A COMPARISON OF THE QUIN SITE EXPLOSIVE EVENT RESULTS TO IMESAFR CONSEQUENCE PREDICTIONS

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ABSTRACT

The Institute of Makers of Explosives (IME) and A-P-T Research, Inc. (APT) have developed and released a quantitative risk assessment tool called IMESAFR (IME Safety Analysis for Risk). This software program has been described in previously published papers and has been compared to available real-world accident results which are summarized in this paper. The most recent edition of the software, IMESAFR Version 1.2, was created for release in February 2011.

On 9 May 2006, an explosion occurred at the Quin Factory in Gladstone, South Australia. The consequences of this accident unfortunately included three fatalities and two additional serious injuries. Modeling this event with IMESAFR provides an opportunity to check the tool's consequence algorithms. DIRE (Prevention of Death and Injuries Resulting from Explosions), a commercially-available consequence analysis software tool, can also model the scenario.

Comparisons have been made between the actual consequences of the Quin event and the predictions of the models. Although one event cannot be used to validate or invalidate any predictive model, this sort of comparison is very useful in corroborating the model with data not otherwise available. No assessment of the cause of the accident is included.

1.0 INTRODUCTION

The explosives safety concepts and tools referenced throughout this paper are described in the following background sections.

1.1 QUANTITATIVE RISK ASSESSMENT

For nearly 100 years in the United States, Quantity-Distance (QD) criteria have been used in making explosives safety judgments. QD is a most basic form of quantitative risk assessment (QRA), taking into account the quantity of explosives and the distance to an exposure. QD methods may include other basic factors such as the presence of a barricade or exposure on a highway. QD standards are generally based on the assumption that the explosive event will occur. QD-based set-back distances are "lines-in-the-sand"; no exposures are allowed inside those distances and any amount of exposure is allowed outside the distances.

QRA recognizes that the probability of an explosives event varies from one activity and type of explosive to another. QRA also recognizes that risk exists at varying degrees depending on many factors, distance being only one of them. Situations that involve very low frequency of occurrence events, very few exposures inside QD distances, and very many exposures just outside QD distances are well suited for QRA assessment. Also, situations where land management is critical because of high population densities necessitate a QRA approach.

For the last 30 years, in the US and NATO defense communities, it has been recognized that explosives risk management by QD could be improved upon by utilizing a more thorough QRA approach. These methods take into consideration the type of explosives activity being conducted, the number of people exposed, exposure time, the relationship of exposed personnel to the explosives activity being conducted, potential explosion site (PES), exposed site (ES) building construction and environment.

1.2 SAFER

With the ability to manage risk in a more reasonable way using QRA in mind, the Department of Defense Explosives Safety Board (DDESB) has coordinated the development of risk-based methods described in DDESB Technical Paper 14 [Ref 1] and the associated computer tool, Safety Assessment for Explosives Risk (SAFER), to determine the risks associated with explosives locations and operations.

SAFER was originally developed to determine the probability of fatality to an individual and the expected fatalities from an explosives accident. Later versions added the ability to predict the expected numbers of major and minor injuries as well. The algorithms in Versions 1 and 2 were designed to evaluate PES-ES pairs at or near inhabited building distance (IBD) and public traffic route (PTR) distances, respectively. The algorithms incorporated in Version 3 (and later) extended the application to include evaluations inside either intraline distance[1] or intermagazine distance[2].

[1] *The DDESB mandated distance to be maintained between any two Ammunition or Explosive (AE) related buildings or sites within an AE related operating line.*

[2] *The DDESB mandated distance to be maintained between two AE storage locations.*

SAFER Version 1.0 was delivered and approved for use by the DDESB in February 2000. Since that time several follow-on versions have been developed. Table 1 provides the release dates for all of the versions of the SAFER software tool.

Table 1. SAFER Release Dates

Version	Release Date
SAFER Version 1.0	February 2000
SAFER Version 2.0	May 2002
SAFER Version 2.1	September 2003
SAFER Version 3.0	February 2007
SAFER Version 3.1	July 2009

1.3 IMESAFR

Recognizing the vast improvements possible to explosives risk management offered by SAFER, the Institute of Makers of Explosives (IME) sponsored the development of IMESAFR (IME Safety Analysis for Risk), released in 2007. IMESAFR follows a long history of collaboration on explosives facility siting standards between the US commercial explosives industry and military. IMESAFR Version 1.0 and SAFER Version 3.0 share the same algorithms and outputs, differing only in certain types of explosives, activities conducted, and types of PES to reflect those used in the commercial explosives industry [Ref 2].

In April 2009, the Institute of Makers of Explosives (IME) and A-P-T Research, Inc. (APT) released IMESAFR Version 1.1. This update incorporated many minor improvements to the user-friendliness of the software and some of the algorithm enhancements made in SAFER Version 3.1. In late 2010, IME, APT and the Israeli Military Industries collaborated on IMESAFR Version 1.2, to be released in early 2011. IMESAFR Version 1.2 includes all the enhancements of SAFER Version 3.1, more interface improvements and two new functional features. This version allows the user to define parameters of the explosives article in the event and can account for potential overpressure reduction through the use of ES barricades.

In 2011, IME and APT began development of IMESAFR Version 2.0 with delivery anticipated in 2012. IMESAFR Version 2.0 will include a graphical information system (GIS) interface, a version using Systeme Internationale (SI) notation, and many more technical enhancements.

1.4 DIRE

The DIRE (Death and Injuries Resulting from Explosions) [Ref 3] software program was designed by APT as a consequence analysis tool and released commercially in 2002. DIRE calculates consequences (in terms of predicted number of fatalities, major injuries and minor injuries) due to direct blast mechanisms, structural response (including glass hazards) and debris resulting from the explosion. The software is a fast-running model that is based on test and accident data as well as physics-based algorithms.

DIRE graphically depicts the predicted consequences as a function of range and also reports the modeled building damage and glass breakage. DIRE only analyzes consequences (rather than risk) and presents results in terms of the most severe consequence predicted (e.g., people who are considered fatalities are not also considered as major or minor injuries). Donor-target pairs are assessed for each DIRE run.

DIRE has "close-in adjustment" algorithms which modify the standard predictions to allow for localized effects and systemic failure of structures. These algorithms were introduced to make the program more useful to the physical security and anti-terrorism communities.

2.0 PREVIOUS COMPARISONS

For a problem as complex as modeling an explosive event, it is difficult to know when the model is producing the "right" answer. Depending on a purely theoretical model would be problematic, so to the extent empirical data from tests, accidents, and terrorist events are available, the models (SAFER, IMESAFR, and DIRE) anchor the algorithms to real-world results. However, too few such data points exist to rely on them entirely, so oftentimes one model is compared against another model.

2.1 TEST DATA

In the defense community, extensive testing has been conducted to support explosives safety regulations and models. Such testing is ongoing [Ref 4] and can be used to anchor the models as well as validation them.

2.1.1 SAFER Comparisons

The US DoD has performed and published comparisons of SAFER versus numerous test data sets, as summarized Table 2.

Table 2. SAFER Comparison Summary

Test	Year Test Conducted	Primary Sponsor	Donor Type	Reference
40 Tonne Trial	1999	UK MoD	Concrete/Masonry	5
5 Tonne Trial	2001	UK MoD	Open	6
SciPan 1	2003	US DoD	Concrete/Masonry	7
SciPan 3	2005	US DoD	Concrete Masonry	8
ISO-3	2009	US DoD	20ft ISO Container	9
ESKIMO	1971	US DoD	Earth Covered Magazine (ECM)	7
Distant Runner	1981	US DoD	Hardened Aircraft Shelter (HAS)	7

A focus of these comparisons is to check SAFER's debris density predictions against the data recovered. Figure 1 shows the comparison of SAFER lethal debris density predictions to the SciPan 1 pick-up data (averaged over all azimuths). It should be noted that the "lethal" debris is that which was thought to have impacted with a kinetic energy of greater than 79 Joules. An over-prediction at close ranges is noticeable, while it appears that the software under-predicted the debris density beyond 2500 ft (at least for the 7.5 in concrete wall).

