Implementation of Prompt Propagation Logic in a QRA Tool

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS

AN	Ammonium Nitrate
ANE	Ammonium Nitrate Emulsions
ANFO	Ammonium Nitrate - Fuel Oil
APT	A-P-T Research, Inc.
ATD	American Table of Distances
ATF	Bureau of Alcohol, Tobacco, Firearms and Explosives
E_f	Group Risk
E_p	Exposure
GUI	Graphical User Interface
HD	Hazard Division
IMESAFR	Institute of Makers of Explosives Safety Analysis for Risk
ISP	IMESAFR Science Panel
LLNL	Lawrence Livermore National Laboratory
MT	Maximum Throw
NATO	North Atlantic Treaty Organization
NEW	Net Explosive Weight
PES	Potential Explosion Site
P_f	Individual Risk
$P_{p\|e}$	Probability of Propagation Given Event
$P_{f\|e}$	Probability of Fatality Given Event
QD	Quantity Distance
QRA	Quantitative Risk Assessment
RMSE	Root Mean Square Error
SSD	Safe Separation Distance
UBM	Upper Bound Multiplier
US DoD	United States Department of Defense

1.0 Abstract

A-P-T Research, Inc. (APT) has investigated incorporating prompt propagation logic into the Institute of Makers of Explosives Safety Analysis for Risk (IMESAFR©) software. This effort was funded by Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) and reviewed by the IMESAFR Science Panel (ISP). ISP members include US and global regulators (current and past) and commercial industry representatives. This work is in response to regulatory and industry personnel requesting an appropriate methodology for handling prompt propagation for a quantitative risk assessment (QRA). Risk-based prompt propagation logic would give regulators a better understanding of the outcomes expected from scenarios where prompt propagation is a possibility and allow for a more accurate determination of whether the risk to the public is acceptable. ATF is interested in the ability to consider prompt propagation when determining whether an IMESAFR-based variance request should be approved. ATF uses variances to allow industry members, who show good cause, to exceed the American Table of Distances (ATD) maximum allowable explosive weight when the IMESAFR-calculated individual risk (P_f) and group risk (E_f) are lower than 1E-06 and 1E-05, respectively, as well as have procedures in place to reduce risk further. Industry members are also required to have procedures in place to reduce risk further.

Currently, no one, on either the industry or defense side (including US DoD or NATO), has a prescribed methodology for addressing prompt propagation within a QRA model. To determine an appropriate method for modeling prompt propagation, ATF developed a strawman for the probability of propagation given an event ($P_{p|e}$), which was reviewed within the ISP. The $P_{p|e}$ was initially modeled using a single inverse sigmoid curve fit with multiple anchor points set at percentages of separation distance. Next, APT proposed the initial post-propagation consequence logic for both blast and debris, using IMESAFR's current algorithms as a starting point. The preliminary prompt propagation model was compared against the current IMESAFR model and the ATF informal method for overall risk and consequences (i.e., combining Net Explosive Weights (NEWs) at each Potential Explosion Site (PES) and assuming a $P_{p|e}$ of 1 for PESs failing separation distances). The existing ATF approach was found to produce non-conservative results in some cases even compared to the current IMESAFR model (which does not consider propagation). Based on these findings, ATF, with ISP consensus, agreed that APT should move forward with refining the model and addressing uncertainty. A Delphi study was used to refine the strawman curve for probability, then the model was further refined using a second Delphi study to consider the effect of beneficial or detrimental factors and establish four different inverse sigmoid curve fits instead of a single curve. Continued work included incorporating additional beneficial or detrimental factors or "curve modifiers" that could shift the $P_{p|e}$ from one curve fit to another. When three or more PESs are considered for prompt propagation, combined curve modifiers are also needed. The next step will be the publication of the logic followed by a review phase, after which the propagation logic will be ready to be included in a risk assessment tool.

2.0 Introduction

2.1 WHAT IS PROPAGATION?

An “explosives event” is defined as an initiation and subsequent release of energy from an explosive. Propagation is the process where explosive effects (blast and debris) from a Potential Explosion Site (PES) during an explosives event cause an explosives event at other nearby PESs. Propagation increases explosive effects, which in turn increases risk.

2.2 WHAT IS PROMPT PROPAGATION?

The analysis described herein only considers prompt propagation. Unless otherwise specified the term “propagation” will mean “prompt propagation” throughout this paper. Generally, prompt propagation is defined as one explosive event causing another explosive event so quickly after the initial event that the blast waves from the two events coalesce. A person at an Exposed Site (ES) would be subject to one bigger blast wave instead of two smaller ones.

2.3 PURPOSE OR REASON FOR RISK-BASED PROPAGATION LOGIC

A-P-T Research, Inc. (APT) decided to investigate incorporating prompt propagation logic into either the Institute of Makers of Explosives Safety Analysis for Risk (IMESAFR©) Quantitative Risk Assessment (QRA) software tool or a separate, standalone propagation tool. This decision was based on input from Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF), the IMESAFR Science Panel (ISP), and other global regulators requesting an appropriate methodology for handling prompt propagation for QRAs. Risk-based prompt propagation logic would give regulators a better understanding of the outcomes expected from scenarios where prompt propagation is a possibility and allow for a more accurate determination of whether the risk to the public is acceptable. ATF is interested in the ability to consider prompt propagation when determining whether an IMESAFR-based variance request should be approved [1]. ATF uses variances to allow industry members, who show good cause, to exceed the American Table of Distances (ATD) maximum allowable explosive weight [2] when the IMESAFR-calculated individual risk (P_f) and group risk (E_f) are lower than 1E-06 and 1E-05, respectively. Industry members are also required to have procedures in place to reduce risk further.

2.4 CURRENT WAYS PROPAGATION IS HANDLED FOR QD AND BY ATF

The Quantity Distance (QD) process for handling the possibility of prompt propagation due to magazine separation distance failures is to sum the quantities of explosives. Currently, no one, on either the industry or defense side (including United States Department of Defense (US DoD) or North Atlantic Treaty Organization (NATO)), has a prescribed methodology for addressing prompt propagation within a QRA model.

ATF’s current process for considering propagation is to combine the Net Explosive Weights (NEWs) at each PES and assume a Probability of Propagation Given Event ($P_{p|e}$) of 1 for PESs failing separation distances. This is an informal process used to assess scenarios that have a probability of propagating and is considered a stopgap until a more appropriate methodology is designed.[1] This further demonstrates the need for a well-defined and peer-reviewed process for assessing risk due to prompt propagation.

2.5 PROCESS USED TO DETERMINE AN APPROPRIATE METHOD FOR ADDRESSING PROMPT PROPAGATION

To determine an appropriate method for addressing prompt propagation in a QRA, APT used IMESAFR's current risk-based logic as a starting point. The overall equation for risk includes three components: the probability of event, the consequences given an event, and the exposure. For the prompt propagation logic, the probability of propagation given an initial event and the consequence given the event needed to be determined. During an ISP meeting, ATF proposed a strawman of predicting the probability of propagation (given an initial event at a "donor magazine" and the presence of one more "receptor magazines") based on the relative distance a PES is from the safe separation distance (SSD), which for the analysis described in this paper was determined using ATD. The generic term "SSD" is meant to represent the distance prescribed by any QD system to prevent prompt propagation; this term is used in this paper to emphasize that any QD system, not just ATD, can be used to determine a method for addressing propagation. Each of the five selected distances was assigned a probability of propagation (e.g., at 1% of the SSD, a probability of propagation of 99% was expected). An inverse sigmoid equation was selected as the curve fit that best modeled this strawman solution. The ISP, which includes representatives from government regulatory departments, Institute of Makers of Explosives (IME), and other commercial explosive companies and meets quarterly to address current issues regarding explosives, agreed that this was an acceptable starting point for addressing propagation. Consequence calculations were adjusted to consider (a) debris using the original NEW but an increase in the debris maximum throw range and (b) blast using the aggregation of NEWs for the involved PESs. A high-level flowchart of the process used to create the propagation logic described in this paper is shown in Figure 2-1.

[1] This informal process is referred to interchangeably within this paper as the "informal ATF model" or the "O'Lena" method, named after Mike O'Lena, ATF's Explosives Industry Programs Branch Chief. Again, this method is a stopgap until an appropriate methodology is finalized and not a method that Mike O'Lena or anyone at ATF is advocating for long-term use.

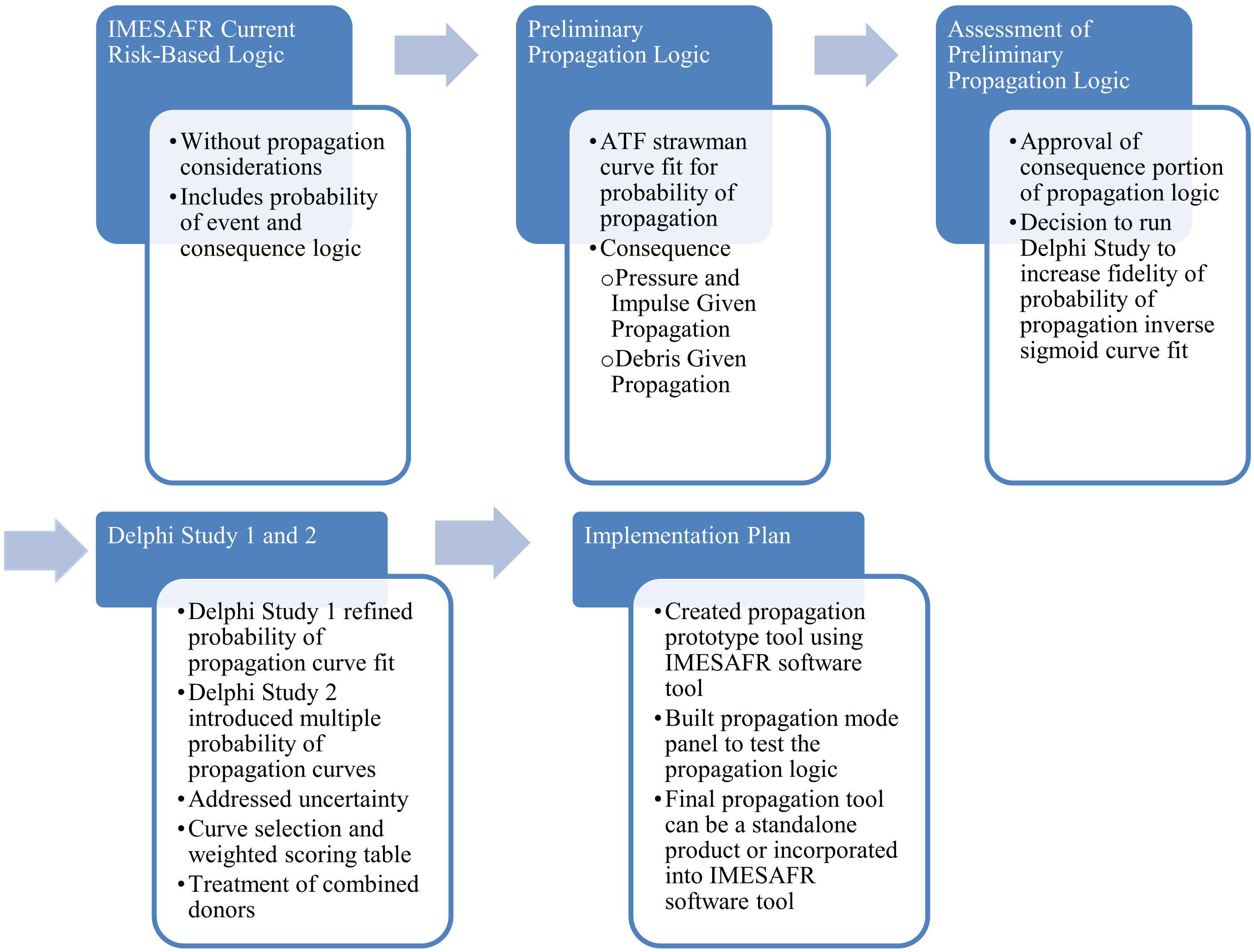


Figure 2-1: Process Used to Develop Propagation Logic in a QRA Tool

3.0 Current QRA Methodology without Propagation (IMESAFR Algorithms)

The QRA methodology used in IMESAFR is based on the concept of risk developed in 1662 by French mathematician Blaise Pascal and is expressed mathematically as an annual probability of fatality (P_f) to any individual using the following equation:

$$\text{Risk} = P_f = P_e \times P_{f|e} \times E_p$$

The P_e is defined as the probability that an explosives event will occur per PES per year. The $P_{f|e}$ is defined as the probability of fatality given an explosives event and the presence of a person. E_p is defined as the exposure of one person (as a fraction of a year) to a particular PES on an annual basis.

A second term that is associated with risk applies to a group of persons or the combined risk of fatality of all persons in a group (referred to as group risk), E_f. This is defined as the summation of individual risks and provides an expectancy or expected value (i.e., the average number of fatalities expected per year) as shown:

$$E_f = \sum_{1}^{n} (P_e \times P_{f|e} \times E_p)$$

This methodology is explained in further detail in the *IMESAFR Technical Manual* [3]. The current IMESAFR algorithms do not take propagation effects into account and only assess the risk from PESs independently.

4.0 Proposed QRA Methodology with Prompt Propagation

The risk equation for considering propagation uses the same basic concept for risk described in Section 3.0. A simple two PES scenario is shown in Figure 4-1 and is used to show a case where the total risk is calculated for two PESs that have the potential to promptly propagate.

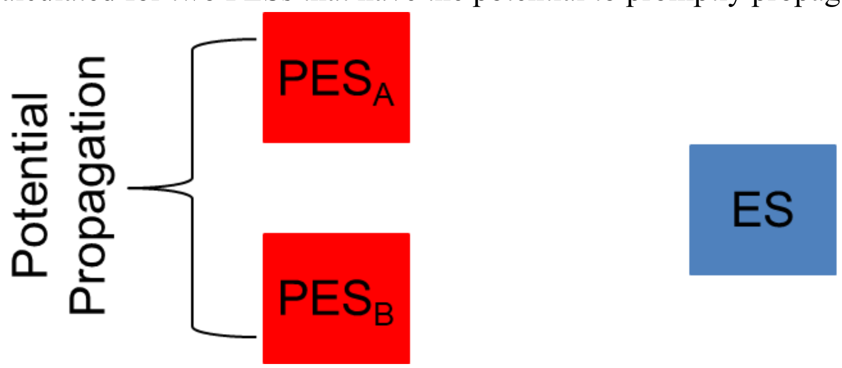


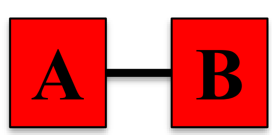
Figure 4-1: Two PES Propagation Scenario

The total risk equation for a two PES propagation scenario is:

$$P_f = P_{e(A)} * P_{A\to B} * P_{f|e(A\to B)} + P_{e(A)} * (1 - P_{A\to B}) * P_{f|e(A)} + P_{e(B)} * P_{B\to A} * P_{f|e(B\to A)} + P_{e(B)} * (1 - P_{B\to A}) * P_{f|e(B)}$$

It should be noted that the E_p term is not shown in this equation since it is the same for a given IMESAFR scenario whether or not propagation is being considered. APT used a probability event tree diagram to map out all possible combinations of PESs and provide insight on how to create an algorithm to perform the P_f calculation for multiple PES donors.

The event tree diagram was created by first considering two PESs failing separation:



There are four possible detonation events: **A**, **B**, **A+B,** or **B+A** (the notation is used here to indicate detonation events, **A+B** indicates that **A** has propagated to **B** and both detonated). There are also other outcomes involving detonations that did not happen. The full probability event tree diagram is shown in Figure 4-2. Each event also has a related consequence, which is left out of the tree for simplicity, and will be discussed later in this section.

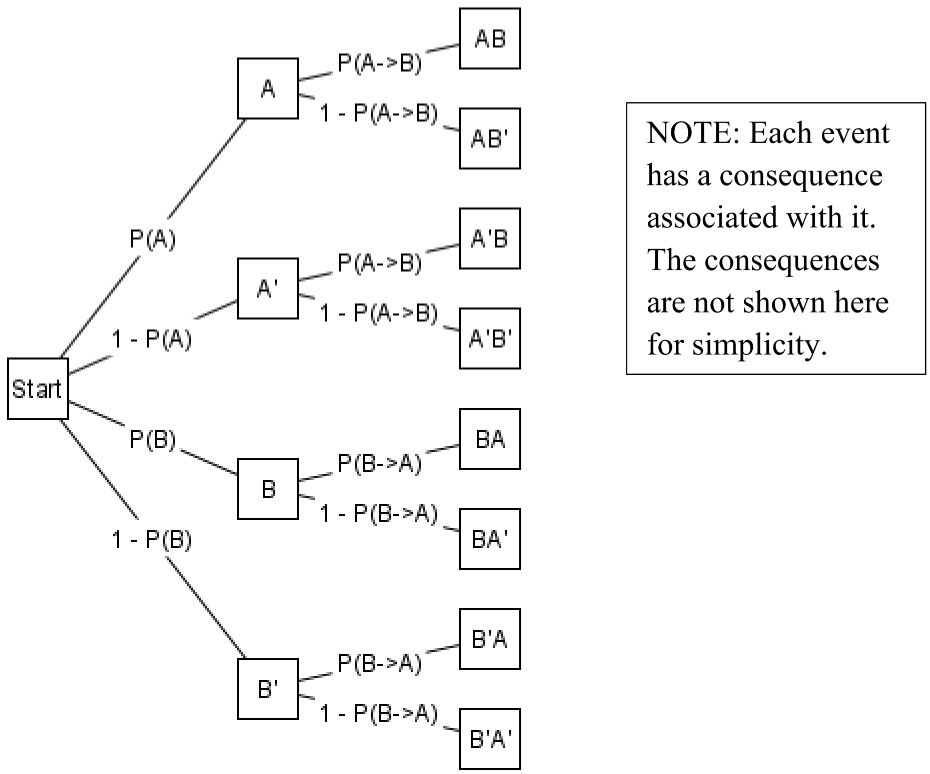


Figure 4-2: Two PES Event Tree

In the event tree, **A** indicates an event where **A** detonated, **A'** indicates an event where **A** did not detonate, and multiple letters indicate combinations of events (**AB** indicates that **A** and **B** detonated). The probability that an event did not happen can be computed by the complement, as shown in Figure 4-2. Obviously, in the two PES case, some of the "events" in the tree are not possible, as will be discussed later in this section.

The event tree diagram has several useful properties. The number along each line is the probability to get from one event to the next and can be used to calculate the probability of an event anywhere on the tree. The probability of **A** and **B** detonating was calculated by multiplying the numbers along the branch: **A** *and* **B** = P(A)P(B->A). The emphasis on the word "and" is used to indicate that probabilities will be multiplied together.

The complements are shown in the tree to emphasize that the sum of the probabilities for each PES of the tree equals 1, as shown by dashed lines in Figure 4-3. Addition implies a logical *or*, so the first level of the tree is **A** or **A'** or **B** or **B'**, where the probabilities for each must sum to 1 since all possible outcomes have been covered.

As mentioned previously, some of the outcomes shown are not possible, and have probabilities that equal to zero. For example, if **A** does not detonate, it cannot propagate to **B**. Also, outcomes where detonation does not occur are not needed, so those branches can be pruned from the tree as shown in red in Figure 4-3.

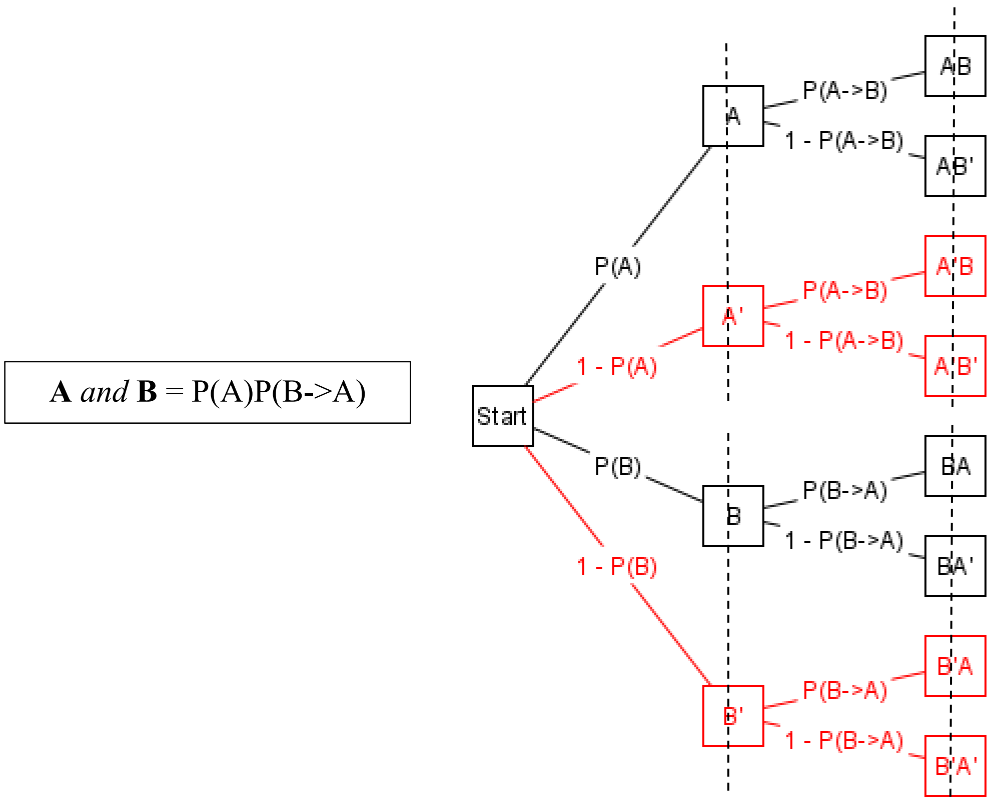


Figure 4-3: Two PES Modified Event Tree

The events at the end of the tree are the ones of interest, as shown in Figure 4-4.

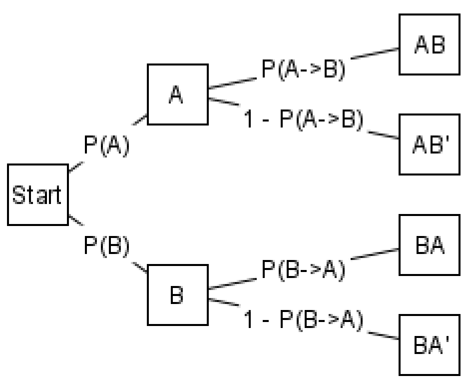


Figure 4-4: Two PES Event Tree End Events

Previously, it was shown that it is easy to pick out the events of interest for a two PES scenario: **A** or **B** or **A+B** or **B+A**. As the tree implies, **A** is **A** and not **B**. That is, the probability of just **A** is the probability of a detonation at **A** that did not result in a detonation at **B**. The equation for the probability of event for these four outcomes (again, ignoring consequences for now) would be:

$$P_e = P_A(1 - P_{A \to B}) + P_A P_{A \to B} + P_B(1 - P_{B \to A}) + P_B P_{B \to A}$$

However, a larger number of PESs increases the number of possible outcomes. A tree of possible outcomes for three PESs is shown in Figure 4-5. It should be noted that the tree does not include the complement cases.

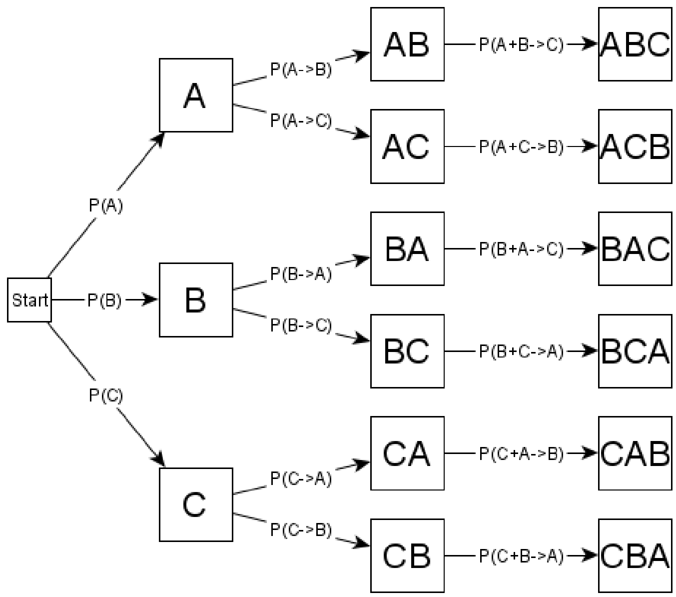


Figure 4-5: Three PES Event Tree

The calculation for the probability of event for three PESs is longer, though not necessarily more complicated. The equation for the **A** branch is (without consequences shown):

$$P_{e_A} = P_A(1 - P_{A \to B})(1 - P_{A \to C}) + P_A P_{A \to B}(1 - P_{A+B \to C}) + P_A P_{A \to C}(1 - P_{A+C \to B}) + P_A P_{A \to B} P_{A+B \to C} + P_A P_{A \to C} P_{A+C \to B}$$

The other branches have the same form. The pattern created when constructing the equations can be turned into an algorithm. A node in the tree could be represented by the data:

Event Node
List of child nodes (descendants)
Probability of this event (e)
Probability of reaching this node or the branch probability (b)

The algorithm for constructing the data for each event in the tree is as shown in Figure 4-6:

Walk(Node n)
For each child c in children:
p = probability to child node
n.e = n.e*(1-p)
c.e = c.b = n.b*p
Walk(c)

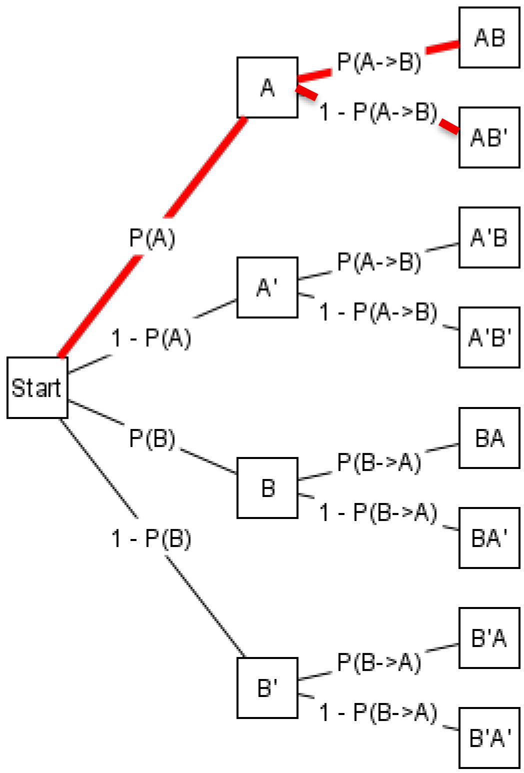


Figure 4-6: Probability of Propagation for Node A

To emphasize the growth of the equation, a partial tree for a four PES scenario showing the complete **A** branch is shown in Figure 4-7.

