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Estimation of Upper Bound Probabilities for Rare Events Resulting from Nearby Explosions

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Introduction

It is sometimes necessary to deploy, transport, and store weapons containing high explosives (HE) in proximity. Accident analyses of these activities may include nearby explosion scenarios in which fragments from an exploding (donor) weapon impact a second (acceptor) weapon. Weapon arrays are designed to mitigate consequences to potential acceptor weapons, but unless initiation of an acceptor’s HE is impossible, outcomes such as detonation must be considered. This paper describes an approach for estimating upper bound probabilities for fragment-dominated scenarios in which outcomes are expected to be rare events. Other aspects of nearby explosion problems were addressed previously.

An example scenario is as follows. A donor weapon is postulated to detonate, and fragments of the donor weapon casing are accelerated outward. Some of the fragments may strike a nearby acceptor weapon whose HE is protected by casing materials. Most impacts are not capable of initiating the acceptor’s HE. However, a sufficiently large and fast fragment could produce a shock-to-detonation transition (SDT), which will result in detonation of the acceptor. Our approach will work for other outcomes of fragment impact, but this discussion focuses on detonation.

Experiments show that detonating weapons typically produce a distribution of casing fragment sizes in which unusually large fragments sometimes occur. Such fragments can occur because fragmentation physics includes predictable aspects as well as those best treated as random phenomena, such as the sizes of individual fragments. Likewise, some of the descriptors of fragment impact can be described as random phenomena, such as fragment orientation at impact (fragments typically are tumbling). Consideration of possibilities resulting from the various manifestations of randomness can lead to worst-case examples that, in turn, lead to the outcomes of concern. For example, an unusually large fragment strikes an acceptor weapon with the worst possible orientation and in the acceptor’s most vulnerable location. Intuitively, such an event clearly is very unlikely. Our approach is based on the quantification of such “unlikelihoods.” The randomness inherent in the physics is modeled explicitly. Worst-case events are predicted in simulations but appear with appropriately small frequencies and lead, in turn, to corresponding probability estimates.

To make the complex physics involved in nearby explosions tractable, we keep some of worst-case approach. For example, we might assume that fragments strike with the worst-case orientation. Because some of the physics is modeled as worst
case, our results become upper bound probability estimates. The remaining physics, which includes the random aspects, is modeled in a way that makes Monte Carlo estimation of probabilities possible.

In the following, the different physical processes involved in nearby explosion scenarios are considered separately: fragmentation of the donor case, transport of the fragments to the acceptor, and impact of the fragment(s) and consequent effects on the acceptor warhead. The discussion focuses on the modeling choices, which inevitably limit the probability range over which outcome probabilities can be bounded by limiting the number of Monte Carlo simulations that are practical.

**Fragmentation Modeling**

For nearby explosion simulation, fragment size and impact location are needed for every fragment that impacts the acceptor. The size of a particular fragment is determined by physical processes that can be treated as random (such as where cracks will intersect) as well as those that can be treated as deterministic. As a consequence, features of individual fragments such as size cannot be predicted, but the probability of obtaining a particular size is predictable for large numbers of fragments, as experiments show. Some analytic models of fragment size distributions are available, but experimental determination is common practice. In some cases, the shape of the probability distribution is known, and only the fitting parameters, such as the average fragment size, need to be determined.

A fragment's impact location is determined by two factors, its birthplace and its subsequent trajectory. “Birthplace” is used here to denote the original (pre-expansion) location of the center of the fragment that will be created when the weapon case expands. In reality a fragment as such does not actually exist until the cracks that create it have intersected and it is no longer connected to other fragments. Thus, if fragmentation processes were to be modeled rigorously, a record of the case expansion would be necessary to obtain a birthplace for each fragment.

For nearby explosion simulations, a geometric fragmentation algorithm is needed to provide a size and birthplace for every fragment. Different treatments are appropriate depending on accuracy needs and computer resources. Physics-based treatments that describe the propagation and intersection of individual cracks provide the greatest accuracy. Often a treatment based on minimal physics is adequate as long as the sizes of the fragments that are generated are in agreement with the desired fragment size probability distribution.

The Mott fragment size distribution has a long history in the weapon community and has been useful in some Los Alamos weapon safety studies. It is based on representing a weapon as a stack of rings, each of which fracture into randomly spaced segments. Figure 1 shows the Mott probability distribution (for fragments of a given size or larger) along with experimental fragment data correspondingly binned into a histogram.

Grady and Kipp\(^3\) describe a fragmentation algorithm that closely matches the Mott distribution (termed “linear exponential” in their paper) in which a rectangular region is fragmented serially by randomly placed fractures. By neglecting the possibility of three-dimensional (3-D) fractures, such a two-dimensional (2-D) algorithm can be used. With this approach, a technique to map 2-D fractures onto a 3-D
weapon case is needed. For the cylindrical case shown in Fig. 2, it is sufficient to simply "wrap" the algorithm results around the weapon case.

For weapon cases that are more complex geometrically, an approximate mapping can be used. For example, if the case has a symmetry axis and the case radius (and thus the surface area) varies along it, fragments mapped directly from a rectangular surface will overlap. This problem can be resolved in a computationally efficient manner by playing a game of "Russian roulette" (a common technique in Monte Carlo radiation transport codes) to reduce the number of fragments (on average) to approximate the proper areal density.

**Fragment Transport Modeling**

Fragment motion is the same as the motion of the weapon case up to the time the fragment is completely formed and freed of its connection to other fragments. From this point, here termed the launch point, further motion is ballistic and is determined by the launch point velocity. For ranges typical of weapon arrays and for sufficiently fast fragments, velocity is approximately constant and fragment trajectory is modeled adequately by ray tracing. (It also is assumed that fragments do not interact with each other.) Thus, the fragment transport model moves each fragment from its birthplace to its launch point, defines a constant velocity to be used for the calculation of subsequent motion, and determines the intersection point, if any, of its trajectory ray with the acceptor.

