

## UPDATED EMERGENCY RESPONSE GUIDANCE FOR THE FIRST 48 H AFTER THE OUTDOOR DETONATION OF AN EXPLOSIVE RADIOLOGICAL DISPERSAL DEVICE

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**Abstract**—This paper updates portions of the guidance originally published in 2006 based on the interpretation of subsequent experiments simulating explosive aerosolization from a radiological dispersal device and three-dimensional modeling of a high-rise urban-canyon type environment and wind field. These new data increase confidence about the predicted range of radioactive ballistic fragments that could endanger first responders and the public. The results of the most recent complete set of experiments indicate that the previously recommended initial hazard boundary corresponding to the potential for acute health effects can be reduced from 500 m to 250 m. This revised recommendation is independent of the total activity of the radioactive material. The assessment of the potential range and effects of dispersal from small particles as aerosol remains unchanged from the guidance issued in 2006. New recommendations are offered on sheltering versus evacuation and how to conduct the initial field measurements so as to make early decisions on protecting the public and responders, and providing coherent data for an assessment scientist to make a first estimate of the source term in the device.

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**Key words:** aerosols; emergency planning; health effects weapons

### INTRODUCTION

FOR MORE than 25 y, researchers at Sandia National Laboratories (SNL) have conducted experiments on the aerosolization of the radioactive material in a Radiological

Dispersal Device (RDD). These results and assessments of the extent of the associated radiological hazards were published so that governmental authorities, such as Emergency Planners, First Responders, and Senior Decision-makers, can refer to the scientific literature to justify the technical basis for their RDD emergency response plans and procedures (Harper et al. 2007; Musolino and Harper 2006). The updated recommendations contained herein reflect a larger number of experiments than before—over 1,000 explosive and other experiments with more than 20 materials and 85 device geometries to determine the aerosol physics and the ballistic properties representative of what might result from the detonation of an actual RDD. The new information in this paper, along with the two previous reports, assures scientifically founded and realistic definitions of hazard boundaries, thereby reducing the uncertainties and any unnecessary conservatism in RDD emergency response planning (Harper et al 2007; Musolino and Harper 2006). The guidance offered is based on the probable effects of an outdoor explosive RDD recognizing, however, larger consequences that are less probable could occur. Thus, the previous and this updated guidance are based on the most probable case versus the worst possible case.

This guidance answers the emergency response community's requests for definitions of the initial Hot Zone that provide an initial conservative stand-off distance from an incident that does not necessitate having specific radiation measurements. This concept is similar to the existing guidance offered by the Emergency Response Guidebook for transportation incidents. Once radiation measurements are used to define the Hot Zone, this guidance adopts the National Council of Radiation Protection and Measurements (NCRP) Hot Zone boundary definition of  $1,000 \text{ Bq cm}^{-2}$  ( $60,000 \text{ dpm cm}^{-2}$ ) for beta- and gamma-ray surface contamination; it is  $100 \text{ Bq cm}^{-2}$  ( $6,000 \text{ dpm cm}^{-2}$ ) for alpha-surface contamination, or less than  $0.1 \text{ mGy h}^{-1}$  ( $10 \text{ mR h}^{-1}$ ) measured at 1 m from the ground (NCRP 2010).

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## UPDATE TO HAZARD BOUNDARY—ACUTE RADIATION EXPOSURE

The initial recommendation was 500 m for setting a hazard boundary to control the potential for acute radiation exposure, assuming there was no knowledge about the device design nor any coherent radiation measurements (Harper et al 2007; Musolino and Harper 2006). Based on results of experiments conducted after 2004, this recommendation is lowered to 250 m. These recent experiments afford higher confidence that debris from radioactive ballistic fragments would fall within 250 m of the explosion. Notably, this revised recommendation carries the caveat that the experiments showed it was unlikely, though possible, for a radioactive ballistic fragment to land beyond 250 m, thus creating a source of non-acute exposure that may not be revealed immediately until a comprehensive radiation survey is completed of the general area impacted by the dispersion. The revised boundary is independent of the total activity of the radioactive material and still suffices to avoid acute effects from inhaling aerosol or exposure by groundshine from the dispersal.

### Shelter versus evacuation—acute and low-level exposure

The 2006 guidance recommended evacuating within a 500-m radius of the detonation site (Musolino and Harper 2006). This recommendation is clarified to define areas where initial sheltering will reduce exposure to the aerosol plume, groundshine from radioactive ballistic fragments, and fallout of aerosol.

