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Characterization of Activity-Size-Distribution of Nuclear Fallout

Gregory D. Spriggs, Kim B. Knight, Richard C. Gostic

Lawrence Livermore National Laboratory
7000 East Avenue
AX-Division, MS L-030
Livermore, CA 94550

925 423-8862
spriggs1@llnl.gov

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Executive Summary:

A generalized model for the distribution of radioactivity as a function of particle size (here, the activity-size distribution or ASD) of nuclear fallout was proposed by Spriggs (2008). According to this model, the specific activity of nuclear fallout particles varies as $1/d$, where d is the diameter of any solid particles drawn into the fireball shortly after a detonation. Knowing that the specific activity varies as $1/d$, the ASD produced by a detonation in any environment can be easily predicted if the size distribution of the solid material in the vicinity of ground zero is known (that is, the particle-size distribution or PSD). Soils samples were collected from historical U.S. atmospheric shots to test if these relationships are upheld. Preliminary analysis of these fallout debris soil samples as well comparison with data from aerial maps of surface activity distributions results in excellent agreement with model predictions of the total activity.

Current State of the Technology

Understanding the distribution of radioactivity as a function of particle size (here, the activity-size distribution or ASD) of nuclear fallout is one of the most important parameters in the prediction of local fallout. This relationship unfortunately remains one of the most elusive topics in the area of nuclear fallout technology largely because the basic, underlying physics of the formation of fallout particles are very complicated and not fully understood. Considerable effort has been made to calculate the ASDs from *first principles* but theoretical models have failed to produce results that correlate well with measured, empirical data, and have thus been largely abandoned. Without a viable theoretical model, most nuclear fallout codes rely on empirically determined ASDs based on data collected at the Nevada National Security Site (NTS) and/or at the Pacific Proving Grounds (PPG). It is common consensus amongst nuclear fallout experts, however, that these empirical ASDs will not work well when trying to predict nuclear fallout in other environments.

Urban environments are a case of considerable interest to many of our government organizations that have some role in preparing for and/or responding to nuclear terrorism emergencies. Experiments performed at Sandia National Laboratory with conventional explosives detonated over both loose, desert soils and large, dust-free steel plates have shown significant differences in cloud behavior and particle-size formulation. Similar differences were observed at NTS during the Double Track and Project 57 experiments. Based on these types of measurements, it is surmised that a detonation over an asphalt or concrete surface will not behave the same as a detonation at NTS. Our inability to predict nuclear fallout in an urban environment represents a major gap in our nuclear fallout technology that needs to be rectified. The only method available for filling this gap is through the development of first-principle, theoretical models that are not only capable of reproducing the historical data from the diversity of tests conducted at NTS and PPG, but also are general enough to correctly predict the ASD in more complex and less explored environments.

New Research

Spriggs (2008) postulated a new theoretical model for ASDs based on a simple physical process that occurs in the fireball during the cooling phase. This model is referred to as the *1/d model*, where *d* is the physical diameter of any solid particle drawn into the fireball shortly after a detonation. The basic assumption used to formulate this model is simple: When a nuclear detonation occurs close to the surface, the soil in the vicinity of ground zero is drawn up into the fireball. While some of the initial amount of incoming soil is vaporized, most of the incoming particles remain intact and act as condensation sites for the hot vapors within the fireball. If it is assumed that this vapor condenses uniformly over the available surface areas of the incoming soil particles, it can be shown that the *specific activity* (*i.e.*, curies per gram of substrate) of the fallout is inversely proportional to the grain diameter (*1/d*). Thus, the initial activity distribution of the cloud forming during any given detonation in any given environment can be calculated if the mass distribution as a function of grain size (*i.e.*, the *particle-size distribution* or PSD) of the solid material drawn into the fireball is known.