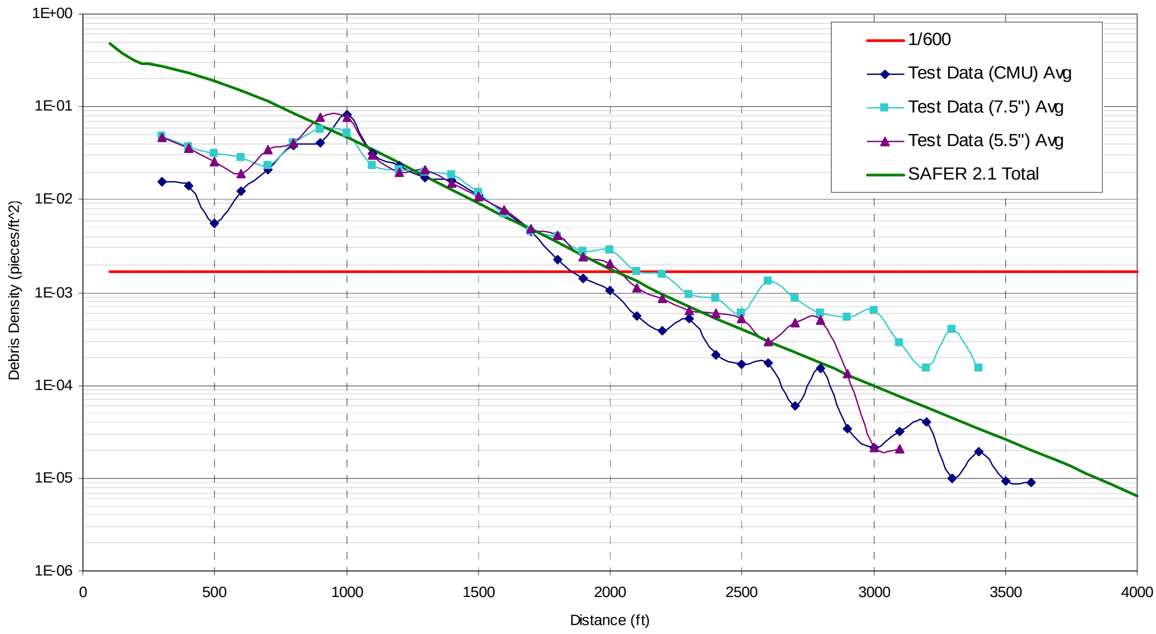

Figure 1. Sample Debris Density Comparison

While Figure 1 considers whether SAFER is predicting the right number of pieces arriving at a given distance, Figure 2 assesses whether the right amount of lethal debris mass is predicted as a function of distance.

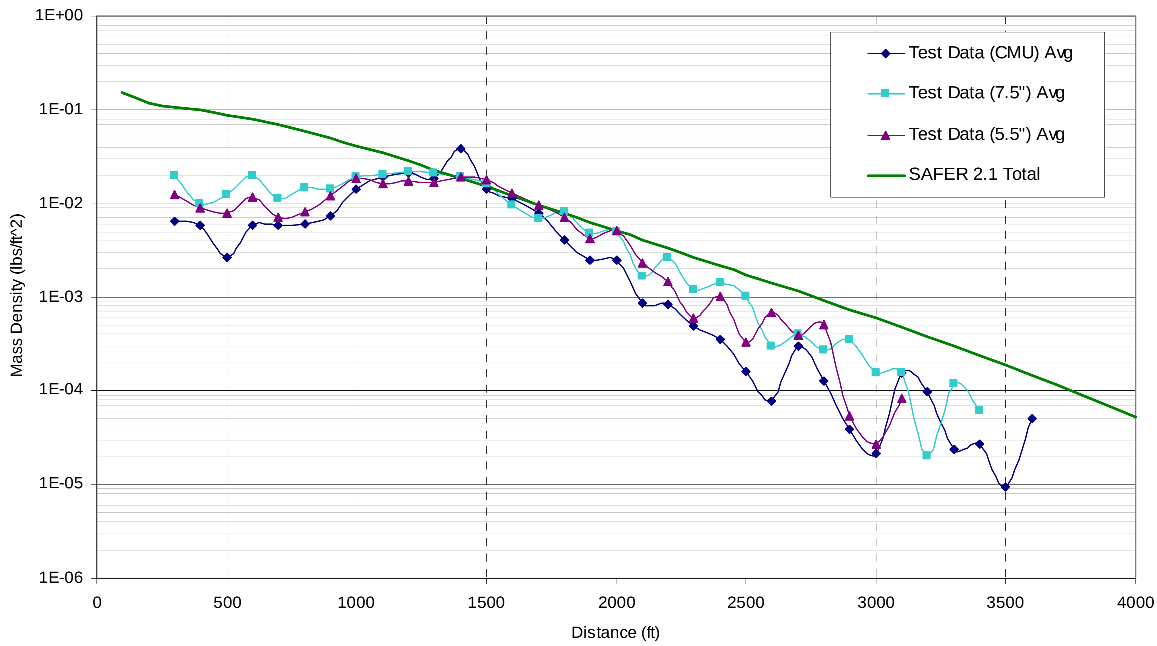

Figure 2. Sample Mass Density Comparison

Taken together, these comparisons suggest that the close-in over-prediction is a "real" issue, whereas the apparent under-prediction at larger distances is not a significant issue (because only small pieces were found at these distances, likely due to the effects of debris shatter at impact).

2.1.2 IMESAFR

IMESAFR predictions have also been compared to test data, such as the ISO-1 and ISO-2 tests [Ref 9]. These tests each involved a 20 ft (6.1 m) ISO container on the bed of a truck. The results of these comparisons have been published and it should be noted that they also indicate an over-prediction of debris density at close range. This can be seen in Figure 3, which displays the peak densities (at any angle) and the averaged density (over all angles) versus the IMESAFR debris density prediction. As before, the "lethal" curves represent only debris that was thought to have impacted with a kinetic energy of greater than 79 Joules.

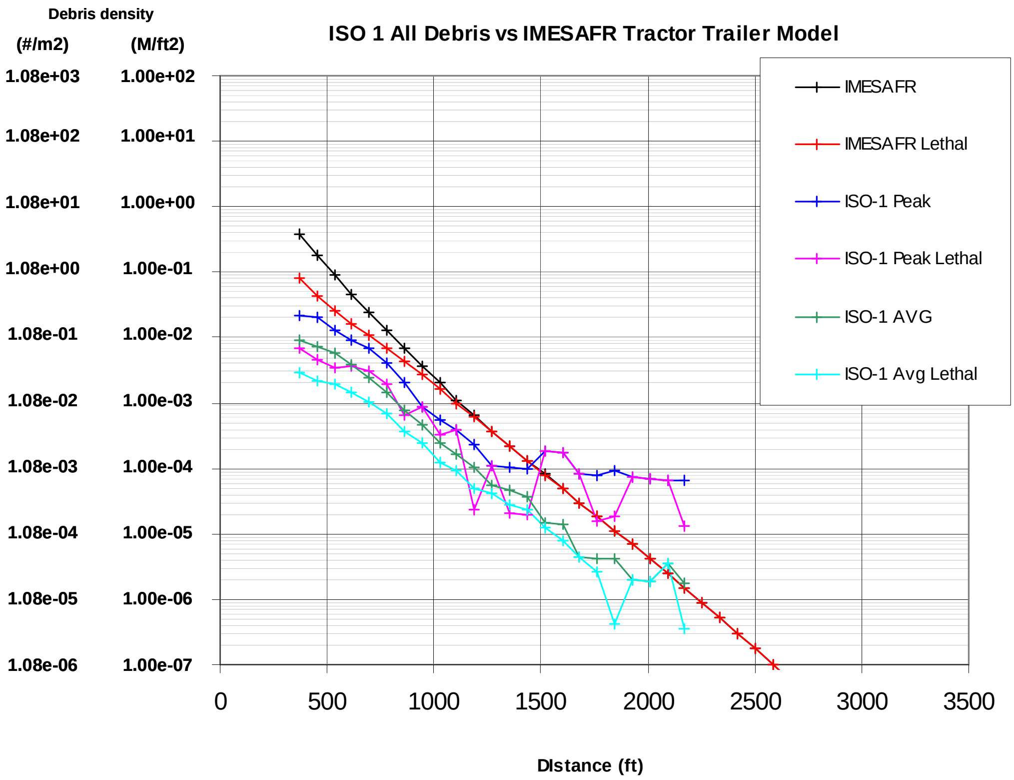

Figure 3. IMESAFR vs. ISO-1 Data

2.2 ASSHETON

In the 1920s, IME analyzed over 100 accidental explosion events in manufacturing plants and adopted the intra-plant QD table. The table is still used today to protect plant workers from events on-site but in another building. The original data compiled by Ralph Assheton was reassessed and two papers have been presented comparing the original data to the consequence predictions of computer models [Ref 10, ref 11].

For each event, the location of the incident, date, Net Explosives Weight (NEW), type of explosive involved, PES type presence of barricades, injury type, number of injuries of that type, ES type, distance from PES, and exposure K-factor[3] were tabulated for each exposure. In the end, 220 distinct PES-ES pairs and 534 individual exposures inside K40 were gleaned from the intra-plant report for analysis. The exposures were grouped into K-factor bins and the injury probabilities averaged.

In the first study [Ref 10], the injuries to people in the open were compared to the consequence predictions of DIRE 1.2 and IMESAFR 1.1. Exposures in the open were selected because this scenario eliminates one major variable: the effect of the ES. Each of the 73 exposures in the open was modeled and the probabilities of injuries within each K-factor bin were averaged.

