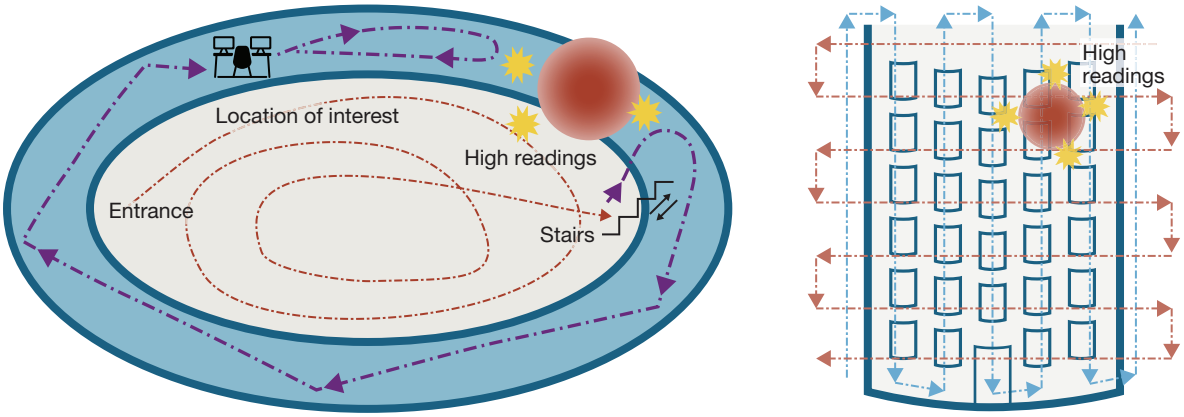
Depending on the space and communication capabilities of the UxS, data could be sent back to the UxS operator. If there is a tether connected to the UxS, it could travel beyond LOS from the operator. If radiation measurements are being sent back to the operator, and those are showing low enough levels to allow the operator to enter, the operator could follow behind the UxS—still close enough to communicate, but at a safe distance from high radiation.

Detector Capability Needs

Gamma Detectors

FIGURE C.3

Notional Illustration of Mixed Interior and Exterior Unmanned System Radiation Measurement



NOTE: The figure represents a mixed interior and exterior with a stadium-like or large interior courtyard building. The left illustration is a top view showing the location of interest, entrance to central area, stairs to the level with location of interest, and the radiation source (red circle). The right illustration is a side view showing the radiation source on an upper level. Multiple routes are shown for a UxS. In the top view, the open space has a UxS surveying in a spiral survey pattern, noting high readings at one end (yellow stars). The interior space has the notional hallways being surveyed on one level, although this could occur on multiple floors. The side view shows an exterior measurement using a UAS (light blue dashed line) traveling up and down the side of the structure and horizontal passes (light red dash-dot line) to see which floors have higher radiation levels (yellow stars).

Gamma detectors are useful in this scenario because most radionuclides emit gammas. These detectors should adhere to ANSI standards for PRDs (IEEE-SA, 2016) and DHS standards for RIIDs (DHS, 2019). The exposure rate meter should read in units of μR/h, per the ANSI standard. These detectors can come in vari-

ous form factors and sensitivities, provided they align with the UxS requirements we discuss later. In general, a PRD would be sufficient for detecting elevated levels of radiation, and a RIID provides the added benefit of also being able to identify identifying isotope(s).

Alpha and Beta Probes

Most radionuclides that emit alpha or beta radiation also emit gamma radiation, which can often be detected at greater distances and altitudes. Therefore, it will be most feasible to measure radiation levels with a gamma detector. Using a RIID or a comparable instrument to identify the radioisotope can be a proxy method to rule the presence of alpha and beta radiation in or out without actually surveying for alpha and beta radiation directly.

In the rare case that the radionuclide emits only alpha or beta particles, an alpha or beta probe would be necessary to detect it. However, because of their limited range, these detectors must be close to the source or contaminated surface to be effective: Measuring alpha particles requires the probe to be no more than 0.5 cm from the surface, and measuring beta particles requires the probe to be no more than 7 to 8 cm from the surface. This level of proximity is not advised for a UAV, given hover and maneuverability capabilities and the potential for contaminating the UAV. A UGV with a robotic arm capable of holding the alpha or beta probe in close proximity to the ground or surface could potentially be used for this used case, although this could lead to contamination of both the UGV and the radiation detector. But, in all cases, it would be extremely difficult to find a source that emits only alpha or beta radiation using any UxS and similarly tedious for a person to conduct such a search.

