

## Probabilistic Modeling of Propagating Explosions

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### Introduction

Weapons containing significant quantities of high explosives (HE) are sometimes located in close proximity to one another. If an explosion occurs in a weapon, the possibility of propagation to one or more additional weapons may exist, with severe consequences possibly resulting. In the general case, a system of concern consists of multiple weapons and various other objects in a complex, three-dimensional geometry. In each weapon, HE is enclosed by (casing) materials that function as protection in the event of a neighbor detonation but become a source of fragments if the HE is initiated. The protection afforded by the casing means that only high-momentum fragments, which occur rarely, are of concern. These fragments, generated in an initial donor weapon are transported to other weapons either directly or by ricochet. Interaction of a fragment with an acceptor weapon can produce a reaction in the acceptor HE and result in a second detonation. In this paper we describe a comprehensive methodology to estimate the probability of various consequences for fragment-induced propagating detonations in arrays of weapons containing HE.

Analysis of this problem requires an approach that can both define the circumstances under which rare events can occur and calculate the probability of such occurrences. Our approach is based on combining process tree methodology with Monte Carlo transport simulation.

A process tree is a logic model used to describe the potential mechanisms available to produce the top condition in the tree; here fragment-induced detonation of an acceptor weapon. At a high level within the tree, processes examined include fragment generation, fragment transport and the interaction of these fragments with the other objects in the array. We use the process tree in several ways: to identify all logically possible sets of physical processes leading to acceptor detonation, to decide which sub-processes will be modeled deterministically and, where a probabilistic approach is required, to provide guidance in selecting suitable models. Further, the structure of the process tree provides the logical framework for developing and combining the conditional probabilities needed for the propagation problem.

In the Monte Carlo model the physics is structured to separate deterministic and random processes. Consider, for example, the proper treatment of a fragment that detonates a target weapon. The outcome, whether or not it strikes a target, is considered to result from a deterministic process. Thus it is necessary to track each fragment individually. On the other hand, the orientation of a rapidly tumbling fragment at impact is considered to be essentially random. While the exact orientation at impact may be very important, for example, to the outcome of a shock-to-detonation process; only the outcome averaged over many fragment impacts is important.

Our Monte Carlo technique very effectively captures important features of these differences. Below we describe process tree methodology, discuss its use for a simplified problem and illustrate the power of Monte Carlo simulation in estimating fragment-induced detonation of an acceptor weapon.

### Process Tree Methodology

A *process tree* is a specialized directed graph that uses logic gates to model the logical relationship between events, conditions and processes in a system (Bott and Eisenhower, 1989). The *logic gates* are principally *AND*, and Exclusive *OR*, although gates representing other logical operations could be used. The *cut sets* of the process tree are sets of events that cause the top condition on the process tree to occur. In disjunctive normal form the cut set equation for the process tree is a complete list of potential mechanisms capable of producing the top condition in the tree. We have used this fact to develop process trees for reconstructing accidents from observational data (Eisenhower and Bott, 1995). It is suggested that the reader refer to Figure 1, which is a truncated version of the full process tree for explosion propagation to understand our definitions of these objects.

A *condition* is defined as a state of the system under study. The system state is described by parameter values and qualitative descriptions of the system status. The top gate in a process tree is usually a condition representing the ultimate system state of interest to the analysts. For example, the top *AND* gate of our tree is "*Single Fragment -Induced Detonation of Acceptor Weapon Condition*". Conditions can also appear in the tree as logical inputs to other gates, for example "*Exothermic Material (HE) at Reaction Site*". This is a truncation of a more detailed sub-branch used to describe the state of the HE at the time of fragment impact. Conditions of this form are associated with a system state that strongly affects the process in the gate above. Necessary conditions appear on the tree as inputs to an *AND* gate. Lists of sufficient alternate conditions will appear as inputs to an *OR* gate.

*Events* are occurrences that affect the system. An example of an event in our process tree is "*First Donor Detonation Event*". Events are represented on the tree by the standard symbols for basic events, undeveloped events, developed events or conditional events.