Both DIRE and IMESAFR significantly over-predicted injuries in the open compared to the data. DIRE 1.2 may overestimate the degree of injury, but its predictions for “no injury” correlate well with the data. IMESAFR overestimated injuries across the board compared to the data.

In the second study [Ref 11], the probability of fatality (P_f) in the Assheton data was compared to the model predictions. The P_f for all exposures and the data subsets of exposures in the open, exposure not in the open, exposures with barricades and exposures without barricades were compared. The results are shown in Table 3.

Table 3. Comparison of Pf for Assheton Data and Models at Various Exposures.

K-factor Bin	All Exposures			Not Open			Open			No Barricade			Barricade		
	Data	IMESAFR	DIRE	Data	IMESAFR	DIRE	Data	IMESAFR	DIRE	Data	IMESAFR	DIRE	Data	IMESAFR	DIRE
1-5	0.33	1	0.91	0.26	1	0.86	0.60	1	1.0	0.35	1	0.90	0/4	1	0.67
6-10	0.040	1	0.32	0.033	1.0	0.33	0.071	0.92	0.21	0.045	1.0	0.29	0/9	1	0.41
11-15	0.017	0.50	0.14	0.017	0.43	0.13	0/5	0.30	0.11	0.019	0.50	0.13	0/17	0.23	0.14
16-20	0.011	0.23	0.061	0.011	0.17	0.062	0/8	0.10	0.028	0.012	0.21	0.061	0/11	0.065	0.073
21-25	0/70	0.033	0.057	0/52	0.10	0.047	0/18	0.094	0.012	0/63	0.10	0.061	0/7	0.083	0.0088
26-35	0/76	0.023	0.0089	0/67	0.012	0.0081	0/9	0.0031	0.0075	0/57	0.017	0.0092	0/19	0.0045	0.0046
36-45	0/46	0.0077	0.0029	0/41	0.0094	0.0015	0/5	0.0026	0.010	0/39	0.013	0.0029	0/7	0.0015	0.00034

In cases where there were no fatalities within a particular K-factor bin, the number of exposures without a fatality is shown as a ratio under zero. For example, within the K21-25 bin there were 70 total individuals exposed without any fatalities occurring. DIRE cannot model barricades, so DIRE’s P_f for barricaded scenarios would be expected to be conservative. The P_f for “All Exposures” shows worst case risk. All other modeled P_f are expected case. Figure 4 shows the P(f) for the “Not Open” cases.

[3] *K-factor is a multiple of scaled range, where scaled range is the distance in feet divided by the cube root of the charge weight in pounds; e.g., when the distance divided by the cube root of the charge weight equals 20,that distance equals K20*

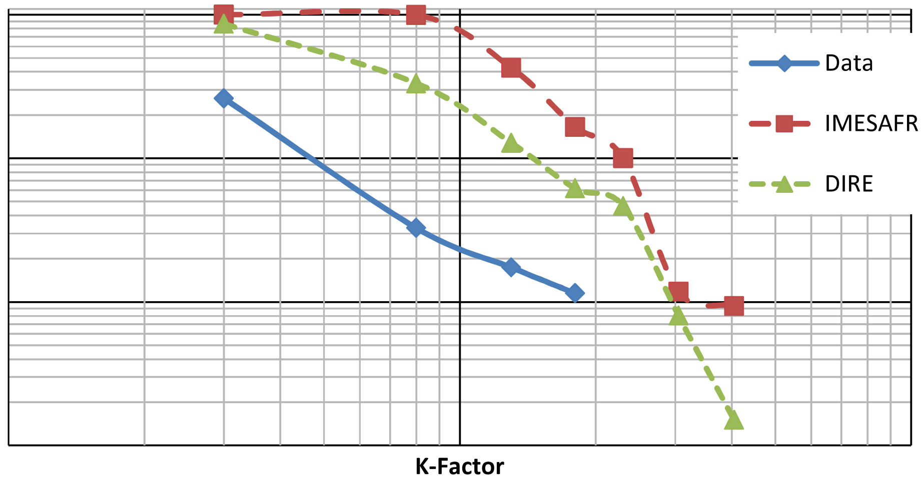

Figure 4. P_f for Exposures Not in the Open.

Several explanations exist for IMESAFR and DIRE over-predicting the consequences, as compared to the Assheton data. Both programs were designed to “err on the side of caution” to some extent, and both were designed to give best estimates from K18 to K40. IMESAFR’s and DIRE’s predictions and the Assheton data start to converge around K30.

IMESAFR employs logic called the Simplified Close-In Fatality Mechanism (SCIFM) out to a scaled range of around K8-12, depending on the ES type. SCIFM is employed because, in this region, little data exists and the actual risk is highly dependent on unique local conditions that do not fit into the models. This logic determines a point at which, inside that scaled range referred to as the SCIFM Plateau Region, the structure collapses and all occupants are fatally injured. The SCIFM Transition Region connects the close-in plateau to the Standard Logic Region that the programs were originally designed to model.

IMESAFR also has an uncertainty routine that affects the point estimate of the answer. As modeled, this uncertainty will always increase the final risk estimate. This may be desirable for general-purpose predictions, but prevents IMESAFR from making a direct comparison to a limited set of actual cases. Uncertainty was not a factor in the Assheton data.

The DIRE results are not affected by uncertainty, so they would be expected to be closer to reality. Also, DIRE does not employ a SCIFM routine, although it’s results are expected to be more conservative as the range between PES and ES decreases. Since DIRE currently cannot consider barricades, the DIRE predictions would otherwise be lower than shown.

Other factors that trend the models towards conservativism are unique shielding effects not present during tests upon which the models are based and relatively high predicted fragment densities. Finally, grouping scenarios by K-factor can create anomalies when scenarios involve very small charges with small distances and cases with the same K-factor involve large charges and large distances. The cube-root scaling of the charge weight is applicable to the blast effects, but not directly applicable to the debris risks.

2.3 TERRORIST EVENTS

On 19 April 1995, terrorists used a truck bomb to target the Murrah Building in Oklahoma City, Oklahoma, USA. A total of 168 people were killed and many more were injured, with the majority of the fatalities occurring at the Murrah Building. The next year (25 June 1996), nineteen US airmen were killed in the Khobar Towers Bombing in Saudi Arabia. Though these events are tragic, the results can be used to assess the accuracy of predictive models.

A paper was presented at the 2004 DDESB Seminar [Ref 3] that detailed the results of a comparison made between DIRE predictions and the actual results of these two terrorist events.

2.3.1 DIRE: Murrah Building

In the case of the Oklahoma City bombing, one scenario was modeled with a truck as the PES and the Murrah Building as the ES. As shown in Table 4, the DIRE fatality prediction is in good agreement with the actual results, trending towards conservatism.

Table 4. Murrah Building Consequences

Item	*DIRE Output*	Actual Observation
Number of Deaths	185.6	163
Number of Major Injuries	117.0	50
Number of Minor Injuries	58.4	106

The major injuries are over-predicted, but the total number of injuries predicted is very close to the actual observation. Thus DIRE seems to be shifting some of the actual minor injuries to the predicted major injury total.

2.3.2 DIRE: Khobar Towers

Two separate donor-target pairs were modeled for the Khobar Towers incident. The first scenario modeled Building #131 as the ES, while the second scenario modeled Building #133 as the ES. Both scenarios used a truck as the PES. It is noteworthy that by using the same donor with two different targets, the ability to "cheat" the comparison (by using whatever input parameters are required to match the output) is removed – or at least severely restricted. This makes the Khobar Towers case even more interesting from a comparative modeling standpoint.

As shown in Table 5, the fatality prediction for Building #131 is very close to the actual results with a slight under-prediction in this case (perhaps due to the over-prediction of major injuries).

Table 5. Building #131 Consequences

Item	DIRE Output	Actual Observation
Number of Deaths	17.5	18
Number of Major Injuries	22.4	12-16
Number of Minor Injuries	3.1	Undetermined

As shown in Table 6, the fatality prediction for Building #133 is again very close to the real-world results. In this case, DIRE is marginally conservative in its fatality prediction.

Table 6. Building #133 Consequences

Item	*DIRE Output*	Actual Observation
Number of Deaths	1.6	1
Number of Major Injuries	14.1	9-11
Number of Minor Injuries	35.3	Undetermined

2.4 Other Models

SAFER has also been compared against other predictive models as part of a NATO exercise to create a standardized protocol for the storage and transport of explosives. The first series of comparison studies was performed and reported in 2003 [Ref 10]. Perhaps the most useful model comparisons are those where test data are also available, thus creating a "right" answer to compare the model predictions against. Such comparisons were made for pressure (Figure 5), impulse (Figure 6), and debris density (Figure 7).