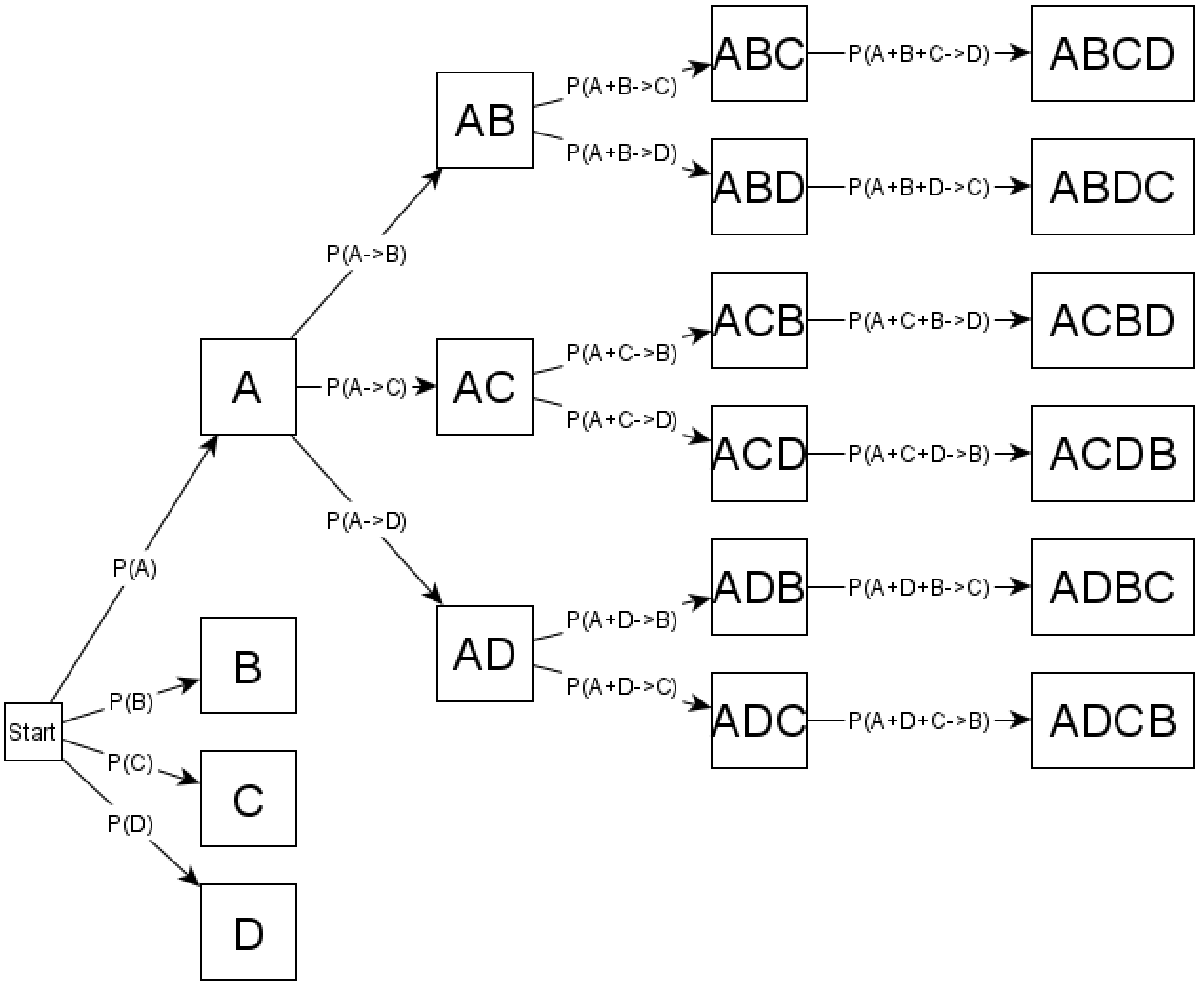


Figure 4-7: Four PES Partial Event Tree

Each event in the tree has a consequence value associated with it. The consequence calculation follows the conditional summation. So, for the two PES example:

$$P(f|e)_{A+B} = P(f|e)_A + P(f|e)_B(1 - P(f|e)_A)$$

The equation can be re-arranged to show that:

$$P(f|e)_{A+B} = P(f|e)_{B+A}$$

This holds for all combinations of any number of PES, so that any grouping has the same consequence value (which is logical since it does not matter how the event was achieved, all PES detonate simultaneously).

The full risk equation for two PESs now matches the equation discussed during a NATO AASTP-4 Custodian Working Group Meeting [4] held in Freiburg, Germany, from April 8 to 10, 2019 (with input from Martijn van der Voort, then of MSIAC)[2]:

$$P_f = P_A(1 - P_{A\to B})P(f|e)_A + P_A P_{A\to B} P(f|e)_{A+B} + P_B(1 - P_{B\to A})P(f|e)_B + P_B P_{B\to A} P(f|e)_{A+B}$$

The risk equation for the **A** branch of the three PES example:

$$P_{f_A} = P_A(1 - P_{A\to B})(1 - P_{A\to C})P(f|e)_A + P_A P_{A\to B}(1 - P_{A+B\to C})P(f|e)_{A+B} + P_A P_{A\to C}(1 - P_{A+C\to B})P(f|e)_{A+C} + P_A P_{A\to B} P_{A+B\to C} P(f|e)_{A+B+C} + P_A P_{A\to C} P_{A+C\to B} P(f|e)_{A+B+C}$$

Unlike consequence, probability of propagation is not commutative:

$$P_{A\to B} \neq P_{B\to A}$$

4.1 ASSESSMENT OF PRELIMINARY PROPAGATION MODEL

This prompt propagation logic was compared against the current IMESAFR methodology (with no consideration for propagation) and the informal ATF model (i.e., combining NEWs and assuming a $P_{p|e}$ of 1). The results of this analysis showed that the preliminary propagation model was a more conservative and consistent predictor of risk than both the current IMESAFR methodology (with no adjustments) and the informal ATF model (with combined NEWs). Although it may seem counter-intuitive, studies confirmed that the ATF model resulted in lower risk for some scenarios than the current IMESAFR model. For example, there were a few cases where the higher loading density (unrealistically so, in some scenarios) used in the O'Lena method, referred to herein as the "informal ATF model," created lower debris consequence results than the current IMESAFR method at some locations of interest, especially for concrete-based PES models.

The preliminary propagation model assessment initial setup description and an example of one set of risk and consequence charts are shown in Appendix A: Preliminary Propagation Model Assessment. While not shown in this paper, risk and consequence charts were produced for 38 scenarios and a total of 1,368 PES-ES pairs during the preliminary propagation model assessment.

4.2 PROBABILITY OF PROPAGATION GIVEN EVENT

The prompt propagation model is always considering propagation; however, unless any two magazines fail SSD (as prescribed by the QD system in use) the risk contributed by propagation

[2] The risk equation for propagation was initially introduced during the *Propagation of PESs* briefing [7], presented by John Tatom (APT), at the Klotz Group Spring Meeting [6] in Freiburg, Germany, from April 2 to 4, 2019, where the discussion was planned for continuation at the AASTP-4 meeting the following week.

will be negligible compared to the total risk calculated not considering propagation (detailed in Section 3.0).

The $P_{p|e}$ term in the total risk equation considering propagation was based on scale setting parameters, or anchor points, which show the estimated probability of propagation at specified percent distances of the SSD, as shown in Table 4-1. It was then determined that an inverse sigmoid curve was the best starting point to model the relationship for this data set. The inverse sigmoid curve fit with anchor points used for the analysis discussed in this paper is shown in Figure 4-8.

Table 4-1: Probability of Propagation Anchor Parameters

Distance (ft)	Probability of Propagation
$D = (0.01) * (SSD)$	0.99
$D = (0.5) * (SSD)$	0.50
$D = (1) * (SSD)$	0.01
$D = (1.1) * (SSD)$	1E-6

The equation for the inverse sigmoid curve is:

$$f(x) = \frac{L}{1 + e^{-k(x - x_0)}}$$

where

L = the curve's maximum value (equals 1 since the function represents a probability)

e = natural logarithm base (Euler's number)

k = the logistic growth rate (the steepness of the curve)

x_0 = the x value of the midpoint of the curve

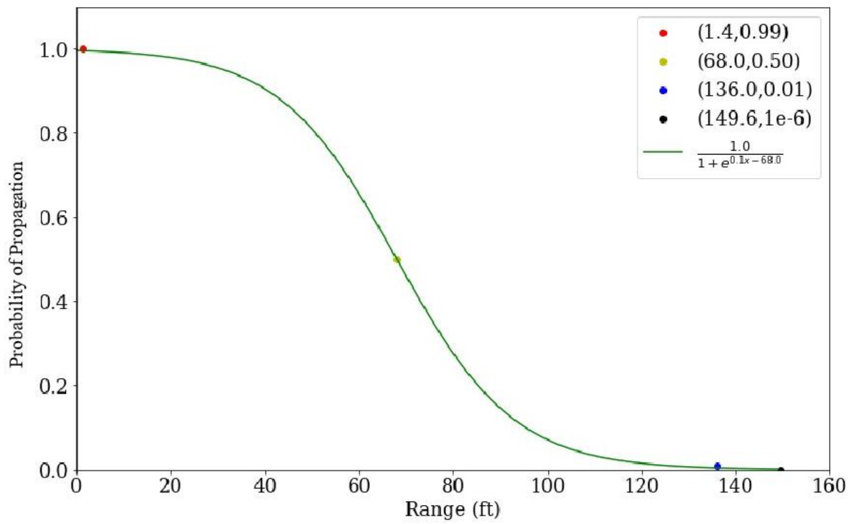


Figure 4-8: Probability of Propagation Given Event Curve Fit

The curve fit anchor points were calculated using the ATD magazine separation distances, as shown in Figure 4-8. This curve fit was initially proposed by ATF and used for the preliminary propagation model scenario assessments, as discussed in Section 0. The edge-to-edge distance between PESs was used to derive the $P_{p|e}$ from the inverse sigmoid curve, even though this is a QRA application. The differences in energetic material (e.g., high explosives, blasting agents, ammonium nitrate) were addressed in the probability of propagation routine by the choice of which separation distance to use. The logic behind which Code of Federal Regulations (CFR) table to use when governed by the ATD is provided in Table 4-2. Excerpts of the tables are shown in Table 4-3 and Table 4-4.

Table 4-2: CFR Table Selection

Donor Magazine		Acceptor Magazine	Table
HE Magazine	to	HE Magazine	555.218
HE Magazine BA Magazine	to to	BA Magazine HE Magazine	555.220: HE is Donor 555.218: BA is Donor Use More Restrictive Distance
HE or BA Magazine	to	AN Storage	555.220
BA Magazine	to	BA Magazine	555.220

Table 4-3: Table of Distances for Storage of Explosive Materials (CFR Part 555.218)

Quantity of Explosives			
Pounds over	Pounds not over	Separation of magazines	
		Barricaded	Unbarricaded
0	5	6	12
↓	↓	↓	↓
275,000	300,000	385	770

Table 4-4: Table of Distances for Ammonium Nitrate and Blasting Agents from Explosives or Blasting Agents (CFR Part 555.220)

Quantity of Explosives		Distances (ft)	
Pounds over	Pounds not over	Ammonium Nitrate	Blasting Agent
0	100	3	11
↓	↓	↓	↓
275,000	300,000	64	230

4.2.1 Delphi Studies

To increase the fidelity of the initial inverse sigmoid curve fit used to model the probability of propagation, two Delphi studies were conducted using subject matter expert (SME) input from ISP members who chose to participate in the effort. A Delphi study is a systematic and interactive method to predict results based on expert opinions. After an anonymous survey, the team of experts meets, discusses the reasoning behind their judgements, and potentially revises their answers based on the group discussion. APT sent the Delphi Study 1 survey to ISP members and received nine responses.

The second Delphi study also considered donor construction, receptor construction, and energetic material in receptor magazine as factors that will impact the probability of propagation. Additional factors (called "curve modifiers" in this report) were reviewed and weighted based on their ability to further affect the probability of propagation. These factors were donor explosives fragmentation (i.e., primary fragments), receptor azimuth (relative to donor, i.e., normal, middle, corner), and receptor door orientation. APT received 11 responses to the Delphi Study 2 survey.

A secondary product of the Delphi studies was the data needed to address uncertainty considerations. Delphi Study 1 and 2 survey responses (with and without outliers) were used to evaluate the accuracy of the initial probability of propagation model from Section 0 against SME responses.

IMESAFR's probability of event uncertainty routine utilizes a point estimate and an upper bound (or 3σ value) with a lognormal distribution assumption to determine the uncertainty associated with a given case. Given that the probability of propagation uncertainty routine would behave similarly, a UBM to generate a 3σ value was derived for the probability of propagation estimations. Calculating a realistic UBM for the Delphi Study 1 curve fit involved baselining the survey results with the original inverse sigmoid curve fit proposed by ATF. This process is further detailed in Section 4.2.1.1. The process used to calculate UBMs for the Delphi Study 2 curve fits involved evaluating the results for probability of propagation curve fits from that study with and without outliers, which is further explained in Section 4.2.1.2.

4.2.1.1 Delphi Study 1

Delphi Study 1 consisted of three scenarios and four questions, as shown in Table 4-5.

Table 4-5: Delphi Study 1 Scenarios and Questions

Magazine	Scenario 1	Scenario 2	Scenario 3
Donor	Medium unreinforced concrete magazine (Type 1/2) storing 80,000 lb of HD1.1 and HD1.5 explosives with a front azimuth of 0°	Small steel magazine (Type 2) storing 2,000 lb of high explosives (boosters and dynamite) with a front azimuth of 0°	Small steel magazine (Type 2) storing 2,000 lb of high explosives (boosters and dynamite) with a front azimuth of 0°
Receptor	60-ton overhead silo storing HD1.5 ammonium nitrate emulsions at 100% capacity placed 330 feet from the Donor (SSD from the Donor), 90° from the front azimuth of the donor mag, with its own front azimuth at 0°	60-ton overhead silo storing HD1.5 ammonium nitrate emulsions at 100% capacity placed 90 feet away from the Donor (SSD from the Donor), 90° from the front azimuth of the donor mag, with its own front azimuth at 0°	Small unreinforced concrete magazine (Type 1/2) at normal capacity storing HD1.1 emulsions in boxes on pallets, placed 90 feet away from the Donor (SSD from the Donor), 90° from the front azimuth of the donor mag, with its own front azimuth at 0°

Question 1	What do you think the probability of prompt propagation (in terms of a percentage) would be for the receptor magazine at the given distance?
Question 2	At what distance (in feet) do you think the probability of prompt propagation would be 0.5 for the receptor magazine?
Question 3	At what distance (in feet) do you think the probability of prompt propagation gets to essentially 1.0 for the receptor magazine?
Question 4	At what distance (in feet) do you think the probability of prompt propagation goes to essentially 0.0 for the receptor magazine?

ISP members who responded answered questions regarding the likelihood of propagation based on location in the form of percentages of SSD. The standard ATD was used instead of the blasting agent separation table as a starting point. Respondents determined their answers in number of different ways including analytically, through experience, and with the IMESAFR software tool as a check. After the first set of responses were received, APT coordinated with participants on any answers that seemed inconsistent or illogical. APT then presented the anonymous results of the first round of the study to responders and gave the participants a chance to revise their initial responses after seeing the results. The revised results from the second round of questioning for Scenario 1 are shown in Table 4-6 and compared against the initial strawman inverse sigmoid curve fit discussed in Section 4.2 and labeled as "Originally Proposed Curve" in Figure 4-9.

Table 4-6: Delphi Study 1 Scenario 1 Revised Responses

Magazine	Scenario 1	Name	Scenario 1			
			Probability of Propagation at SSD (330 ft)?	Distance (ft) for 50% Probability of Propagation?	Distance (ft) for 100% Probability of Propagation?	Distance (ft) for 0% Probability of Propagation?
Donor	Medium unreinforced concrete magazine (Type 1/2) storing 80,000 lb of HD1.1 and HD1.5 explosives with a front azimuth of 0°	Respondent 1	10%	100	25	400
		Respondent 2	10%	150	50	600
		Respondent 3	0%	175	150	200
		Respondent 4	5%	135	45	600
Receptor	60-ton overhead silo storing HD1.5 ammonium nitrate emulsions at 100% capacity placed 330 feet from the Donor (SSD from the Donor), 90° from the front azimuth of the donor mag, with its own front azimuth at 0°	Respondent 5	0.0001%	65	30	275
		Respondent 6	0%	125	50	330
		Respondent 7	2%	100	50	607
		Respondent 8	10%	172	43	862
		Respondent 9	0.50%	110	40	500
		Originally Proposed Curve	1%	165	~4	~363

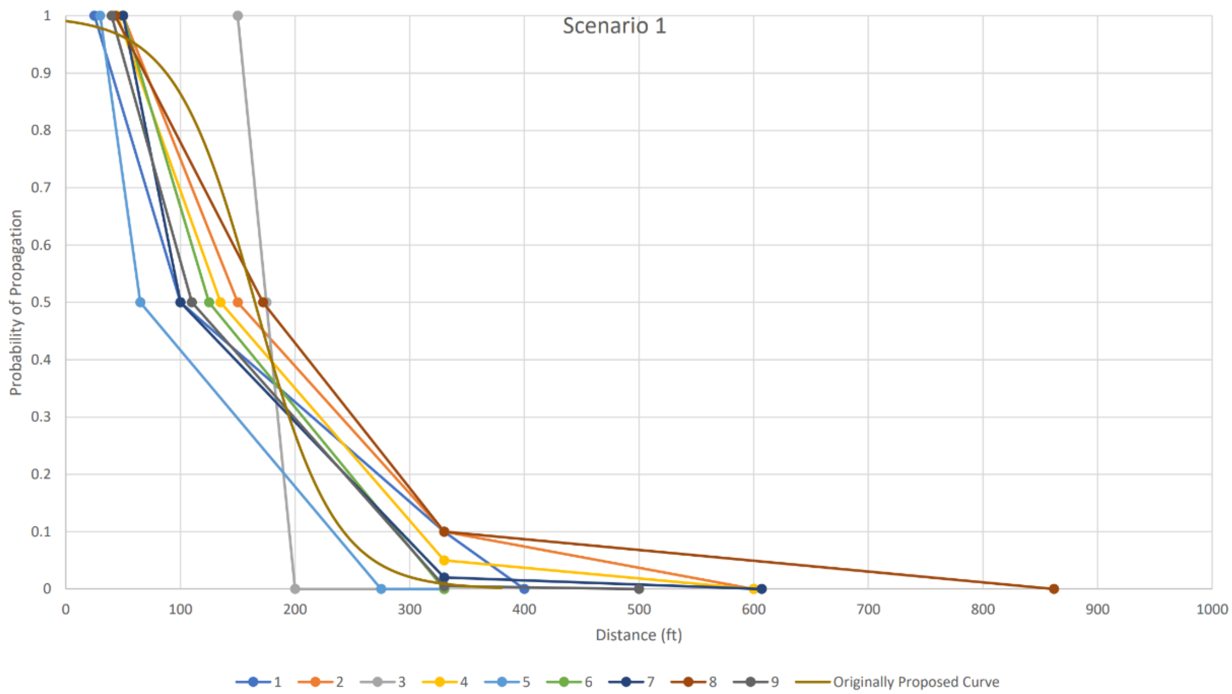


Figure 4-9: Comparison of Delphi Study 1 Scenario 1 Responses to Original Curve

The revised results from the second round of questioning for Scenario 2 are shown in Table 4-7 and compared against the originally proposed curve in Figure 4-10.

Table 4-7: Delphi Study 1 Scenario 2 Revised Responses

Magazine	Scenario 2	Name	Scenario 2			
			Probability of Propagation at SSD (90 ft)?	Distance (ft) for 50% Probability of Propagation?	Distance (ft) for 100% Probability of Propagation?	Distance (ft) for 0% Probability of Propagation?
Donor	Small steel magazine (Type 2) storing 2,000 lb of high explosives (boosters and dynamite) with a front azimuth of 0°	Respondent 1	5%	30	15	150
		Respondent 2	15%	30	12	180
		Respondent 3	30%	65	45	160
		Respondent 4	5%	50	10	100
Receptor	60-ton overhead silo storing HD1.5 ammonium nitrate emulsions at 100% capacity placed 90 feet away from the Donor (SSD from the Donor), 90° from the front azimuth of the donor mag, with its own front azimuth at 0°	Respondent 5	0.0100%	20	10	80
		Respondent 6	10%	125	70	171
		Respondent 7	7%	30	15	175
		Respondent 8	10%	50	13	250
		Respondent 9	0.25%	25	10	125
		Originally Proposed Curve	1%	45	~1	~99

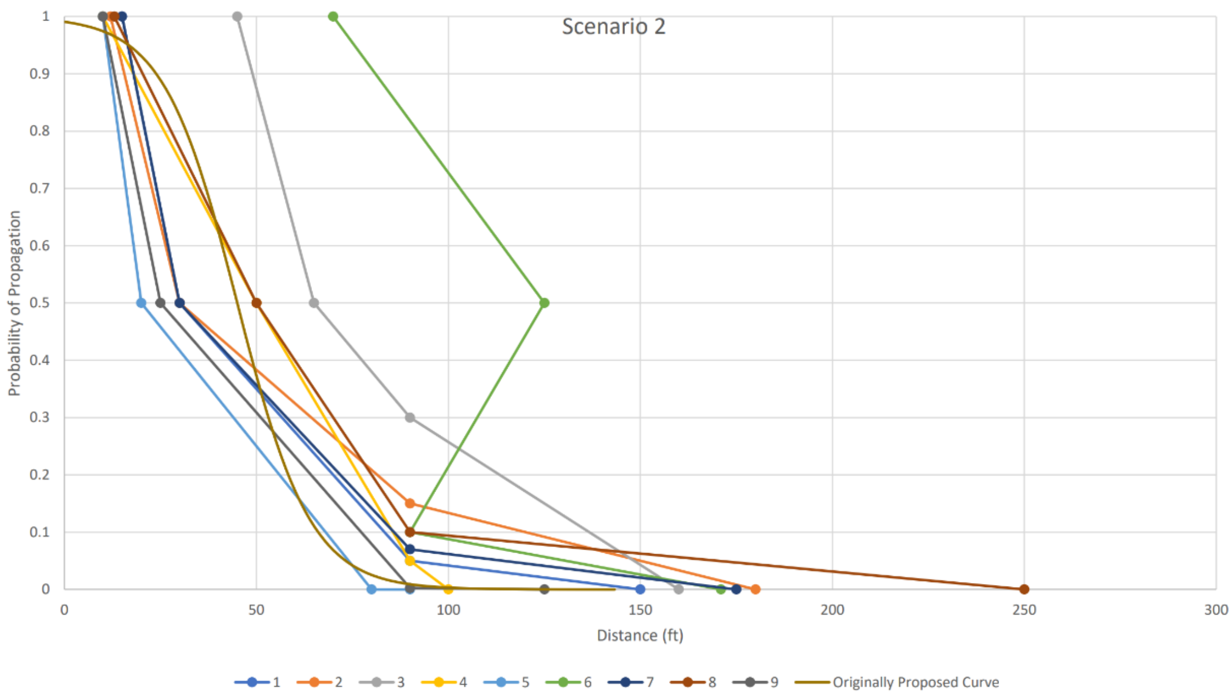


Figure 4-10: Comparison of Delphi Study 1 Scenario 2 Responses to Original Curve

The revised results from the second round of questioning for Scenario 3 are shown in Table 4-8 and compared against the originally proposed curve in Figure 4-11.

Table 4-8: Delphi Study 1 Scenario 3 Revised Responses

Magazine	Scenario 3	Name	Scenario 3			
			Probability of Propagation at SSD (90 ft)?	Distance (ft) for 50% Probability of Propagation?	Distance (ft) for 100% Probability of Propagation?	Distance (ft) for 0% Probability of Propagation?
Donor	Small steel magazine (Type 2) storing 2,000 lb of high explosives (boosters and dynamite) with a front azimuth of 0°	Respondent 1	1%	25	15	100
		Respondent 2	5%	45	20	150
		Respondent 3	0%	60	45	90
		Respondent 4	10%	40	10	100
Receptor	Small unreinforced concrete magazine (Type 1/2) at normal capacity storing HD1.1 emulsions in boxes on pallets, placed 90 feet away from the Donor (SSD from the Donor), 90° from the front azimuth of the donor mag, with its own front azimuth at 0°	Respondent 5	0.01%	20	10	80
		Respondent 6	10%	70	50	90
		Respondent 7	0.10%	25	10	91
		Respondent 8	2%	45	13	250
		Respondent 9	0.10%	20	8	100
		Originally Proposed Curve	1%	45	~1	~99

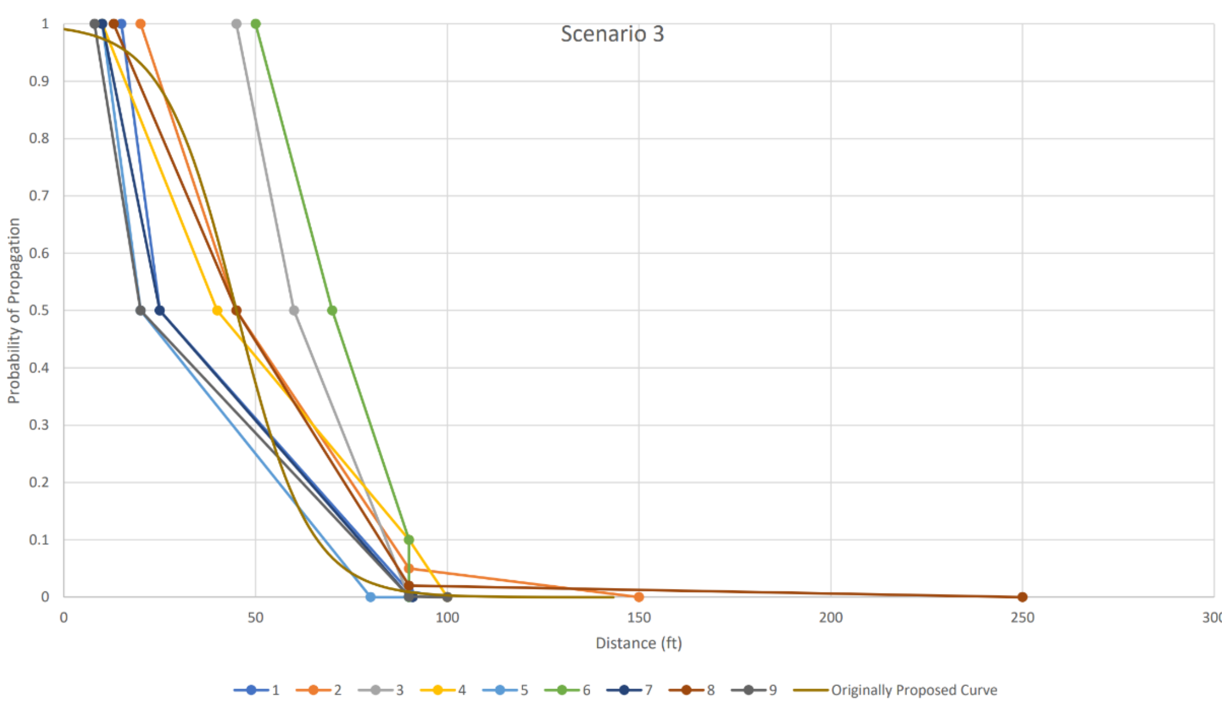


Figure 4-11: Comparison of Delphi Study 1 Scenario 3 Responses to Original Curve

The mean results from Delphi Study 1 are shown in Table 4-9 and compared to the originally proposed curve in Figure 4-12.

Table 4-9: Delphi Study 1 Mean Results

	Magazine Sep. Distance (ft)	Mean Distance from Study (ft)	Mean/Mag. Sep.	Probability of Propagation
Scenario 1	330	53.7	0.16	100%
	330	125.8	0.38	50%
	330	330	1	4%
	330	486.0	1.47	0%
Scenario 2	90	22.2	0.25	100%
	90	47.2	0.52	50%
	90	90	1	9%
	90	154.6	1.72	0%
Scenario 3	90	20.1	0.22	100%
	90	38.9	0.43	50%
	90	90	1	3%
	90	116.8	1.30	0%

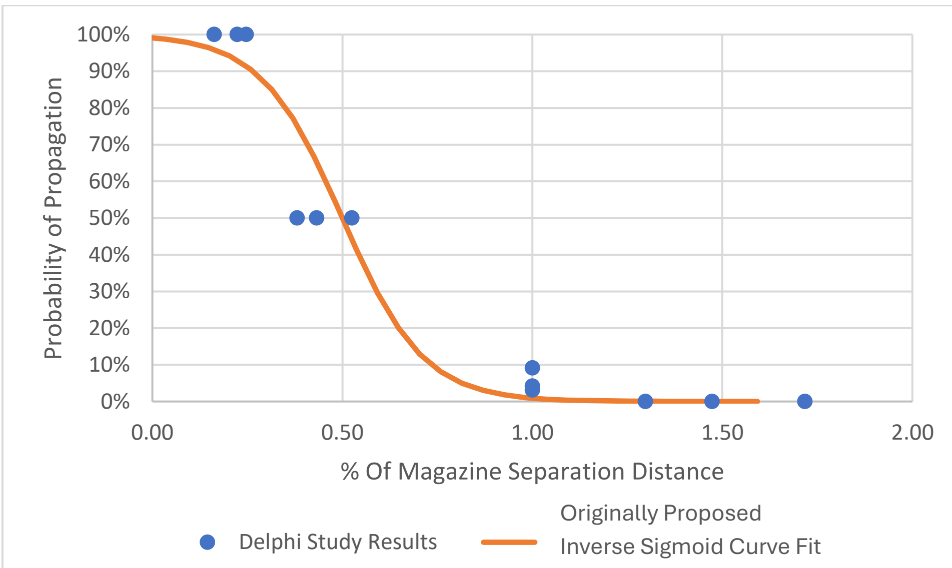


Figure 4-12: Delphi Study 1 Mean Results vs Original Curve

The adjusted inverse sigmoid curve fit from the Delphi Study 1 results became the new "baseline" curve for probability of propagation curve, as shown in Figure 4-13. The baseline curve fit incorporates the Delphi Study 1 results with the originally proposed ATF inverse sigmoid curve fit.