A *process* is the means by which the system transitions between states. An example of a process in our tree is the gate "*Transition to Detonation Process*". This process describes the growth of a chemical reaction in the HE to a detonation. Processes are brought about by events occurring under different conditions, so they may be developed logically by linking together interacting events and system conditions using *AND* and *OR* gates. When developed in sufficient detail, processes can be tied directly to specific physical or chemical models.

### Process Tree for Propagating Explosions

A complete process tree for a propagating explosion problem is situation- and weapon-specific and is quite large. The tree shown in Fig.1 is a truncated version intended to illustrate the general approach. In general fragment-induced detonation of an acceptor can occur by a direct reaction of the HE, by inadvertent direct activa-

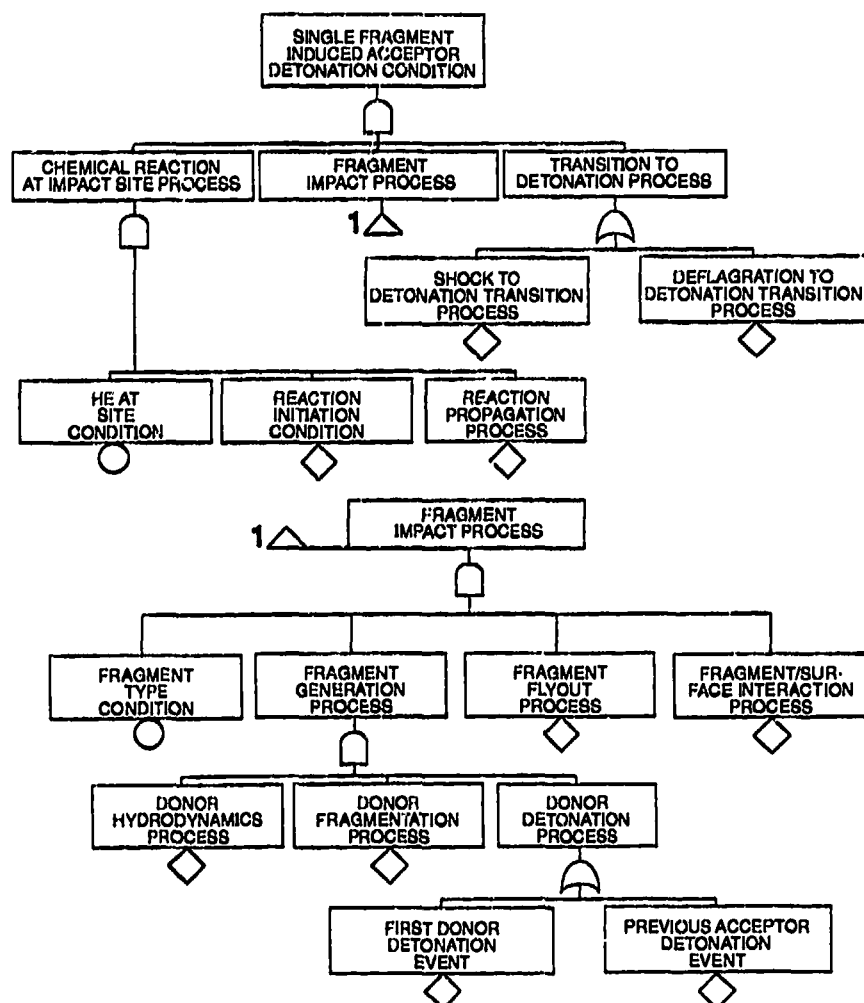


Fig. 1. Simplified process tree.

tion of a detonator or by inadvertent actuation of the firing system. However in this paper we have restricted ourselves to follow only the path associated with direct initiation of the HE by a single fragment. Detonations resulting from multiple fragments or areal impacts are not discussed. Single fragment induced detonation requires the impact of a fragment, the initiation of a reaction at the impact site and then a subsequent transition to detonation. The latter two branches are continued for only one level. The "Shock to Detonation Transition Process" (SDT) and the "Deflagration to Detonation Transition Process" (DDT) sub-branches describe fundamentally different paths to detonation. SDT is well-understood and is a threshold effect defined by delivered impulse. DDT is far more complicated and its occurrence is highly system-dependent. Below we discuss only SDT. We may consider the development of these branches as the necessary information required to estimate the conditional probability of detonation given the impact of a particular fragment. The specification of the

fragment characteristics is considered in the fragment impact branch.