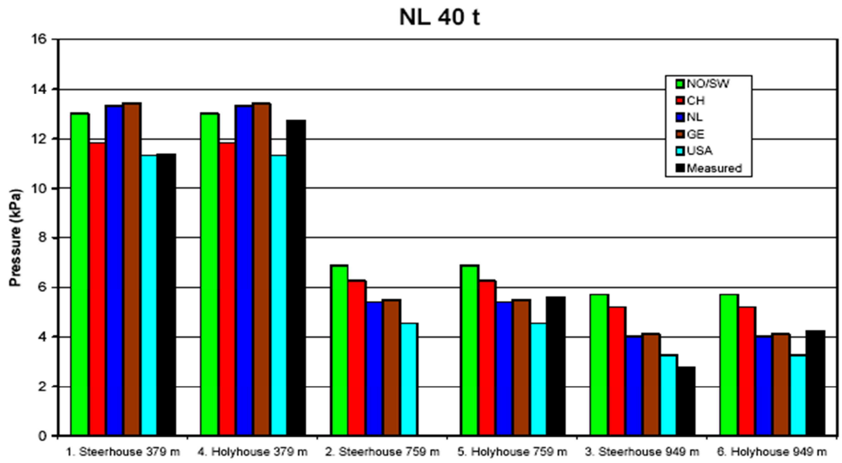

Figure 5. Pressure Prediction Comparison

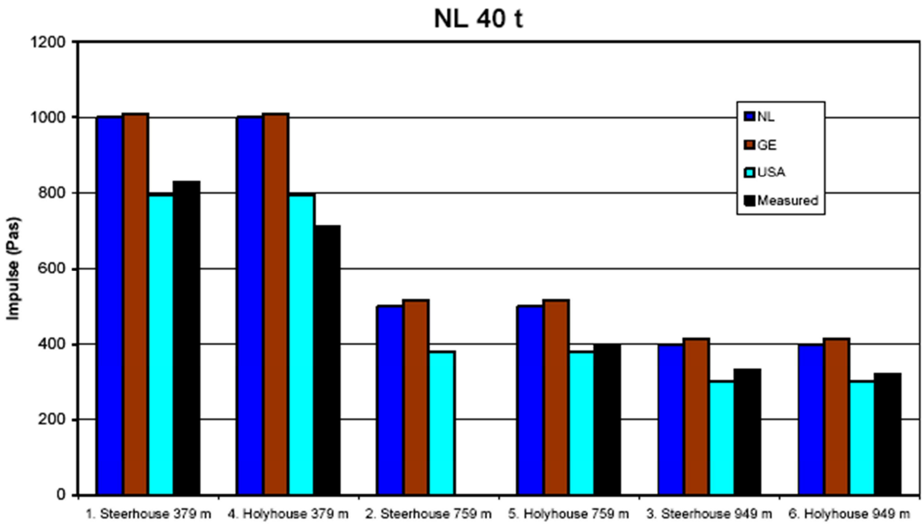

Figure 6. Impulse Prediction Comparison

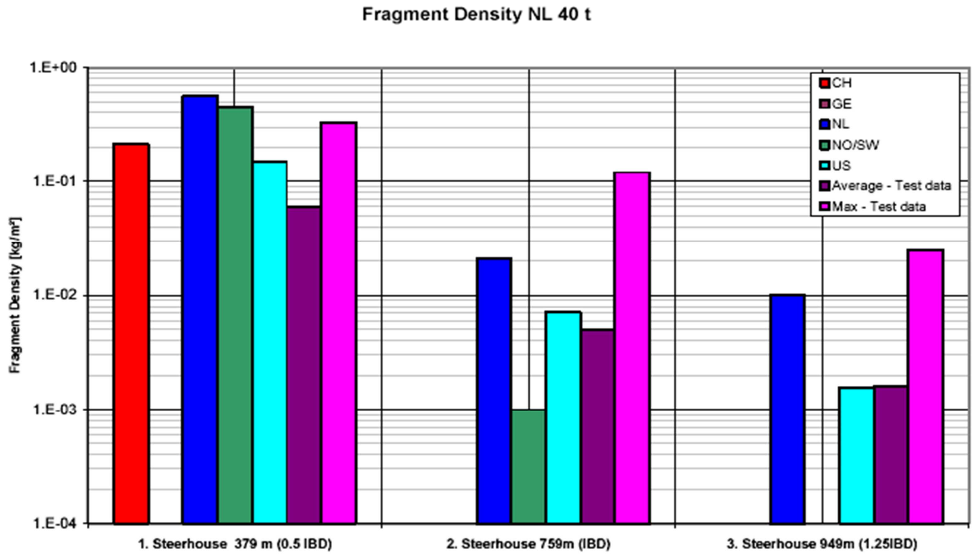

Figure 7. Debris Density Comparison

It should be noted that SAFER over-predicts the average debris density from the test for the measurements at half-IBD (by NATO definition; in this case at 379 meters).

These comparisons were again conducted in 2010 using updated models from the different countries, but the results have not yet been published.

SAFER has also been compared against the KGET (Klotz Group Engineering Tool) and United Kingdom (UK) debris density prediction models. These comparisons were presented in 2008 [Ref 5] and included checks against test data from the SciPan test series. Program sponsors were encouraged by the model agreement and corroboration by the test data.

3.0 GLADSTONE

In the spring of 2006, a joint United Kingdom/Australia explosive test series, consisting of two 5 tonne detonations, was to be held in Woomera, South Australia. Each explosive charge was cast TNT. The TNT charges were cast and stored at the Quin Factory in Gladstone, South Australia. Two of the authors of this paper were scheduled to participate in this trial. On 10 May 2006, the Trial Director sent out an email announcing that an explosion had occurred at the Gladstone site and that one of the TNT charges had been consumed in the ensuing fire. As a result, the test series was postponed until the following spring. Although the TNT was consumed in the fire, it did not detonate or contribute to the severity of the event.

In April 2007, after conducting the postponed tests [Ref 12], two of the authors received permission to visit the Quin Site—not as part of any formal investigation but to try to gain information that could be used to improve the consequence algorithms that were incorporated into the SAFER software. Some details presented in this paper are based on that visit and are therefore unofficial.

3.1 Scenario Description

In early May 2006, an explosion occurred at the Watergel Plant at the Quin Site located in Gladstone, South Australia. There were five people present in the immediate vicinity of the plant at the time of the explosion: three perished and two survived. The evidence at the scene suggests a detonation of the contents of the pre-mix hopper followed by an ensuing fire. The movement of material appears to be radially outward from the area of the pre-mix hopper and there is a crater in the concrete directly beneath the location of the hopper. Figure 8 is a photograph of the immediate vicinity around the accident site [Ref 13] showing the estimated location of the detonation.

The amount of material that detonated is not exactly known, however, estimates put its value at approximately 1,360 kg.

Figure 8. Quin Site Accident

The exact locations of the five people who were either killed or injured in the event are not known; however, their estimated positions have been determined. The first, designated P1, was located in the Packaging Room, within 3.7 to 6.1 meters from the event. The second and third, designated P2 and P3, were located on the loading dock, approximately 6.1 to 7.6 meters from the event. P3 was shielded from some of the effects of the event by material that was stacked on the dock awaiting transport. The fourth person, designated P4, was standing on the ground, just below the loading dock. He was about 5.5 to 7.6 meters from the event. His location, below the level of the dock, provided some shielding from the event. The final person, P5, was located in an unreinforced cinderblock outhouse, located about 15.2 to 19.8 meters from the event. These locations are nominally shown in Figure 9 andFigure 10 (NB: This sketch represents the authors' interpretation of the locations, and does not represent firmly established data). P3 and P4 survived the event. Sadly, P1, P2 and P5 were killed.

