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IMPLEMENTATION OF PROMPT PROPAGATION LOGIC IN A QRA TOOL

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INTRODUCTION

- What is prompt propagation? 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.
- Reason for risk-based propagation logic: Regulatory and industry personnel are requesting since 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.
- Current QRA Methodology without Propagation uses IMESAFR Algorithms* based on basic risk concept $= P_f = P_e \times P_{f|e} \times E_p$

*See Tatom, J., Romano, J. "Quantitative Risk Assessment for Regulatory Applications Using IMESAFR," IESSE, Phoenix, AZ, January 2026 paper for further details.

PROCESS USED TO DETERMINE AN APPROPRIATE METHOD FOR ADDRESSING PROMPT PROPAGATION

IMESAFR Current Risk-Based Logic

- Without propagation considerations
- Includes probability of event and consequence logic

Preliminary Propagation Logic

- ATF strawman curve fit for probability of propagation
- Consequence
  - Pressure and Impulse Given Propagation
  - Debris Given Propagation

Assessment of Preliminary Propagation Logic

- Approval of consequence portion of propagation logic
- Decision to run Delphi Study to increase fidelity of probability of propagation inverse sigmoid curve fit

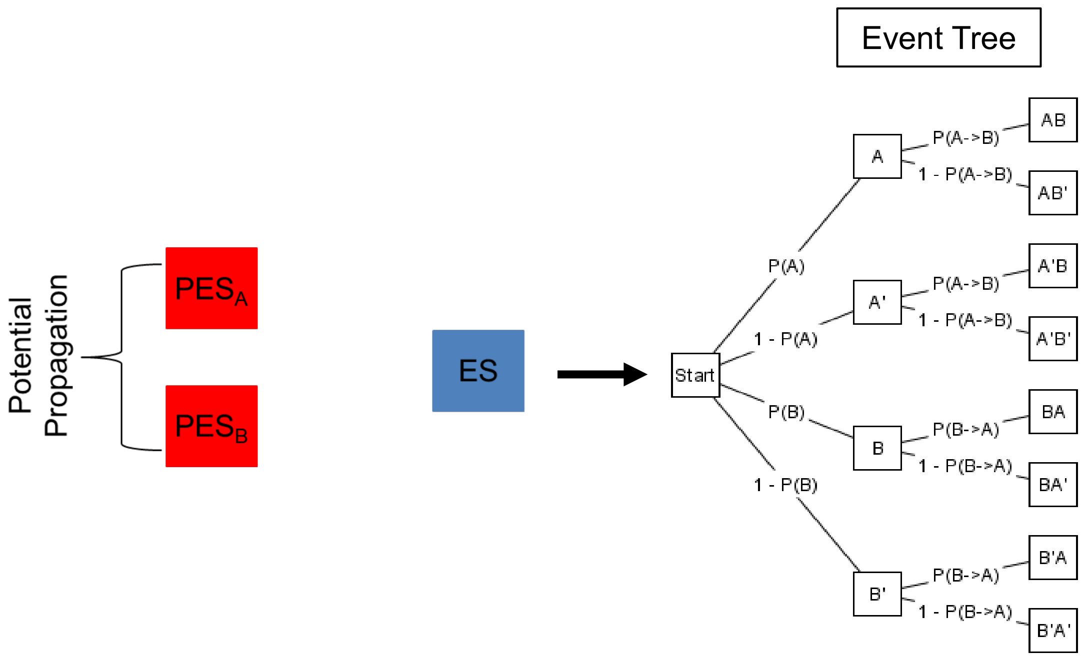