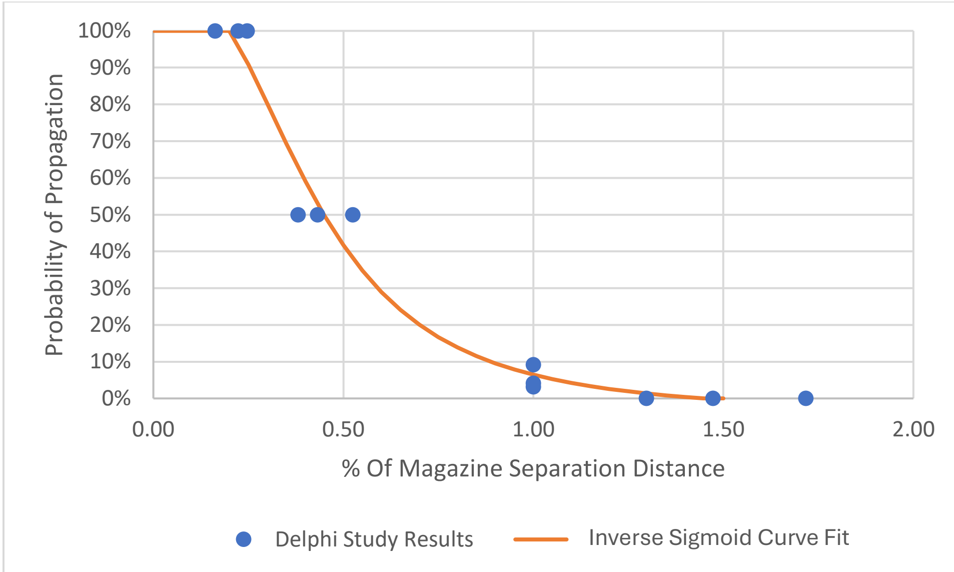


Figure 4-13: New Delphi Study 1 Baseline Probability of Propagation Curve

The equation for the new baseline curve with outliers is:

$$y = -0.043009043 + \frac{1.1469229 + 0.043009043}{1 + \left(\frac{x}{0.42034228}\right)^{2.6602434}}$$

The next step was to determine the UBM by first removing the outliers from the new baseline probability of propagation curve, as shown in Figure 4-14. The highest and lowest responses were removed as outliers to establish the new baseline curve, but they were not removed from the study results since the outlier points were still used to determine the UBMs.

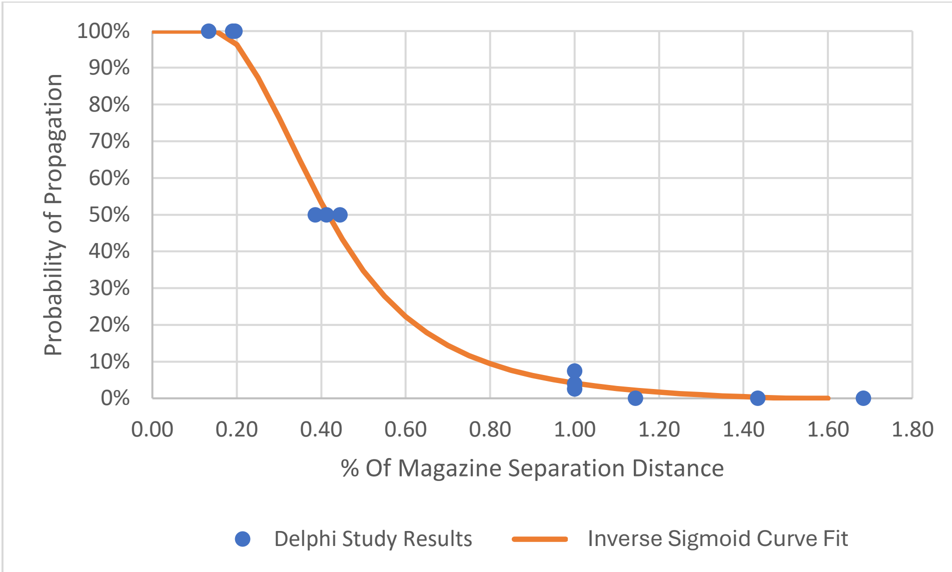


Figure 4-14: New Delphi Study 1 Baseline Curve with Outliers Removed

The equation for the new Delphi Study 1 baseline curve without outliers is:

$$y = -0.015900472 + \frac{1.0682112 + 0.015900472}{1 + \left(\frac{x}{0.40317477}\right)^{3.1816214}}$$

A comparison of the baseline inverse sigmoid curve fit with and without outliers is shown in Figure 4-15.

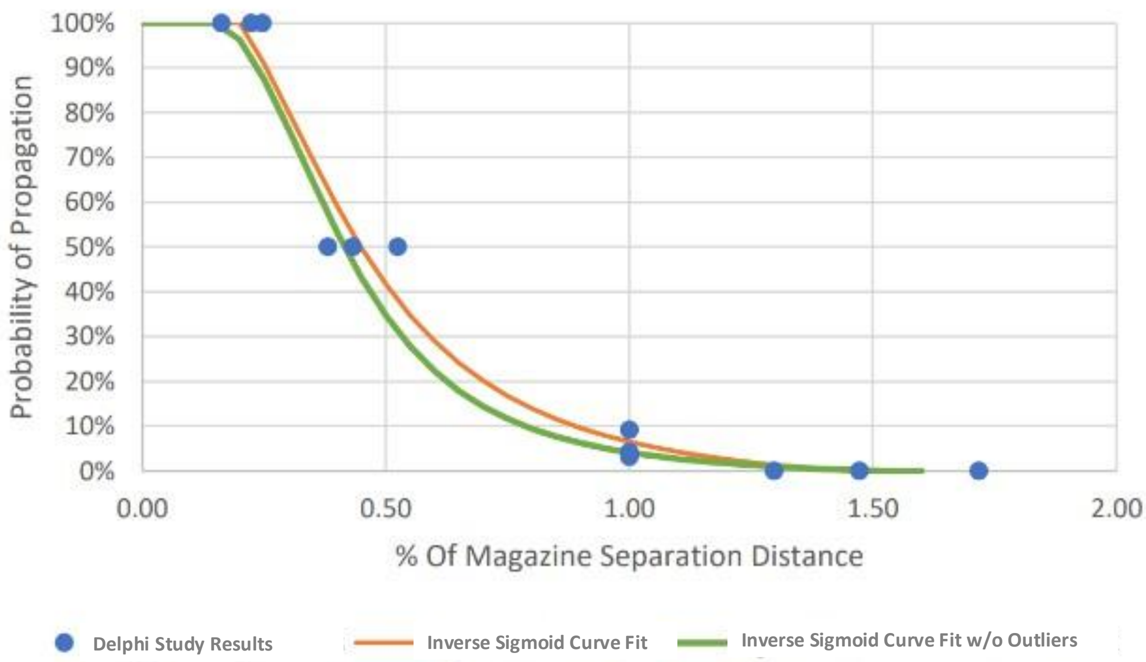


Figure 4-15: Comparison of Delphi Study 1 Inverse Sigmoid Curves with and without Outliers

The calculated UBM values for the Delphi Study 1 baseline curve fit with outliers, the Delphi Study 1 baseline curve fit without outliers, and the originally proposed inverse sigmoidal curve are shown in Table 4-10. Root Mean Square Error (RMSE) was calculated to measure the difference between the predicted and actual values for these three curve fit options. The third option, labeled "Original Curve" in Table 4-10, resulted in the highest UBM with 10.03. The larger the UBM, the higher the uncertainty in a given scenario. A UBM value greater than 3.0 can suggest a level of uncertainty indicative of an insufficient understanding of the distribution. The high UBM calculated for the original curve fit suggested that it was not the best equation to move forward with, based on the responses in the Delphi study. After reviewing the remaining two options for establishing the UBM, it was determined that the best option method was to use the Delphi Study 1 baseline inverse sigmoidal curve fit without outliers as the baseline curve fit for the next iteration of the probability of propagation logic. This resulted in the UBM value of 2.22 being selected. This can be characterized as selecting a more optimistic baseline curve, but a more pessimistic treatment of uncertainty.

Table 4-10: UBM Results from Delphi Study 1

Fraction Of Sep. Dist.	Study Results	Rebaseline	UBM (Study Results / Curve Results)	Rebaseline, remove outliers	UBM (Study Results / Curve Results)	Original Curve	UBM (Study Results / Curve Results)
0.16	100%	100%	1.0	100%	1.0	96%	1.04
0.38	50%	63%	0.8	57%	0.9	75%	0.66
1.00	4%	6%	0.6	4%	1.0	1%	4.57
1.47	0%	0%	1.0	0%	0.0	0%	0.00
0.25	100%	91%	1.1	88%	1.1	91%	1.09
0.52	50%	38%	1.3	31%	1.6	44%	1.13
1.00	9%	6%	1.4	4%	2.2	1%	10.03
1.72	0%	0%	1.0	0%	1.0	0%	0.00
0.22	100%	96%	1.0	92%	1.1	93%	1.07
0.43	50%	53%	0.9	47%	1.1	65%	0.76
1.00	3%	6%	0.5	4%	0.8	1%	3.44
1.30	0%	1%	0	1%	0.0	0%	0.00
			1.41		2.22		10.03

The Delphi Study 1 results and the method established for calculating UBM were reviewed by two statisticians, one from LLNL and one from APT. Neither statistician had an issue with using the inverse sigmoidal curve fit without outliers as the baseline curve fit for calculating the probability of propagation, given the higher associated UBM.

4.2.1.2 Delphi Study 2

The ISP requested a second Delphi study to generate multiple probability of propagation curves to account for beneficial or detrimental factors not considered by the original baseline curve. Delphi Study 2 consisted of 12 scenarios and considered donor construction, receptor construction, and energetic material in receptor magazine. The questions asked of respondents remained the same, as did the process of compiling responses and coordinating with respondents on any answers that seemed inconsistent. For this study, a steel magazine was the assumed baseline. A concrete magazine was considered worse as a donor and better as a receptor. Open was considered better as a donor and worse as a receptor. For the energetic material in the receptor magazine, Hazard Division (HD) 1.5 water-based blasting agents was the assumed baseline. Non-water-based blasting agents (Ammonium Nitrate - Fuel Oil (ANFO)) and HD 1.1 material were worse, and HD 5.1 Ammonium Nitrate Emulsions (ANEs) and Ammonium Nitrate (AN) were better.

Scenarios were defined in sets to represent cases that were both better and worse than the scenario considered in Delphi Study 1, as shown in Table 4-11. The idea behind the different groupings is that the probability of propagation curve used in an assessment would be based on the input the user defined for the scenario. The study participants were not told whether they were looking at a "bad" or "good" case when participating in the study.

The final implemented curve fits calculated using the Delphi Study 2 data were the "without outliers" results with associated UBM values, which was in line the decision by ISP to use the baseline curve fit without outliers for the Delphi Study 1 results and the statistical review by APT and LLNL.

Table 4-11: Delphi Study 2 Scenario Grouping

Probability of Propagation Curve	Curve Generated By:
Worst Case	Scenarios 1, 2, 3 of Second Study
Bad Case	Scenarios 4, 5, 6 of Second Study
Baseline Case	Original Delphi Study
Better Case	Scenarios 7, 8, 9 of Second Study
Best Case	Scenarios 10, 11, 12 of Second Study

The Delphi Study 2 scenario details are shown in Table 4-12.

Table 4-12: Delphi Study 2 Scenarios

Magazine	Scenario 1	Scenario 2	Scenario 3
Donor	Small unreinforced concrete magazine (Type 1/2) storing 10,000 lb of HD1.1 and HD1.5 explosives with a front azimuth of 0 degrees	Medium unreinforced concrete magazine (Type 1/2) storing 40,000 lb of HD1.1 and HD1.5 explosives with a front azimuth of 0 degrees	Large unreinforced concrete magazine (Type 1/2) storing 80,000 lb of HD1.1 and HD1.5 explosives with a front azimuth of 0 degrees
Receptor	An open store of pallets of HD1.1A non-water-based material placed 156 feet from the Donor (SSD from the Donor), 90 degrees from the front azimuth of the donor mag, with its own front azimuth at 0 degrees	An open store of pallets of storing 2,000 lb of high explosives (boosters, detonators and dynamite) placed 248 feet from the Donor (SSD from the Donor), 90 degrees from the front azimuth of the donor mag, with its own front azimuth at 0 degrees	An open store of pallets of bags of ANFO placed 330 feet away from the Donor (SSD from the Donor), 90 degrees from the front azimuth of the donor mag, with its own front azimuth at 0 degrees
Magazine	**Scenario 4**	**Scenario 5**	**Scenario 6**
Donor	Small steel magazine (Type 2) storing 10,000 lb of HD1.1 and HD1.5 explosives with a front azimuth of 0 degrees	Medium unreinforced concrete magazine (Type 1/2) storing 40,000 lb of HD1.1 and HD1.5 explosives with a front azimuth of 0 degrees	Large unreinforced concrete magazine (Type 1/2) storing 80,000 lb of HD1.1 and HD1.5 explosives with a front azimuth of 0 degrees
Receptor	An open store of pallets of HD1.1A non-water based material placed 156 feet from the Donor (SSD from the Donor), 90 degrees from the front azimuth of the donor mag, with its own front azimuth at 0 degrees	Small unreinforced concrete magazine (Type 1/2) storing 2,000 lb of high explosives (boosters, detonators and dynamite) placed 248 feet from the Donor (SSD from the Donor), 90 degrees from the front azimuth of the donor mag, with its own front azimuth at 0 degrees	60-ton overhead silo storing HD1.5 ammonium nitrate emulsions at 100% capacity placed 330 feet away from the Donor (SSD from the Donor), 90 degrees from the front azimuth of the donor mag, with its own front azimuth at 0 degrees

Magazine	Scenario 7	Scenario 8	Scenario 9
Donor	Small steel magazine (Type 2) storing 2,000 lb of high explosives (boosters, detonators and dynamite) with a front azimuth of 0 degrees	Pre-engineered metal building operating with/storing 10,000 lb of HD1.1 and HD1.5 explosives with a front azimuth of 0 degrees	An open store of pallets of high explosives (boosters, detonators and dynamite) material storing 5,000 lb of material
Receptor	Small unreinforced concrete magazine (Type 1/2) at normal capacity storing HD1.5 emulsions in boxes on pallets, placed 90 feet away from the Donor (SSD from the Donor), 90 degrees from the front azimuth of the donor mag, with its own front azimuth at 0 degrees	Medium unreinforced concrete magazine (Type 1/2) at normal capacity storing HD5.1 ANEs in bags on pallets, placed 156 feet away from the Donor (SSD from the Donor), 90 degrees from the front azimuth of the donor mag, with its own front azimuth at 0 degrees	Small unreinforced concrete magazine (Type 1/2) at normal capacity storing high explosives (boosters, detonators and dynamite), placed 122 feet away from the Donor (SSD from the Donor), 90 degrees from the front azimuth of the donor mag, with its own front azimuth at 0 degrees
Magazine	**Scenario 10**	**Scenario 11**	**Scenario 12**
Donor	An open store of pallets storing 2,000 lb of high explosives (boosters, detonators and dynamite) with a front azimuth of 0 degrees	An open store of pallets storing 10,000 lb of HD1.1 and HD1.5 explosives with a front azimuth of 0 degrees	An open store of pallets of high explosives (boosters, detonators and dynamite) material storing 5,000 lb of material
Receptor	Small unreinforced concrete magazine (Type 1/2) at normal capacity storing HD5.1 ANEs in bags on pallets, placed 90 feet away from the Donor (SSD from the Donor), 90 degrees from the front azimuth of the donor mag, with its own front azimuth at 0 degrees	Medium unreinforced concrete magazine (Type 1/2) at normal capacity storing HD5.1 ANEs in bags on pallets, placed 156 feet away from the Donor (SSD from the Donor), 90 degrees from the front azimuth of the donor mag, with its own front azimuth at 0 degrees	Small unreinforced concrete magazine (Type 1/2) at normal capacity storing AN prill in boxes/bags on pallets, placed 122 feet away from the Donor (SSD from the Donor), 90 degrees from the front azimuth of the donor mag, with its own front azimuth at 0 degrees

The Delphi Study 2 revised results from the second round of questioning for Scenario 1 (Worst Case) are shown in Table 4-13 and compared against the Delphi Study 1 proposed curve in Figure 4-16. The final Delphi Study 1 curve is referred to as "Baseline Curve" in comparison to the Delphi Study 2 results.

Table 4-13: Delphi Study 2 Scenario 1 (Worst Case) Revised Responses

Magazine	Scenario 1	Respondent #	Scenario 1			
			Probability of Propagation at SSD (156 ft)?	Distance (ft) for 50% Probability of Propagation?	Distance (ft) for 100% Probability of Propagation?	Distance (ft) for 0% Probability of Propagation?
Donor	Small unreinforced concrete magazine (Type 1/2) storing 10,000 lb of HD1.1 and HD1.5 explosives with a front azimuth of 0°	1	2.50%	65	20	200
		2	70.00%	200	100	400
		3	100.00%	450	140	620
		4	0.00%	78	10	100
		5	25.00%	120	60	250
Receptor	An open store of pallets of HD1.1A non-water based material placed 156 feet from the Donor (SSD from the Donor), 90 degrees from the front azimuth of the donor mag, with its own front azimuth at 0°	6	95.00%	1015	70	2100
		7	10.00%	75	50	400
		8	10.00%	20	10	200
		9	12.00%	90	45	200
		10	50.00%	156	44	440
		11	75.00%	172	29	220
		Baseline Curve from First Study	4.12%	64.8	26.9	236

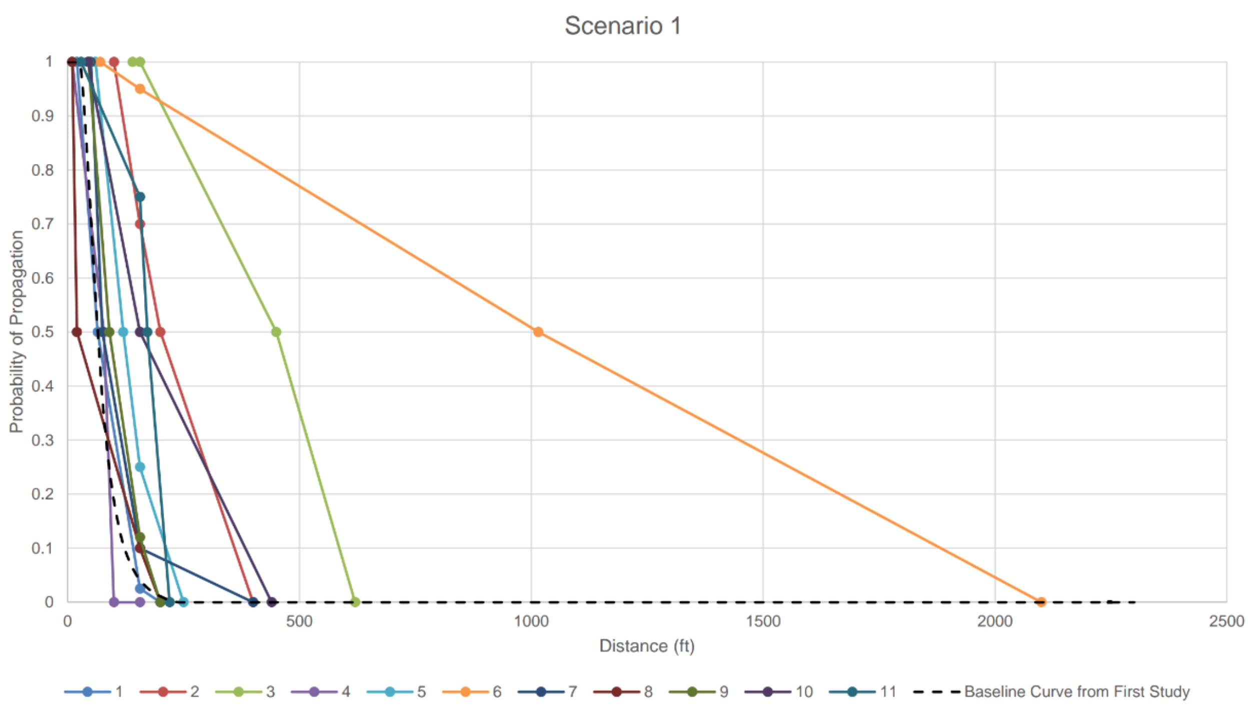


Figure 4-16: Comparison of Delphi Study 2 Scenario 1 (Worst Case) Responses to Baseline Curve

The Delphi Study 2 revised results from the second round of questioning for Scenario 2 (Worst Case) are shown in Table 4-14 and compared against the baseline curve in Figure 4-17.

Table 4-14: Delphi Study 2 Scenario 2 (Worst Case) Revised Responses

Magazine	Scenario 2	Respondent #	Scenario 2			
			Probability of Propagation at SSD (248 ft)?	Distance (ft) for 50% Probability of Propagation?	Distance (ft) for 100% Probability of Propagation?	Distance (ft) for 0% Probability of Propagation?
Donor	Medium unreinforced concrete magazine (Type 1/2) storing 40,000 lb of HD1.1 and HD1.5 explosives with a front azimuth of 0°	1	5.00%	125	30	300
		2	60.00%	500	150	600
		3	100.00%	700	200	960
		4	0.00%	124	10	200
		5	30.00%	190	100	400
Receptor	An open store of pallets of storing 2,000 lb of high explosives (boosters, detonators and dynamite) placed 248 feet from the Donor (SSD from the Donor), 90 degrees from the front azimuth of the donor mag, with its own front azimuth at 0°	6	95.00%	1645	110	3400
		7	5.00%	125	75	350
		8	10.00%	25	12.5	250
		9	10.00%	140	60	300
		10	50.00%	248	44	440
		11	60.00%	274	45	350
		Baseline Curve from First Study	4.12%	103.1	42.8	375.2

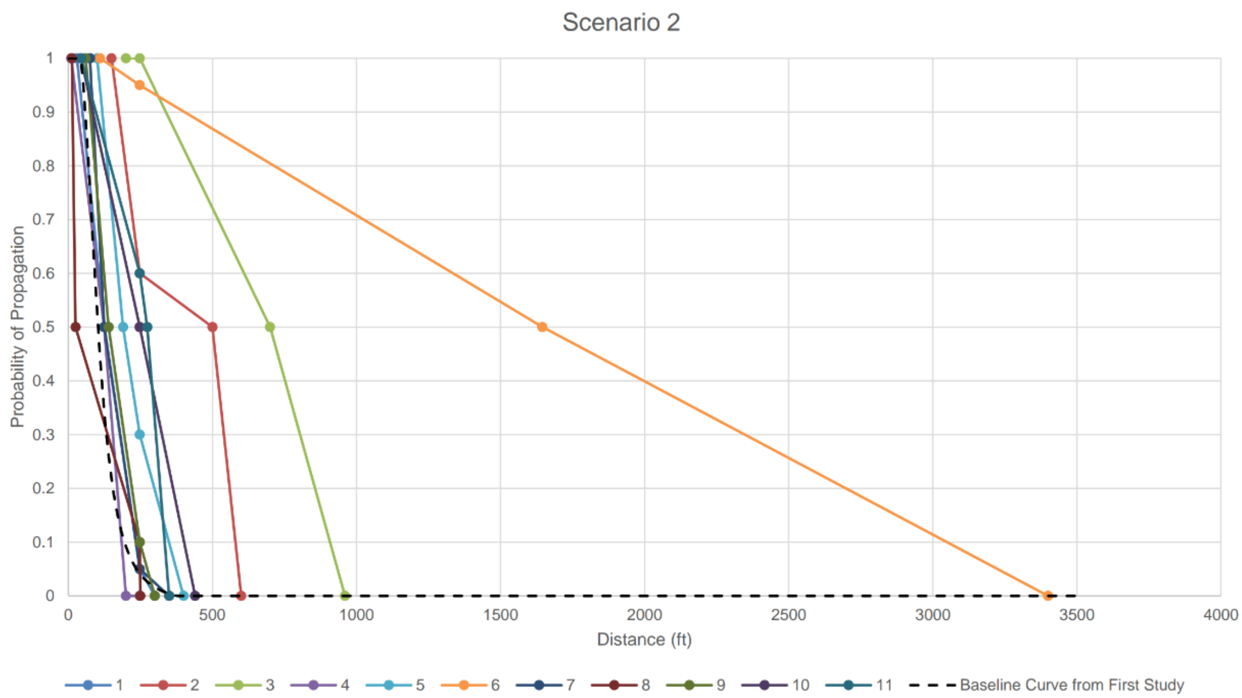


Figure 4-17: Comparison of Delphi Study 2 Scenario 2 (Worst Case) Responses to Baseline Curve

The Delphi Study 2 revised results from the second round of questioning for Scenario 3 (Worst Case) are shown in Table 4-15 and compared against the baseline curve in Figure 4-18.

Table 4-15: Delphi Study 2 Scenario 3 (Worst Case) Revised Responses

Magazine	Scenario 3	Respondent #	Scenario 3			
			Probability of Propagation at SSD (330 ft)?	Distance (ft) for 50% Probability of Propagation?	Distance (ft) for 100% Probability of Propagation?	Distance (ft) for 0% Probability of Propagation?
Donor	Large unreinforced concrete magazine (Type 1/2) storing 80,000 lb of HD1.1 and HD1.5 explosives with a front azimuth of 0°	1	1.00%	130	50	350
		2	20.00%	175	120	700
		3	0.00%	50	30	170
		4	0.00%	165	10	200
		5	15.00%	198	100	500
Receptor	An open store of pallets of bags of ANFO placed 330 feet away from the Donor (SSD from the Donor), 90 degrees from the front azimuth of the donor mag, with its own front azimuth at 0°	6	10.00%	250	150	350
		7	0.10%	60	30	350
		8	0.000001%	50	25	500
		9	9.00%	160	70	450
		10	12.50%	242	40	400
		11	10.00%	100	50	350
		Baseline Curve from First Study	4.12%	137.1	56.9	499.3

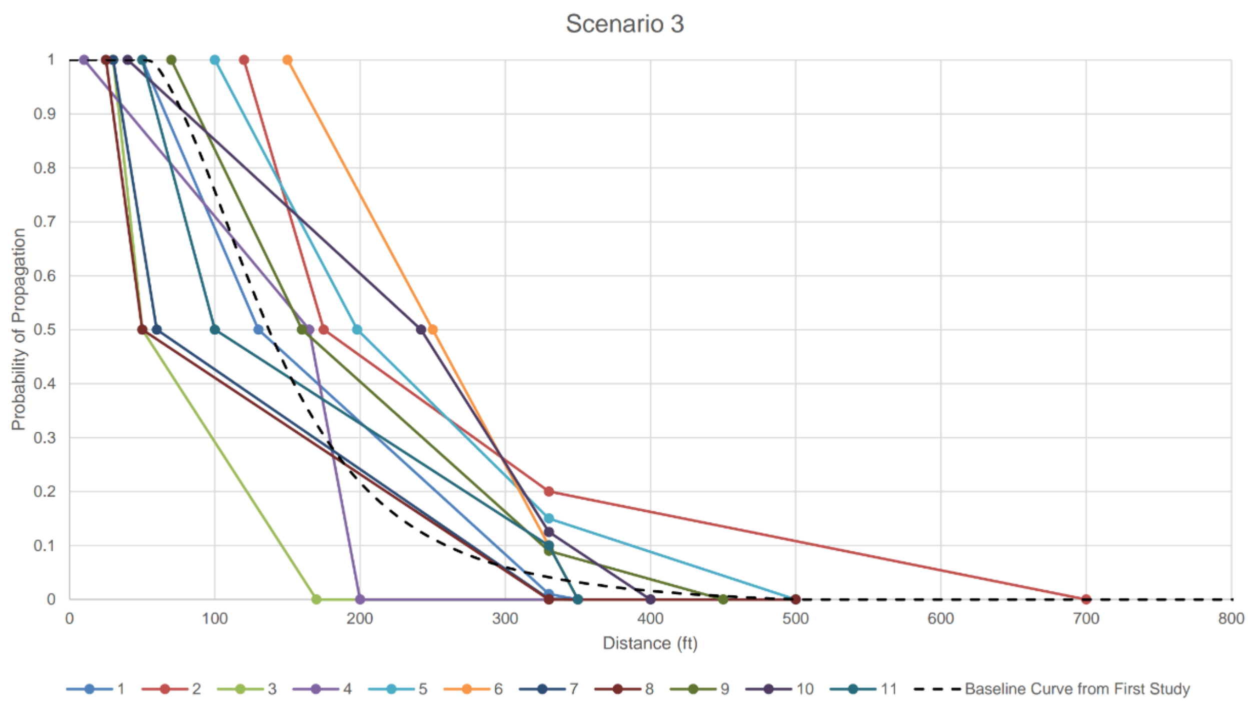


Figure 4-18: Comparison of Delphi Study 2 Scenario 3 (Worst Case) Responses to Baseline Curve

The Delphi Study 2 revised results from the second round of questioning for Scenario 4 (Bad Case) are shown in Table 4-16 and compared against the baseline curve in Figure 4-19.