After a detonation, the most effective countermeasure to avoid or reduce exposure for those who may

be in a potentially contaminated environment depends on their location:

- Close to the detonation site, persons inside a building that is intact should stay there. Leaving it immediately after the detonation could result in encountering the undiluted aerosol plume and hence an acute exposure from inhalation (if the device generated significant aerosol), shine from a highly radioactive fragment, or injury from the detonation of a secondary improvised explosive device;
- Persons who are outside, or in a significantly damaged or “smoky” building, should immediately move to the nearest robust, intact structure; if the event is a small one, people should move out of the immediate area provided that there is a clear path but still take shelter in an intact nearby building;
- In both cases, people should remain in the shelter until the local officials direct them to proceed to an uncontaminated evacuation route; and
- Downwind of the detonation site, sheltering should be extended out to 2,000 m to avoid a lower level exposure to the aerosol plume.

Fig. 1 graphically depicts the combined set of recommendations for mitigating acute and low-level radiation hazards; the two key zones are overlaid on a notional dense urban environment:

1. an initial Hot Zone that extends 250 m in all directions from the site of the incident; and
2. a wider initial Shelter-in-Place Zone, 500 m in all directions from the incident site and 2,000 m downwind.

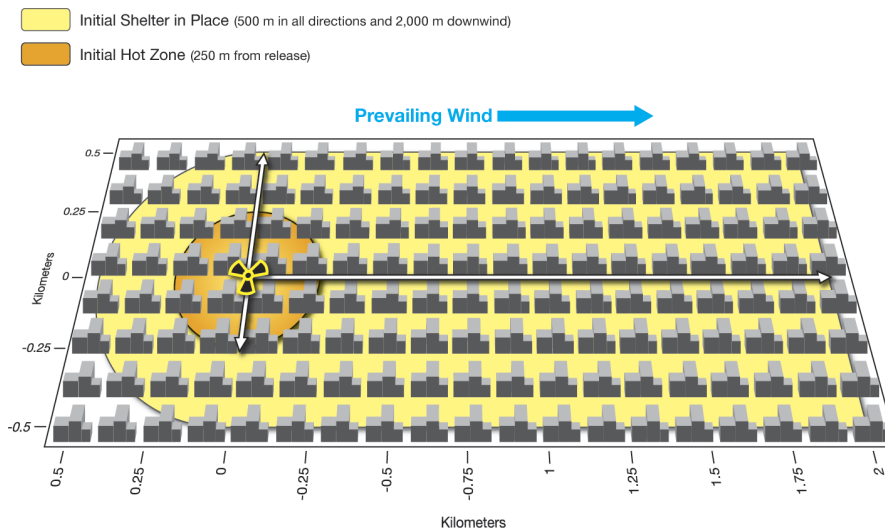


Fig. 1. Recommended boundaries for initial Shelter-in-Place and the Hot Zones.

Immediate (prompt) evacuation should be avoided for the following reasons:

- In the initial confusion of the event, evacuees inadvertently may leave an area that is uncontaminated or move from places of low contamination into those with high levels of contamination;
- Immediate self-evacuation would tend to be rushed, thereby increasing breathing rates and hence increasing the intake of airborne radioactivity, as well as raising the risk of accidental injury; and
- Sheltering minimizes the number of people outdoors who evacuate through an active emergency-response area, potentially complicating or interfering with the emergency response.

Prompt evacuation is effective if it is carried out before explosion, but it is not an effective countermeasure for an unexpected explosion and dispersal:

- Persons who are outdoors or in buildings near the event will not have time to leave before the aerosol plume arrives.
- The radiological nature of the event may not be recognized until after the first responders arrive.