Delphi Study 1 and 2

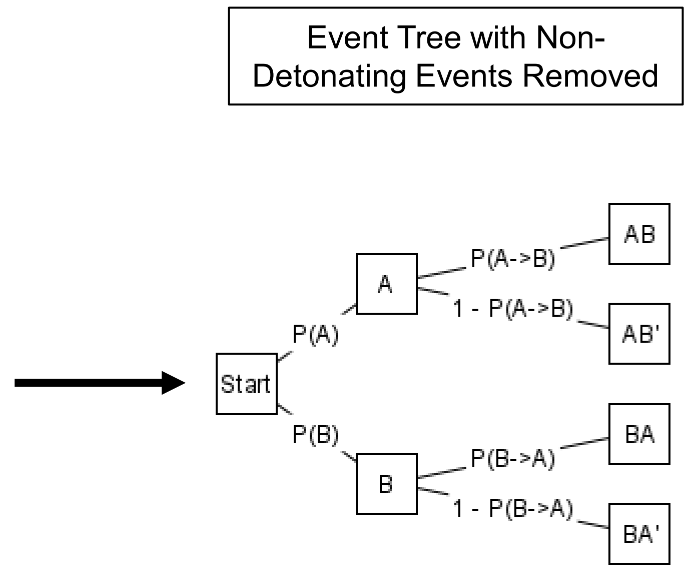
- Delphi Study 1 refined probability of propagation curve fit
- Delphi Study 2 introduced multiple probability of propagation curves
- Addressed uncertainty
- Curve selection and weighted scoring table
- Treatment of combined donors

Implementation Plan

- Created propagation prototype tool using IMESAFR software tool
- Built propagation mode panel to test the propagation logic
- Final propagation tool can be a standalone product or incorporated into IMESAFR software tool

PROPOSED QRA METHODOLOGY WITH PROMPT PROPAGATION





Note: Each event has a consequence associated with it. The consequences are not shown here for simplicity.

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

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

PROPOSED QRA METHODOLOGY WITH PROMPT PROPAGATION

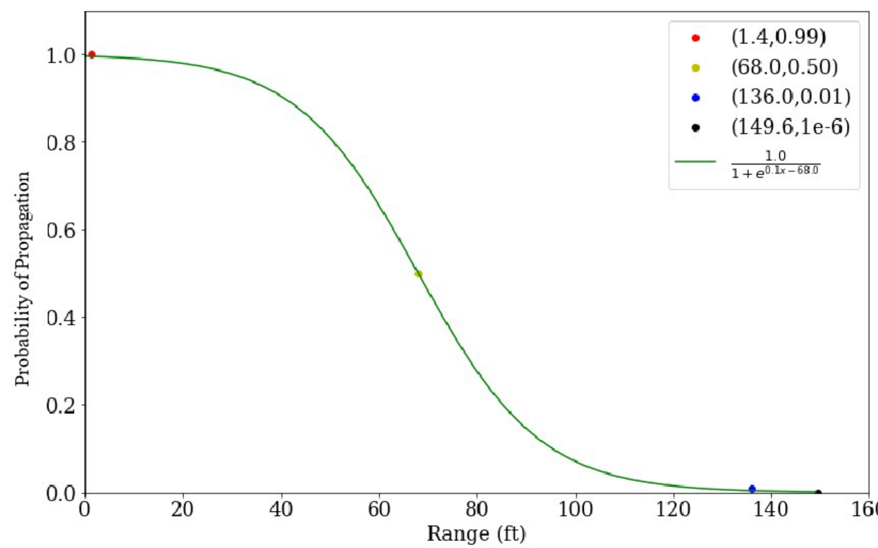
For the probability of propagation ($P_{p|e}$) term of the risk equation, ATF proposed inverse sigmoid curve fit with anchor points as a strawman, which show the estimated $P_{p|e}$ at specified % distances of the Safe Separation Distance (SSD*)

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

*The generic term “SSD” is meant to represent the distance prescribed by any QD system to prevent prompt propagation.