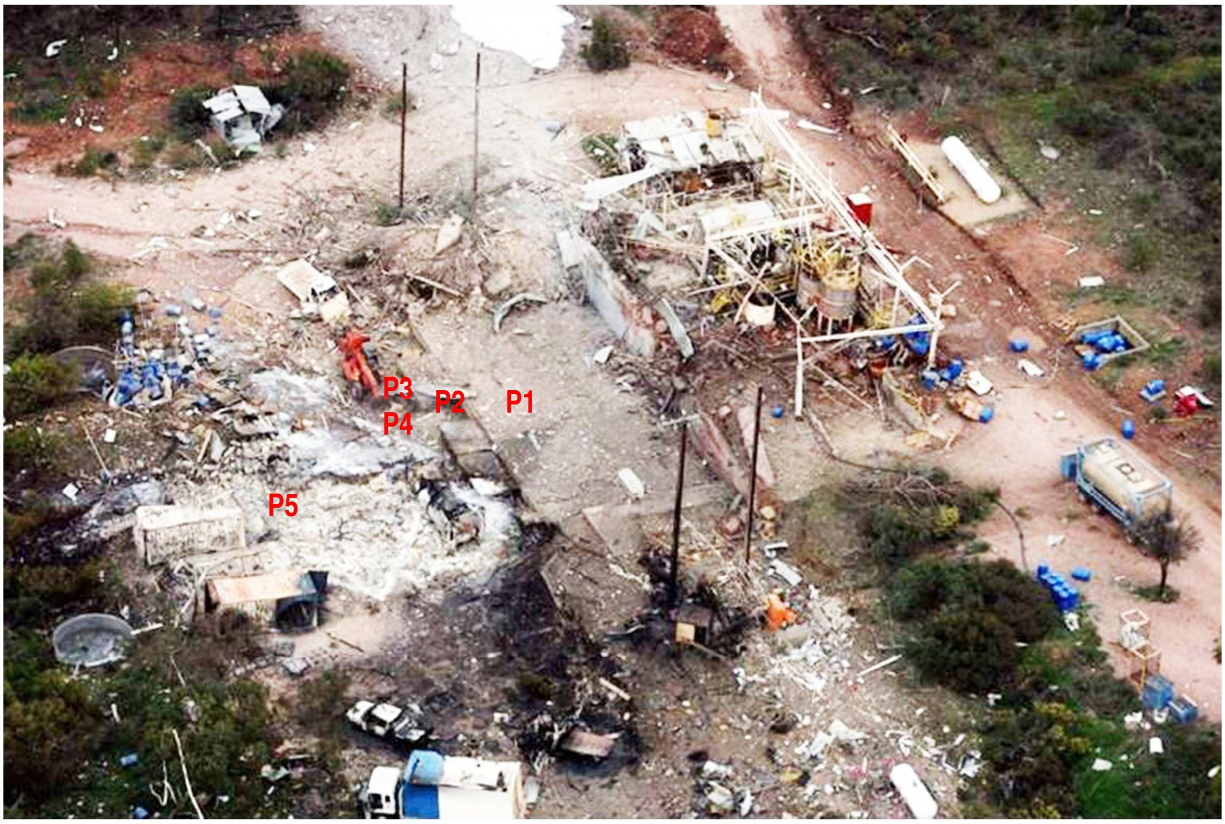

Figure 9. Personnel Locations (Plan View)

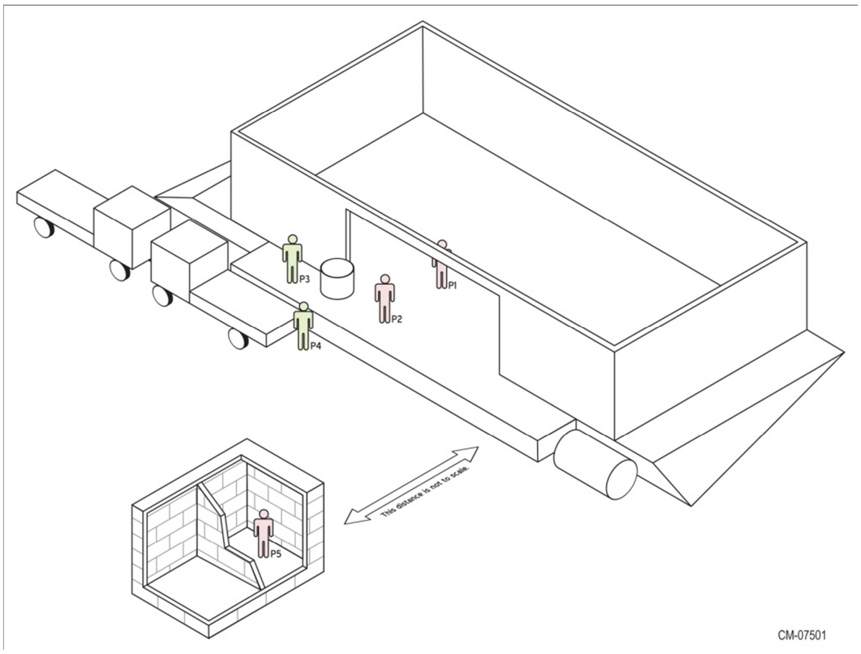

Figure 10. Personnel Locations (Isometric)

Table 7 shows the approximate distances of P1 through P5 from the estimated location of the explosion (NB: The distances shown were estimated by the authors and do not represent any other information).

Table 7. Personnel Locations

Person	Distance (m)	Description
P1	3.7-6.1	In open
P2	5.5-7.6	In open
P3	6.1-7.6	In open – shielding provided by material on loading dock
P4	6.1-8.0	In open – on ground below loading dock; shielding provided by dock
P5	15.2-19.8	In unreinforced masonry structure

3.2 IMESAFR Comparison

The event was modeled as the detonation in the open of a quantity of Hazard Division (HD) 1.1 material in bags, boxes or bulk packaging. The soil type was selected as concrete. The Net Explosive Quantity (NEQ) of material was varied between 200 kg and 2,000 kg. The PES was chosen as open. A range of distances was used to generate the prediction curves.

P1 and P2 were modeled using the open ES option. Their distance from the PES was varied between 1.5 and 61 meters. P3 and P4 were also modeled as open ESs. Their distance from the PES was also varied from 1.5 to 61 meters. For both P3 and P4, a 3 m by 3 m barricade was placed 1 meter in front of their location to represent the shielding provided by the material on the dock (P3) and the dock itself (P4). P5 was modeled as an unreinforced brick/masonry structure with a 4.6 m^2 floor area. The distance between the PES and this ES was varied between 1.5 and 61.5 meters.

3.2.1 IMESAFR v1.1

The predicted probability of fatality as a function of range, NEQ, and consequence mechanism is given for persons in the open (Table 8) and persons in the open behind a barricade (Table 9). They are also shown in Figure 11 for a person in the open and Figure 12 for a person behind a barricade. The box that is shown on the figures represents the range of locations for these personnel. The shielding provided to P3 and P4 had no apparent effect on the probability of fatality. This is because at these short distances (near the explosion source) there are multiple fatality mechanisms: (1) horizontal debris, (2) vertical debris, and (3) blast (lung rupture, whole body displacement, and skull fracture). Even with the horizontal debris removed by the barricade, multiple other mechanisms would produce a fatality.

Table 10 shows the predicted probability of fatality as a function of range, NEQ and consequence mechanism for the unreinforced brick/masonry structure (P5). Rather than helping the situation, the weak structure of unreinforced masonry/brick actually adds another fatality mechanism—structural failure/building collapse. This is also shown in Table 10.