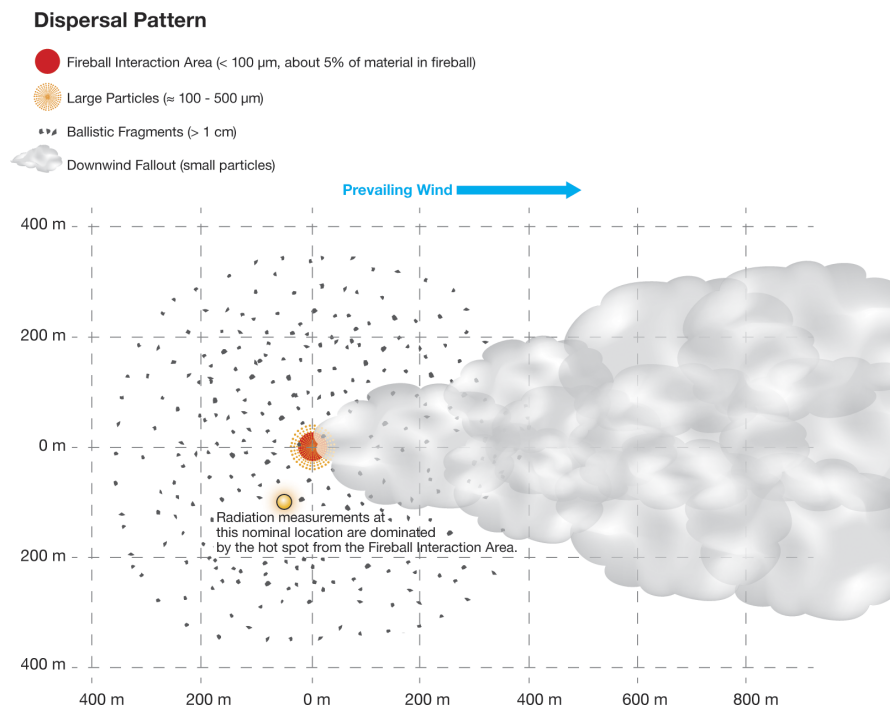
Although sheltering is the preferred countermeasure, it is recognized that some situations do warrant prompt evacuation:

- if the explosion occurred indoors, such as in an office building, a stadium, or a subway; or
- if there are non-radiological threats to life and limb at the location of the shelter, such as fire, collapse of a building, or the presence of a secondary explosive device.

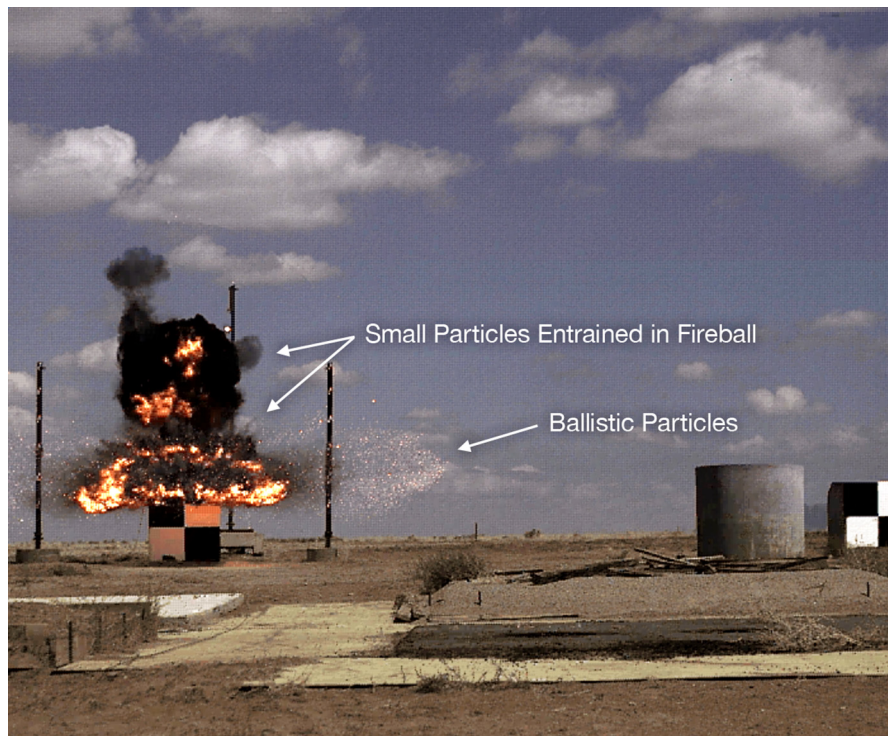
## DEPOSITION PATTERN

Without prior law enforcement intelligence about the design of the device, it is impossible to predict accurately the aerosol fraction and the environmental consequences so as to guide the early response. Initially, it will not be known if the fate of the radioactive material was a large aerosol fraction that could disperse and deposit fallout far away from the point of detonation, or if the outcome was predominately radioactive ballistic particles and/or fragments resulting in localized deposition, or a combination of aerosol and ballistics. Fig. 2 is a notional representation of the potential fate of the radiological fragments, particles, or aerosol that could result from such an explosion.