Table 4-16: Delphi Study 2 Scenario 4 (Bad Case) Revised Responses

Magazine	Scenario 4	Respondent #	Scenario 4			
			Probability of Propagation at SSD (156 ft)?	Distance (ft) for 50% Probability of Propagation?	Distance (ft) for 100% Probability of Propagation?	Distance (ft) for 0% Probability of Propagation?
Donor	Small steel magazine (Type 2) storing 10,000 lb of HD1.1 and HD1.5 explosives with a front azimuth of 0°	1	2.00%	56	25	210
		2	40.00%	125	100	550
		3	95.00%	460	140	620
		4	10.00%	125	25	175
		5	20.00%	90	50	225
Receptor	An open store of pallets of HD1.1A non-water based material placed 156 feet from the Donor (SSD from the Donor), 90 degrees from the front azimuth of the donor mag, with its own front azimuth at 0°	6	100.00%	875	750	1000
		7	5.00%	60	50	300
		8	15.00%	100	50	1280
		9	15.00%	100	55	250
		10	25.00%	117	44	330
		11	90.00%	250	29	330
		Baseline Curve from First Study	4.12%	64.8	26.9	236

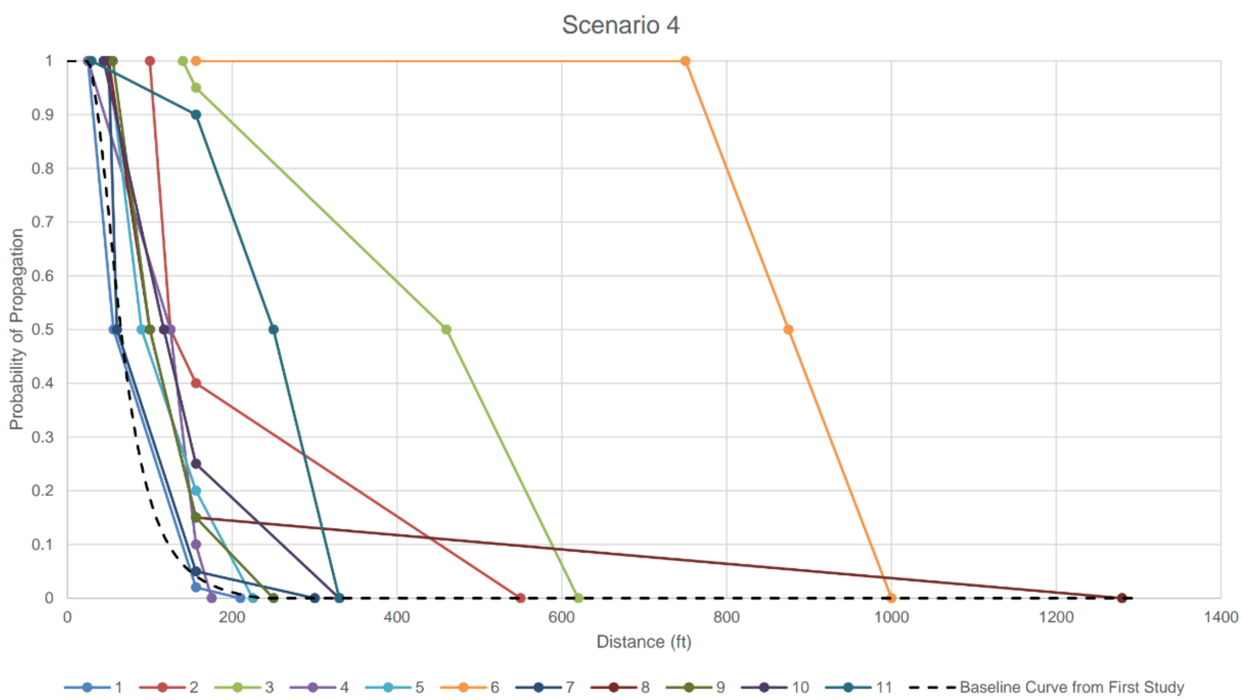


Figure 4-19: Comparison of Delphi Study 2 Scenario 4 (Bad Case) Responses to Baseline Curve

The Delphi Study 2 revised results from the second round of questioning for Scenario 5 (Bad Case) are shown in Table 4-17 and compared against the baseline curve in Figure 4-20.

Table 4-17: Delphi Study 2 Scenario 5 (Bad Case) Revised Responses

Magazine	Scenario 5	Respondent #	Scenario 5			
			Probability of Propagation at SSD (248 ft)?	Distance (ft) for 50% Probability of Propagation?	Distance (ft) for 100% Probability of Propagation?	Distance (ft) for 0% Probability of Propagation?
Donor	Medium unreinforced concrete magazine (Type 1/2) storing 40,000 lb of HD1.1 and HD1.5 explosives with a front azimuth of 0°	1	0.00%	120	40	200
		2	10.00%	125	50	500
		3	90.00%	550	125	960
		4	0.00%	75	25	250
		5	10.00%	124	75	350
Receptor	Small unreinforced concrete magazine (Type 1/2) storing 2,000 lb of high explosives (boosters, detonators and dynamite) placed 248 feet from the Donor (SSD from the Donor), 90 degrees from the front azimuth of the donor mag, with its own front azimuth at 0°	6	0.00%	168	110	226
		7	0.10%	75	30	300
		8	0.000001%	50	25	328
		9	5.00%	110	60	300
		10	5.00%	150	100	350
		11	30.00%	200	35	280
		Baseline Curve from First Study	4.12%	103.1	42.8	375.2

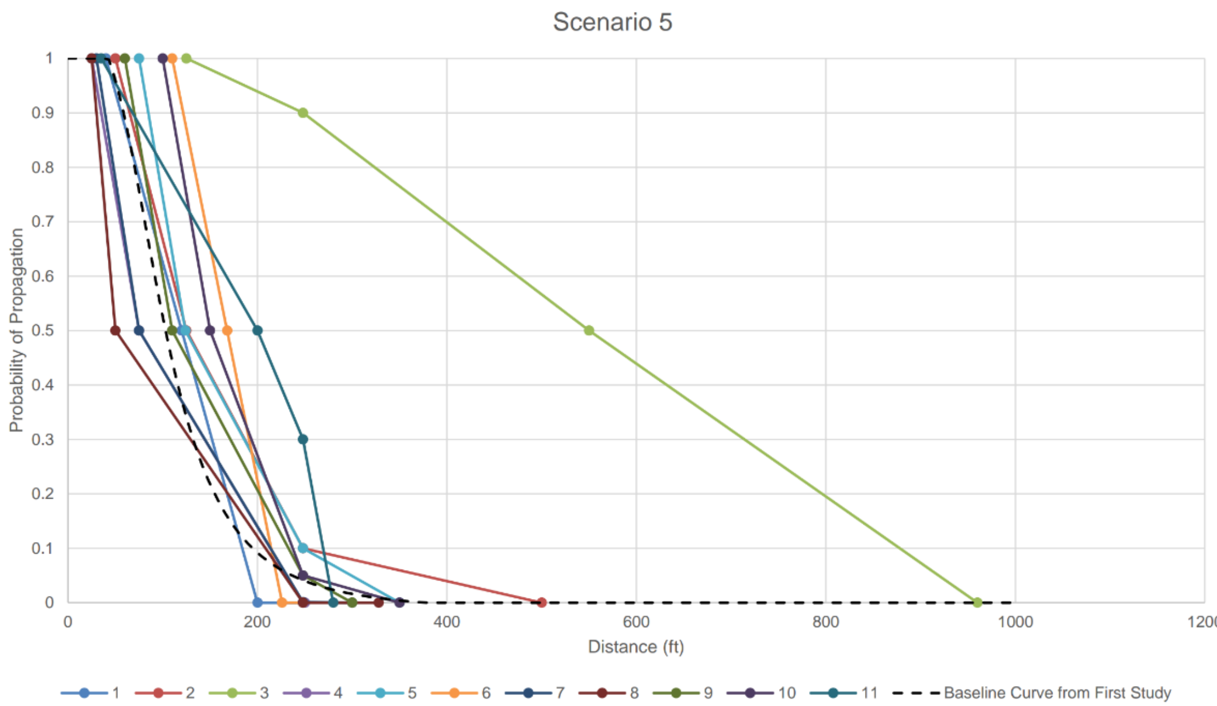


Figure 4-20: Comparison of Delphi Study 2 Scenario 5 (Bad Case) Responses to Baseline Curve

The Delphi Study 2 revised results from the second round of questioning for Scenario 6 (Bad Case) are shown in Table 4-18 and compared against the baseline curve in Figure 4-21.

Table 4-18: Delphi Study 2 Scenario 6 (Bad Case) Revised Responses

Magazine	Scenario 6	Respondent #	Scenario 6			
			Probability of Propagation at SSD (330 ft)?	Distance (ft) for 50% Probability of Propagation?	Distance (ft) for 100% Probability of Propagation?	Distance (ft) for 0% Probability of Propagation?
Donor	Large unreinforced concrete magazine (Type 1/2) storing 80,000 lb of HD1.1 and HD1.5 explosives with a front azimuth of 0°	1	0.00%	120	40	250
		2	1.00%	100	50	500
		3	0.00%	50	30	170
		4	0.00%	125	50	171
		5	10.00%	140	85	460
Receptor	60-ton overhead silo storing HD1.5 ammonium nitrate emulsions at 100% capacity placed 330 feet away from the Donor (SSD from the Donor), 90 degrees from the front azimuth of the donor mag, with its own front azimuth at 0°	6	0.00%	175	150	200
		7	0.10%	60	30	350
		8	0.000001%	50	25	400
		9	15.00%	170	80	420
		10	15.00%	200	42	420
		11	0.00%	75	40	300
		Baseline Curve from First Study	4.12%	137.1	56.9	499.3

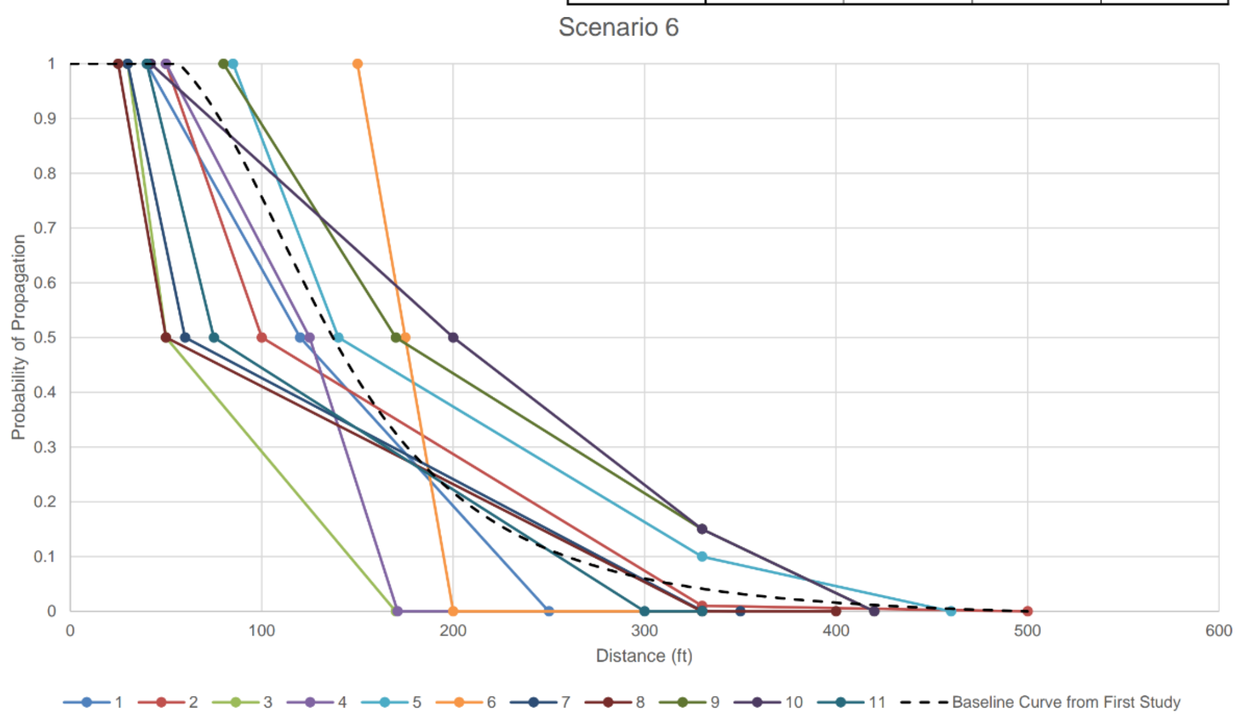


Figure 4-21: Comparison of Delphi Study 2 Scenario 6 (Bad Case) Responses to Baseline Curve

Responses to the worst case and bad case scenarios were generally more pessimistic than the baseline curve, as expected.

The Delphi Study 2 revised results from the second round of questioning for Scenario 7 (Better Case) are shown in Table 4-19 and compared against the baseline curve in Figure 4-22.

Table 4-19: Delphi Study 2 Scenario 7 (Better Case) Revised Responses

Magazine	Scenario 7	Respondent #	Scenario 7			
			Probability of Propagation at SSD (90 ft)?	Distance (ft) for 50% Probability of Propagation?	Distance (ft) for 100% Probability of Propagation?	Distance (ft) for 0% Probability of Propagation?
Donor	Small steel magazine (Type 2) storing 2,000 lb of high explosives (boosters, detonators and dynamite) with a front azimuth of 0°	1	0.00%	30	5	70
		2	1.00%	30	15	150
		3	50.00%	90	30	370
		4	10.00%	49	10	100
		5	5.00%	32	20	120
Receptor	Small unreinforced concrete magazine (Type 1/2) at normal capacity storing HD1.5 emulsions in boxes on pallets, placed 90 feet away from the Donor (SSD from the Donor), 90 degrees from the front azimuth of the donor mag, with its own front azimuth at 0°	6	0.00%	35	21	50
		7	0.10%	30	15	100
		8	0.000001%	20	10	330
		9	5.00%	45	30	120
		10	1.00%	50	30	120
		11	10.00%	29	14	120
		Baseline Curve from First Study	4.12%	37.4	15.5	136.2

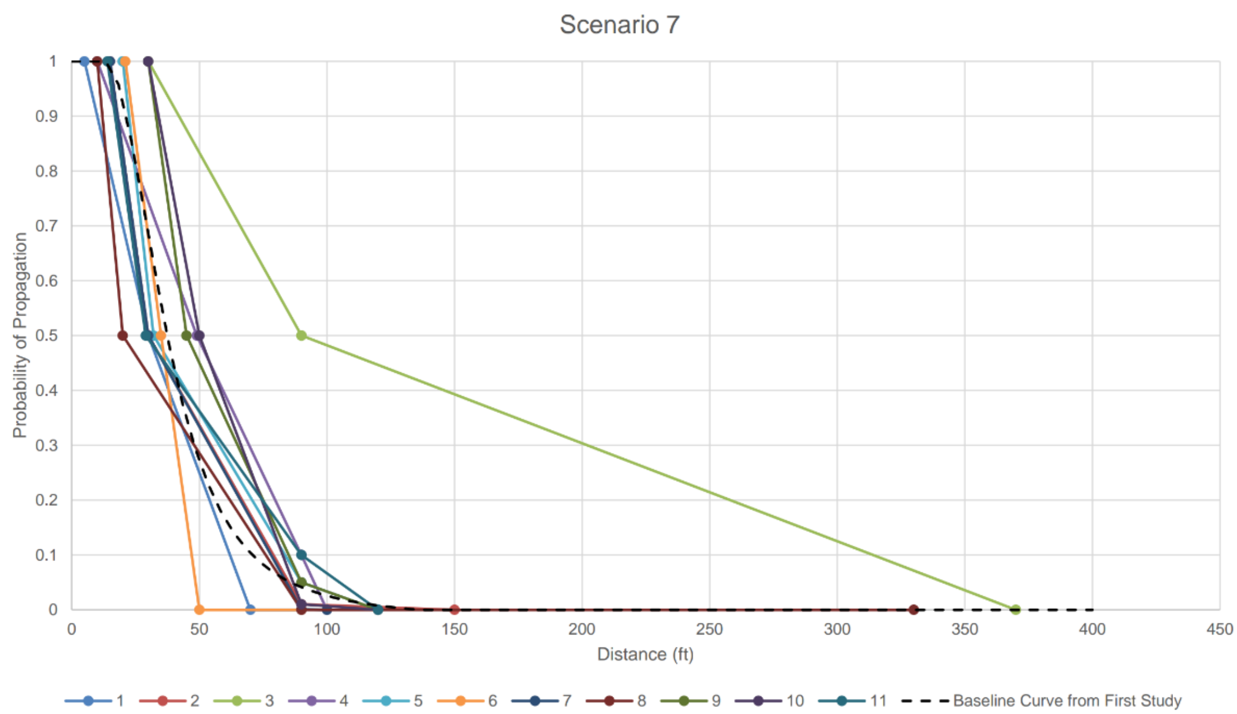


Figure 4-22: Comparison of Delphi Study 2 Scenario 7 (Better Case) Responses to Baseline Curve

The Delphi Study 2 revised results from the second round of questioning for Scenario 8 (Better Case) are shown in Table 4-20 and compared against the baseline curve in Figure 4-23.

Table 4-20: Delphi Study 2 Scenario 8 (Better Case) Revised Responses

Magazine	Scenario 8	Respondent #	Probability of Propagation at SSD (156 ft)?	Distance (ft) for 50% Probability of Propagation?	Distance (ft) for 100% Probability of Propagation?	Distance (ft) for 0% Probability of Propagation?
Donor	Pre-engineered metal building operating with/storing 10,000 lb of HD1.1 and HD1.5 explosives with a front azimuth of 0°	1	0.00%	50	5	100
		2	0.10%	50	25	200
		3	50.00%	350	80	620
		4	0.00%	78	10	110
		5	5.00%	50	30	200
Receptor	Medium unreinforced concrete magazine (Type 1/2) at normal capacity storing HD5.1 ANEs in bags on pallets, placed 156 feet away from the Donor (SSD from the Donor), 90 degrees from the front azimuth of the donor mag, with its own front azimuth at 0°	6	0.00%	38	35	40
		7	0.00%	25	10	50
		8	1.00%	20	10	250
		9	2.00%	70	40	225
		10	0.10%	43	21	200
		11	75.00%	170	30	225
		Baseline Curve from First Study	4.12%	64.8	26.9	236

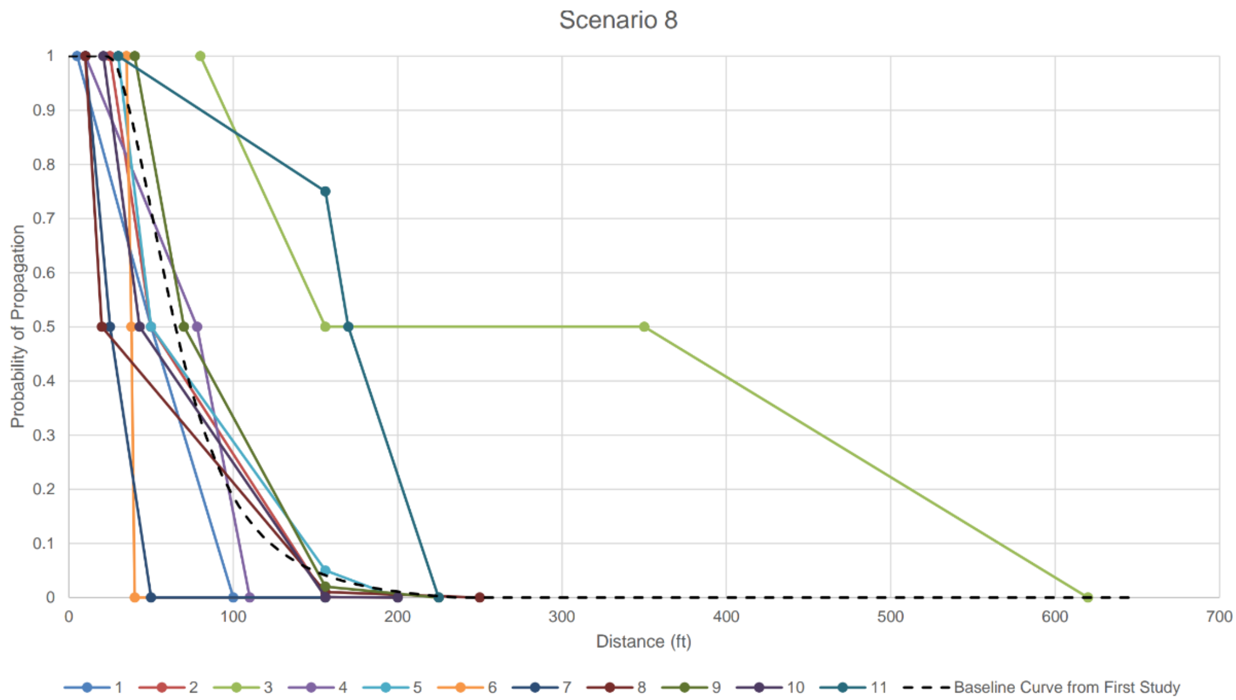


Figure 4-23: Comparison of Delphi Study 2 Scenario 8 (Better Case) Responses to Baseline Curve

The Delphi Study 2 revised results from the second round of questioning for Scenario 9 (Better Case) are shown in Table 4-21 and compared against the baseline curve in Figure 4-24.

Table 4-21: Delphi Study 2 Scenario 9 (Better Case) Revised Responses

Magazine	Scenario 9	Respondent #	Scenario 9			
			Probability of Propagation at SSD (122 ft)?	Distance (ft) for 50% Probability of Propagation?	Distance (ft) for 100% Probability of Propagation?	Distance (ft) for 0% Probability of Propagation?
Donor	An open store of pallets of high explosives (boosters, detonators and dynamite) material storing 5,000 lb of material	1	0.00%	25	5	90
		2	0.50%	50	25	180
		3	90.00%	360	100	500
		4	0.00%	61	10	90
		5	10.00%	50	30	170
Receptor	Small unreinforced concrete magazine (Type 1/2) at normal capacity storing high explosives (boosters, detonators and dynamite), placed 122 feet away from the Donor (SSD from the Donor), 90 degrees from the front azimuth of the donor mag, with its own front azimuth at 0°	6	0.00%	38	28	50
		7	0.10%	50	25	150
		8	0.00%	10	5	100
		9	2.00%	50	30	200
		10	0.10%	52	26	150
		11	70.00%	140	22	175
		Baseline Curve from First Study	4.12%	50.7	21	184.6

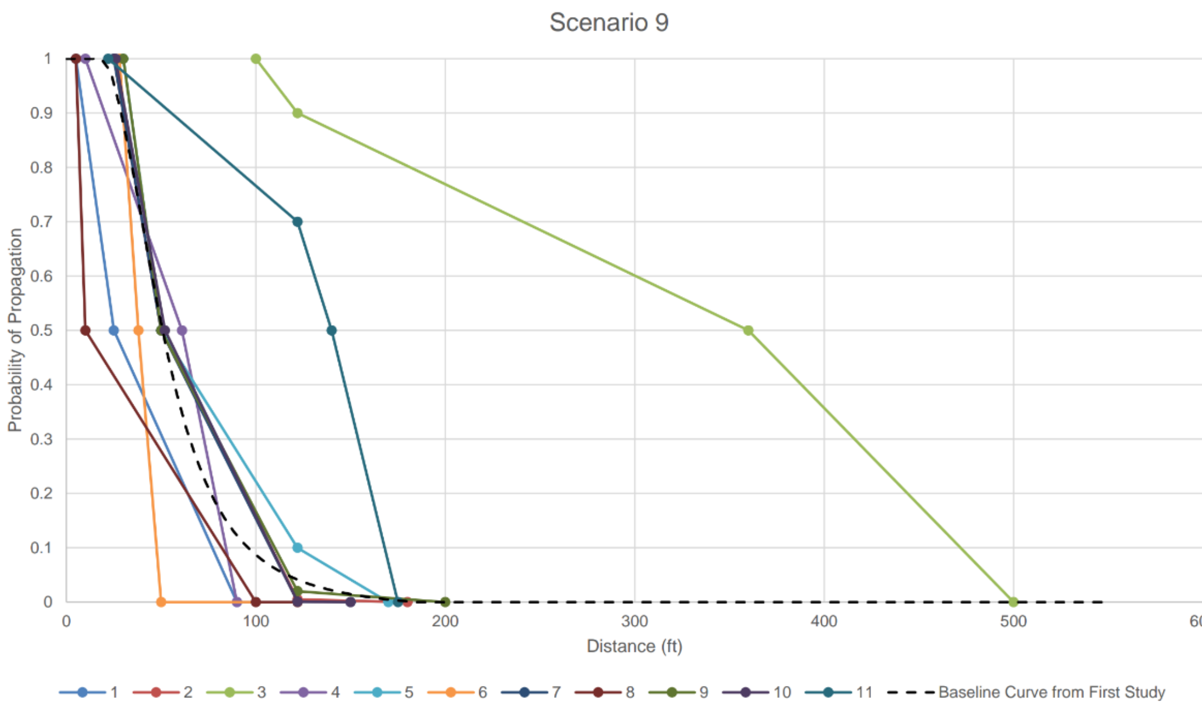


Figure 4-24: Comparison of Delphi Study 2 Scenario 9 (Better Case) Responses to Baseline Curve

The Delphi Study 2 revised results from the second round of questioning for Scenario 10 (Best Case) are shown in Table 4-22 and compared against the baseline curve in Figure 4-25.