Table 8. Probability of Fatality—Person in Open

NEQ	Range	Probability of Fatality			
		Blast	Debris		Total
(kg)	(m)		Horizontal	Vertical	
200	1.5	1.000	1.000	1.000	1.000
	3.0	1.000	1.000	0.928	1.000
	4.6	1.000	1.000	0.698	1.000
	6.1	1.000	1.000	0.369	1.000
	7.6	1.000	1.000	0.130	1.000
	9.1	1.000	1.000	0.035	1.000
	10.7	0.997	1.000	0.009	1.000
	12.2	0.040	1.000	0.002	1.000
	13.7		1.000	0.001	1.000
	15.2		1.000		1.000
	18.3		1.000		1.000
	21.3		0.822		0.822
	24.4		0.606		0.606
	27.4		0.444		0.444
	30.5		0.326		0.326
	36.6		0.181		0.181
	45.7		0.081		0.081
	61.0		0.025		0.025
300	1.5	1.000	1.000	1.000	1.000
	3.0	1.000	1.000	1.000	1.000
	4.6	1.000	1.000	0.915	1.000
	6.1	1.000	1.000	0.667	1.000
	7.6	1.000	1.000	0.355	1.000
	9.1	1.000	1.000	0.137	1.000
	10.7	1.000	1.000	0.044	1.000
	12.2	1.000	1.000	0.013	1.000
	13.7	0.483	1.000	0.004	1.000
	15.2		1.000	0.001	1.000
	18.3		1.000		1.000
	21.3		1.000		1.000
	24.4		0.858		0.858
	27.4		0.657		0.657
	30.5		0.499		0.499
	36.6		0.288		0.288
	45.7		0.133		0.133
	61.0		0.042		0.042
500	1.5	1.000	1.000	1.000	1.000
	3.0	1.000	1.000	1.000	1.000
	4.6	1.000	1.000	1.000	1.000
	6.1	1.000	1.000	0.962	1.000
	7.6	1.000	1.000	0.770	1.000
	9.1	1.000	1.000	0.481	1.000
	10.7	1.000	1.000	0.233	1.000
	12.2	1.000	1.000	0.094	1.000
	13.7	1.000	1.000	0.035	1.000
	15.2	1.000	1.000	0.012	1.000
	18.3	0.007	1.000	0.002	1.000
	21.3		1.000		1.000
	24.4		1.000		1.000
	27.4		0.986		0.986
	30.5		0.796		0.796
	36.6		0.496		0.496
	45.7		0.243		0.243
	61.0		0.081		0.081
700	1.5	1.000	1.000	1.000	1.000
	3.0	1.000	1.000	1.000	1.000
	4.6	1.000	1.000	1.000	1.000
	6.1	1.000	1.000	1.000	1.000
	7.6	1.000	1.000	0.965	1.000
	9.1	1.000	1.000	0.783	1.000
	10.7	1.000	1.000	0.511	1.000
	12.2	1.000	1.000	0.270	1.000
	13.7	1.000	1.000	0.122	1.000
	15.2	1.000	1.000	0.051	1.000
	18.3	0.985	1.000	0.008	1.000
	21.3	0.001	1.000	0.001	1.000
	24.4		1.000		1.000
	27.4		1.000		1.000
	30.5		1.000		1.000
	36.6		0.683		0.683
	45.7		0.353		0.353
	61.0		0.122		0.122
1000	1.5	1.000	1.000	1.000	1.000
	3.0	1.000	1.000	1.000	1.000
	4.6	1.000	1.000	1.000	1.000
	6.1	1.000	1.000	1.000	1.000
	7.6	1.000	1.000	1.000	1.000
	9.1	1.000	1.000	0.987	1.000
	10.7	1.000	1.000	0.846	1.000
	12.2	1.000	1.000	0.602	1.000
	13.7	1.000	1.000	0.357	1.000
	15.2	1.000	1.000	0.184	1.000
	18.3	1.000	1.000	0.039	1.000
	21.3	0.978	1.000	0.008	1.000
	24.4	0.007	1.000	0.002	1.000
	27.4		1.000		1.000
	30.5		1.000		1.000
	36.6		0.913		0.913
	45.7		0.511		0.511
	61.0		0.186		0.186
1361	1.5	1.000	1.000	1.000	1.000
	3.0	1.000	1.000	1.000	1.000
	4.6	1.000	1.000	1.000	1.000
	6.1	1.000	1.000	1.000	1.000
	7.6	1.000	1.000	1.000	1.000
	9.1	1.000	1.000	1.000	1.000
	10.7	1.000	1.000	1.000	1.000
	12.2	1.000	1.000	0.894	1.000
	13.7	1.000	1.000	0.679	1.000
	15.2	1.000	1.000	0.440	1.000
	18.3	1.000	1.000	0.130	1.000
	21.3	1.000	1.000	0.031	1.000
	24.4	0.969	1.000	0.007	1.000
	27.4	0.019	1.000	0.002	1.000
	30.5		1.000		1.000
	36.6		1.000		1.000
	45.7		0.684		0.684
	61.0		0.266		0.266
2000	1.5	1.000	1.000	1.000	1.000
	3.0	1.000	1.000	1.000	1.000
	4.6	1.000	1.000	1.000	1.000
	6.1	1.000	1.000	1.000	1.000
	7.6	1.000	1.000	1.000	1.000
	9.1	1.000	1.000	1.000	1.000
	10.7	1.000	1.000	1.000	1.000
	12.2	1.000	1.000	1.000	1.000
	13.7	1.000	1.000	0.992	1.000
	15.2	1.000	1.000	0.860	1.000
	18.3	1.000	1.000	0.433	1.000
	21.3	1.000	1.000	0.148	1.000
	24.4	1.000	1.000	0.043	1.000
	27.4	1.000	1.000	0.012	1.000
	30.5	0.385	1.000	0.003	1.000
	36.6		1.000		1.000
	45.7		0.932		0.932
	61.0		0.404		0.404

Table 9. Probability of Fatality—Person in Open Behind Barricade

NEQ	Range	Probability of Fatality			
		Blast	Debris		Total
(kg)	(m)		Horizontal	Vertical	
200	1.5	1.000		1.000	1.000
	3.0	1.000		0.928	1.000
	4.6	1.000		0.698	1.000
	6.1	1.000		0.369	1.000
	7.6	1.000		0.130	1.000
	9.1	1.000		0.035	1.000
	10.7	0.997		0.009	1.000
	12.2	0.040		0.002	0.042
	13.7			0.001	0.001
	15.2				
	18.3				
	21.3				
	24.4				
	27.4				
	30.5				
	36.6				
	45.7				
	61.0				
300	1.5	1.000		1.000	1.000
	3.0	1.000		1.000	1.000
	4.6	1.000		0.915	1.000
	6.1	1.000		0.667	1.000
	7.6	1.000		0.355	1.000
	9.1	1.000		0.137	1.000
	10.7	1.000		0.044	1.000
	12.2	1.000		0.013	1.000
	13.7	0.483		0.004	0.486
	15.2			0.001	0.001
	18.3				
	21.3				
	24.4				
	27.4				
	30.5				
	36.6				
	45.7				
	61.0				
500	1.5	1.000		1.000	1.000
	3.0	1.000		1.000	1.000
	4.6	1.000		1.000	1.000
	6.1	1.000		0.962	1.000
	7.6	1.000		0.770	1.000
	9.1	1.000		0.481	1.000
	10.7	1.000		0.233	1.000
	12.2	1.000		0.094	1.000
	13.7	1.000		0.035	1.000
	15.2	1.000		0.012	1.000
	18.3	0.007		0.002	0.009
	21.3				
	24.4				
	27.4				
	30.5				
	36.6				
	45.7				
	61.0				
700	1.5	1.000		1.000	1.000
	3.0	1.000		1.000	1.000
	4.6	1.000		1.000	1.000
	6.1	1.000		1.000	1.000
	7.6	1.000		0.965	1.000
	9.1	1.000		0.783	1.000
	10.7	1.000		0.511	1.000
	12.2	1.000		0.270	1.000
	13.7	1.000		0.122	1.000
	15.2	1.000		0.051	1.000
	18.3	0.985		0.008	0.993
	21.3	0.001		0.001	0.003
	24.4				
	27.4				
	30.5				
	36.6				
	45.7				
	61.0				
1000	1.5	1.000		1.000	1.000
	3.0	1.000		1.000	1.000
	4.6	1.000		1.000	1.000
	6.1	1.000		1.000	1.000
	7.6	1.000		1.000	1.000
	9.1	1.000		0.987	1.000
	10.7	1.000		0.846	1.000
	12.2	1.000		0.602	1.000
	13.7	1.000		0.357	1.000
	15.2	1.000		0.184	1.000
	18.3	1.000		0.039	1.000
	21.3	0.978		0.008	0.986
	24.4	0.007		0.002	0.008
	27.4				
	30.5				
	36.6				
	45.7				
	61.0				
1361	1.5	1.000		1.000	1.000
	3.0	1.000		1.000	1.000
	4.6	1.000		1.000	1.000
	6.1	1.000		1.000	1.000
	7.6	1.000		1.000	1.000
	9.1	1.000		1.000	1.000
	10.7	1.000		1.000	1.000
	12.2	1.000		0.894	1.000
	13.7	1.000		0.679	1.000
	15.2	1.000		0.440	1.000
	18.3	1.000		0.130	1.000
	21.3	1.000		0.031	1.000
	24.4	0.969		0.007	0.976
	27.4	0.019		0.002	0.021
	30.5				
	36.6				
	45.7				
	61.0				
2000	1.5	1.000		1.000	1.000
	3.0	1.000		1.000	1.000
	4.6	1.000		1.000	1.000
	6.1	1.000		1.000	1.000
	7.6	1.000		1.000	1.000
	9.1	1.000		1.000	1.000
	10.7	1.000		1.000	1.000
	12.2	1.000		1.000	1.000
	13.7	1.000		0.992	1.000
	15.2	1.000		0.860	1.000
	18.3	1.000		0.433	1.000
	21.3	1.000		0.148	1.000
	24.4	1.000		0.043	1.000
	27.4	1.000		0.012	1.000
	30.5	0.385		0.003	0.389
	36.6				
	45.7				
	61.0				