Sub-processes associated with impact are the "*Fragment Generation Process*" in the donor, the "*Fragment Flyout Process*" which includes geometric considerations associated with transport from the donor to the acceptor (including ricochet where appropriate) and the "*Fragment/Acceptor Surface Interaction Process*". We also specify the type of fragment as a condition. The "*Fragment Generation Process*" is of particular interest. Here we consider the detonation of the donor and the subsequent processes leading to fragment production. The specification of fragment properties using probability distribution functions is discussed below. Note that the donor may be either the first weapon to explode or a previous acceptor which has detonated. The development of the relative probabilities associated with these two possibilities is discussed elsewhere (Luck, Eisenhower and Bott 1996).

### Monte Carlo Model

In the process tree we used deductive logic to organize the physics associated with detonation. Now we consider how to apply this logic to obtain new information about the probability of detonation. To do so we employ an analogue Monte Carlo technique; first fragments are created, next they are tracked individually through the problem geometry, and then the outcome produced by each is recorded. A fragment history created by recording each event as it occurred would consist of one possible path through the process tree. Finally, the desired event probabilities are estimated by tallying the aggregate outcomes for many fragment histories.

Incidentally, it should be noted that these simulations are quite similar to those performed by Monte Carlo radiation transport codes<sup>4</sup>. In fact, the powerful mathematical techniques developed in that field are applicable and we have used some of them successfully.

Our technique is illustrated by model problem adapted from a safety study performed at Los Alamos. Figure 2 shows the arrangement along with some fragment trajectories sampled from a Monte Carlo simulation. (Note that the lines shown on the weapons are artifacts of the illustration process.) In the actual safety study there are several potential donors and acceptors, along with other objects.

The donor is shown at the time of incipient fragmentation. The fragmentation model specifies the size, shape, birth location, and velocity of