The density of radioactive ballistic fragments (chunks versus particles) of about 1 cm or larger is reduced significantly beyond 250 m and likely will occur; however, this material tends to be that from the device's case material and other structures and not the radioactive material itself. The chemical and physical forms of typical radioactive



**Fig. 2.** Notional representation of dispersal possibilities. One or more of these fates is possible depending on the form of the radioactive material and the design of the device. Note: These patterns are representative only of the behavior of the radioactive material in the device. Chunks of non-radioactive debris could fall beyond the indicated range for ballistic fragments.



**Fig. 3.** Experiment at the Sandia National Laboratory showing a test device wherein all or part of the surrogate radioactive material was converted into ballistic fragments approximately 100- to 500- $\mu\text{m}$  in size (aerodynamic). If the device had generated small particles,  $< 100 \mu\text{m}$  (aerodynamic), this debris would be entrained inside the fireball and subjected to the buoyant rise and dispersal by local meteorological conditions.

materials licensed for routine applications makes ballistic deposition unlikely beyond 250 m.

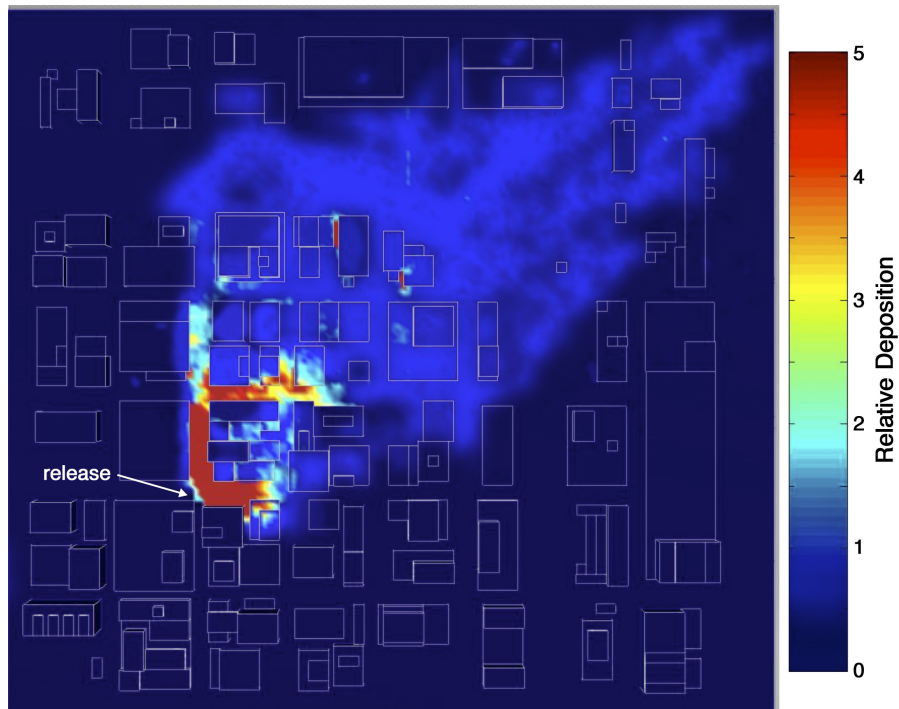
Experiments showed that when the detonation of a device was both close to the ground and generated small particles ( $< 100 \mu\text{m}^{\dagger\dagger}$ ) inside the fireball, that between 3–20% of these small particles in the fireball are “painted” on the ground in the Fireball Interaction Area (Harper et al 2007). Note that this is a relative fraction with respect to the portion of the radioactive material that is converted to small particles and not with respect to the original radioactive mass. As a general rule, it can be assumed that when the fireball “paints” a hotspot, 5% of the small particles from the fireball remain on the ground. The remainder (95%) of the small particles will disperse as aerosol. The absolute fractions of particles smaller and/or larger than  $100 \mu\text{m}$  depends on the physical and chemical form of the radioactive material and the device geometry; nevertheless, many materials of concern are expected to result in almost 100% radioactive ballistic particles  $> 100 \mu\text{m}$  (Fig. 3). Therefore, measuring the radiological “footprint” of the Fireball Interaction Area and the vicinity around it will engender insights on the extent

to which small particles were produced and on what fraction of the radioactive material was transported downwind as aerosol. Close to the point of detonation, groundshine from small particles and radioactive ballistic particles ( $> 100 \mu\text{m}$ ) may be indistinguishable other than by the high radiation levels existing in the general vicinity. Measurements to characterize the “footprint” close to the detonation are discussed below. The remainder of small particles will be lofted by the buoyant rise of the fireball and transported in the plume to create a downwind “footprint” of fallout in accordance with current meteorological conditions and local micrometeorology in the urban wind field. The concentration of the material on the ground a few fireball radii downwind was experimentally observed to be lower than the concentration near the point of detonation by a factor of  $10^3$  to  $10^4$ .<sup>‡‡</sup>