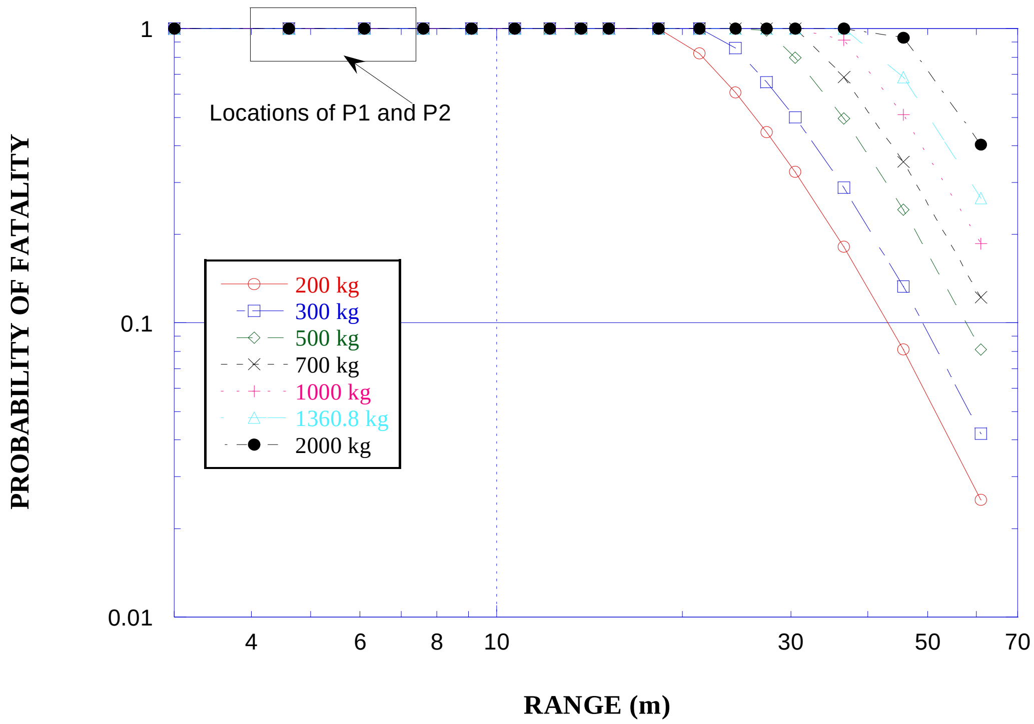

Figure 11. Probability of Fatality—Person in Open

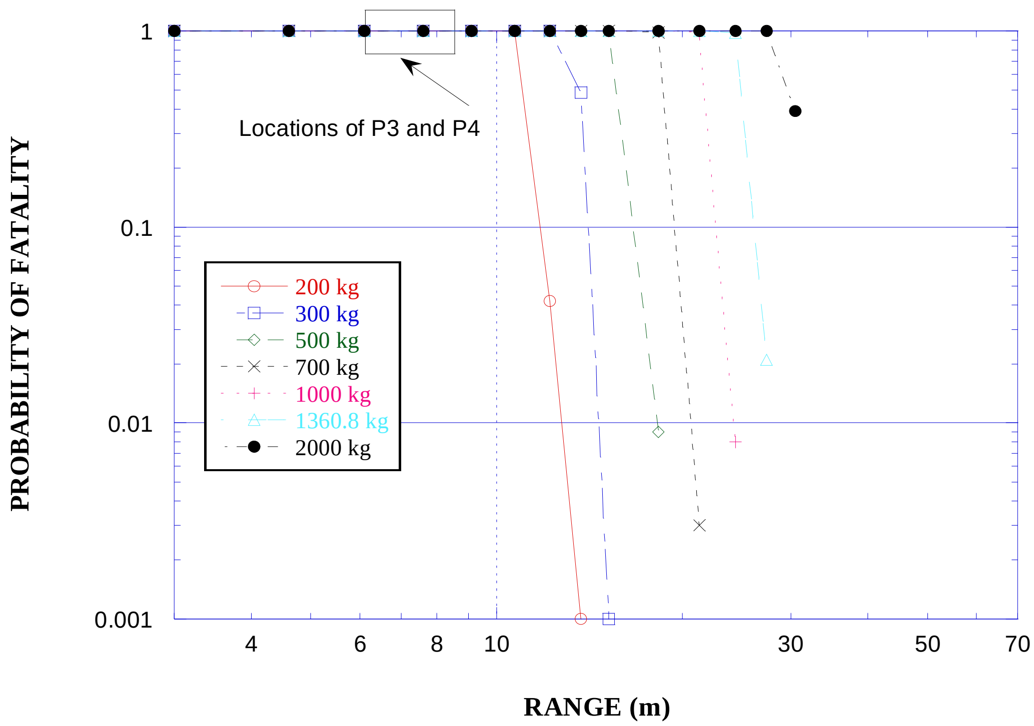

Figure 12. Probability of Fatality—Person in Open Behind Barricade

Table 10. Probability of Fatality—Unreinforced Brick/Masonry Structure

NEQ	Range	Probability of Fatality					NEQ	Range	Probability of Fatality				
		Blast	Structural	Debris		Total			Blast	Structural	Debris		Total
(kg)	(m)			Horizontal	Vertical		(kg)	(m)			Horizontal	Vertical	
200	1.5	1.000	1.000	1.000	1.000	1.000	1000	1.5	1.000	1.000	1.000	1.000	1.000
	3.0	1.000	1.000	1.000	0.928	1.000		3.0	1.000	1.000	1.000	1.000	1.000
	4.6	1.000	1.000	1.000	0.698	1.000		4.6	1.000	1.000	1.000	1.000	1.000
	6.1	1.000	1.000	1.000	0.369	1.000		6.1	1.000	1.000	1.000	1.000	1.000
	7.6	1.000	1.000	1.000	0.130	1.000		7.6	1.000	1.000	1.000	1.000	1.000
	9.1	0.827	1.000	1.000	0.035	1.000		9.1	1.000	1.000	1.000	0.987	1.000
	10.7		1.000	1.000	0.009	1.000		10.7	1.000	1.000	1.000	0.846	1.000
	12.2		1.000	1.000	0.002	1.000		12.2	1.000	1.000	1.000	0.602	1.000
	13.7		1.000	1.000	0.001	1.000		13.7	1.000	1.000	1.000	0.357	1.000
	15.2		1.000	1.000		1.000		15.2	1.000	1.000	1.000	0.184	1.000
	18.3		1.000	1.000		1.000		18.3	0.563	1.000	1.000	0.039	1.000
	21.3		0.996	0.822		0.999		21.3		1.000	1.000	0.008	1.000
	24.4		0.792	0.605		0.918		24.4		1.000	1.000	0.002	1.000
	27.4		0.273	0.442		0.595		27.4		1.000	1.000		1.000
	30.5		0.166	0.324		0.436		30.5		1.000	1.000		1.000
	36.6		0.142	0.126		0.250		36.6		0.998	0.913		1.000
	45.7		0.055	0.051		0.103		45.7		0.678	0.511		0.843
	61.0			0.005		0.005		61.0		0.173	0.186		0.326
300	1.5	1.000	1.000	1.000	1.000	1.000	1361	1.5	1.000	1.000	1.000	1.000	1.000
	3.0	1.000	1.000	1.000	1.000	1.000		3.0	1.000	1.000	1.000	1.000	1.000
	4.6	1.000	1.000	1.000	0.915	1.000		4.6	1.000	1.000	1.000	1.000	1.000
	6.1	1.000	1.000	1.000	0.667	1.000		6.1	1.000	1.000	1.000	1.000	1.000
	7.6	1.000	1.000	1.000	0.355	1.000		7.6	1.000	1.000	1.000	1.000	1.000
	9.1	1.000	1.000	1.000	0.137	1.000		9.1	1.000	1.000	1.000	1.000	1.000
	10.7	0.924	1.000	1.000	0.044	1.000		10.7	1.000	1.000	1.000	1.000	1.000
	12.2	0.001	1.000	1.000	0.013	1.000		12.2	1.000	1.000	1.000	0.894	1.000
	13.7		1.000	1.000	0.004	1.000		13.7	1.000	1.000	1.000	0.679	1.000
	15.2		1.000	1.000	0.001	1.000		15.2	1.000	1.000	1.000	0.440	1.000
	18.3		1.000	1.000		1.000		18.3	1.000	1.000	1.000	0.130	1.000
	21.3		1.000	1.000		1.000		21.3	0.241	1.000	1.000	0.031	1.000
	24.4		0.997	0.858		1.000		24.4		1.000	1.000	0.007	1.000
	27.4		0.838	0.657		0.945		27.4		1.000	1.000	0.002	1.000
	30.5		0.440	0.498		0.719		30.5		1.000	1.000		1.000
	36.6		0.169	0.287		0.407		36.6		1.000	1.000		1.000
	45.7		0.138	0.091		0.216		45.7		0.927	0.684		0.977
	61.0		0.009	0.009		0.018		61.0		0.176	0.266		0.395
500	1.5	1.000	1.000	1.000	1.000	1.000	2000	1.5	1.000	1.000	1.000	1.000	1.000
	3.0	1.000	1.000	1.000	1.000	1.000		3.0	1.000	1.000	1.000	1.000	1.000
	4.6	1.000	1.000	1.000	1.000	1.000		4.6	1.000	1.000	1.000	1.000	1.000
	6.1	1.000	1.000	1.000	0.962	1.000		6.1	1.000	1.000	1.000	1.000	1.000
	7.6	1.000	1.000	1.000	0.770	1.000		7.6	1.000	1.000	1.000	1.000	1.000
	9.1	1.000	1.000	1.000	0.481	1.000		9.1	1.000	1.000	1.000	1.000	1.000
	10.7	1.000	1.000	1.000	0.233	1.000		10.7	1.000	1.000	1.000	1.000	1.000
	12.2	1.000	1.000	1.000	0.094	1.000		12.2	1.000	1.000	1.000	1.000	1.000
	13.7	0.546	1.000	1.000	0.035	1.000		13.7	1.000	1.000	1.000	0.992	1.000
	15.2		1.000	1.000	0.012	1.000		15.2	1.000	1.000	1.000	0.860	1.000
	18.3		1.000	1.000	0.002	1.000		18.3	1.000	1.000	1.000	0.433	1.000
	21.3		1.000	1.000		1.000		21.3	1.000	1.000	1.000	0.148	1.000
	24.4		1.000	1.000		1.000		24.4	0.583	1.000	1.000	0.043	1.000
	27.4		1.000	0.986		1.000		27.4		1.000	1.000	0.012	1.000
	30.5		0.958	0.796		0.991		30.5		1.000	1.000	0.003	1.000
	36.6		0.376	0.496		0.685		36.6		1.000	1.000		1.000
	45.7		0.171	0.242		0.371		45.7		0.999	0.932		1.000
	61.0		0.124	0.053		0.170		61.0		0.707	0.404		0.825
700	1.5	1.000	1.000	1.000	1.000	1.000							
	3.0	1.000	1.000	1.000	1.000	1.000							
	4.6	1.000	1.000	1.000	1.000	1.000							
	6.1	1.000	1.000	1.000	1.000	1.000							
	7.6	1.000	1.000	1.000	0.965	1.000							
	9.1	1.000	1.000	1.000	0.783	1.000							
	10.7	1.000	1.000	1.000	0.511	1.000							
	12.2	1.000	1.000	1.000	0.270	1.000							
	13.7	1.000	1.000	1.000	0.122	1.000							
	15.2	0.903	1.000	1.000	0.051	1.000							
	18.3		1.000	1.000	0.008	1.000							
	21.3		1.000	1.000	0.001	1.000							
	24.4		1.000	1.000		1.000							
	27.4		1.000	1.000		1.000							
	30.5		1.000	1.000		1.000							
	36.6		0.841	0.683		0.949							
	45.7		0.175	0.353		0.466							
	61.0		0.157	0.121		0.259							