The equation for the inverse sigmoid curve is:

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

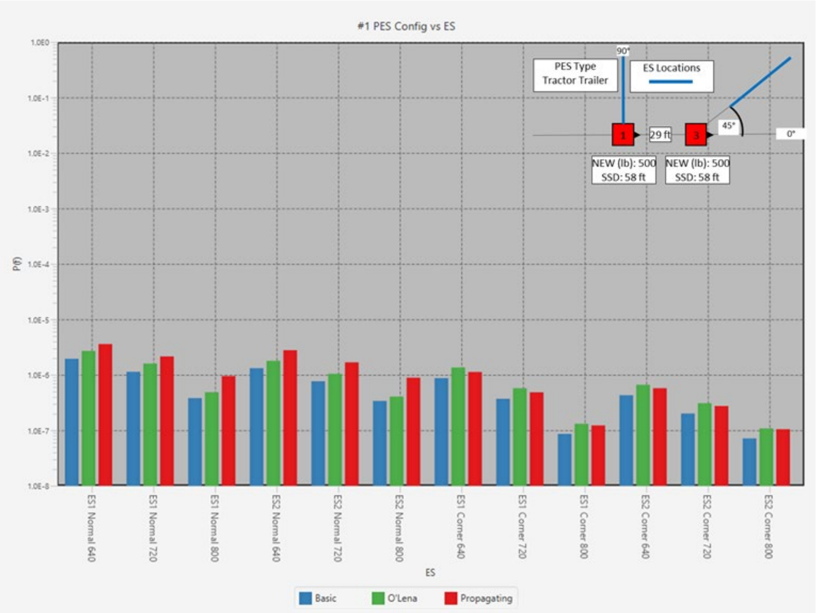


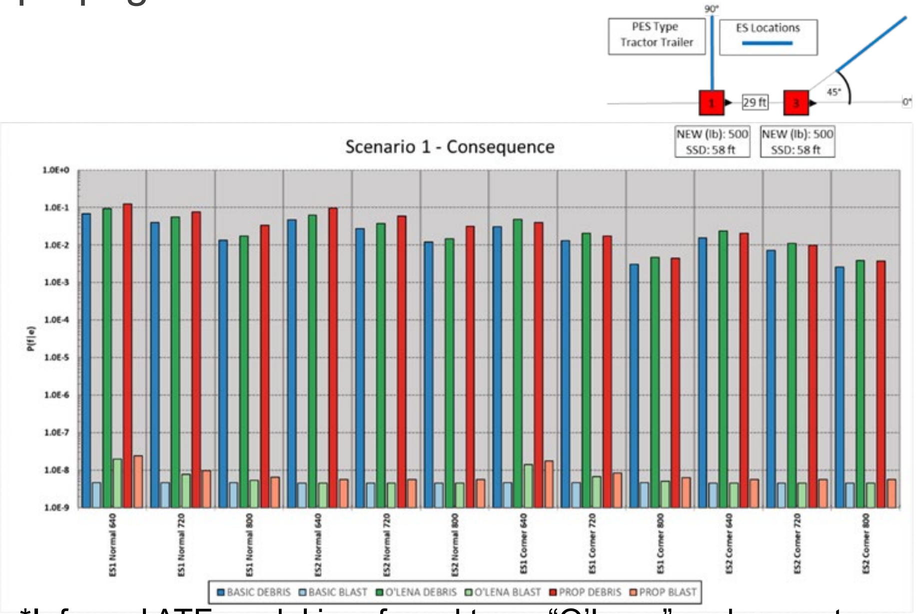
PROPOSED QRA METHODOLOGY WITH PROMPT PROPAGATION

- For the consequence (probability of fatality given an event ($P_{f|e}$)) term of the risk equation, two consequence given propagation models are used
  - Pressure and Impulse Given Propagation: The blast consequence is modeled by aggregating the NEWs of failing magazines. The aggregation sums the NEW of all failing magazines (worst-case) and places the final NEW in each magazine for the pressure and impulse calculations.
  - Debris Given Propagation: The debris consequence is modeled by increasing the maximum throw values of the generated secondary debris and crater ejecta by a 1.2 multiplier. This was selected as a starting point for "jetting effects" expected from multiple explosion-produced debris sources in proximity to each other, based on the US Army Corps of Engineers' testing of munition stack effects.
- The debris and blast consequences are assessed at the original location of each PES.