The above process is complicated somewhat by the fact that the PSD in the cloud can change dramatically as a function of time. During the early stages of the cloud rise,

the upward draft of the cloud is strong enough to entrain the entire PSD of the soil found at the ground zero, which may include a significant fraction of gravel and large rocks. Because refractory material in the bomb debris vapor condenses first, the ASD formed during this early stage will correspond to the area-distribution of the entire native PSD of the soil in the vicinity of ground zero. During the later stages of the cloud rise, however, the upward draft of the cloud will slow down considerably and the heavier particles will rapidly settle out, leaving behind the lighter portion of the native PSD. As the cloud continues to cool, the volatile material in the bomb debris vapor begins to condense. The ASD formed during this cooling stage will correspond to the area-distribution of this *late-stage* PSD, which is depleted of the heavier particles. As a consequence of this rapid change in PSD during the cooling phase, the isotopic composition of the radioactive material on the heavier fallout particles is different than the isotopic composition found on the smaller particles (a process known as *fractionation*).

Despite the added complexities introduced by fractionation, the specific activity of the *refractory* particles and the *volatile* particles still appear to follow the *1/d* model. For example, the specific activity of the fallout particles produced during the Small Boy shot showed the *1/d* dependence (on the tail of the distribution) at both near-range and far-range locations (see Figure 1). Presumably, the near-range particles were mostly refractory particles and the far-range particles were mostly volatile particles. They separated naturally due to differences in their settling rates: heavier, refractory particles fell in close to ground zero while the lighter, volatile particles fell much farther out.

To further test the *1/d* model, we collected and analyzed soil samples from two different low-yield, surface shots at NTS. Small Boy was detonated in Area 5, which is a dried-up lakebed comprised of very small particles mostly of form of clays and silts. Johnie Boy was detonated in Area 18, where soil is comprised of relatively larger particles mostly in the form of medium- and coarse-grain sands and gravel. Using a newly developed fallout code that implements the *1/d* model, the fallout patterns produced by detonations over these two different soil types were compared to their measured fallout patterns. As can be observed in Figure 2, the predicted fallout pattern is in excellent agreement with the classic teardrop pattern that was measured for Johnie Boy. As can be observed in Figure 3, the predicted fallout pattern for Small Boy is also in agreement with the more-complicated fallout pattern that shows *two hotspots* downwind of ground zero. This type of agreement between model and measurement for both shots could not have been obtained without considering the change in the PSDs found in Area 5 and Area 18.

Conclusions

The *1/d* model appears to explain the shape of the specific activity curves of the local fallout particles collected downwind of ground zero. Furthermore, when the ASD is estimated using the *1/d* model based on the measured PSD of the soil in the vicinity of ground zero, the measured and predicted fallout patterns also appear to be in excellent agreement. If further research substantiates this model, it may be possible to more accurately predict nuclear fallout detonated in other environments assuming that the PSDs of the soil has been or can be characterized. Additional studies are underway to understand the sources of fractionation affecting the distribution of specific elements including some fission and fuel products.

References

Spriggs, Gregory D., et al., *The Activity Size Distribution for Johnie Boy*, Lawrence Livermore National Laboratory, UCRL-PRES-227071, August 2008.

Auspices Statement

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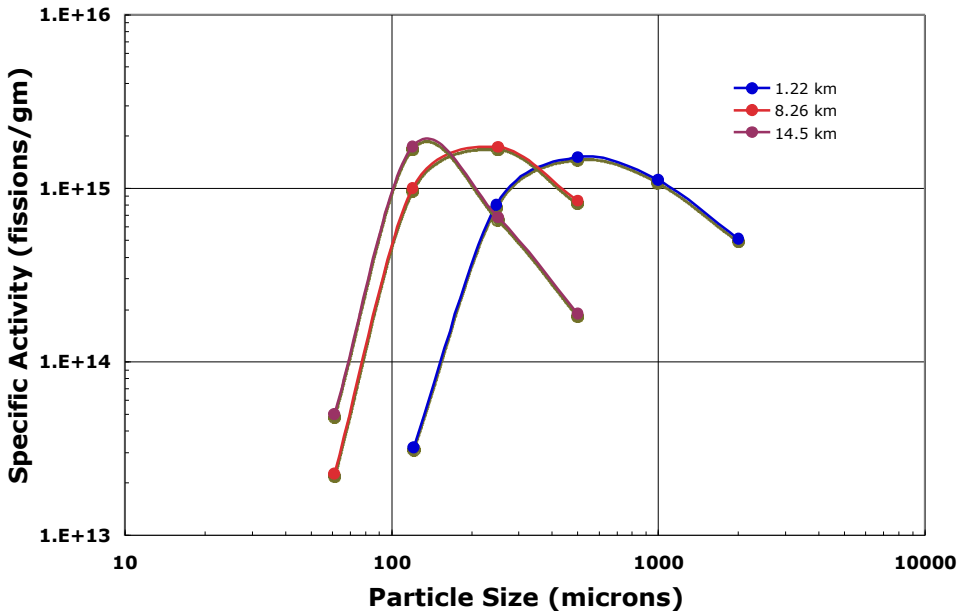