Table 4-22: Delphi Study 2 Scenario 10 (Best Case) Revised Responses

Magazine	Scenario 10	Respondent #	Scenario 10 Probability of Propagation at SSD (90 ft)?	Scenario 10 Distance (ft) for 50% Probability of Propagation?	Scenario 10 Distance (ft) for 100% Probability of Propagation?	Scenario 10 Distance (ft) for 0% Probability of Propagation?
Donor	An open store of pallets storing 2,000 lb of high explosives (boosters, detonators and dynamite) with a front azimuth of 0°	1	0.00%	20	2	45
		2	0.05%	20	10	120
		3	35.00%	55	20	370
		4	0.00%	61	10	90
		5	1.00%	22	13	100
Receptor	Small unreinforced concrete magazine (Type 1/2) at normal capacity storing HD5.1 ANEs in bags on pallets, placed 90 feet away from the Donor (SSD from the Donor), 90 degrees from the front azimuth of the donor mag, with its own front azimuth at 0°	6	0.00%	23	20	25
		7	0.00%	15	10	30
		8	0.00%	5	1	75
		9	9.00%	30	20	150
		10	0.05%	48	24	100
		11	25.00%	75	15	100
		Baseline Curve from First Study	4.12%	37.4	15.5	136.2

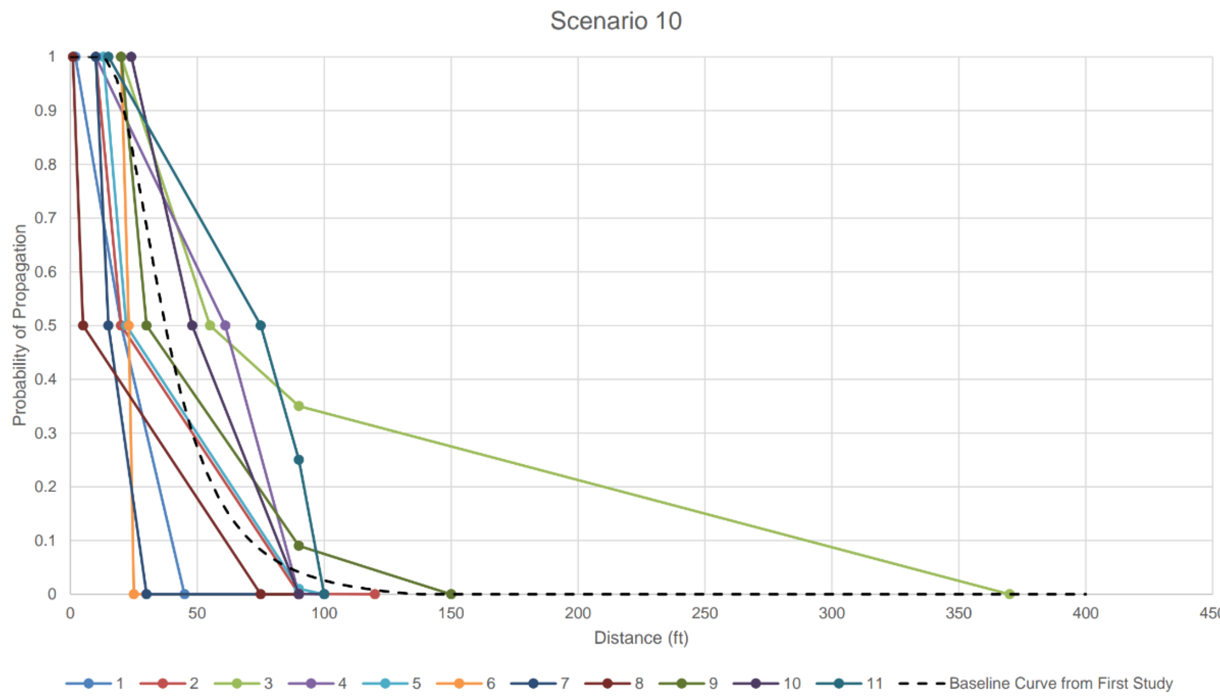


Figure 4-25: Comparison of Delphi Study 2 Scenario 10 (Best Case) Responses to Baseline Curve

The Delphi Study 2 revised results from the second round of questioning for Scenario 11 (Best Case) are shown in Table 4-23 and compared against the baseline curve in Figure 4-26.

Table 4-23: Delphi Study 2 Scenario 11 (Best Case) Revised Responses

Magazine	Scenario 11	Respondent #	Scenario 11: Probability of Propagation at SSD (156 ft)?	Distance (ft) for 50% Probability of Propagation?	Distance (ft) for 100% Probability of Propagation?	Distance (ft) for 0% Probability of Propagation?
Donor	An open store of pallets storing 10,000 lb of HD1.1 and HD1.5 explosives with a front azimuth of 0°	1	0.00%	40	5	80
		2	0.05%	40	20	200
		3	80.00%	225	140	620
		4	0.00%	78	10	100
		5	1.00%	40	25	170
Receptor	Medium unreinforced concrete magazine (Type 1/2) at normal capacity storing HD5.1 ANEs in bags on pallets, placed 156 feet away from the Donor (SSD from the Donor), 90 degrees from the front azimuth of the donor mag, with its own front azimuth at 0°	6	0.00%	43	36	50
		7	0.00%	45	30	200
		8	0.00%	20	5	100
		9	2.00%	75	45	200
		10	0.001%	44	22	180
		11	30.000%	125	20	175
		Baseline Curve from First Study	4.12%	64.8	26.9	236

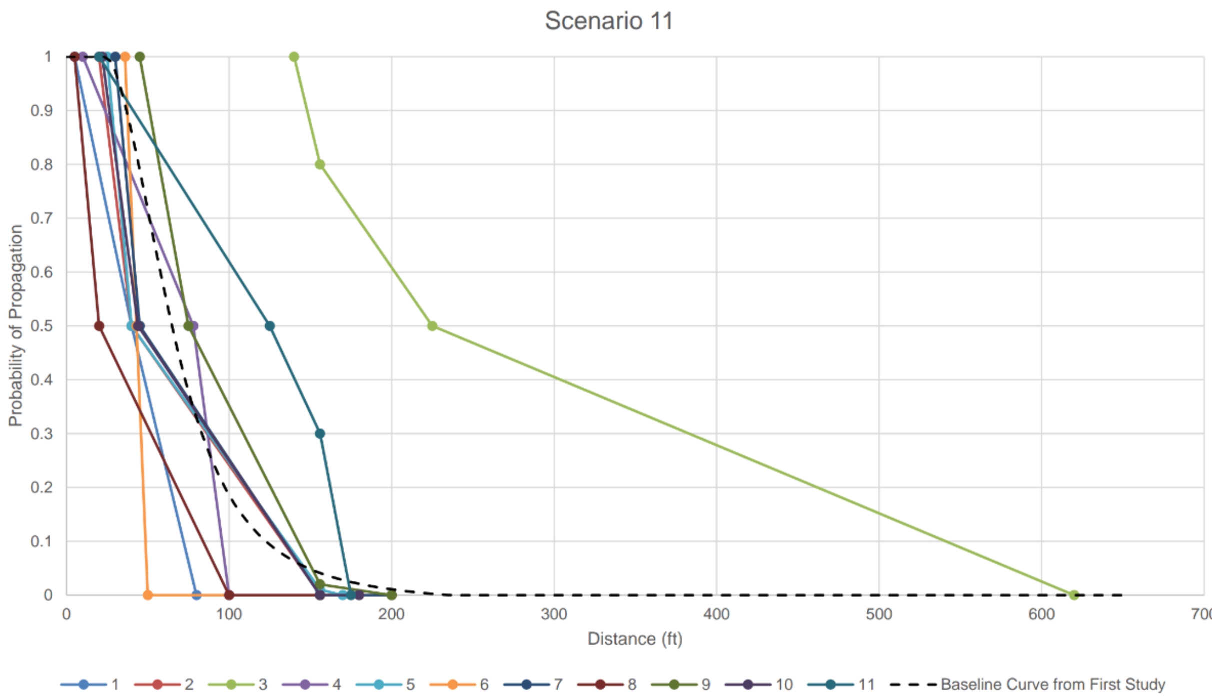


Figure 4-26: Comparison of Delphi Study 2 Scenario 11 (Best Case) Responses to Baseline Curve

The Delphi Study 2 revised results from the second round of questioning for Scenario 12 (Best Case) are shown in Table 4-24 and compared against the baseline curve in Figure 4-27.

Table 4-24: Delphi Study 2 Scenario 12 (Best Case) Revised Responses

Magazine	Scenario 12	Respondent #	Scenario 12			
			Probability of Propagation at SSD (122 ft)?	Distance (ft) for 50% Probability of Propagation?	Distance (ft) for 100% Probability of Propagation?	Distance (ft) for 0% Probability of Propagation?
Donor	An open store of pallets of high explosives (boosters, detonators and dynamite) material storing 5,000 lb of material	1	0.00%	20	3	70
		2	0.01%	20	10	150
		3	0.00%	20	10	65
		4	0.00%	61	10	90
		5	0.00%	25	12	122
Receptor	Small unreinforced concrete magazine (Type 1/2) at normal capacity storing AN prill in boxes/bags on pallets, placed 122 feet away from the Donor (SSD from the Donor), 90 degrees from the front azimuth of the donor mag, with its own front azimuth at 0°	6	0.00%	39	28	50
		7	0.00%	30	15	150
		8	0.00%	5	1	100
		9	5.00%	65	30	180
		10	0.0001%	36	18	125
		11	45.0000%	110	25	150
		Baseline Curve from First Study	4.12%	50.7	21	184.6

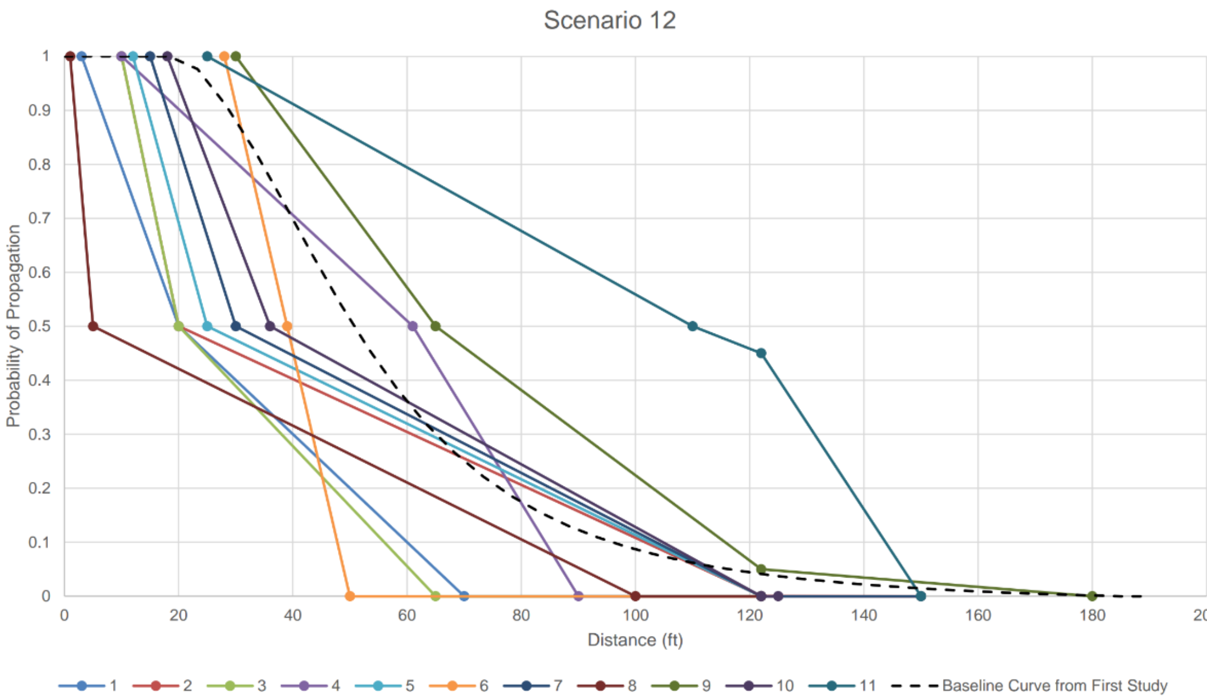


Figure 4-27: Comparison of Delphi 2 Scenario 12 (Best Case) Responses to Baseline Curve

The mean results for worst case curve with outliers are shown in Table 4-25 and Figure 4-28.

Table 4-25: Delphi Study 2 Mean Worst Case Results (with Outliers)

	Magazine Sep. Distance (ft)	Mean Distance from Study (ft)	Mean/Mag. Sep.	Probability of Propagation
Scenario 1	156	52.5	0.337	100%
	156	221.9	1.422	50%
	156	156	1	41%
	156	466.4	2.990	0%

	Magazine Sep. Distance (ft)	Mean Distance from Study (ft)	Mean/Mag. Sep.	Probability of Propagation
Scenario 2	248	76.0	0.307	100%
	248	372.4	1.501	50%
	248	248	1	39%
	248	686.4	2.768	0%

	Magazine Sep. Distance (ft)	Mean Distance from Study (ft)	Mean/Mag. Sep.	Probability of Propagation
Scenario 3	330	61.4	0.186	100%
	330	143.6	0.435	50%
	330	330	1	7%
	330	392.7	1.190	0%

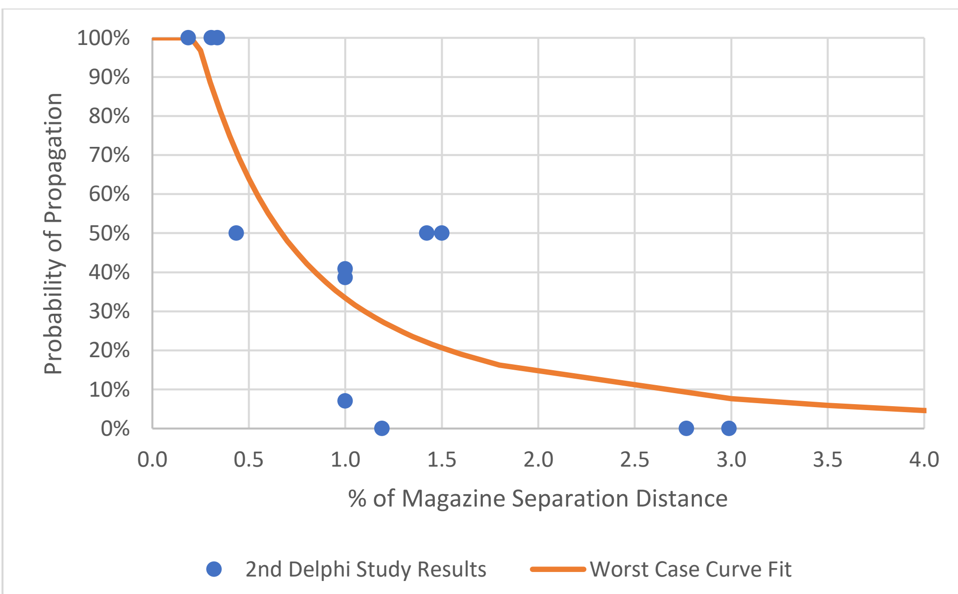


Figure 4-28: Delphi Study 2 Mean Worst Case Curve (with Outliers)

The equation for the Delphi Study 2 Worst Case Curve with outliers is:

$$y = -0.02022642 + \frac{1.414484 + 0.02022642}{1 + \left(\frac{x}{0.4445654}\right)^{1.375861}}$$

The mean results for worst case curve without outliers are shown in Table 4-26 and Figure 4-29.

Table 4-26: Delphi Study 2 Worst Case Results (without Outliers)

	Magazine Sep. Distance (ft)	Mean Distance from Study (ft)	Mean/Mag. Sep.	Probability of Propagation
Scenario 1	156	47.6	0.305	100%
	156	156.2	1.001	50%
	156	156	1	39%
	156	325.6	2.087	0%

	Magazine Sep. Distance (ft)	Mean Distance from Study (ft)	Mean/Mag. Sep.	Probability of Propagation
Scenario 2	248	69.6	0.281	100%
	248	269.6	1.087	50%
	248	248	1	36%
	248	438.9	1.770	0%

	Magazine Sep. Distance (ft)	Mean Distance from Study (ft)	Mean/Mag. Sep.	Probability of Propagation
Scenario 3	330	57.2	0.173	100%
	330	142.2	0.431	50%
	330	330	1	6%
	330	383.3	1.162	0%

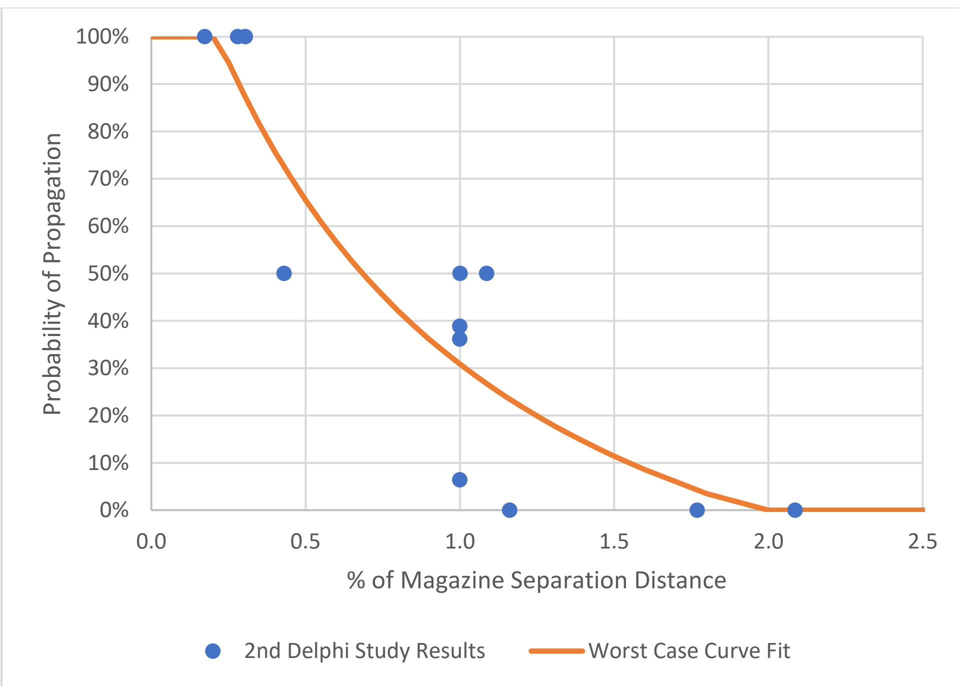


Figure 4-29: Delphi Study 2 Worst Case Curve (without Outliers)

The equation for the Delphi Study 2 Worst Case Curve without outliers is:

$$y = -0.5139992 + \frac{1.367026 + 0.5139992}{1 + \left(\frac{x}{0.7915763}\right)^{1.079696}}$$

The mean results for bad case curve with outliers are shown in Table 4-27 and Figure 4-30.

Table 4-27: Delphi Study 2 Bad Case Results (with Outliers)

	Magazine Sep. Distance (ft)	Mean Distance from Study (ft)	Mean/Mag. Sep.	Probability of Propagation
Scenario 4	156	119.8	0.768	100%
	156	214.4	1.374	50%
	156	156	1	38%
	156	479.1	3.071	0%

	Magazine Sep. Distance (ft)	Mean Distance from Study (ft)	Mean/Mag. Sep.	Probability of Propagation
Scenario 5	248	61.4	0.247	100%
	248	158.8	0.640	50%
	248	248	1	14%
	248	367.6	1.482	0%

	Magazine Sep. Distance (ft)	Mean Distance from Study (ft)	Mean/Mag. Sep.	Probability of Propagation
Scenario 6	330	56.5	0.171	100%
	330	115.0	0.348	50%
	330	330	1	4%
	330	331.0	1.003	0%

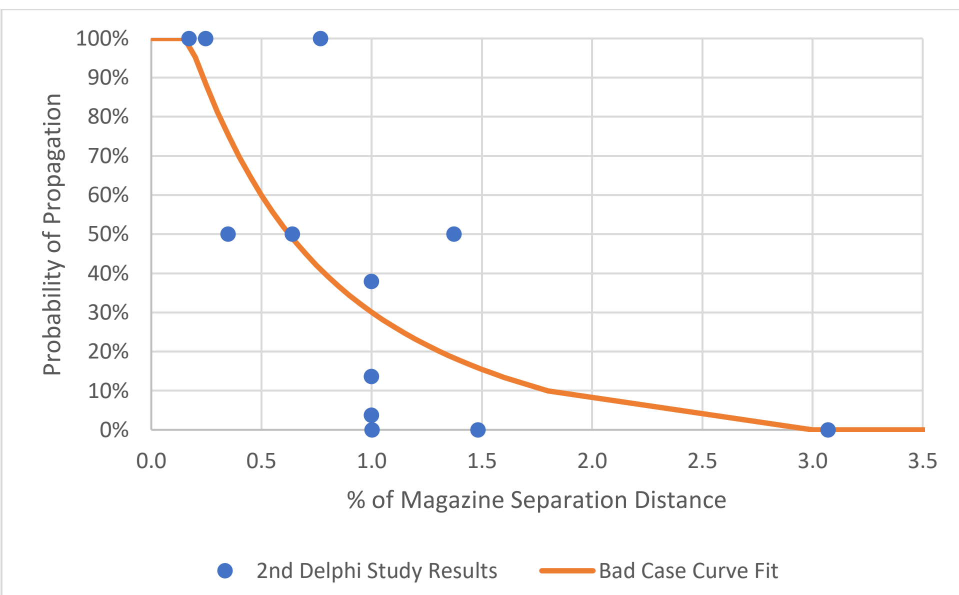


Figure 4-30: Delphi Study 2 Bad Case Curve (with Outliers)

The equation for the Delphi Study 2 Bad Case Curve with outliers is:

$$y = -0.1903417 + \frac{1.272123 + 0.1903417}{1 + \left(\frac{x}{0.5703864}\right)^{1.216126}}$$

The mean results for bad case curve without outliers are shown in Table 4-28 and Figure 4-31.

Table 4-28: Delphi Study 2 Bad Case Mean Results (without Outliers)

	Magazine Sep. Distance (ft)	Mean Distance from Study (ft)	Mean/Mag. Sep.	Probability of Propagation
Scenario 4	156	60.3	0.387	100%
	156	158.6	1.016	50%
	156	156	1	35%
	156	423.9	2.717	0%

	Magazine Sep. Distance (ft)	Mean Distance from Study (ft)	Mean/Mag. Sep.	Probability of Propagation
Scenario 5	248	58.3	0.235	100%
	248	127.4	0.514	50%
	248	248	1	7%
	248	320.4	1.292	0%

	Magazine Sep. Distance (ft)	Mean Distance from Study (ft)	Mean/Mag. Sep.	Probability of Propagation
Scenario 6	330	49.7	0.151	100%
	330	112.8	0.342	50%
	330	330	1	3%
	330	330.1	1.000	0%

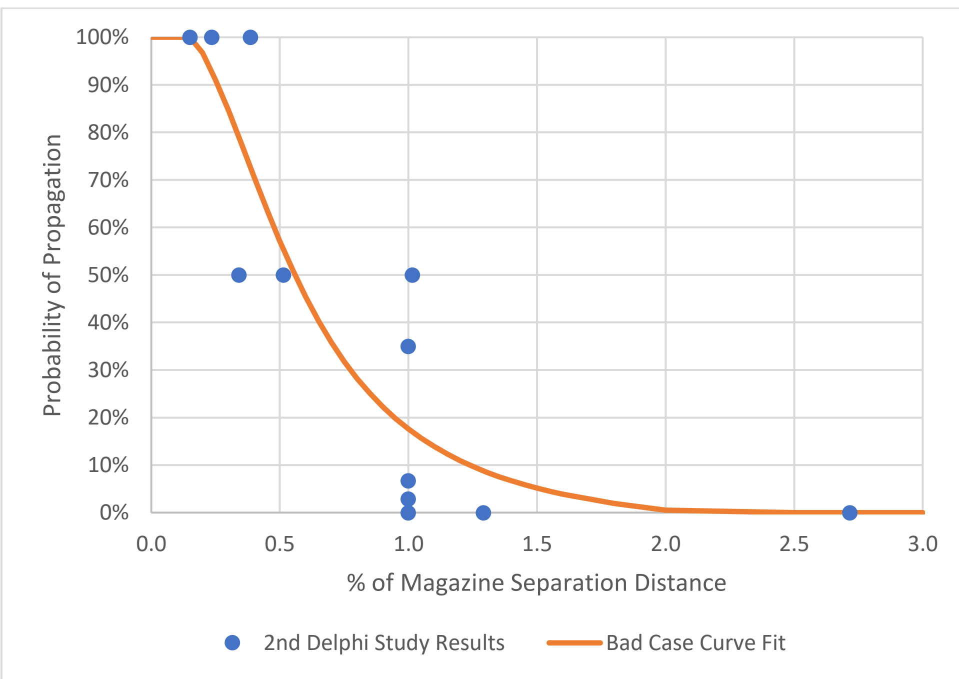


Figure 4-31: Delphi Study 2 Bad Case Curve (without Outliers)

The equation for the Delphi Study 2 Bad Case Curve without outliers is:

$$y = -0.04837043 + \frac{1.063202 + 0.04837043}{1 + \left(\frac{x}{0.5524764}\right)^{2.317861}}$$

The mean results for better case curve with outliers are shown in Table 4-29 and Figure 4-32.

Table 4-29: Delphi Study 2 Better Case Mean Results (with Outliers)

	Magazine Sep. Distance (ft)	Mean Distance from Study (ft)	Mean/Mag. Sep.	Probability of Propagation
Scenario 7	90	18.2	0.202	100%
	90	40.0	0.444	50%
	90	90	1	7%
	90	150.0	1.667	0%

	Magazine Sep. Distance (ft)	Mean Distance from Study (ft)	Mean/Mag. Sep.	Probability of Propagation
Scenario 8	156	26.9	0.172	100%
	156	85.8	0.550	50%
	156	156	1	12%
	156	201.8	1.294	0%

	Magazine Sep. Distance (ft)	Mean Distance from Study (ft)	Mean/Mag. Sep.	Probability of Propagation
Scenario 9	122	27.8	0.228	100%
	122	80.5	0.660	50%
	122	122	1	16%
	122	168.6	1.382	0%

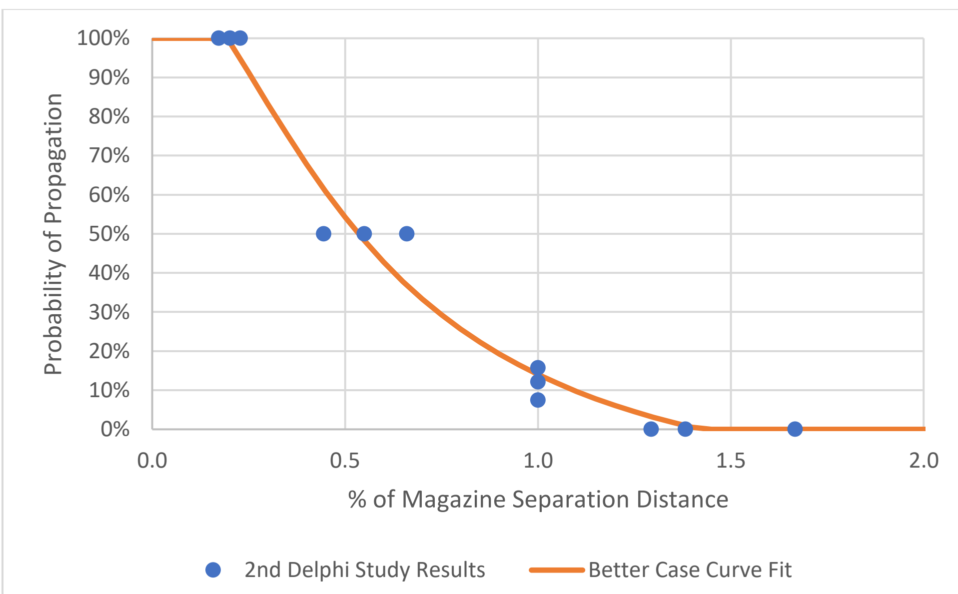


Figure 4-32: Delphi Study 2 Better Case Curve (with Outliers)

The equation for the Delphi Study 2 Better Case Curve with outliers is:

$$y = -0.2122825 + \frac{1.192503 + 0.2122825}{1 + \left(\frac{x}{0.5432938}\right)^{1.791837}}$$

The mean results for better case curve without outliers are shown in Table 4-30 and Figure 4-33.