Compared to visualizations of typical modeling of a dispersal that does not take urban buildings and three-dimensional wind fields into account, the near-field of a real-world deposition pattern will be nonuniform and chaotic compared with the typical predictions from modeling with flat plane geometry. These types of models typically

<sup>††</sup>All particle sizes are stated as Activity Median Aerodynamic Diameter.

<sup>‡‡</sup> For example, the Department of Homeland Security offers a smartphone application, RadResponder, that collects data and performs mapping.



**Fig. 4.** A notional representation of the dispersion from a device that created a large aerosol fraction and the spatially varying and non-Gaussian footprint that may ensue in the general vicinity of the dispersal.

display two-dimensional Gaussian-like patterns compared to Fig. 4, based on a three-dimensional QUIC<sup>§§</sup> simulation of the wind field and buildings that display more spatial variation. The Gaussian-like representations of postulated dispersals are useful in planning to define the types and ranges of effects in the near and far fields; e.g., 250 m hazard boundary for both aerosol and fragments. However, in a real-time operational environment, models are not useful to guide responders on a distance scale of 100 m, but they are valuable in the far field when data from the 10-Point survey, described below, can be used to normalize projections at distances much greater than 100 m. Thus, Fig. 4 is a more realistic representation and provides insight on what a deposition pattern might look like close to the point of release; it can encompass non-uniform areas of high and low contamination that could appear ambiguous before sufficient field data are collected. Therefore, rapid mapping of the near-field pattern with radiation survey instruments versus modeling is vital to managing the exposure of responders, protecting the public, and gaining insight to the character and scale of the contamination.

<sup>§§</sup>Quick Urban and Industrial Complex (QUIC) Dispersion Modeling System is a fast response urban dispersion model that runs on a desktop or laptop computer. QUIC is comprised of a three-dimensional wind field model, a Lagrangian-based random-walk transport and dispersion model, and a user-friendly graphical user interface.

## MEDICAL EMERGENCIES AND LIFE SAFETY AND MONITORING PRIORITIES

Medical emergencies and lifesaving take priority over radiological monitoring and the concern for the presence of radionuclide contamination. Radiation monitoring equipment, although desirable, *is not required* to begin lifesaving operations (NCRP 2010). As life safety issues, such as injuries, fire, and building collapse are mitigated and additional resources become available, then the direction and size of the default hazard boundaries set for responders and the public safety can be assessed and adjusted to actual conditions.

## MONITORING STRATEGY TO SUPPORT PROTECTIVE ACTIONS AND CHARACTERIZATION OF THE CONTAMINATION

### Initial monitoring to assess the need for sheltering—first priority

For an outdoor explosive RDD, it is assumed that first responders, who may already be in the vicinity of the detonation or will arrive quickly thereafter, will detect its radiation signature. Confirmation of the signature is sufficient to issue the recommendation to shelter in accordance with Fig. 1. As soon as possible, collect a gamma spectrum to help define relative radiation health hazards and optimize field-monitoring methods.

### Preliminary characterization of the far-field—second and third priorities

The second priority is to begin to measure and approximate the actual shape and extent of the “footprint” of contamination while recognizing that default boundaries may have to be adjusted. While the radius of the initial Hot Zone of 250 m is conservative and likely to be reduced, the size and shape of the Shelter-in-Place Zone was chosen with the recognition that 2 km is a relatively long distance in a large city and could already encompass a vast number of people. Therefore, radiation monitoring and contamination monitoring undertaken in approximately the first hour or two after detonation of a device should be optimized to provide enough data to justify protective action decisions but not delay their implementation.