Non–Radiation-Detection Capabilities

Regardless of the sensor suite used on the UxS, it needs the ability to communicate with the response team in real time or have the ability to record radiation levels and GPS coordinates for offline review. If data are recorded, the sensor suite should be able to offload data in a format that can be easily uploaded to the incident map (e.g., CBRNResponder).

Unmanned System Capability Needs

For CI assessment missions, operations involving UxS should consider platforms with the characteristics we describe in this section.

Carry and Effectively Employ Radiation Detectors

Gamma detection is likely to be the most effective for this use case and needs to be facilitated by the UxSs. The detector should be fitted to the UxS in a location that does not interfere with readings or UxS operation. Power for the detector(s) can come from its own battery, which may increase the payload weight for the platform, or from the UxS, which may require additional reconfiguration.

Given information obtained from initial readings or prior knowledge of the source, alpha and beta probes may need to be fitted to the UxS to properly assess the situation. If this capability is needed, the UxS must be able to facilitate either fast and simple detector swapping or must be able to easily hold multiple detectors and in close proximity from the ground or surface being scanned.

Provide Clear Scans of Critical Infrastructure

The UxS needs to be able to move and navigate in indoor or outdoor environments to facilitate radiation measurements in a timely manner. The UxS must be able to maneuver at the desired height and speed to get the best readings at the operator's direction or to follow a preprogrammed path. All UxS location and flight altitude data must be in a format the operator can use.

Meet Needs of the Environment

The UxS must be able to operate in or around the CI, which may involve air, land, or maritime environments (e.g., UAV, UGV). Required capabilities can vary depending on several factors, including inclement weather and the type of space (i.e., indoor or outdoor), which can greatly affect UxS selection and performance. Indoor measurements can be facilitated by both air- and ground-based UxS; however, UAVs may not be suitable for some indoor environments that require tight navigation or where resuspension of radioactive material may be a concern. If there are multiple floors and stairs, a walking robot might be a better option for navigating between floors than a crawling UxS.

Remain Powered and Functional During Operation

The CI mission may involve long distances to reach locations of interest, depending on the emergency and the details of the location. This time frame may strain UxS power limits. A UxS may need to have either sufficient energy storage to support its operations throughout the measurement-collection process or the ability to return to the operator to have an energy solution swap or recharge.

Key Performance Parameters

Each of the UxS and detector needs we have discussed is tied to key performance parameters, as shown in Table C.1.

Advantages and Disadvantages of Using Unmanned Systems

Table C.2 summarizes the advantages and disadvantages of using UxS for CI assessment. First responder entities can use this table to aid their decisionmaking about acquiring and employing UxSs for missions. These should be considered along with such factors as cost, staffing, training, and maintenance in any decision to acquire and use UxSs.

Variations for Similar Use Cases

The CI assessment use case covers many different scenarios. The subset presented here demonstrates a use case needing a search pattern or mapping of radiation levels for an indoor or outdoor situation. Other similar use cases could include the following:

- background radiation monitoring
- preevent survey
- prerelease monitoring
- locate lost, stolen, or orphaned source; directionality

TABLE C.1
Key Performance Parameters

Capability Need	Key Performance Parameter
Carry and effectively employ radiation detectors	• UxS payload capacity • UxS configuration and detector mounting • UxS speed and detector response time
Receive measurement locations	• Effective communication distance • Communication frequency bands compatible with other systems being used • Communication protocol compatible with other systems being used
Place detector at appropriate height above ground	• Detector mounting • Detector height (possibly UxS altitude) control
Send radiation measurement with location and time stamp to incident map	• Communication distance • Communication frequency bands compatible with other systems being used • Communication protocol compatible with other systems being used
Maneuver around potential blockages	• UxS maneuverability (e.g., around buildings, trees, rubble)
Remain powered and functional during operation	• UxS power capacity • UxS power consumption • UxS repower capability (e.g., battery swapping, simple refueling) for additional sorties