Table 4-30: Delphi Study 2 Better Case Mean Results (without Outliers)

	Magazine Sep. Distance (ft)	Mean Distance from Study (ft)	Mean/Mag. Sep.	Probability of Propagation
Scenario 7	90	18.3	0.204	100%
	90	36.7	0.407	50%
	90	90	1	4%
	90	136.7	1.519	0%

	Magazine Sep. Distance (ft)	Mean Distance from Study (ft)	Mean/Mag. Sep.	Probability of Propagation
Scenario 8	156	23.4	0.150	100%
	156	63.8	0.409	50%
	156	156	1	6%
	156	173.3	1.111	0%

	Magazine Sep. Distance (ft)	Mean Distance from Study (ft)	Mean/Mag. Sep.	Probability of Propagation
Scenario 9	122	22.3	0.183	100%
	122	57.3	0.470	50%
	122	122	1	9%
	122	145.0	1.189	0%

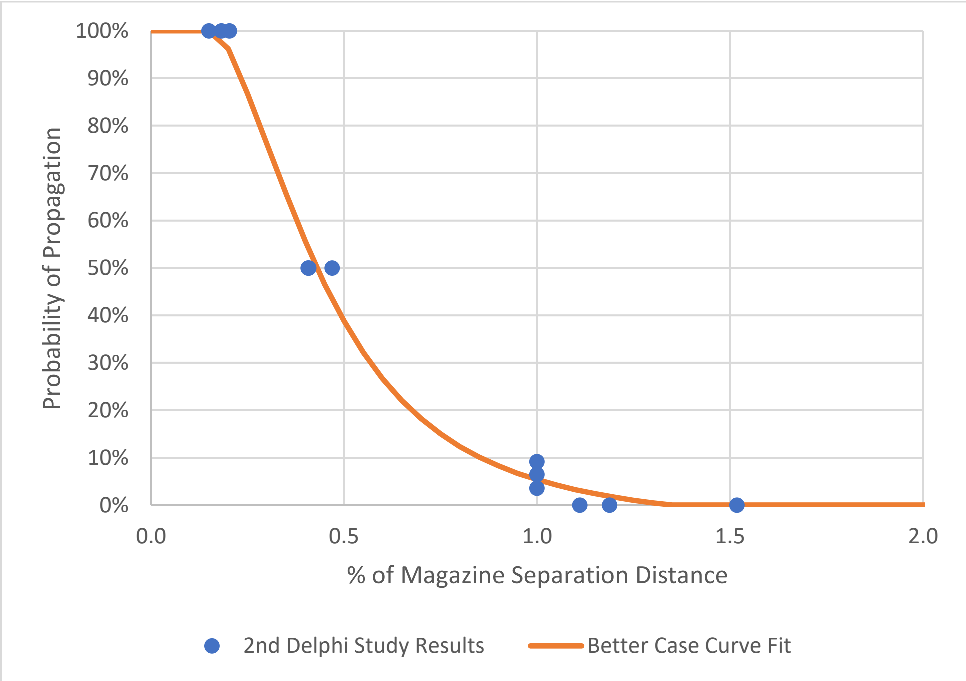


Figure 4-33: Delphi Study 2 Better Case Curve (without Outliers)

The equation for the Delphi Study 2 Better Case Curve without outliers is:

$$y = -0.0490243 + \frac{1.111819 + 0.0490243}{1 + \left(\frac{x}{0.4128261}\right)^{2.638173}}$$

The mean results for best case curve with outliers are shown in Table 4-31 and Figure 4-34.

Table 4-31: Delphi Study 2 Best Case Mean Results (with Outliers)

	Magazine Sep. Distance (ft)	Mean Distance from Study (ft)	Mean/Mag. Sep.	Probability of Propagation
Scenario 10	90	13.2	0.146	100%
	90	34.0	0.378	50%
	90	90	1	6%
	90	109.5	1.217	0%

	Magazine Sep. Distance (ft)	Mean Distance from Study (ft)	Mean/Mag. Sep.	Probability of Propagation
Scenario 11	156	32.5	0.209	100%
	156	70.5	0.452	50%
	156	156	1	10%
	156	188.6	1.209	0%

	Magazine Sep. Distance (ft)	Mean Distance from Study (ft)	Mean/Mag. Sep.	Probability of Propagation
Scenario 12	122	14.7	0.121	100%
	122	39.2	0.321	50%
	122	122	1	5%
	122	113.8	0.933	0%

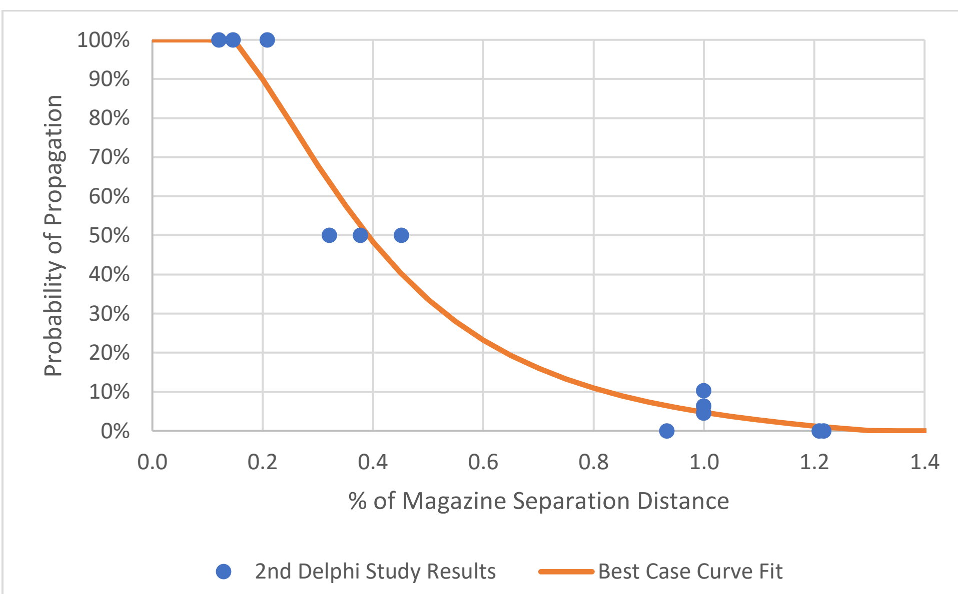


Figure 4-34: Delphi Study 2 Best Case Curve (with Outliers)

The equation for the Delphi Study 2 Best Case Curve with outliers is:

$$y = -0.0578224 + \frac{1.117827 + 0.0578224}{1 + \left(\frac{x}{0.3740889}\right)^{2.361243}}$$

The mean results for best case curve without outliers are shown in Table 4-32 and Figure 4-35.

Table 4-32: Delphi Study 2 Best Case Mean Results (without Outliers)

	Magazine Sep. Distance (ft)	Mean Distance from Study (ft)	Mean/Mag. Sep.	Probability of Propagation
Scenario 10	90	13.3	0.148	100%
	90	32.7	0.363	50%
	90	90	1	4%
	90	90.0	1.000	0%

	Magazine Sep. Distance (ft)	Mean Distance from Study (ft)	Mean/Mag. Sep.	Probability of Propagation
Scenario 11	156	23.7	0.152	100%
	156	58.9	0.377	50%
	156	156	1	4%
	156	156.1	1.001	0%

	Magazine Sep. Distance (ft)	Mean Distance from Study (ft)	Mean/Mag. Sep.	Probability of Propagation
Scenario 12	122	14.6	0.119	100%
	122	35.1	0.288	50%
	122	122	1	1%
	122	113.6	0.931	0%

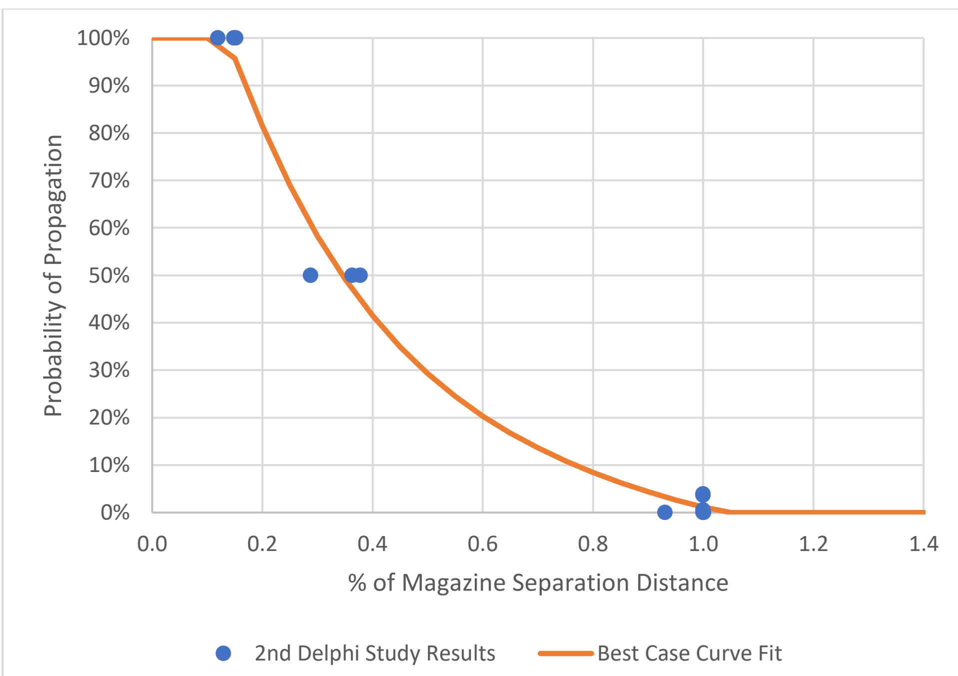


Figure 4-35: Delphi Study 2 Best Case Curve (without Outliers)

The equation for the Delphi Study 2 Best Case Curve without outliers is:

$$y = -0.2124578 + \frac{1.353396 + 0.2124578}{1 + \left(\frac{x}{0.3064302}\right)^{1.513717}}$$

A comparison of the Delphi Study 1 Baseline Curve and the four Delphi Study 2 curves (all without outliers) is shown in Figure 4-36. The Better Case curve was slightly more pessimistic than the baseline curve, which was unexpected.

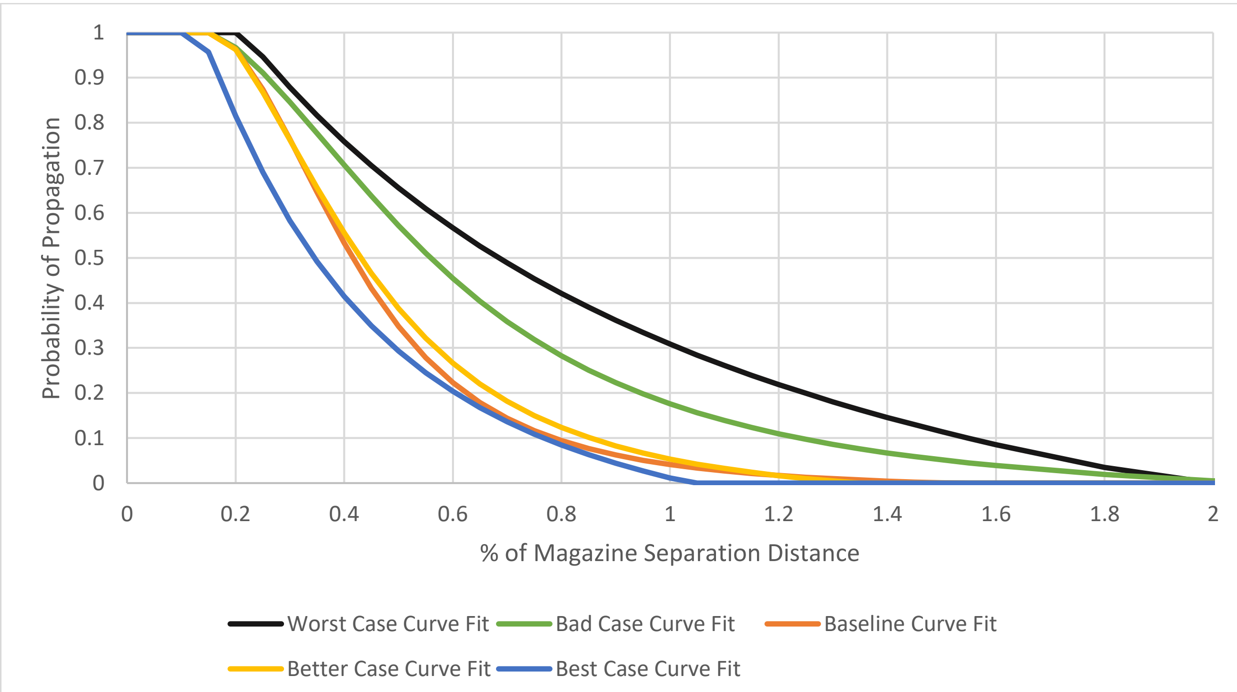


Figure 4-36: Probability of Propagation Curves (All Cases, without Outliers)

The process for calculating UBM during Delphi Study 1 was superseded by the method developed during Delphi Study 2. For the new method, the inverse sigmoid curve fits without outliers were selected to predict probability of propagation and the outliers were used to establish the UBMs. The UBMs for all case curves are shown in Table 4-33.

Table 4-33: UBMs for All Cases

Case	UBM
Baseline	2.22
Worst	1.87
Bad	2.96
Better	1.72
Best	3.39

It was initially thought that the Delphi Study 1 Baseline curve fit would be used in conjunction with the four curve fits developed using the Delphi Study 2 results. However, after reviewing the data, the ISP decided that only the four Delphi Study 2 curve fits would be used to model the probability of propagation, instead of the Delphi Study 1 baseline curve, which was based on fewer inputs.

4.2.2 Probability of Propagation Curve Selection

APT and ISP further discussed the need to consider additional beneficial and detrimental factors or "curve modifiers" that can cause the probability of propagation to shift from one curve to another, and possibly by up to two curves. These curve modifiers are *Donor Explosives Fragmentation* (i.e., primary fragments), *Receptor Azimuth* (relative to donor, i.e., normal, middle, corner), and *Receptor Door Orientation*. A "weighted scoring table" was designed to score factors that will increase or decrease the probability of propagation. The weighted scoring table also included the factors analyzed in Delphi Study 2, which were *Donor Construction*, *Receptor Construction*, *Energetic Receptor Species*, *Primary Fragments*, *Receptor Azimuth*, and *Receptor Door Orientation*, as shown in Figure 4-37. A seventh factor not included in either Delphi study was also added to the weighted scoring table, *Debris Varies with Azimuth*, to account for special cases where there is no azimuthal variation.

Delphi Study 1 Factors	Delphi Study 2 Factors or "Curve Modifiers"	Probability of Propagation Weighted Scoring Table Factors
(1) Donor Construction	(4) Donor Explosive Fragmentation	(1) Donor Construction
(2) Receptor Construction	(5) Receptor Azimuth	(2) Receptor Construction
(3) Energetic Receptor Species	(6) Receptor Door Orientation	(3) Energetic Receptor Species
		(4) Donor Explosive Fragmentation
		(5) Receptor Azimuth
		(6) Receptor Door Orientation
		(7) Debris Varies with Azimuth

Figure 4-37: Probability of Propagation Weighted Scoring Table Factors

The Delphi Study 2 scenarios were included in the weighted scoring table as the initial test scenarios with the assumptions that there were no primary fragments and no facing receptor doors for curve modifiers. Facing receptor doors are counted as a detrimental factor since there is a possibility that the door will be open at the time of a potential explosive event. All Delphi Study 2 scenarios were positioned with the receptor azimuth on the normal of the donor. Additional test scenarios were created by modifying the initial 12 scenarios to test the effectiveness of the scoring table to determine which curve should be used to predict the probability of propagation. Factors were weighted based on how large their influence is on reducing or increasing the probability of propagation. For example, a receptor azimuth position of corner will score a “4” since this factor is capable a producing a two-curve positive jump, whereas a receptor door orientation of facing donor will score a “-1” since it has a smaller influence on the probability of propagation. A flowchart of the curve selection logic used to create the probability of propagation weighted scoring table is shown in Figure 4-38. The seventh factor of no azimuthal variation is shown under the *Receptor Azimuth* curve modifier since it results in the same sub-score as “on the normal” *Receptor Azimuth* positioning which is a score of “-1.”

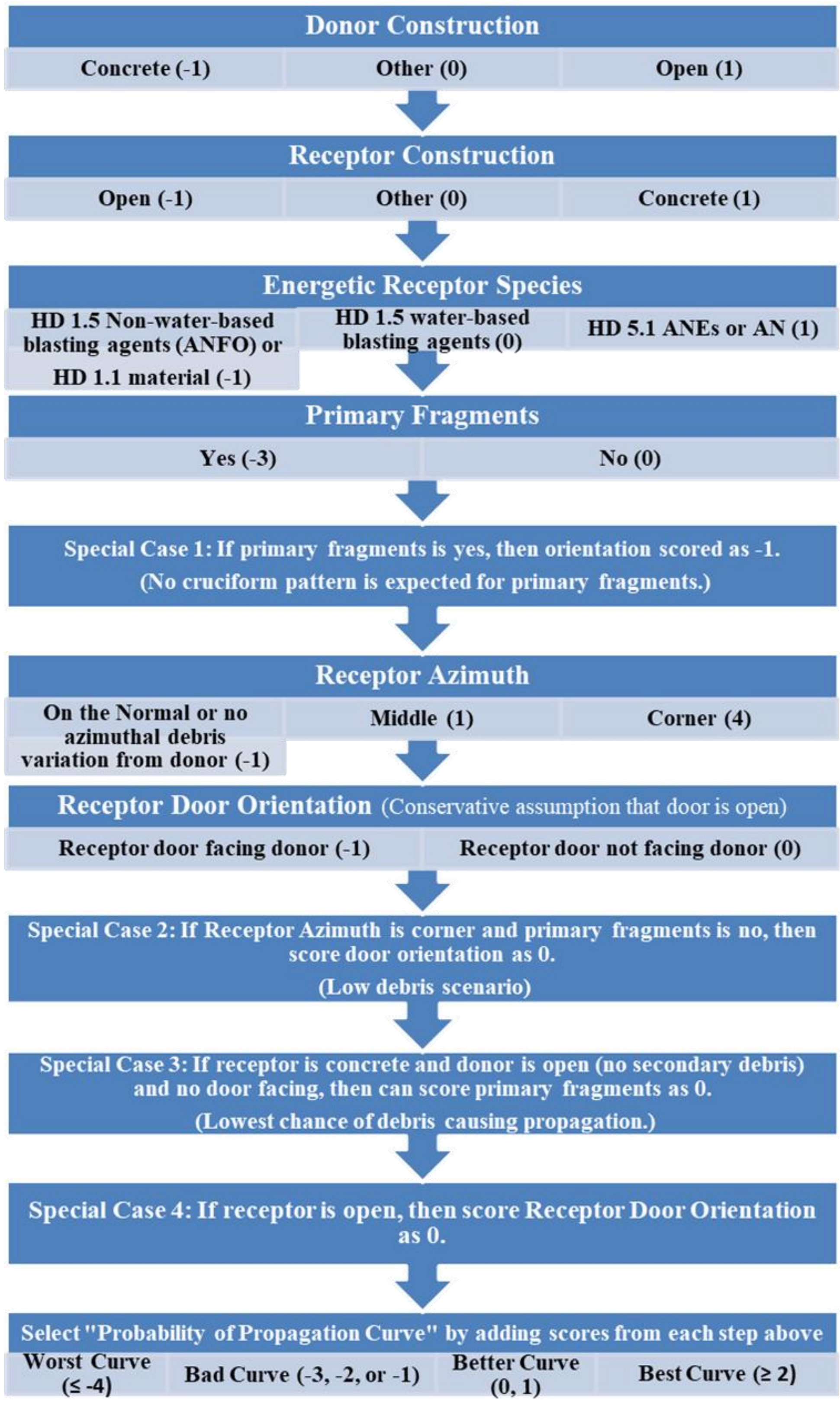


Figure 4-38: Probability of Propagation Weighted Scoring Table Logic Flowchart

The following designations were used for the curve modifiers:

- For *Receptor Azimuth*, Corner = Greater than 22.5° off the normal of any PES wall (i.e., outside the high debris density portion of the cruciform pattern); Middle = 10°-22.5° off the normal; Normal = within 10° of perpendicular of any donor wall
- For *Receptor Door Orientation*, the receptor door is considered facing if it is less than 45° off the normal of any donor wall
- *Primary Fragments* designation includes the following explosive types: Metal-Cased Explosive Article (MCEA), Metal Container (MC), Intermediate Bulk Container (IBC), and User-Defined Explosive Article (UDEA)[3]

The curve selection is defined using the resulting score for the seven criteria listed in the "Probability of Propagation Weighted Scoring Table Factors" column of Figure 4-37. The $P_{p|e}$ is calculated as a point value result from one of the four inverse sigmoid curves, Worst, Bad, Better, or Best, as shown in Figure 4-39. It is a function of $\frac{Distance}{SSD}$.

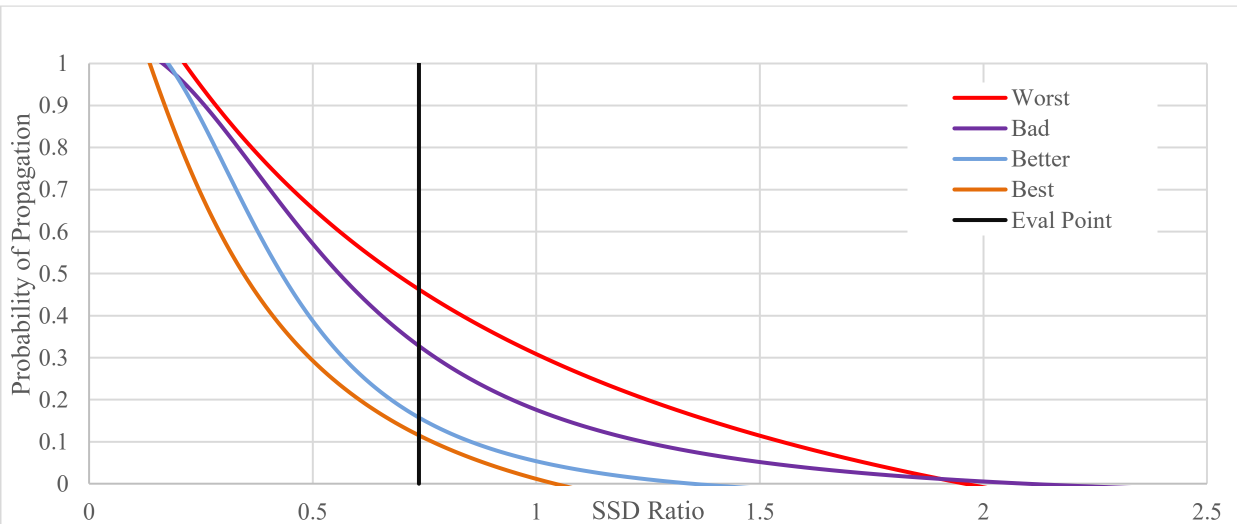


Figure 4-39: Comparison Between Four Inverse Sigmoid Curves

Since distance is accounted for in the curve equation, it is not a factor considered in the weighted scoring table. As a result, Delphi Study 2 Scenarios 1, 2, and 3 all scored the same, i.e., no difference between these scenarios was captured in this table. The same is true for Delphi Study 2 Scenarios 10, 11, and 12. The scores for each Delphi Study 2 scenario are shown in Figure 4-40, sorted by curve selection category (i.e., worst, bad, better, or best).

[3] UDEA will only be designated as having primary fragments if the user defines it as containing primary fragments.

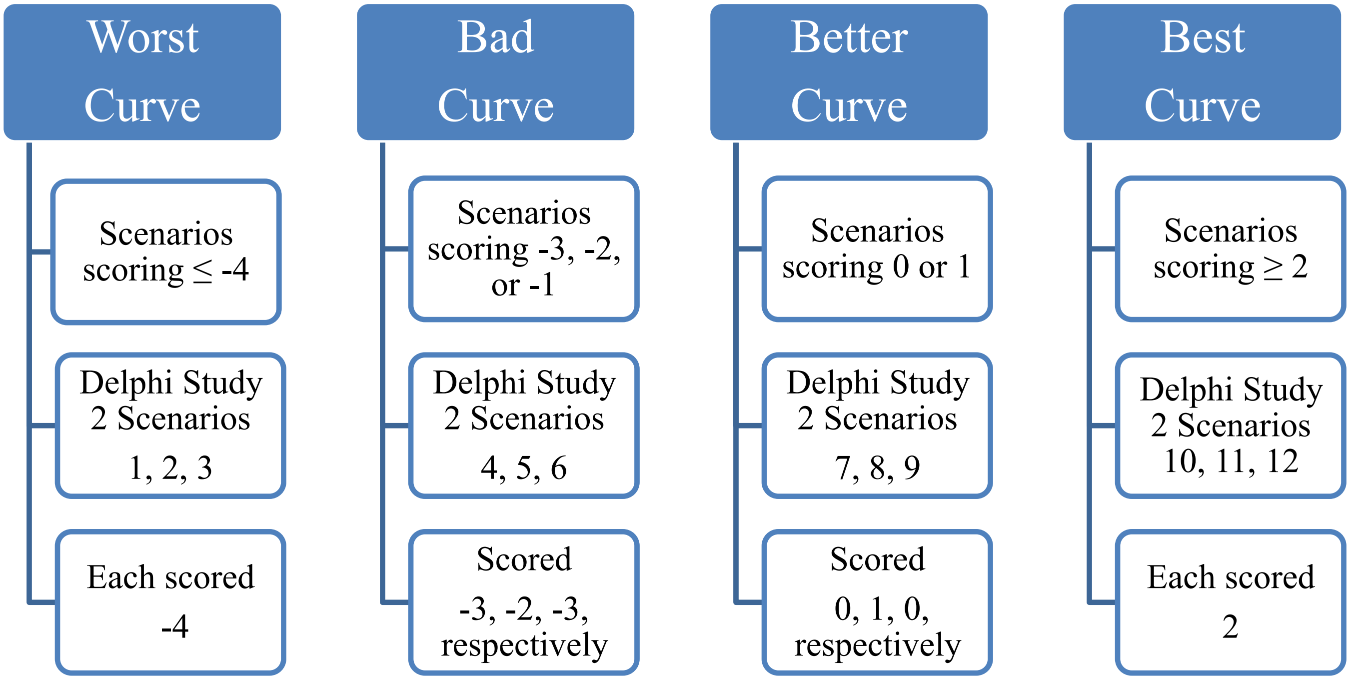


Figure 4-40: Delphi Study 2 Scenarios Sorted by Weighted Scoring Table Output Value

The scoring for the bad curve includes a range of three values (i.e., -3, -2, and -1), whereas the other three curves only include a range of two values each. This causes inconsistent "curve jumping" for factors with a smaller weight, such as "middle" *Receptor Azimuth*. For example, changing the *Receptor Azimuth* to "corner" will consistently cause a scenario that originally falls on the bad or better curve to "jump" or move to a curve with a lower probability of propagation since a "corner" Receptor Azimuth position has a sub-score of "4." Despite this issue, the weighted scoring table was considered acceptable to include in the probability of propagation logic. The curve modifier weighted scoring table was reviewed by the ISP and there were no objections to the scoring method used to weigh curve modifiers.

Once the curve modifier scoring method was approved, APT developed a propagation logic tool to test the propagation logic. Testing highlighted the need for treatment of combined donors to determine which PES or combination of PESs should be considered first when a scenario includes three or more PESs. When three or more PESs are considered for propagation, there is a combined term from the propagation tree where parameters from a donor must be used to determine the $P_{p|e}$. For example, the $P_{p|e}$ equation for three PESs will include a term for A and B propagating to C, as highlighted in red in the following equation:

$$P_{f_A} = \begin{pmatrix} P_A(1 - P_{A\to B})(1 - P_{A\to C})P(f|e)_A + \\ P_A P_{A\to B}(1 - P_{A+B\to C})P(f|e)_{A+B} + \\ P_A P_{A\to C}(1 - P_{A+C\to B})P(f|e)_{A+C} + \\ P_A P_{A\to B} P_{A+B\to C} P(f|e)_{A+B+C} + \\ P_A P_{A\to C} P_{A+C\to B} P(f|e)_{A+B+C} \end{pmatrix}$$

Since there is only one general methodology for calculating the probability of propagation, APT carefully reviewed and compared several methods for handling curve assignments for combined PES terms. Continuing with the same example of A and B propagating to C, four options were evaluated to determine which method most accurately depicted risk for the scenario without being non-conservative. In other words, APT evaluated whether the $P_{p|e}$ curve for A or B should be selected as the probability of propagation for the A+B combined term or whether a different value should be calculated based on an amalgam donor of the “worst” inputs. The four options evaluated were:

- Method 1 (Closest) - Select the $P_{p|e}$ result from the closest donor to receptor
- Method 2 (Worst Curve) - Select the $P_{p|e}$ result from the worst curve
- Method 3 (Worst $P_{p|e}$) - Evaluate each donor/receptor relationship and choose the “worst” $P_{p|e}$
- Method 4 (Amalgam Donor) - Create a hypothetical donor of the “worst” options from the combined donors to calculate the $P_{p|e}$

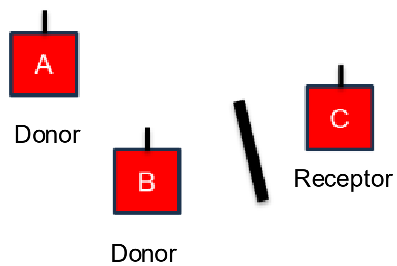


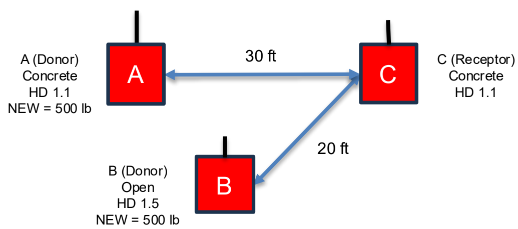
Figure 4-41: Treatment of Combined Donors Example

Method 1 only uses distance to determine which PES’s $P_{p|e}$ value will be used for the combined term. Using Figure 4-41 to continue with the example case where C is the receptor, Method 1 would select the $P_{p|e}$ of PES B since it is the closest donor, without considering any other variables such as a barricade or donor energetics species. Method 2 would select the $P_{p|e}$ value from whichever donor had the “worst curve” designation; however, since the curve designation does not account for distance between the donor and receptor or the energetics species, sometimes the “worst curve” will not necessarily produce the highest $P_{p|e}$. This means that while Methods 1 and 2 are easy to calculate, these methods can sometimes be overly optimistic.