The next phase of monitoring is to begin to define the actual boundaries of the Hot Zone ( $> 0.1 \text{ mGy h}^{-1}$ ) and Shelter-in-Place Zone and roughly assess the extent of downwind contamination (or the lack thereof) to determine if and where the default Hot and Shelter-in-Place Zones need adjustment. Traditionally, this would be performed with a 10-Point survey template (USDOE 2012); however, the near-field urban environment can perturb the homogeneity of the contamination pattern greatly within a few blocks of the release point. To mitigate this concern, measurements must be made sufficiently downwind to ensure adequate mixing in the urban environment. This goal of characterizing the far-field contamination can be accomplished as soon as field-monitoring resources permit and become available by conducting surveys that, as the second priority, transect (cut across) the Shelter-in-Place Zone, and as the third priority, apply the 10-point template at longer distances (Fig. 5). The points in the grid and downwind distances are given for guidance and are

intended to be adjusted to account for the area’s topography, such as roads, intersections, waterways, etc. If measurements are associated with accurate latitude and longitude from the Global Positioning System and transmitted to mapping software, this will support rapid assessment and adjustments of the protective zone.

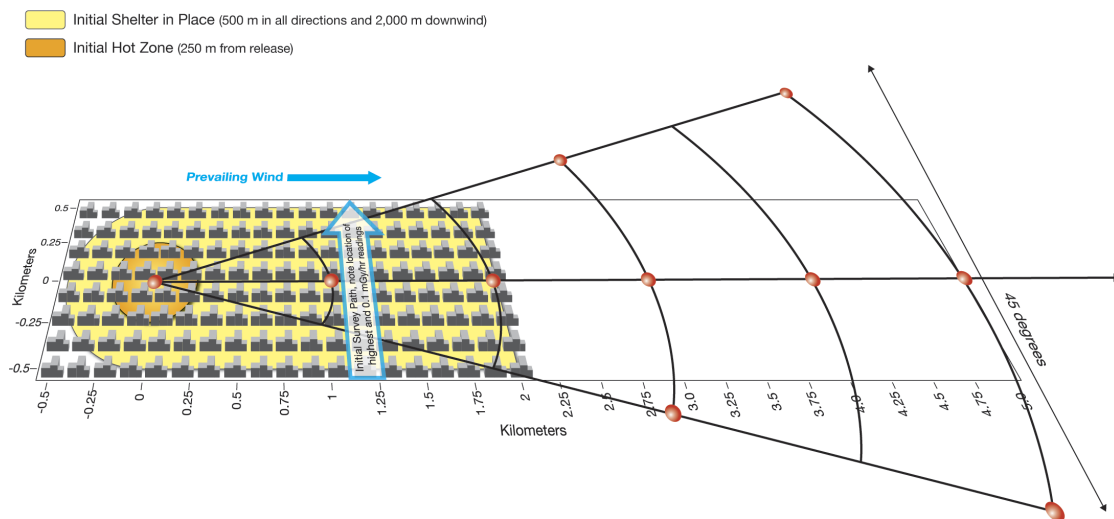
The first transect should be conducted at approximately one to two kilometers downwind from the point of detonation, Fig. 5. A significant number of survey points ( $> 10$ ) should be made along the path, and the measurements should encompass the following parameters:

- Exposure rates at 1 m from the ground;
- Alpha surface contamination measurements (if the proper instrumentation is available);
- Notation of the location of the  $0.1 \text{ mGy h}^{-1}$  measurements (Hot Zone boundary); and
- Notation of the location and magnitude of the maximum reading found along the transect.

If all of the radiation levels are found to be  $\leq 0.1 \text{ mGy h}^{-1}$ , then the next transect should be made approximately midway between the current location and the point of detonation. If the centerline of the contamination appears to be more than 250 m ( $\sim 2$  blocks) off the presumed downwind direction, the Shelter-in-Place Zone should be rotated to match the actual contamination. If there are areas of contamination  $> 0.1 \text{ mGy h}^{-1}$  outside the default Hot Zone, then the boundary should be expanded.

### Preliminary characterization of the near-field—fourth priority

Once the Shelter-in-Place Zone has been verified, the fourth priority is a more detailed survey that should be



**Fig. 5.** Strategy to verify the size and orientation of the Shelter-in-Place Zone by transecting across the zone and implementing the 10-Point survey at more distant points. The location of the detonation and potential release is notional.

mounted as resources permit. It should encompass the following actions:

1. Characterize the type of radioactive material in the device;
2. Characterize the near-field exposure rates to ensure protection of responders and the public; and
3. Provide a minimum of data for an assessment scientist to make a first estimate of the source term.