ASSESSMENT OF PRELIMINARY PROPAGATION MODEL

- Prompt propagation logic was compared against the current Institute of Makers of Explosives Safety Analysis for Risk (IMESAFR©) methodology (with no consideration for propagation) and the informal ATF model* (i.e., combining NEWs and assuming a $P_{p|e}$ of 1).
- Risk and consequence charts were analyzed for 38 scenarios and a total of 1,368 PES-ES pairs.
- The results showed that the preliminary propagation model was a more conservative and consistent predictor of risk.





*Informal ATF model is referred to as “O'Lena” and current IMESAFR model is referred to as “Basic” on charts

DELPHI STUDY 1

To increase the fidelity of the ATF strawman inverse sigmoid curve fit used to model the probability of propagation, two Delphi studies were conducted using Subject Matter Expert (SME) input from IMESAFR Science Panel (ISP) members who chose to participate.

Delphi Study 1 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?

Scenario 1 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

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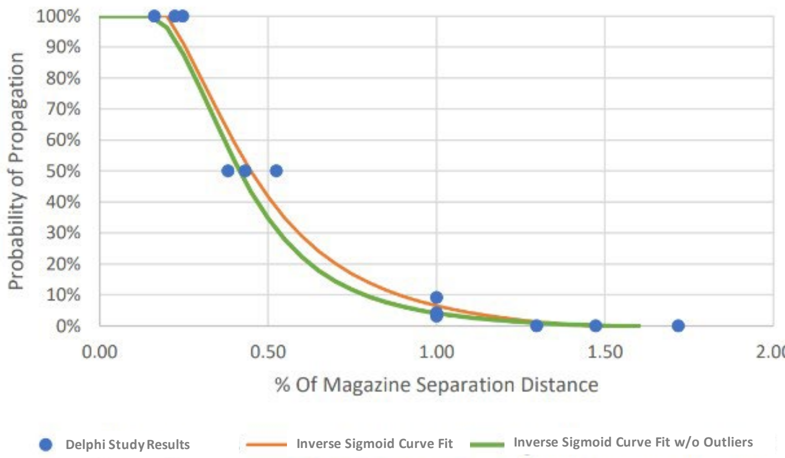
DELPHI STUDY 1 RESULTS

Comparison of Delphi Study 1 Inverse Sigmoid Curves with and without Outliers



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

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

- The curve fit was re-baselined to incorporate the Delphi Study 1 results with the original ATF strawman curve fit.
- The baseline curve fit without outliers was selected for the next iteration of the $P_{p|e}$ logic.
- The outlier points were used to establish the uncertainty associated with the baseline curve. An Upper Bound Multiplier (UBM) of 2.22 was calculated.

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.