Method 3 uses all inputs, including distance and donor/receptor energetic species, to determine which donor’s $P_{p|e}$ result should be used as the $P_{p|e}$ result for the combined donor term. Method 3 is the most logical option but can be optimistic for special cases and has a calculation penalty, as it requires more work for the software tool to evaluate each donor/receptor relationship before calculating a result. Method 4 selects the most detrimental factors from each donor to create an “amalgam donor” which is then used to calculate a hypothetical $P_{p|e}$ result to use for the combined donor term. This method can lead to overly conservative and unrealistic results. However, it would catch most special cases, including scenarios where an event at one donor can blow out the barricade of another donor or where one donor blows debris from another donor into the receptor, but it will not catch some scenarios that cannot be currently modeled, such as jetting effects. It would also result in the same calculation penalty as Method 3 since the additional calculations would slow down the software tool.

APT analyzed multiple scenarios to compare the four possible methods to determine which could be used to automate donor selection in the propagation logic across all cases without being unconservative and still make sense logically. Examples of the scenarios analyzed are shown in Figure 4-42 through Figure 4-49.

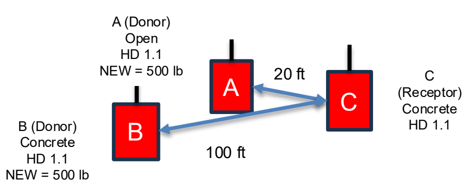
Scenario 1, shown in Figure 4-42, is a case where the closet donor has a lower $P_{p|e}$ due to the donor energetic species and demonstrates why basing the selection of $P_{p|e}$ value for the combined donor term solely on closest distance is overly optimistic.



Method	Distance (ft)	SSD (ft)	Curve	$P_{p\|e}$ Result
Closest	20	42	Best	0.32
Worst Curve	30	78	Bad	0.73
Worst $P_{p\|e}$	30	78	Bad	0.73
Amalgam Donor	20	78	Bad	0.90

Figure 4-42: Propagation Sequencing Method Comparison Scenario 1

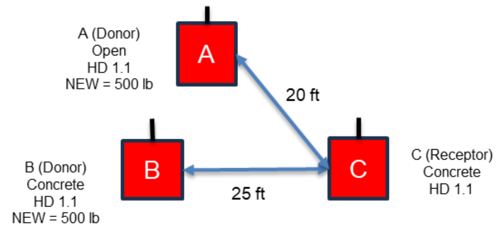
Scenario 2, shown in Figure 4-43, is a case where the donor/receptor combination with the most detrimental score, or "Worst Curve," had the lowest $P_{p|e}$. This is due to the final $P_{p|e}$ result being significantly affected by the large distance between the donor, PES B, and receptor, PES C. This example was designed to show that Method 2 can also be overly optimistic.



Method	Distance (ft)	SSD (ft)	Curve	$P_{p\|e}$ Result
Closest	20	78	Better	0.85
Worst Curve	100	78	Bad	0.09
Worst $P_{p\|e}$	20	78	Better	0.85
Amalgam Donor	20	78	Bad	0.90

Figure 4-43: Propagation Sequencing Method Comparison Scenario 2

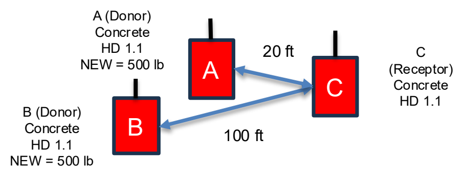
Scenario 3, shown in Figure 4-44, is a case where Method 3 and Method 4 produce similar results. Method 4 results in a slightly higher $P_{p|e}$ value since it uses the shorter distance between PES A (donor) and PES C (receptor) and combines it with the more detrimental building type from PES B (donor) to produce the hypothetical amalgam donor with a higher $P_{p|e}$.



Method	Distance (ft)	SSD (ft)	Curve	$P_{p\|e}$ Result
Closest	20	78	Best	0.68
Worst Curve	25	78	Bad	0.82
Worst $P_{p\|e}$	25	78	Bad	0.82
Amalgam Donor	20	78	Bad	0.90

Figure 4-44: Propagation Sequencing Method Comparison Scenario 3

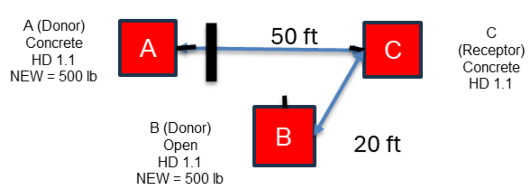
Scenario 4, shown in Figure 4-45, is a case where Method 2 can result in different $P_{p|e}$ results. This example and the case shown in Scenario 2 support the argument for excluding Method 2 as a viable option for selecting the $P_{p|e}$ value that will be used for combined PES terms in the probability of propagation calculation.



Method	Distance (ft)	SSD (ft)	Curve	$P_{p\|e}$ Result
Closest	20	78	Bad	0.90
Worst Curve	20,100	78	Bad, Bad	0.90 or 0.09
Worst $P_{p\|e}$	20	78	Bad	0.90
Amalgam Donor	20	78	Bad	0.90

Figure 4-45: Propagation Sequencing Method Comparison Scenario 4

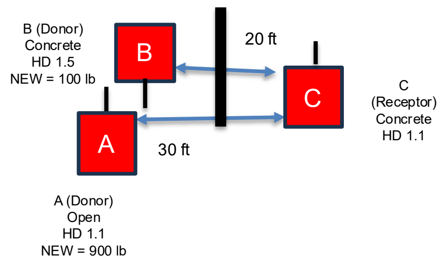
Scenario 5, shown in Figure 4-46, is a case where Method 4 is unrealistically conservative. Since it takes the worst factors from each donor, it is disregarding the barricade between PES A (donor) and PES C (receptor), using the greater SSD, and closest distance to calculate the $P_{p|e}$ result.



Method	Distance (ft)	SSD (ft)	Curve	$P_{p\|e}$ Result
Closest	20	78	Best	0.68
Worst Curve	50	39	Worst	0.19
Worst $P_{p\|e}$	20	78	Best	0.68
Amalgam Donor	20	78	Worst	0.94

Figure 4-46: Propagation Sequencing Method Comparison Scenario 5

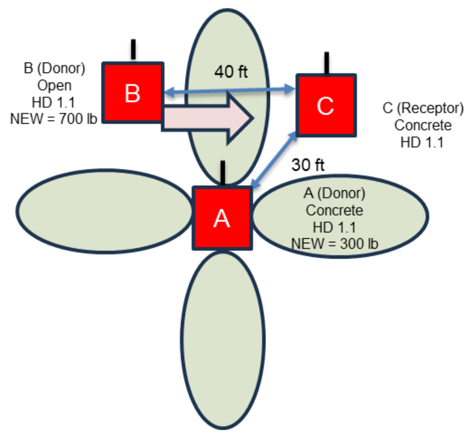
Scenario 6, shown in Figure 4-47, is an example where PES A (donor) blows out the barricade between PES B (donor) and PES C (receptor) while propagating to PES B. In this special case, Method 3 would be non-conservative and Method 4 would best model the $P_{p|e}$ for the combined term.



Method	Distance (ft)	SSD (ft)	Curve	$P_{p\|e}$ Result
Closest	20	7	Bad	0.0
Worst Curve	20	7	Bad	0.0
Worst $P_{p\|e}$	30	78	Better	0.59
Amalgam Donor	20	78	Bad	0.90

Figure 4-47: Propagation Sequencing Method Comparison Scenario 6

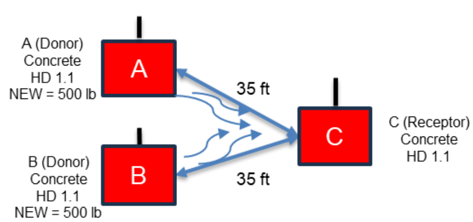
Scenario 7, shown in Figure 4-48, is an example of a situation where PES B (donor) blows debris from PES A (donor) into PES C (receptor) during propagation. This is a scenario in which Method 3 would be overly optimistic, and Method 4 would better model the propagation effects.



Method	Distance (ft)	SSD (ft)	Curve	$P_{p\|e}$ Result
Closest	30	78	Best	0.44
Worst Curve	40	78	Better	0.37
Worst $P_{p\|e}$	30	78	Best	0.44
Amalgam Donor	30	78	Bad	0.73

Figure 4-48: Propagation Sequencing Method Comparison Scenario 7

Scenario 8, shown in Figure 4-49, is an example of an explosives event that could lead to jetting effects that would not be accurately represented by any of these four methods since the foundational logic used to model propagation in this paper does not account for this type of behavior.



Method	Distance (ft)	SSD (ft)	Curve	$P_{p\|e}$ Result
Closest	35	78	Bad	0.64
Worst Curve	35	78	Bad	0.64
Worst $P_{p\|e}$	35	78	Bad	0.64
Amalgam Donor	35	78	Bad	0.64

Figure 4-49: Propagation Sequencing Method Comparison Scenario 8

As expected, the $P_{p|e}$ result from Method 4 is always equal to or greater than the Method 3 result. Methods 1 and 2 are easy but can produce multiple results for the same criteria (e.g., different donors can receive a scoring of "Worst Curve" from the Curve Modifier Weighted Scoring Table but have different $P_{p|e}$ results such as in Scenario 4 (Figure 4-45)) or produce overly optimistic results (e.g., Method 2 can result in the lowest $P_{p|e}$ value being selected as shown in Scenario 1

(Figure 4-42)). For most cases, Method 3 is the most logical method. Special cases demonstrate the need to keep Method 4 available for user consideration in a propagation tool. After reviewing this analysis, the ISP decided that the best option would be to implement Method 3 as a default and include Method 4 as an option for comparison.

4.3 CONSEQUENCE (PROBABILITY OF FATALITY)

After the probability of propagation was determined, the next step in the risk assessment was to determine the $P_{f|e}$. For cases where a single PES detonates and no propagation is assumed, the typical IMESAFR consequence models can be used. For cases where prompt propagation is assumed, adjustments to the effects that generate the consequences had to be considered. The blast and debris consequences, when prompt propagation occurs, are considered using the following two models: Pressure and Impulse Given Propagation model and Debris Given Propagation model. Each model is used to calculate the probability of fatality given propagation at (only) each original location of each PES involved. The calculated consequences are conditionally summed for combined PESs. Extensive work studying the consequences component of the probability of propagation model was completed during the Preliminary Propagation Model Assessment, which is discussed further in Section 8.0.

For the consequence given propagation logic, the ISP agreed to use a UBM of 1.0 as the consequence models were considered quite conservative (before considering uncertainty). The models are already looking at the worst-case scenario and there are no additional parameters that could make any case worse. The UBM value of 1.0 is considered a conservative placeholder and may change in the long term.

4.3.1 Pressure and Impulse Given Propagation

The Pressure and Impulse Given Propagation model incorporates an aggregation methodology to determine an increased NEW at each PES to feed into the pressure and impulse calculations for probability of fatality given an event. This increased NEW is only used for the pressure and impulse calculations and is not used in the debris methodology. For the initial model, the NEW is aggregated in accordance with the QD system prescribed by the ATD. This means that the entire NEW for each magazine is added to the others in the failing separation distance relationship. It should be noted that the propagation failures must be reassessed after each NEW aggregation like in a QD analysis. For example, after the first PES pair is evaluated, then the next pair is evaluated. This process repeats until all PES pairs have been evaluated.

4.3.2 Debris Given Propagation

The debris calculations are based on the NEW in each separate PES. The combined NEW discussed for pressure and impulse is not used in the debris logic. The method for handling debris throw in the propagation methodology is to increase the maximum throw values of the generated secondary debris and crater ejecta by a 1.2 multiplier. A 1.2 multiplier for debris distance was selected as a starting point based on the US Army Corps of Engineers' testing of munition stack effects, which showed a 20% increase in debris distance for stacked munitions [5]). This is accomplished by applying an increase to the calculated initial velocities such that the calculated maximum throw ($MT_{Calculated}$) is 1.2 times larger than the non-propagation answer. The maximum throw cutoff values (MT_{Max}) would also need to be increased by the factor of 1.2. The factor for increasing velocity can be determined from the initial velocity and maximum throw equations built into IMESAFR.

The initial velocity equation is:

$$v_0 = ar^b$$

where

v_0 is the initial velocity

a and *b* are constants based on the type of PES

r is the explosive weight to PES volume ratio

The equation for maximum throw is:

$$t_M = c_1 {v_0}^{c_2} {m_a}^{c_3}$$

where

t_M is the maximum throw distance

c_1, c_2, and c_3 are constants based on the type of material (steel or concrete)

m_a is the average fragment mass for the bin[4]

To increase the maximum throw distance by 1.2, the initial velocity should be increased by some factor *x*:

$$1.2t_M = c_1 (xv_0)^{c_2} {m_a}^{c_3}$$

Isolating x on one side of the equation:

$$(xv_0)^{c_2} = \frac{1.2t_M}{c_1 {m_a}^{c_3}} = x^{c_2} {v_0}^{c_2}$$

$$x^{c_2} = \frac{1.2t_M}{c_1 {m_a}^{c_3} {v_0}^{c_2}}$$

Everything on the right-hand side is constant, so a variable can be substituted in and used as the change of basis to solve for *x*:

$$x^{c_2} = C$$

$$\log_{c_2} x^{c_2} = \log_{c_2} C$$

$$x = \log_{c_2} C$$

[4] The IMESAFR QRA model discretizes fragments into multiple classes, referred to herein as bins. [3]

$$x = \frac{\log_{10} C}{\log_{10} c_2}$$

Once x is calculated, the originally calculated initial velocity will be multiplied by x and the max throw limit by 1.2. The ISP supported using the 1.2 factor for consequences while accepting that it is a conservative method and is based on Army Corps of Engineers' test data for stacked munitions and not on propagation between PESs.

4.3.3 Consequence Model Analysis

As first mentioned in Section 4.1, the consequence component of the propagation model was thoroughly assessed during the Preliminary Propagation Model Assessment. The Probability of Propagation Given Event component of the propagation logic was further refined, as discussed in Section 4.2. However, the Consequence model used in the Preliminary Propagation Model Assessment and, described in detail earlier in this section, was determined to be acceptable without further adjustments. An example of one of the 38 consequence graphs analyzed during this work is shown in Figure 4-50. Each of the 38 consequence graphs compared the blast and debris consequences for 12 variations of ESs per propagation scenario for the current IMESAFR model, informal ATF model (i.e., O'Lena), and proposed propagation consequence model.

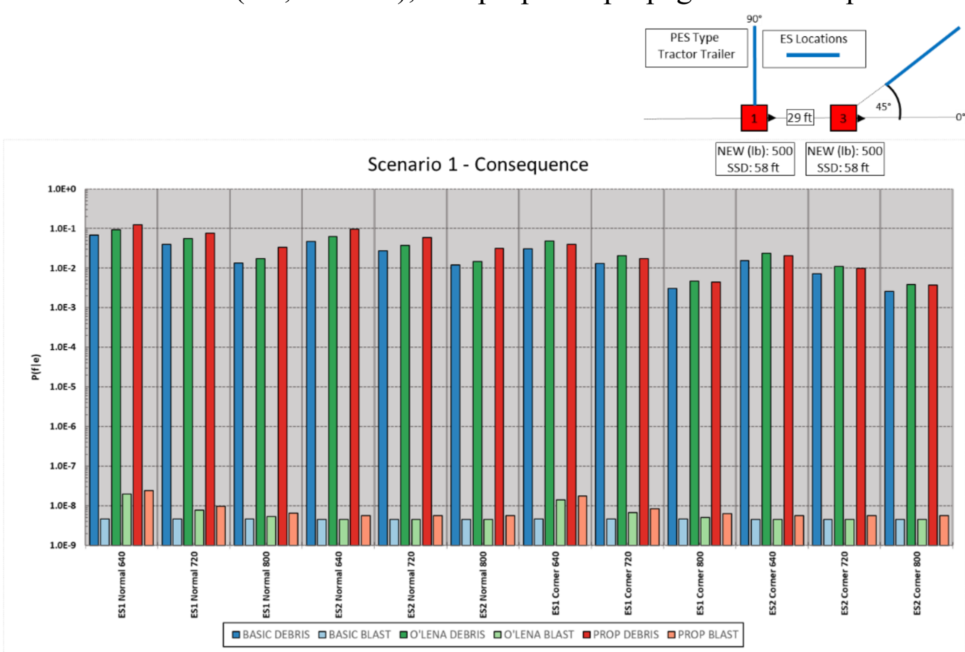


Figure 4-50: Propagation Model Assessment Scenario 1 (Consequence)

5.0 Implementation Plan

APT can implement the propagation logic in a standalone tool or as a feature in its current risk assessment tool, IMESAFR. For testing purposes, the propagation logic was implemented using IMESAFR 2.2, which was the current version of the software at the time of testing. IMESAFR implements a user-friendly Graphical User Interface (GUI), logical framework, and reporting capabilities for defining and reporting site plan scenarios for a broad range of defined building and explosive types. IMESAFR can use user-created scenario definitions, in conjunction with QD and risk-based calculations for all the steps involved in propagation logic. APT's propagation prototype tool includes all the capabilities of IMESAFR v2.2 and has a separate propagation mode which enables a panel on the GUI to assess the probability of propagation logic for scenarios, as shown in Figure 5-1. The prototype tool is functional and able to accurately implement the propagation logic detailed in this paper.

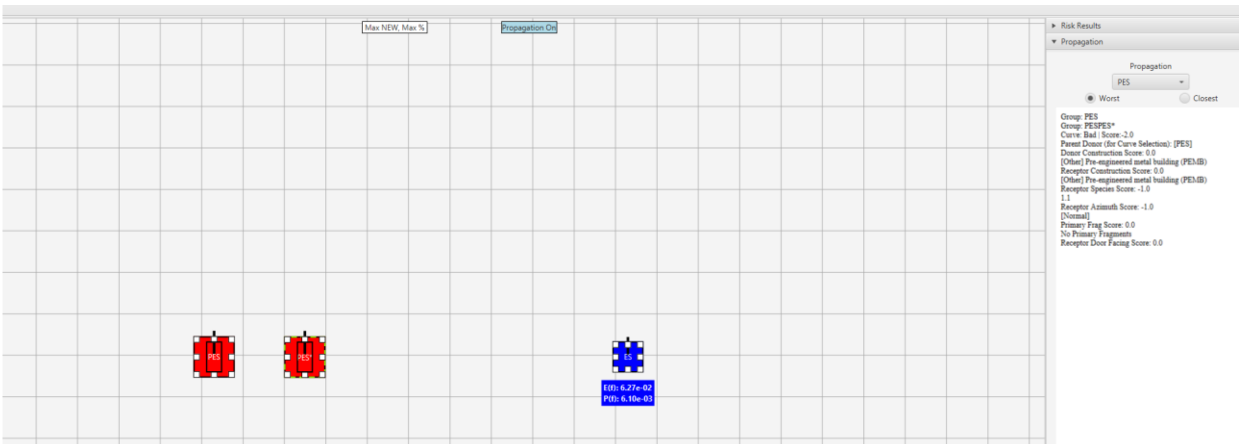


Figure 5-1: APT Prototype Propagation Tool

In the current version of the prototype propagation tool, building construction is divided into three categories: concrete, other, and open, as shown in Figure 5-2.

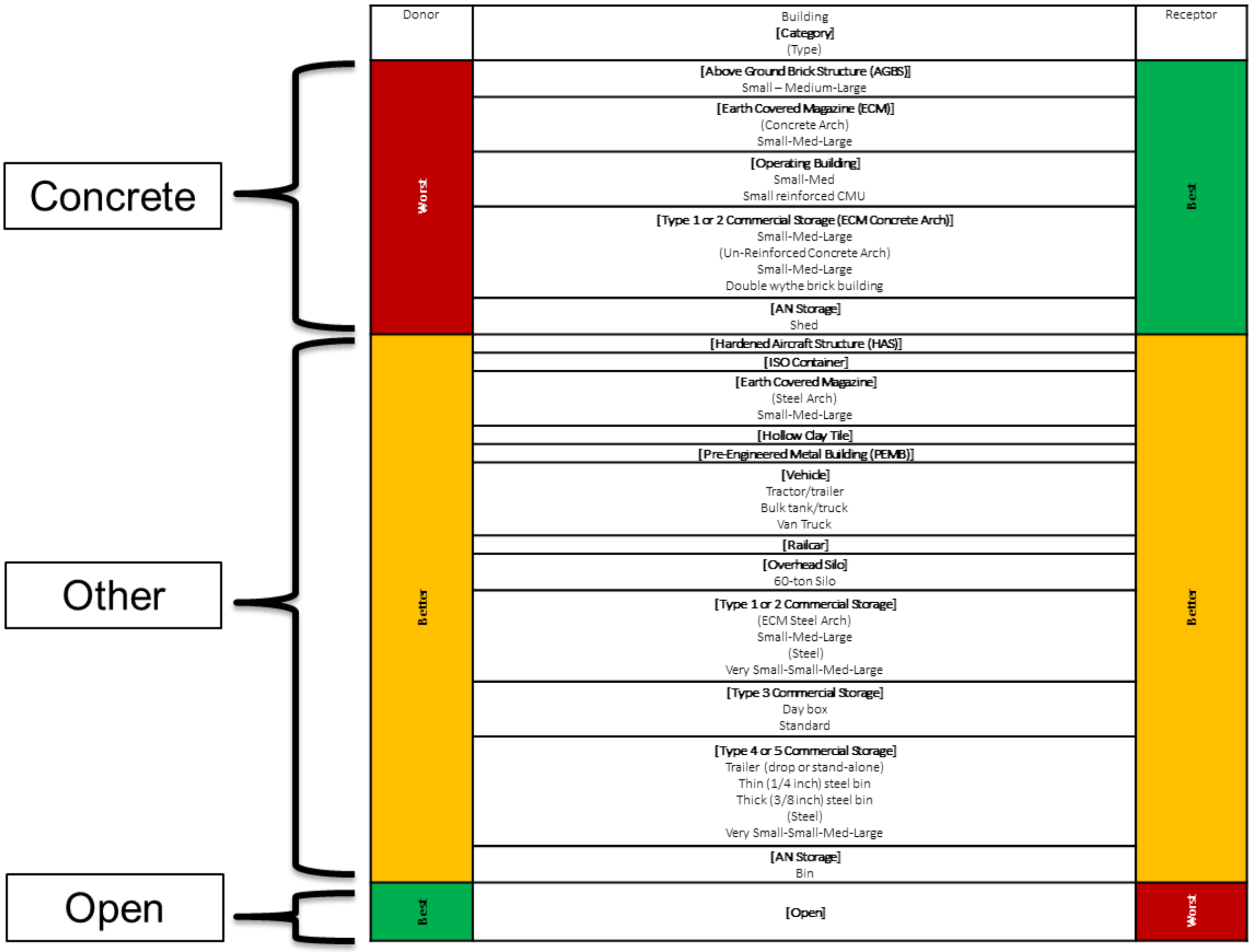


Figure 5-2: Building Construction Categories

Open is the best building category for a donor PES since it produces the lowest debris hazard, followed by other (e.g., steel, wood), then concrete. The opposite holds true for the receptor building protection level, in which case concrete offers the best protection, followed by other, then open. Grouping of IMESAFR building models into these three building categories will be reviewed further before the propagation tool is finalized.

After acceptance of the proposed propagation logic, the next step in the implementation plan is to determine whether the propagation tool will be a standalone tool or incorporated into the next version of the IMESAFR risk assessment tool. Once the tool is finalized it will be rigorously tested before release to the public.

6.0 Conclusion

APT's proposed propagation model is a first step towards creating risk-based propagation logic. The process of creating the model encompassed establishing probability of propagation curve fits which were refined using Delphi studies, rigorous testing of the consequence equations, and additional work to create a prototype tool for testing the model and finding the best method for treatment of combined donors when a scenario includes three or more PESs. ATF and ISP members were contributors to development of the prompt propagation logic throughout the multi-year process and active participants in the review and approval of the logic. In addition to contributing to the development of the logic, ATF provided financial support for this analysis. No other collaborative team has constructed prompt propagation logic for a risk-based tool, so while the model might not be perfect, it is at least a first step in creating the required logic. The next phase of this project will be the implementation of the propagation logic into a finalized risk assessment tool. Implementation of the logic into the risk assessment tool will undergo rigorous testing before release.

7.0 References

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[2] ATF, "Table of Distances," 26 October 2021. [Online]. Available: https://www.atf.gov/explosives/table-distances. [Accessed 2024].

[3] A-P-T Research, Inc. (APT), "Institute of Makers Of Explosives Safety Analysis for Risk - Technical Manual, 5th Edition," APT, Huntsville, AL, 2026.

[4] "Minutes from Meeting in AASTP-4 Custodian Working Group (PFP(AC/326-SG/C)(NO)IWP-01-19)," Freiburg, Germany, April 8 to 10, 2019.

[5] DDESB, Methodologies for Calculating Primary Fragment Characteristics, DDESB Technical No. 16, revision 5, 15 September 2016.

[6] Fraunhofer Institute for High-Speed Dynamics, Ernst-Mach-Institut (EMI), "Minutes of the Klotz Group Meeting Spring 2019," Freiburg, Germany, April 2 to 4, 2019.

[7] B. Fryman and J. Tatom, "Propagation of PESs," in *Klotz Group Meeting Spring 2019*, Freiburg, Germany, April 2019.

8.0 Appendix A: Preliminary Propagation Model Assessment

To assess the validity of the preliminary propagation model, it was compared against the current IMESAFR model (no propagation considered) and the current IMESAFR model with a secondary attempt to account for propagation. These three IMESAFR variations were called Propagation model, Basic model, and informal ATF model, respectively. The three variations were chosen to allow the ISP group to compare the preliminary propagation model results to the original IMESAFR results and the results generated by the current, informal ATF protocol for assessing propagation with IMESAFR (i.e., O'Lena model).

The Propagation model used the following considerations:

- The probability of event was modeled by the inverse sigmoid curve fit discussed in Section 4.2.
- The debris consequence was modeled by increasing the maximum throw values of the debris by increasing initial velocities by 20% (similar to the US Army Corps of Engineers' 1.2 multiplier for debris distance of stacked munitions).
- The blast consequence was modeled by aggregating the NEWs of failing magazines. The aggregation summed the NEW of all failing magazines (worst-case) and placed the final NEW in each magazine for the pressure and impulse calculations.
- The debris and blast consequences were assessed at the original location of each PES.

The Basic (i.e., IMESAFR v2.1) model used the following considerations:

- The same PES and ES inputs were used but each scenario was assessed using IMESAFR v2.1 algorithms.
- IMESAFR algorithms do not (currently) take propagation effects into account and only assess the risk from PESs independently.
- The probability of event term was not altered in any way for this methodology.

The O'Lena model used the following considerations:

- This method used the IMESAFR v2.1 model but attempted to account for propagation by aggregating the NEW of all separation failing PESs into each PES in the failure. The remaining PES inputs and the ES inputs remained the same as the previous methods.
- There was no change to the location, volume, or mass of any PES.
- The probability of event term was not altered in any way for this methodology.

The O'Lena model has been used in the past to try to account for propagation but there are known IMESAFR algorithm concerns related to artificially increasing the weight/volume of the PES created by this methodology.

A total of 38 scenarios were run using these three IMESAFR model variations. Each scenario featured either two, three, or four PESs that failed ATD prescribed magazine separation distance to each other, as shown in Figure 8-1. The ES locations relative to the PESs for the various scenarios are shown in Figure 8-2 and Figure 8-3. Each scenario included twelve different ES cases. A total of 1,368 PES-ES pairs were assessed for each of the three IMESAFR variations.