Figure 1. Measured specific activity (expressed as the number of fissions per gram as opposed to curies per gram) of fallout particles for Small Boy. Note that the farther downrange, the smaller the mean particle size. As expected, the tail of each curve follows, to a first approximation, a 1/d dependence.

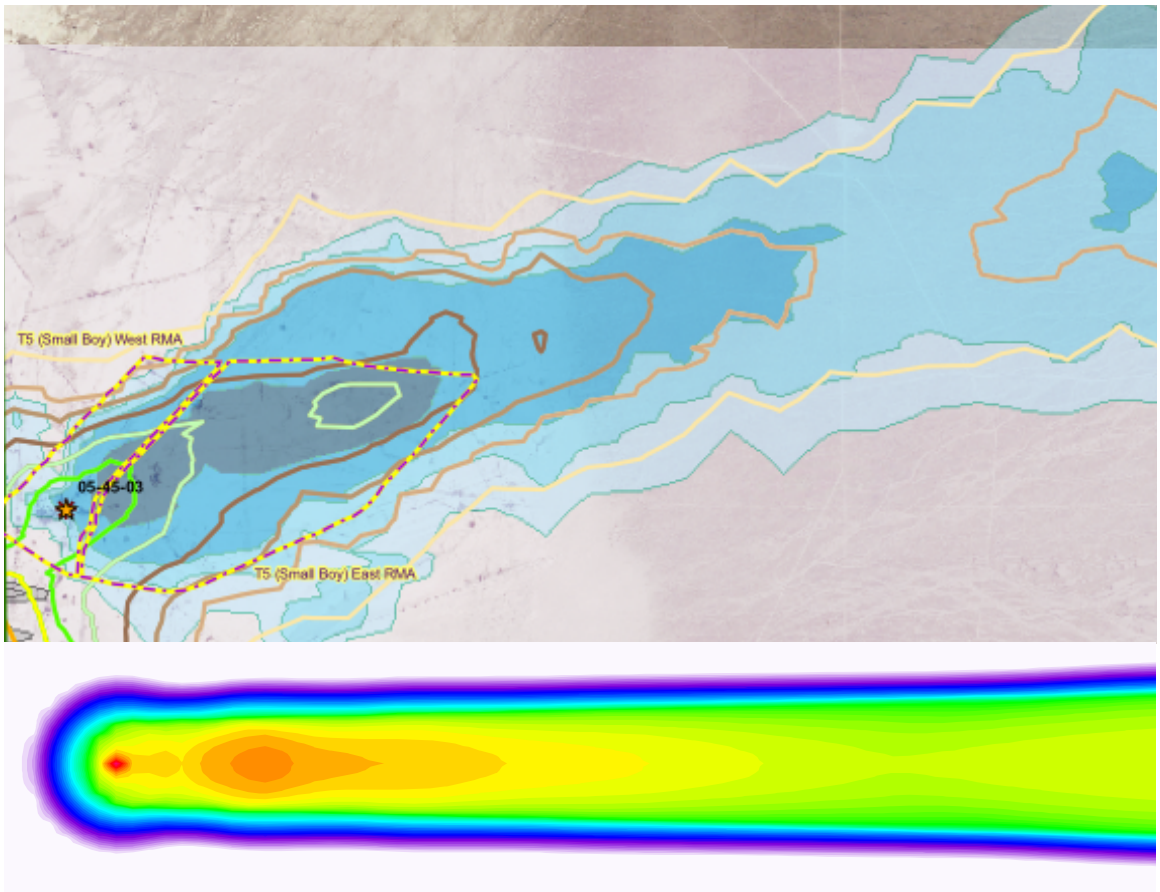

Figure 2. Scaled comparison of the measured (top) and predicted (bottom) fallout pattern for Small Boy using the 1/d model. This model prediction was produced using constant winds since the new fallout code does not yet have complex weather capability. As can be observed, there are two hotspots downwind of ground zero. This fallout pattern could only be produced using the ASD calculated from the measured PSD of the soil at ground zero of Small Boy.