TABLE C.2
Advantages and Disadvantages of Unmanned Systems for Critical Infrastructure Assessment

Category	Issue
Advantages	
Responder safety	• UxS use can allow responders to take measurements with minimal exposure to radiation. • UxSs are more resilient to radiation than are humans and can be operated at a safe distance in areas with dangerous radiation hazards. The advantage is greater for incidents involving radiation sources with high radiation levels. • UxSs, especially UGVs, can recover any needed physical samples, further limiting human exposure.
Mobility	• UAVs can survey areas too high for human operators to reach. • UGVs can reach confined spaces, such as culverts or underneath rubble, that are too tight for human operators. Some UGVs can climb upstairs, traverse debris, or open doors, making them useful inside buildings.
Efficient use of resources	• UxSs can combine different operational roles in one platform (e.g., viewing scene with video while measuring radiation levels, measuring other contaminants with additional sensors). • Use of UxSs may allow some personnel to return to roles other than taking radiation measurements, especially if fewer people are required to operate the UxS-detector system than if only personnel conducted measurements.
Disadvantages	
Environmental limitations	• Operating in dense urban areas or areas with large amounts of RF traffic can limit communications between operators and UxSs. • Weather will affect different modalities differently (e.g., wind will limit UAVs), so the UxSs may not be available at all times. • Precipitation will affect communications with all UxSs. This includes the ability to directly operate and receive data from the systems. Using preplanned routes or autonomous control, and if postsortie data are appropriate, can minimize this disadvantage.
Regulatory limitations	• Regulations limit UAV operations beyond visual LOS; thus, in some areas, the operators or others need to follow any UAVs. This limitation does not apply to UGVs

Table C.2—Continued

Category	Issue
Technology limitations	• Power sources for UxSs and related operational time may be short. This can be a real challenge for this use case because it can require using UAVs over large areas far from a power resupply (battery change, add fuel, etc.). • Connectivity issues between the operator and UxS are not uncommon. Wi-Fi and cellular communications may not always be available in a location or in an emergency, and UxSs typically do not use first responder frequencies, which might be available. • UxS and radiation detector integration may not be well developed. This is a consideration for system acquisition but can be overcome with time and effort.

- outlying area survey
- wide-area survey
- grid survey
- boundary resurveys
- waterway monitoring
- deposition monitoring
- remediation sampling and analysis
- verify remediation.

When considering the acquisition and use of UxS, an entity may wish to include these use cases in the decision process.

Abbreviations

ALARA	as low as reasonably achievable
ANSI	American National Standards Institute
Bq	becquerel (unit)
CBRN	chemical, biological, radiological, and nuclear
CFR	Code of Federal Regulations
Ci	curie (unit)
CI	critical infrastructure
C/kg	coulomb per kilogram (unit)
CONOPS	concept of operations
DHS	U.S. Department of Homeland Security
DIU	Defense Innovation Unit
DIY	do-it-yourself
DoD	U.S. Department of Defense
FAA	Federal Aviation Administration
FEMA	Federal Emergency Management Agency
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
Gy	gray (unit)
IEEE-SA	Institute of Electrical and Electronic Engineers Standards Association
LOS	line of sight
µR/h	microroentgens per hour (unit)
NRC	U.S. Nuclear Regulatory Commission
NUSTL	National Urban Security Technology Laboratory
PPE	personal protective equipment
PRD	personal radiation detector
R	roentgen (unit)
rad	radiation absorbed dose (unit)
rem	roentgen equivalent man (unit)
RIID	radioisotope identification device
RDD	radiological dispersal device
RED	radiological exposure device
RF	radio frequency
SI	International System of Units
Sv	sievert (unit)
SLTT	state, local, tribal, and territorial
UAS	unmanned aerial system
UAV	unmanned aerial vehicle
UGV	unmanned ground vehicle

USB	universal serial bus
USV	unmanned surface vessel
UxS	unmanned system
VTOL	vertical takeoff and landing

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