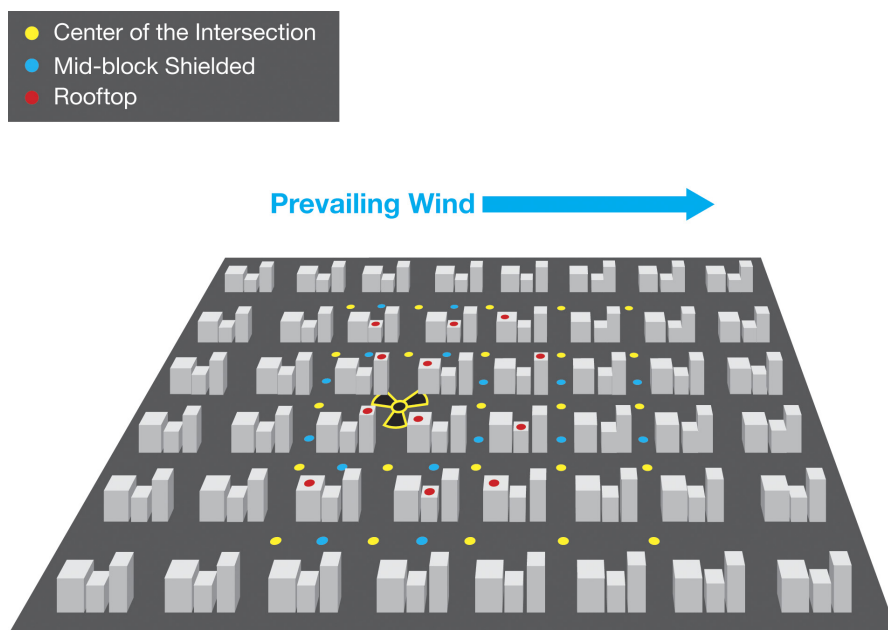
**Monitoring strategy.** A detailed gamma spectrum, preferably with a high resolution, high-purity germanium (HPGe) detector, should be obtained from samples taken near the initial release point and transmitted to “reachback” scientists for analysis. The analysis of the specific mixture of radioactive material present will support improved hazard assessments and law enforcement investigations.

The monitoring strategy for a high-rise, urban-canyon type of environment requires a different approach to that for a terrain that approximates a flat-plane geometry, such as a low-rise area with structures only a few stories high, single-story residential homes, and rural land (Musolino et al. 2012). A preliminary set of 41 survey points should be collected, using the grid pattern established by the city’s streets (Fig. 6). The yellow dots are located in the center of the intersections, and the blue dots are in the midpoints between intersections. The latter were chosen adjacent to the intersections that have line-of-sight to the point of detonation where groundshine from contamination at the survey point might be indistinguishable from direct shine from a possible hotspot from the Fireball Interaction Area, as described above. The mid-block reading will assist in making the determination

on whether there is direct shine from the Fireball Interaction Area that influenced the measurement in the center of the intersection. This initial grid extends three blocks in the direction of the prevailing wind, one block upwind and two blocks on either side of the point of detonation. These data should be plotted on the map and given to the HAZMAT Branch/Incident Commander, who should ensure that the results of the first survey are transmitted as soon as possible to their “reachback” assessment scientist; the two should confer by telephone when communication is established.

**Near-field monitoring methods—characterization of the Fireball Interaction Area.** If physical conditions permit, a rapid means to characterize the Fireball Interaction Area (one of the 41 points) would be for a survey team to drive a vehicle through it with a low-range and a high-range instrument capable of measuring levels  $>100 \text{ mGy h}^{-1}$ . This measurement is extremely important in allowing an assessment scientist to make a first judgment on whether a large aerosol fraction occurred and/or whether a large quantity of radioactivity was incorporated into the device. The value of this measurement justifies contaminating a vehicle to facilitate the data collection in order to characterize the Fireball Interaction Area.

**Near-field monitoring methods—characterization of the vicinity near the point of detonation.** The near-field characterization can be accomplished with completion of the remaining 40 survey points collecting four types of measurements. To make these measurements, responders should dismount from their vehicles and make measurements in the center of the intersection or in the



**Fig. 6.** Strategy for characterizing the near-field and data points necessary for an assessment scientist to make a first estimate of the source term. The location of the detonation and potential release is notional (Musolino et al. 2012).

center of the mid-block roadway, as appropriate. If the survey team is traveling by vehicle, it should be parked away from the survey point, and they should walk to the location to take the following measurements:

- Exposure- or dose-rate from gamma radiation at 1 m from the road surface with an energy-compensated Geiger-Mueller-, ion chamber-, sodium iodide-, or plastic scintillator-based instrument;
- Beta surface contamination with a pancake-type Geiger-Mueller probe (Note the surface area of the probe and monitor often for gross shoe contamination that may confound the surface measurements);
- Alpha surface contamination. A 100 cm<sup>2</sup> area probe is preferable but not necessary. Pancake Geiger-Mueller type probes are not recommended for measuring alpha radiation; and
- Gamma spectroscopy, preferably with a germanium-based detector, at a location that is less than 5 μGy h<sup>-1</sup> as well as a background measurement in an uncontaminated location as close to the area as practical. If resources permit, replicate the spectral acquisitions.