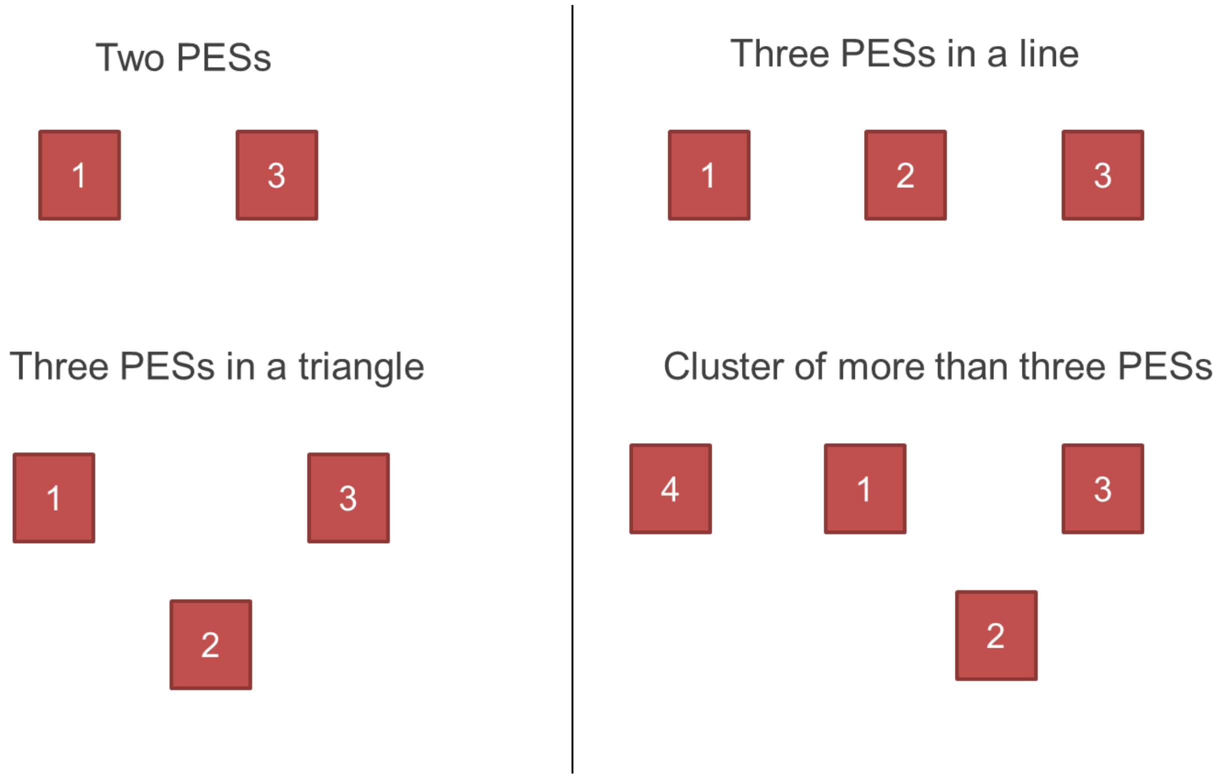

Figure 8-1: IMESAFR Scenario PES Layouts

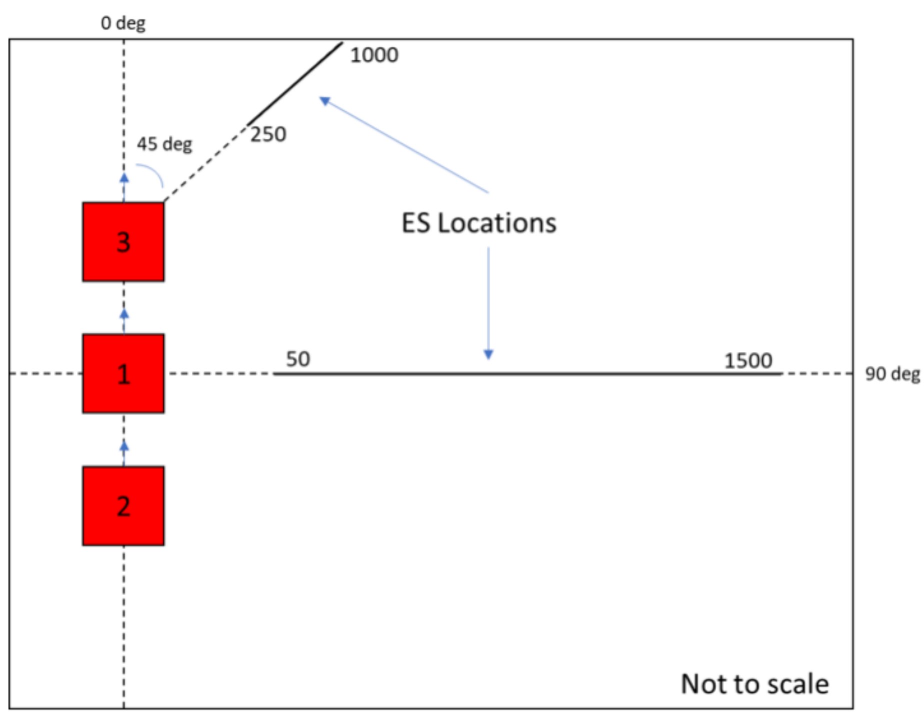

Figure 8-2: IMESAFR ES Locations for In-Line Scenario Layouts

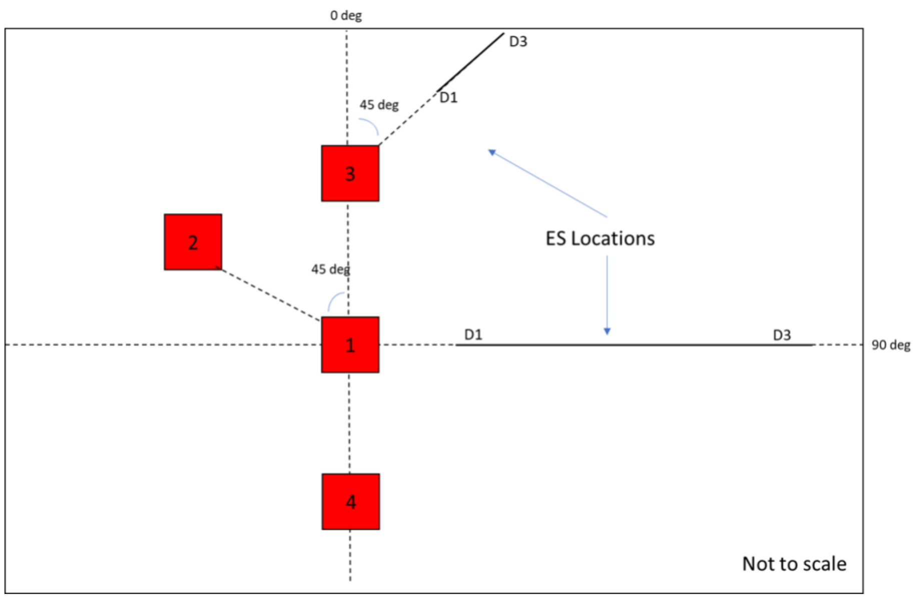

Figure 8-3: IMESAFR ES Locations for Triangular/Cluster Scenario Layouts

Note 1: In all scenarios, the ES configurations were oriented off PES 1 and 3. Therefore, for all two PES scenarios, PES 1 and 3 were used instead of PES 1 and 2.

Note 2: For the three PESs in a triangle layout, the PESs were oriented off PES 1 for the triangle scenarios and were separated based on edge-to-edge distances. PES 3 was located at a 90° heading from PES 1. PES 2 was located at a 135° heading from PES 1. Due to the edge-to-edge separation, the triangular setup did not result in an equilateral triangle as shown here.

Note 3: For the cluster of more than three PESs layout, PESs 1, 2, and 3 were located using the same logic as the triangular setup. PES 4 was located at a 270° heading from PES 1.

Two PES types were used for the scenarios. The PES types were chosen so that one PES would produce a large amount of debris and one PES would produce significantly less debris.

The PES types were:

- ATF Type 1/2 Large Unreinforced Concrete (i.e., high debris hazard)
- Tractor Trailer (i.e., lower debris hazard)

Two ES types were also used for the scenarios. The ES types were chosen so that one ES was susceptible to a building collapse hazard and one was not. ESs were assessed directly on the normal of a selected PES and on the diagonal (i.e., on the corner) of a selected PES, as shown in the schematics included with the results in Figure 8-5 as well as in Figure 8-4.

The ES types were:

- Personal Residence (ES 1): Wood Frame (Low Building Collapse Hazard), 15% Dual Pane Glass

- Commercial Building (ES 2): Large Unreinforced Masonry with a Steel Roof (High Building Collapse Hazard), 25% Tempered Glass

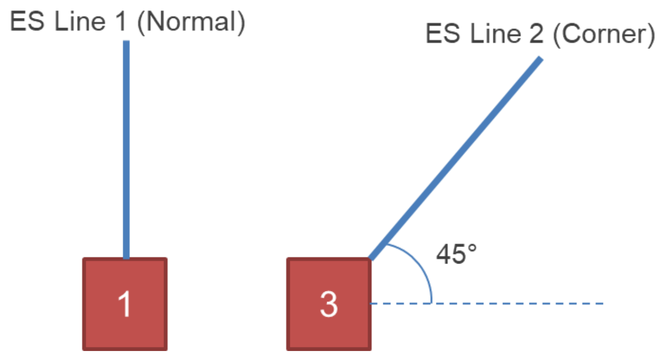

Figure 8-4: ES Azimuthal location

Each ES type/ES line pair featured three individual ESs at different distances (for a total of 12 ES cases per scenario) for which risk was calculated. The first ES distance was decided by the Inhabited Building Distance (IBD) value of the original NEW in the magazine off which the ES was positioned. The third ES distance was decided by the IBD value assigned based on the aggregated NEW after separation failure considerations in the magazine off which the ES was positioned. The second ES distance was decided by the average of the first and third distance. The ATD features a plateau in IBD values at 2,000 ft for a large range of NEW. If both the original NEW and the aggregated NEW IBD values were 2,000 ft, the third ES distance was set to 3,000 ft to provide different distances for the ESs. The scenario descriptions are shown in Table 8-1.

Risk and consequence values were calculated at each ES in the scenario list. Each scenario output set includes ES individual risk for each of the three IMESAFR variations and a combined consequence value at the ES from all PESs present in the scenario. The consequences are broken down into debris and blast (overpressure, building collapse, glass).

To generate consequence values for the scenarios, the probability of event was set to 1 in the equations that were used to calculate risk for each IMESAFR variation. These equations are:

$$C_{Basic\ and\ O'Lena} = 1 * C_A + 1 * C_B$$

and

$$C_{Propagation} = 1 * P_{A\rightarrow B} * C_{A+B} + 1 * (1 - P_{A\rightarrow B}) * C_A + 1 * P_{B\rightarrow A} * C_{A+B} + 1 * (1 - P_{B\rightarrow A}) * C_B$$

The overall risk presented by default in IMESAFR is the calculated base risk (R) that has been altered by an uncertainty factor (U) and a correlation factor (C). The final risk equation is:

Overall Risk = R * U * C

The risk values for each scenario of this effort are the base risk (R). These values do not consider uncertainty and the correlation factor is set to 1 since "No Correlation" was entered for all options in the IMESAFR inputs. The refinement of the probability of propagation model and implementation of uncertainty in the propagation model are discussed in Section 4.2.1.2.

Table 8-1: Preliminary Propagation Model Assessment Scenarios

PES Configuration	PES 1 Original IBD (ft)	PES 3 Original IBD (ft)	PES 1/3 Aggregated IBD (ft)	House Distance (edge to edge) [ft] from PES 1 on the Normal			Commercial Building Distance (edge to edge) [ft] from PES 1 on the Normal			House Distance (edge to edge) [ft] from PES 3 on the Corner			Commercial Building Distance (edge to edge) [ft] from PES 3 on the Corner		
				ES 1	ES 2	ES 3	ES 4	ES 5	ES 6	ES 7	ES 8	ES 9	ES 10	ES 11	ES 12
2 PES-Same NEW-Tractor Trailer-500-500	640	640	800	640	720	800	640	720	800	640	720	800	640	720	800
2 PES-Diff NEW-Tractor Trailer-5,000-10,000	1,370	1,730	1,770	1,370	1,570	1,770	1,370	1,570	1,770	1,730	1,750	1,770	1,730	1,750	1,770
2 PES-Diff NEW-T1/2 L UR Concrete-50,000-75,000	2,000	2,000	2,000	2,000	2,500	3,000	2,000	2,500	3,000	2,000	2,000	2,000	2,000	2,000	2,000
3 PES, Line-Same NEW, Close-Tractor Trailer-1,000-1,000-1,000	800	800	1,160	800	980	1,160	800	980	1,160	800	980	1,160	800	980	1,160
3 PES, Line-Same NEW, Same Dist-Tractor Trailer-100-100-100	380	380	540	380	460	540	380	460	540	380	460	540	380	460	540
3 PES, Line-Diff NEW, Same Dist -Tractor Trailer-100-200-300	380	540	680	380	530	680	380	530	680	540	610	680	540	610	680
3 PES, Line-Diff NEW, Diff Dist -Tractor Trailer-100-200-300	380	540	680	380	530	680	380	530	680	540	610	680	540	610	680
3 PES, Line-Same NEW, Same Dist-Tractor Trailer-1,000-1,000-1,000	800	800	1,160	800	980	1,160	800	980	1,160	800	980	1,160	800	980	1,160
3 PES, Line-Diff NEW, Same Dist -Tractor Trailer-1,000-2,000-3,000	800	1,160	1,460	800	1,130	1,460	800	1,130	1,460	1,160	1,310	1,460	1,160	1,310	1,460
3 PES, Line-Diff NEW, Diff Dist -Tractor Trailer-1,000-2,000-3,000	800	1,160	1,460	800	1,130	1,460	800	1,130	1,460	1,160	1,310	1,460	1,160	1,310	1,460
3 PES, Line-Same NEW, Same Dist-Tractor Trailer-10,000-10,000-10,000	1,730	1,730	2,000	1,730	1,865	2,000	1,730	1,865	2,000	1,730	1,865	2,000	1,730	1,865	2,000

PES Configuration	PES 1 Original IBD (ft)	PES 3 Original IBD (ft)	PES 1/3 Aggregated IBD (ft)	House Distance (edge to edge) [ft] from PES 1 on the Normal			Commercial Building Distance (edge to edge) [ft] from PES 1 on the Normal			House Distance (edge to edge) [ft] from PES 3 on the Corner			Commercial Building Distance (edge to edge) [ft] from PES 3 on the Corner		
				ES 1	ES 2	ES 3	ES 4	ES 5	ES 6	ES 7	ES 8	ES 9	ES 10	ES 11	ES 12
3 PES, Line-Diff NEW, Same Dist -Tractor Trailer-10,000-20,000-30,000	1,730	2,000	2,000	1,730	1,865	2,000	1,730	1,865	2,000	2,000	2,500	3,000	2,000	2,500	3,000
3 PES, Line-Diff NEW, Diff Dist -Tractor Trailer-10,000-20,000-30,000	1,730	2,000	2,000	1,730	1,865	2,000	1,730	1,865	2,000	2,000	2,500	3,000	2,000	2,500	3,000
3 PES, Line-Same NEW, Same Dist-T1/2 L UR Concrete-5,000-5,000-5,000	1,370	1,370	1,770	1,370	1,570	1,770	1,370	1,570	1,770	1,370	1,570	1,770	1,370	1,570	1,770
3 PES, Line-Diff NEW, Same Dist -T1/2 L UR Concrete-5,000-7,500-10,000	1,370	1,730	1,950	1,370	1,660	1,950	1,370	1,660	1,950	1,730	1,840	1,950	1,730	1,840	1,950
3 PES, Line-Diff NEW, Diff Dist -T1/2 L UR Concrete-5,000-7,500-10,000	1,370	1,730	1,950	1,370	1,660	1,950	1,370	1,660	1,950	1,730	1,840	1,950	1,730	1,840	1,950
3 PES, Line-Same NEW, Same Dist-T1/2 L UR Concrete-10,0000-10,0000-100,000	2,000	2,000	2,275	2,000	2,138	2,275	2,000	2,138	2,275	2,000	2,138	2,275	2,000	2,138	2,275
3 PES, Line-Diff NEW, Same Dist -T1/2 L UR Concrete-100,000-150,000-200,000	2,000	2,030	3,832	2,000	2,916	3,832	2,000	2,916	3,832	2,030	2,931	3,832	2,030	2,931	3,832
3 PES, Line-Diff NEW, Diff Dist -T1/2 L UR Concrete-100,000-150,000-200,000	2,000	2,030	3,832	2,000	2,916	3,832	2,000	2,916	3,832	2,030	2,931	3,832	2,030	2,931	3,832
3 PES, Triangle-Same NEW, Close-Tractor Trailer-1,000-1,000-1,000	800	800	1,160	800	980	1,160	800	980	1,160	800	980	1,160	800	980	1,160
3 PES, Triangle-Same NEW, Same Dist-Tractor Trailer-100-100-100	380	380	540	380	460	540	380	460	540	380	460	540	380	460	540
3 PES, Triangle-Diff NEW, Same Dist -Tractor Trailer-100-200-300	380	540	680	380	530	680	380	530	680	540	610	680	540	610	680
3 PES, Triangle-Diff NEW, Diff Dist -Tractor Trailer-100-200-300	380	540	680	380	530	680	380	530	680	540	610	680	540	610	680
3 PES, Triangle-Same NEW, Same Dist-Tractor Trailer-1,000-1,000-1,000	800	800	1,160	800	980	1,160	800	980	1,160	800	980	1,160	800	980	1,160

PES Configuration	PES 1 Original IBD (ft)	PES 3 Original IBD (ft)	PES 1/3 Aggregated IBD (ft)	House Distance (edge to edge) [ft] from PES 1 on the Normal			Commercial Building Distance (edge to edge) [ft] from PES 1 on the Normal			House Distance (edge to edge) [ft] from PES 3 on the Corner			Commercial Building Distance (edge to edge) [ft] from PES 3 on the Corner		
				ES 1	ES 2	ES 3	ES 4	ES 5	ES 6	ES 7	ES 8	ES 9	ES 10	ES 11	ES 12
3 PES, Triangle-Diff NEW, Same Dist -Tractor Trailer-1,000-2,000-3,000	800	1,160	1,460	800	1,130	1,460	800	1,130	1,460	1,160	1,310	1,460	1,160	1,310	1,460
3 PES, Triangle-Diff NEW, Diff Dist -Tractor Trailer-1,000-2,000-3,000	800	1,160	1,460	800	1,130	1,460	800	1,130	1,460	1,160	1,310	1,460	1,160	1,310	1,460
3 PES, Triangle-Same NEW, Same Dist-Tractor Trailer-10,000-10,000-10,000	1,730	1,730	2,000	1,730	1,865	2,000	1,730	1,865	2,000	1,730	1,865	2,000	1,730	1,865	2,000
3 PES, Triangle-Diff NEW, Same Dist -Tractor Trailer-10,000-20,000-30,000	1,730	2,000	2,000	1,730	1,865	2,000	1,730	1,865	2,000	2,000	2,500	3,000	2,000	2,500	3,000
3 PES, Triangle-Diff NEW, Diff Dist -Tractor Trailer-10,000-20,000-30,000	1,730	2,000	2,000	1,730	1,865	2,000	1,730	1,865	2,000	2,000	2,500	3,000	2,000	2,500	3,000
3 PES, Triangle-Same NEW, Same Dist-T1/2 L UR Concrete-5,000-5,000-5,000	1,370	1,370	1,770	1,370	1,570	1,770	1,370	1,570	1,770	1,370	1,570	1,770	1,370	1,570	1,770
3 PES, Triangle-Diff NEW, Same Dist -T1/2 L UR Concrete-5,000-7,500-10,000	1,370	1,730	1,950	1,370	1,660	1,950	1,370	1,660	1,950	1,730	1,840	1,950	1,730	1,840	1,950
3 PES, Triangle-Diff NEW, Diff Dist -T1/2 L UR Concrete-5,000-7,500-10,000	1,370	1,730	1,950	1,370	1,660	1,950	1,370	1,660	1,950	1,730	1,840	1,950	1,730	1,840	1,950
3 PES, Triangle-Same NEW, Same Dist-T1/2 L UR Concrete-100,000-100,000-100,000	2,000	2,000	2,275	2,000	2,138	2,275	2,000	2,138	2,275	2,000	2,138	2,275	2,000	2,138	2,275
3 PES, Triangle-Diff NEW, Same Dist -T1/2 L UR Concrete-100,000-150,000-200,000	2,000	2,030	3,832	2,000	2,916	3,832	2,000	2,916	3,832	2,030	2,931	3,832	2,030	2,931	3,832
3 PES, Triangle-Diff NEW, Diff Dist -T1/2 L UR Concrete-100,000-150,000-200,000	2,000	2,030	3,832	2,000	2,916	3,832	2,000	2,916	3,832	2,030	2,931	3,832	2,030	2,931	3,832
4 PES, Cluster-Same NEW-Tractor Trailer-500-500-500-500	640	640	1,010	640	825	1,010	640	825	1,010	640	825	1,010	640	825	1,010

PES Configuration	PES 1 Original IBD (ft)	PES 3 Original IBD (ft)	PES 1/3 Aggregated IBD (ft)	House Distance (edge to edge) [ft] from PES 1 on the Normal			Commercial Building Distance (edge to edge) [ft] from PES 1 on the Normal			House Distance (edge to edge) [ft] from PES 3 on the Corner			Commercial Building Distance (edge to edge) [ft] from PES 3 on the Corner		
				ES 1	ES 2	ES 3	ES 4	ES 5	ES 6	ES 7	ES 8	ES 9	ES 10	ES 11	ES 12
4 PES, Cluster-Diff NEW-Tractor Trailer-5,000-10,000-20,000-15,000	1,370	1,950	2,000	1,370	1,685	2,000	1,370	1,685	2,000	1,950	1,975	2,000	1,950	1,975	2,000
4 PES, Cluster-Diff NEW-T1/2 L UR Concrete-50,000-75,000-60,000-50,000	2,000	2,000	2,100	2,000	2,050	2,100	2,000	2,050	2,100	2,000	2,050	2,100	2,000	2,050	2,100

PES Configuration Key = # of PESs, Shape of PESs-NEW/Distance Case-PES Type-NEW of PES 1-NEW of PES 2-NEW of PES 3 (if applicable)-NEW of PES 4 (if applicable)

The bar charts for Scenario 1 are shown below in Figure 8-5 (i.e., risk bar chart) and Figure 8-6 (i.e., consequence bar chart) as an example of the charts created for each scenario analyzed in the assessment. The Basic model is shown in blue, the O'Lena model is shown in green, and the Propagation model is shown in red. When evaluating overall risk, the trend in risk was expected to follow a Basic model < O'Lena model < Propagation model pattern. The Basic model was expected to have the least amount of risk because it is only considering the PESs individually instead of aggregating NEWs or adjusting the probability of event due to potential propagation. The O'Lena model was expected to have higher risk than the Basic model because the NEWs are aggregated for the PESs that fail SSD to account for propagation. The Propagation model was expected to have the highest risk because the probability of event increases according to the inverse sigmoidal curve, the blast is aggregated, and the max throw value and debris distance increase due to the aggregated blast. This pattern was followed by most, but not all cases.

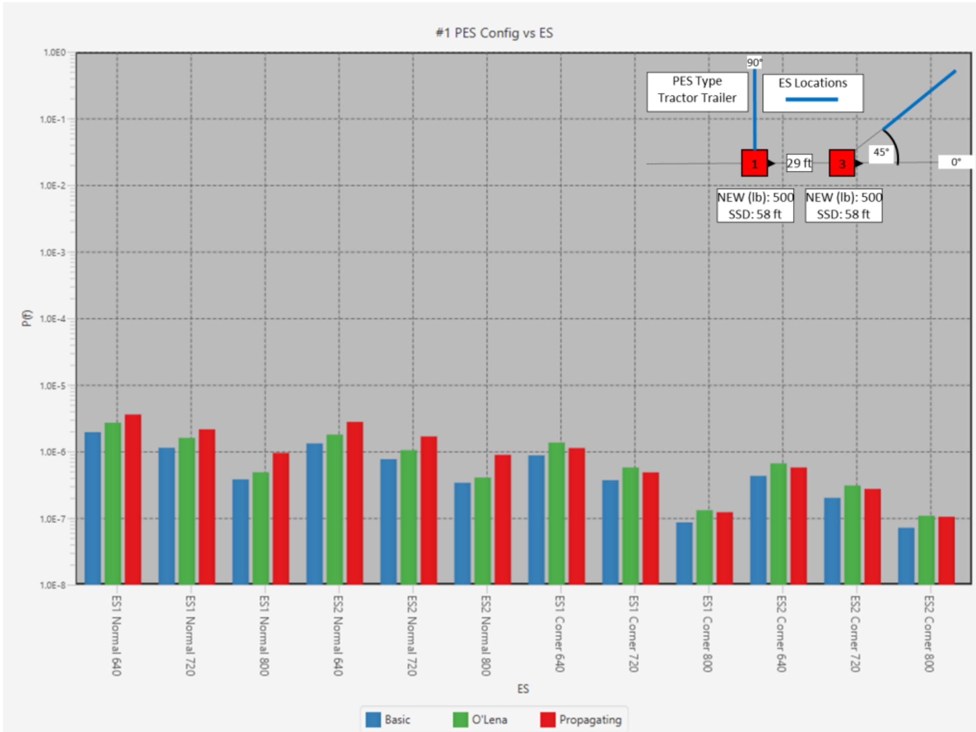

Figure 8-5: Propagation Model Assessment Scenario 1 (Risk)

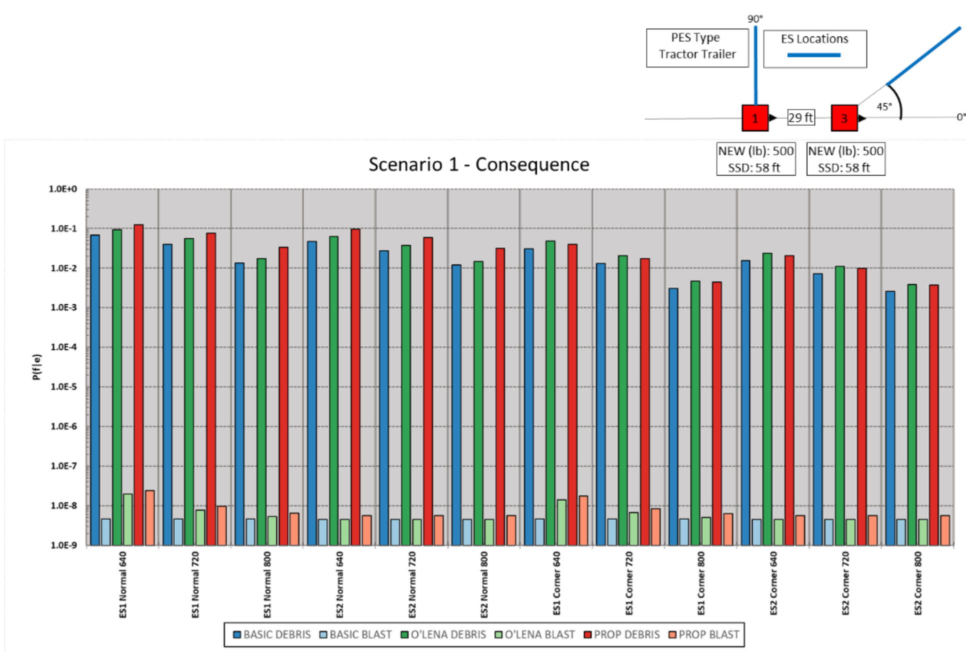

Figure 8-6: Propagation Model Assessment Scenario 1 (Consequence)

APT found no major surprises in the results of this study. APT believes that all results can be explained using the IMESAFR algorithms and the proposed propagation methodology. The study demonstrated that the debris methodology controls the risk in all but a handful of cases when using the Propagation model. Cases in which the blast consequence was the risk driver featured low risk values compared to other cases in the study. This study also demonstrated that handling the debris “properly” is important. The O’Lena model cannot be used to ensure conservative risk results and there were examples in the study results where the risk was not even as high as the normal IMESAFR logic risk. The O’Lena model method of handling propagation was not always appropriate because it increased the loading density of the PESs and inaccurately modeled debris generation.