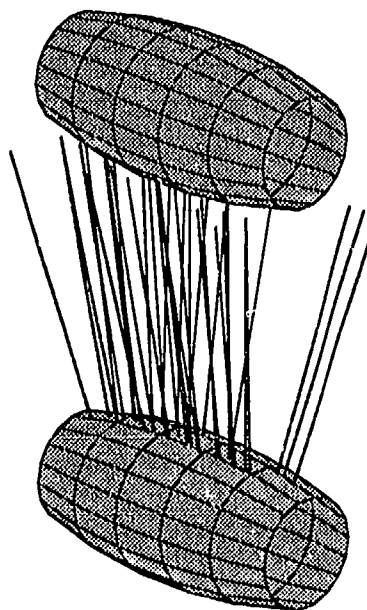


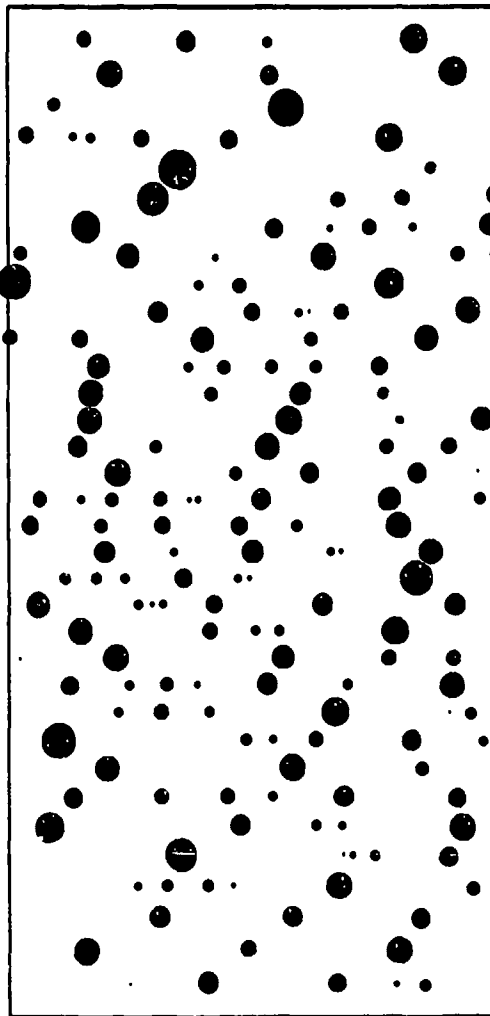
Fig. 2. Illustration of our model problem.

each fragment. Each of these quantities is randomly chosen subject to constraints. The aggregate collection of fragment sizes was required to fit an experimentally determined size probability distribution. Similarly the geometric fragmentation pattern was required to agree in certain respects with a pattern characterized from a post-fragmentation radiograph. The direction of each fragment was given by a directional model that was calibrated by off-line hydrocode simulations. Fragment speed was calibrated by experiment data and hydrocode simulation. A random component was added to fragment velocity to account for uncertainty.

The physics of dynamic fracture and fragmentation is documented extensively in the literature<sup>5,6,7</sup>. However, the theory is not sufficient by itself to determine a size probability distribution or a geometric fragmentation pattern without resort to experiment. We have used information from several experiments; in a typical setup a witness plate is supported above a donor. The donor was then detonated and the sizes of holes created by fragments were recorded by the witness plate.

To check the fragmentation and trajectory algorithms for proper fragment size distribution and direction, typical witness plate impact patterns (each was one Monte Carlo simulation) were generated and compared to the experimental results. Figure 3 shows a typical simulation result for which good agreement was obtained. Note that this information could be directly used to improve weapon safety.

In the safety study we were interested in the occurrence of shock-to-detonation transition (SDT) in the acceptor. SDT depends on the size of the impacting fragment and other quantities. In our Monte Carlo model each fragment carries along a complete set of descriptive attributes; thus the occurrence of quite complex acceptor impact conditions can be identified. The occurrence or non-occurrence of SDT is evaluated by a response function for each fragment impact.



In this and other studies, we have used two different treat-  
Fig. 3. Simulated results of witness plate impacts.

ments of ricochet. Some analytic models are sufficiently economical to evaluate that they can be directly used in the Monte Carlo calculation. If it is necessary to treat ricochet more rigorously, hydrodynamic computer codes can be used off-line. In this case, important physics must be characterized by a few parameters so that all situations likely to be encountered in the Monte Carlo simulations can be treated by interpolation.

Calculation of probabilities of occurrence for the situations of interest is the last step. The desired probabilities were obtained by repetitive simulation of donor explosions and subsequent calculation of acceptor impact locations. In some cases events are independent and it is more efficient to obtain probabilities for subevents and mathematically combine them.

### **Summary and Conclusions**

Probabilistic modeling has been shown to be quite useful in the analysis of propagating explosions. Development of a process tree for a particular weapon array is an efficient method for structuring the relevant physics and identifying modeling approaches. We have found that the process tree methodology and Monte Carlo modeling are excellent complements. This synergism results from the fact that the physics of the problem involves both deterministic and random processes; Monte Carlo techniques are ideally suited to such problems. We have fulfilled the need to incorporate complex physics in the simulations by developing specific response functions for fragment - object interactions and HE reaction. If simple physics models are adequate they can be evaluated in-line or if detailed hydrocode calculations are necessary they can be performed offline and the results characterized by simple functions. Our experience with the process-tree, Monte Carlo transport-simulation approach to propagating explosions on actual systems has been favorable. We further conclude that the approach is quite robust and can be applied to a wide range of problems.

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