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

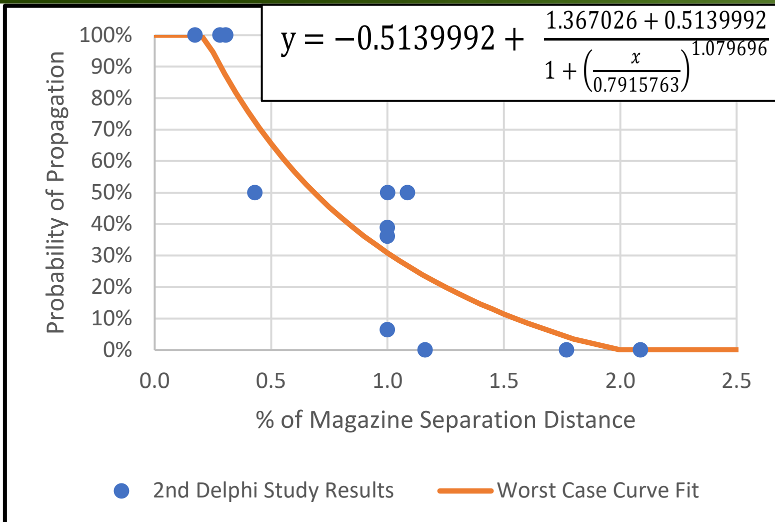
Worst Case Curve

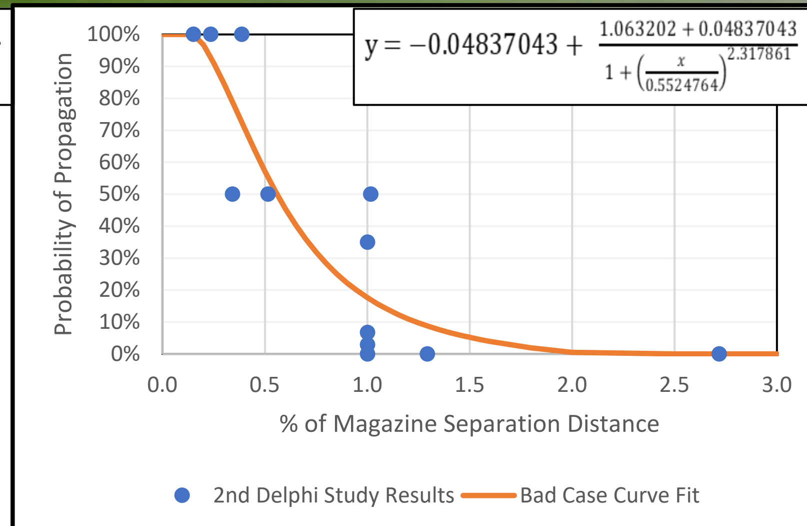
Bad Case Curve

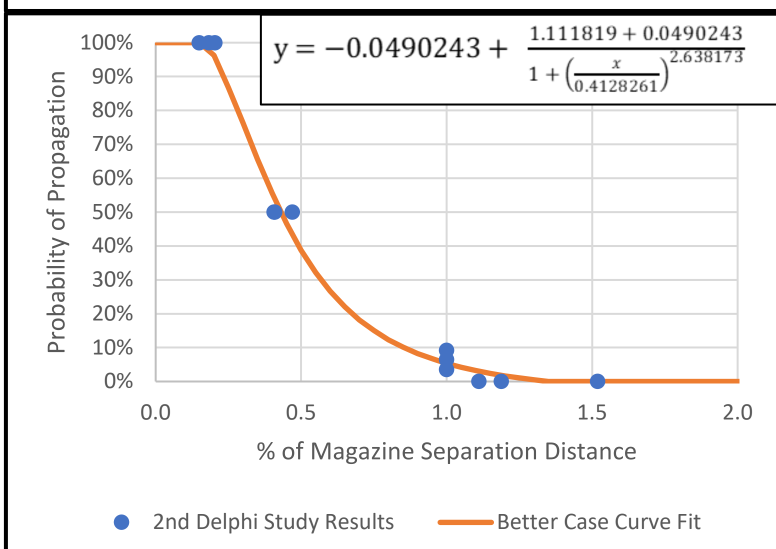
Better Case Curve

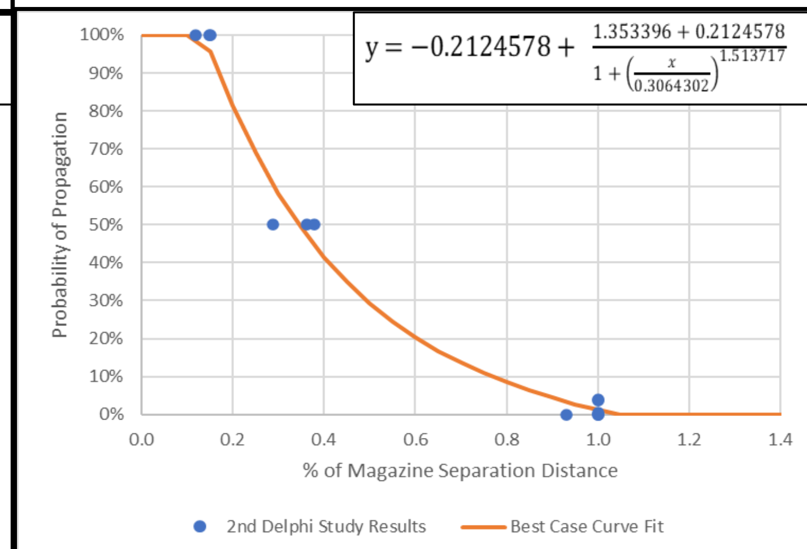
Best Case Curve

DELPHI STUDY 2 RESULTS (WITHOUT OUTLIERS)