**Near-field monitoring methods—planning the next survey.** Subsequent surveys should be undertaken based on an assessment and interpretation of the initial results. From those data, the assessment scientist can make recommendations to the Command Post to optimize the tactics for additional surveys:

- Eliminate one or both of the surface contamination surveys from subsequent measurements;

- Decide where and in what direction to collect additional more detailed data within the near- and far-field;
- If resources permit, initiate measurement of gamma radiation at 1 m on some rooftops up- and down-wind within the range of 100 m according to the grid of red dots (Fig. 6); and
- The assessment scientist needs the rooftop data to estimate the source term and characterize the device (Musolino et al 2012).

Table 1 is a summary of the recommended radiation surveys, order of priority, timeframe, and number of survey points.

### RESPIRATORY PROTECTION FOR AN RDD AIRBORNE HAZARD

Because the initial plume will pass in approximately 10–15 min, responders who arrive after 15 min are not likely to be exposed to high airborne concentrations of particulates because they will arrive after the plume has passed or first encounter it downstream when concentrations have become diluted. Therefore, because the remaining levels of airborne radioactivity, along with any additional contribution from resuspension, will be relatively low, using an air-purifying respirator is sufficient for respiratory protection (Musolino and Harper 2006). The exception to this recommendation is when first responders already are in position near the incident when it occurs and their response is within approximately less than 10–15 min, and/or avoidance of the undiluted plume is not possible, nor is it

**Table 1.** Summary of radiation surveys and parameters to support decisions on protection of responders and the public and initial characterization of the source term.<sup>a</sup>

Survey type	Where	When	Timeframe	Number of points	Type	Reason
Initial	Near-field	Immediate	First 15 min	1	γ S	Confirm presence of radiation and support a decision to issue the default Hot Zone and Shelter-in-Place boundaries
Transect	1 – 2 km downwind	Second priority	30 – 60 min	Minimum of 10	γ α (if possible)	Begin to define zones with measurement data and adjust to actual contamination “footprint”
10-point	Far-field	Third priority in the first few hours	A few hours	10	γ	Adjust range and azimuth of the Shelter-in-Place boundary and define extent of protective actions; provide data to normalize initial modeling of far field
41-point	Near-field	Fourth priority as resources become available	2 – 3 h	41 plus some rooftops if possible	α β γ S	Collect data for an Assessment Scientist to make a first estimate of the source term

<sup>a</sup>α — alpha probe;

β — pancake GM probe;

γ — High range and low range gamma detector, as appropriate; and

S — Gamma spectrometer, preferably a germanium-based detector.

practical or desirable from the standpoint of initiating life-saving measures.

To protect the responders from inhaling airborne radioactivity while assuring an optimal immediate response to the incident, using a positive-pressure, self-contained breathing apparatus (SCBA) to the extent practical is recommended for the first to 10–15 min after the detonation. Recognizing that wearing an SCBA may not be possible while driving a vehicle, then drivers should wear a full-face air-purifying respirator with a P-100 filter or a HEPA filter instead. To further minimize the driver's exposure to airborne particulates inside the cab, the windows of the vehicle should be closed and remain so, and the ventilation system set to recirculation. These recommendations are aimed specifically toward protecting the responders/drivers from inhaling radioactive particulates; they do not address protection against other airborne non-radioactive contaminants.

## CONCLUSION

The previous and updated guidance answers requests from the emergency response community on how to set the initial boundaries for the Hot Zone and Shelter-in-Place with simple qualitative radiation measurements in a conservative manner. The recommendations for the initial Hot Zone and Shelter-in-Place Zone herein are similar to the typical guidance offered by the Emergency Response Guidebook for transportation incidents (USDOT 2012). Once sufficient quantitative radiation measurements are collected and mapped, the recommendations by the National Council of Radiation Protection and Measurements should be used to define the Hot Zone boundary more precisely (NCRP 2010). Monitoring strategies to assess the extent of the zone for controlling the dose to the public and for collecting the data for an initial assessment of the source term also were discussed.

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