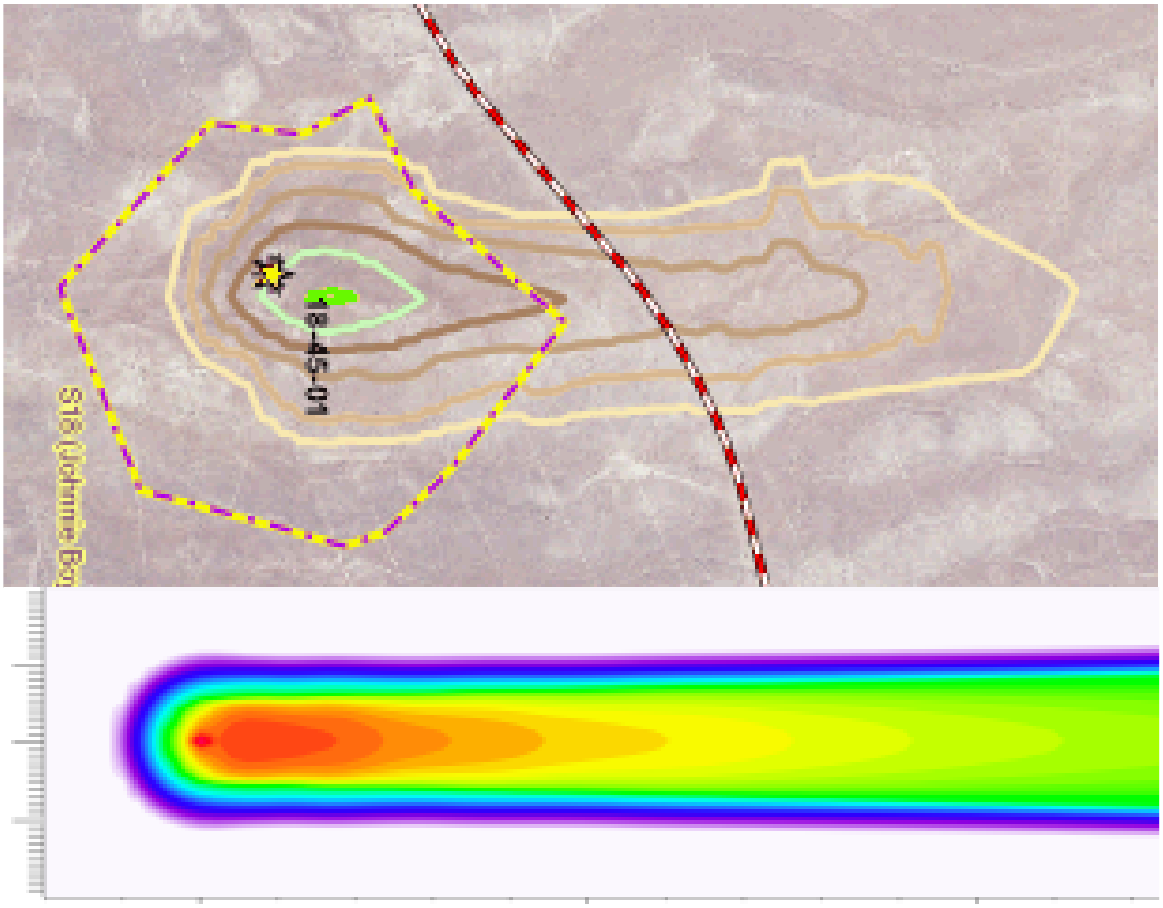

Figure 3. Scaled comparison of the measured (top) and predicted (bottom) fallout pattern for Johnie Boy using the 1/d model. Note that the largest exposure rate occurs somewhat downwind of ground zero. This pattern could not be produced using the same ASD that was predicted for Small Boy and vice versa.