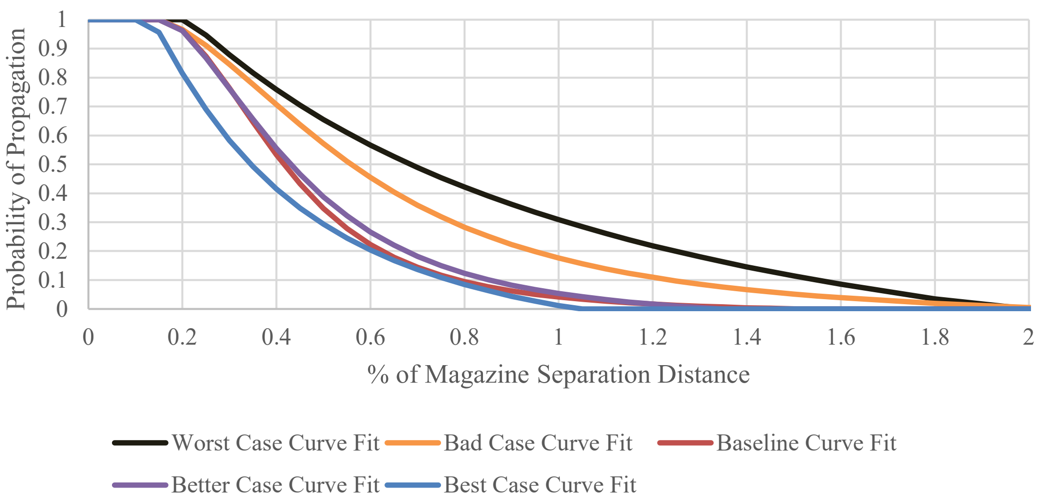








DELPHI STUDY 2 RESULTS



The Delphi Study 2 inverse sigmoid curve fits without outliers were selected to predict $P_{p|e}$ and the outliers were used to establish the UBMs.

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

After reviewing the data, the ISP decided that only the four Delphi Study 2 curve fits would be used to model the $P_{p|e}$, instead of the Delphi Study 1 baseline curve, which was based on fewer inputs.

PROBABILITY OF PROPAGATION CURVE SELECTION

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

A weighted scoring table was used to consider additional factors or “curve modifiers” that would cause the $P_{p|e}$ to shift from one curve fit to another.

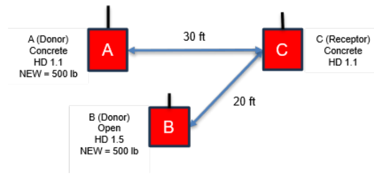
TREATMENT OF COMBINED DONORS

- 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:

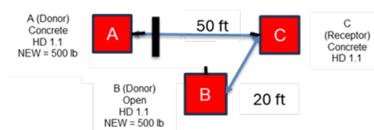
$$P_{f\,A} = \left(\begin{array}{c} P_A(1 - P_{A\to B})(1 - P_{A\to C})P(f|e)_A + \\ P_A P_{A\to B}(1 - P_{A+B\to C})P(f|e)_{A+B} + \\ P_A P_{A\to C}(1 - P_{A+C\to B})P(f|e)_{A+C} + \\ P_A P_{A\to B}\color{red}{P_{A+B\to C}}P(f|e)_{A+B+C} + \\ P_A P_{A\to C}P_{A+C\to B}P(f|e)_{A+B+C} \end{array} \right)$$

- Compared four different methods for handling $P_{p|e}$ curve fit assignments for combined PES terms

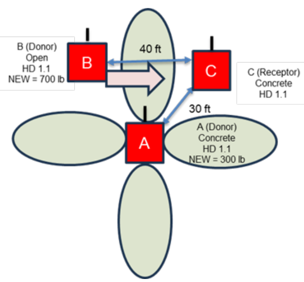
Example scenarios comparing methods:



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



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

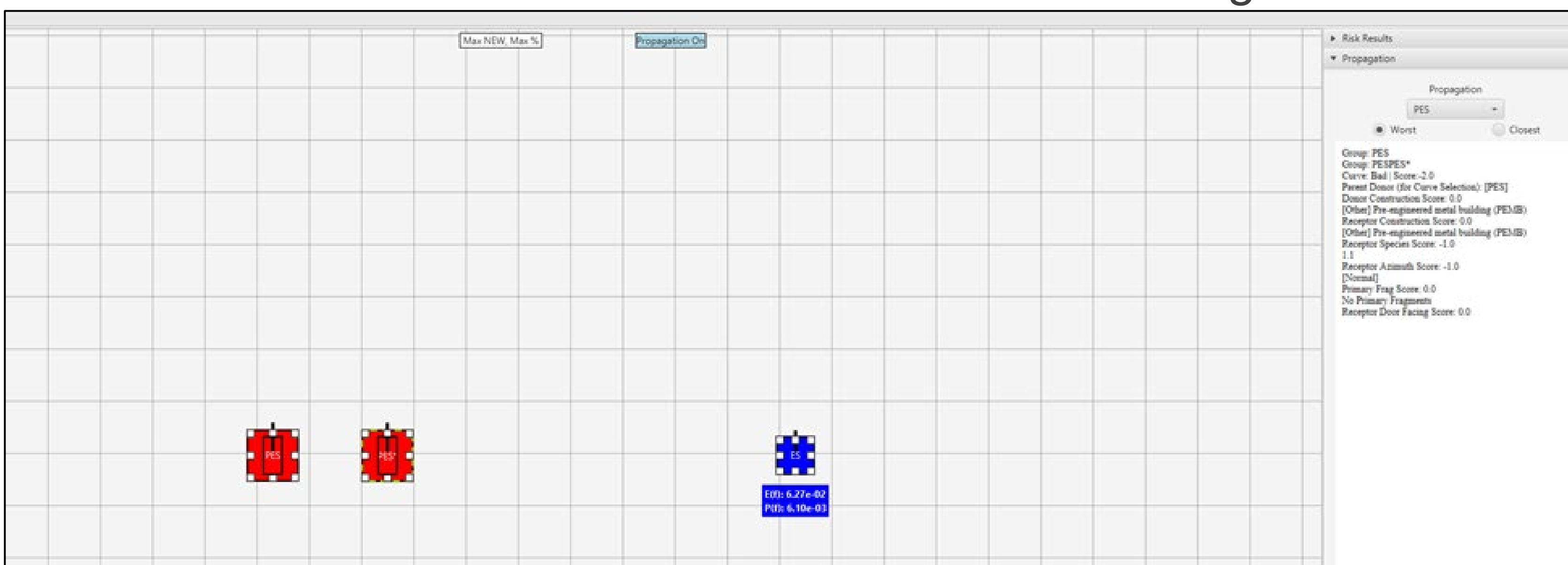


Method	Distance (ft)	SSD (ft)	Curve	$P_{p|e}$ Result
Closest	30	78	Best	0.44
Worst Curve	40	78	Better	0.37
Worst $P_{p|e}$	30	78	Best	0.44
Amalgam Donor	30	78	Bad	0.73

Implementation Outcome: ISP determined that “Worst $P_{p|e}$” method is best default option with the “Amalgam Donor” option available for user selection.

IMPLEMENTATION PLAN

- APT can implement the propagation logic in a standalone tool or as a feature in a future version of its current risk assessment tool, IMESAFR.
- For "proof of concept" testing purposes, the propagation logic was implemented in a prototype tool based on MESAFR 2.2, which was the current version of the software at the time of testing.



SPECIAL ACKNOWLEDGEMENTS

- APT would like to thank ATF for contributing to the development of the prompt propagation logic and providing financial support for the analysis.
- Additional thanks to ISP members for also contributing to the development, review, and approval of the logic. ISP members include US and global regulators (current and past) and commercial industry representatives.

Questions?