Weapon case expansion is affected by passage of the HE detonation wave, variations in case areal density from point to point (heavier regions lag and "bend" the expanding case), and other effects. Thus, different models for case expansion and fragment velocity are appropriate, depending on the weapon design and the accuracy needed.
It is simple and easy to assume that each fragment travels directly outward from its birthplace. In this case, the birthplace and launch point coincide. The fragment's direction is the direction of the surface normal to the weapon case at its birthplace. An estimate of the fragment speed completes the velocity determination. This approach has been used for the illustration problem below.

A more accurate approach involves the calculation of weapon case expansion using detailed hydrodynamic computer codes. A grid is inscribed on the weapon case, thus defining the starting location of "tracer" particles, before case expansion. The calculation is terminated when fragmentation is predicted. The position of the tracer particle at this point becomes the fragment's launch point, and the position and velocity are recorded. A table then is formed from the collection of tracer particles that associates birthplaces with fragment launch conditions. Then, for nearby explosion simulations, fragment launch points and velocities can be obtained for any fragment birthplace by interpolation.

If there is any significant stretching of the weapon case before it fractures, fragments will be thinner than the original weapon case thickness and correspondingly larger in area. This effect may be important for impact modeling because fragment thickness can affect the outcome of fragment impact (i.e., SDT or not). Stretching can be predicted from the case expansion and material properties, or measured experimentally. With the hydrocode approach, fragment stretching is normally provided by the calculation.

**Fragment Impact Modeling**

Different physical processes may be triggered by fragment impact. This paper focuses on detonation caused by isolated fragment impact. SDT normally is modeled by a hydrocode, given the conditions of impact. However, a different hydrocode calculation is not needed for each impact. It is sufficient to use the hydrocode to determine a size threshold for a bounding (conservative) set of conditions. It then is a simple matter to check each impact against the threshold (or a table if the threshold varies with details of the impact) for nearby explosion simulations and make a determination of SDT or no SDT.

In the physics of SDT, fragment size, speed, and acceptor impact location typically are important. However, additional factors, such as yaw and impact obliquity also affect the outcome. Because of the computer resources required by the hydrocode calculations, it is desirable to solve a few idealized problems that represent bounding situations. The resulting SDT threshold is then conservative and produces upper bound probabilities in nearby explosion simulations. For example, use of a maximum fragment speed eliminates impact speed as a parameter. Yaw and obliquity can be eliminated by assuming that each fragment strikes perpendicular to the acceptor surface and with a fragment area reduced to the projected area. With these assumptions, SDT thresholds become a function only of fragment size and impact location.

**Monte Carlo Simulation Code**

A computer code based on the above concepts was developed to calculate a Monte Carlo sequence of nearby explosion problems. Each problem determines the
outcome of a donor explosion and possible fragment impact on one acceptor, both of which are modeled by 3-D geometric surfaces. The outcome is the occurrence or nonoccurrence of an event of interest, such as SDT. The event of interest occurs if a set of threshold conditions is violated. The models described above are invoked in the following sequence: donor explosion (using a random number sequence to generate fragment sizes and birthplaces), transport of the fragments to the acceptor, and evaluation of any acceptor impacts. A Monte Carlo sequence consists of obtaining outcomes for repeated problems using different random number sequences for each. Finally, the outcome probability is estimated by the outcome frequency.

A nearby explosion problem is illustrated in Fig. 3, where the donor and acceptor are represented by segments of cylinders. The donor fragments according to the Grady-Kipp algorithm described above. Fragments are directed radially outward. The outcome depends on fragment size only, unlike more realistic problems that also depend on impact location and fragment yaw.

**Illustration Problem Results**

The simulation code described above was used to solve the nearby explosion problem shown in Fig. 3. Normally, at the end of each simulation, the event of interest occurs or does not occur, leading to a single value for the outcome probability estimate. However, the nature of nearby explosion problems is better revealed by treating the event-of-interest threshold as variable. Thus, the outcome probability becomes variable as well.

Outcomes for the illustration problem depend only on fragment size, so the outcome probability is shown as a function of the threshold fragment size. (This is done easily by recording all acceptor impacts and screening for threshold size after the simulation sequence is completed.) Typically, outcome probability drops rapidly as the threshold size is increased. The fragment size distribution shown in Fig. 1 is not the only factor; smaller fragments are born closer together and thus more are likely to strike the acceptor. The probability would drop even faster if conditions on impact location and yaw were imposed.

For the illustration problem, axial segments of a donor and identical acceptor weapon were positioned 5 diameters (130 cm) center to center. Fragmentation was calculated for a square region (13 cm x 13 cm) and then mapped onto the segment...
shown. An average fragment size of 0.5 cm² was used. Acceptor impacts for 1,000,000 simulations were recorded. Figure 4 shows the probability estimates generated from multiple screens of size thresholds. Upper error bars bound the statistical error. (The probability is 0.9 that the “true” value is lower.) Lower bounds are not plotted because in more realistic problems worst-case physics assumptions are made. Thus, the “true” value could be even lower for those problems. These results were obtained in ~3 h of computing time using a 160 MHz SPARC 20 workstation.

Conclusions

Some rare, worst-case scenarios for nearby explosion accidents result from a series of unlikely outcomes for the underlying physical processes. The physics-based modeling approach described here captures the essential features of those processes. Model implementation can be based on simplified physics or hydrocode and experiment results. Use of the resulting models in Monte Carlo simulations is an effective tool for estimating bounding probabilities.

References