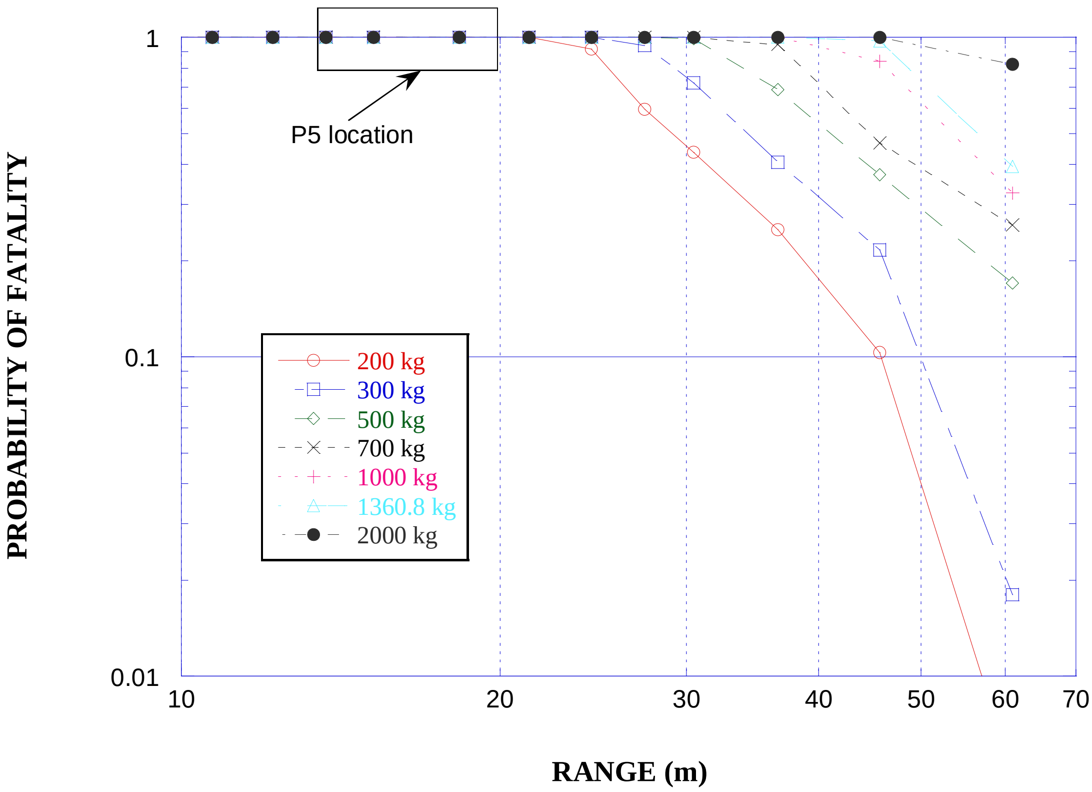

Figure 13. Probability of Fatality – Person in Unreinforced Brick/Masonry Structure

3.2.2 IMESAFR v1.2

For the purposes of this paper, the only difference between Version 1.1 and 1.2 of IMESAFR is the credit that is given for a barricade. Version 1.1 only allows a barricade to shield from horizontal debris, essentially setting the horizontal debris density to zero without affecting the vertical debris. In Version 1.2, this still occurs. In addition, credit may also be given for blast shielding directly behind the barricade. Variations in the charge weight and locations of the PES and the ES with respect to the barricade have the effect of reducing the peak pressure and airblast by as much as 95%. For the Quin Site scenario (as modeled), it is expected that the pressures and impulses would be reduced by about 75%. The effect of this shielding is that the blast fatality mechanisms (lung rupture, whole body displacement, and skull fracture) are “turned off” for these locations. The results of this operation for the scenario with a person in the open behind a barricade are shown in Table 11 demonstrating that the vertical debris consequence is dominating the results.

Table 11. IMESAFR Version 1.2—Person in Open Behind Barricade

NEQ (kg)	Range (m)	Probability of Fatality				NEQ (kg)	Range (m)	Probability of Fatality			
		Blast	Debris		Total			Blast	Debris		Total
			Horizontal	Vertical					Horizontal	Vertical	
200	1.5			1.000	1.000	1000	1.5			1.000	1.000
	3.0			0.928	0.928		3.0			1.000	1.000
	4.6			0.698	0.698		4.6			1.000	1.000
	6.1			0.369	0.369		6.1			1.000	1.000
	7.6			0.130	0.130		7.6			1.000	1.000
	9.1			0.035	0.035		9.1			0.987	0.987
	10.7			0.009	0.009		10.7			0.846	0.846
	12.2			0.002	0.002		12.2			0.602	0.602
	13.7			0.001	0.001		13.7			0.357	0.357
	15.2						15.2			0.184	0.184
	18.3						18.3			0.039	0.039
	21.3						21.3			0.008	0.008
	24.4						24.4			0.002	0.002
	27.4						27.4				
	30.5						30.5				
300	1.5			1.000	1.000	1361	1.5			1.000	1.000
	3.0			1.000	1.000		3.0			1.000	1.000
	4.6			0.915	0.915		4.6			1.000	1.000
	6.1			0.667	0.667		6.1			1.000	1.000
	7.6			0.355	0.355		7.6			1.000	1.000
	9.1			0.137	0.137		9.1			1.000	1.000
	10.7			0.044	0.044		10.7			1.000	1.000
	12.2			0.013	0.013		12.2			0.894	0.894
	13.7			0.004	0.004		13.7			0.679	0.679
	15.2			0.001	0.001		15.2			0.440	0.440
	18.3						18.3			0.130	0.130
	21.3						21.3			0.031	0.031
	24.4						24.4			0.007	0.007
	27.4						27.4			0.002	0.002
	30.5						30.5				
500	1.5			1.000	1.000	2000	1.5			1.000	1.000
	3.0			1.000	1.000		3.0			1.000	1.000
	4.6			1.000	1.000		4.6			1.000	1.000
	6.1			0.962	0.962		6.1			1.000	1.000
	7.6			0.770	0.770		7.6			1.000	1.000
	9.1			0.481	0.481		9.1			1.000	1.000
	10.7			0.233	0.233		10.7			1.000	1.000
	12.2			0.094	0.094		12.2			1.000	1.000
	13.7			0.035	0.035		13.7			0.992	0.992
	15.2			0.012	0.012		15.2			0.860	0.860
	18.3			0.002	0.002		18.3			0.433	0.433
	21.3						21.3			0.148	0.148
	24.4						24.4			0.043	0.043
	27.4						27.4			0.012	0.012
	30.5						30.5			0.003	0.003
700	1.5			1.000	1.000						
	3.0			1.000	1.000						
	4.6			1.000	1.000						
	6.1			1.000	1.000						
	7.6			0.965	0.965						
	9.1			0.783	0.783						
	10.7			0.511	0.511						
	12.2			0.270	0.270						
	13.7			0.122	0.122						
	15.2			0.051	0.051						
	18.3			0.008	0.008						
	21.3			0.001	0.001						
	24.4										
	27.4										
	30.5										

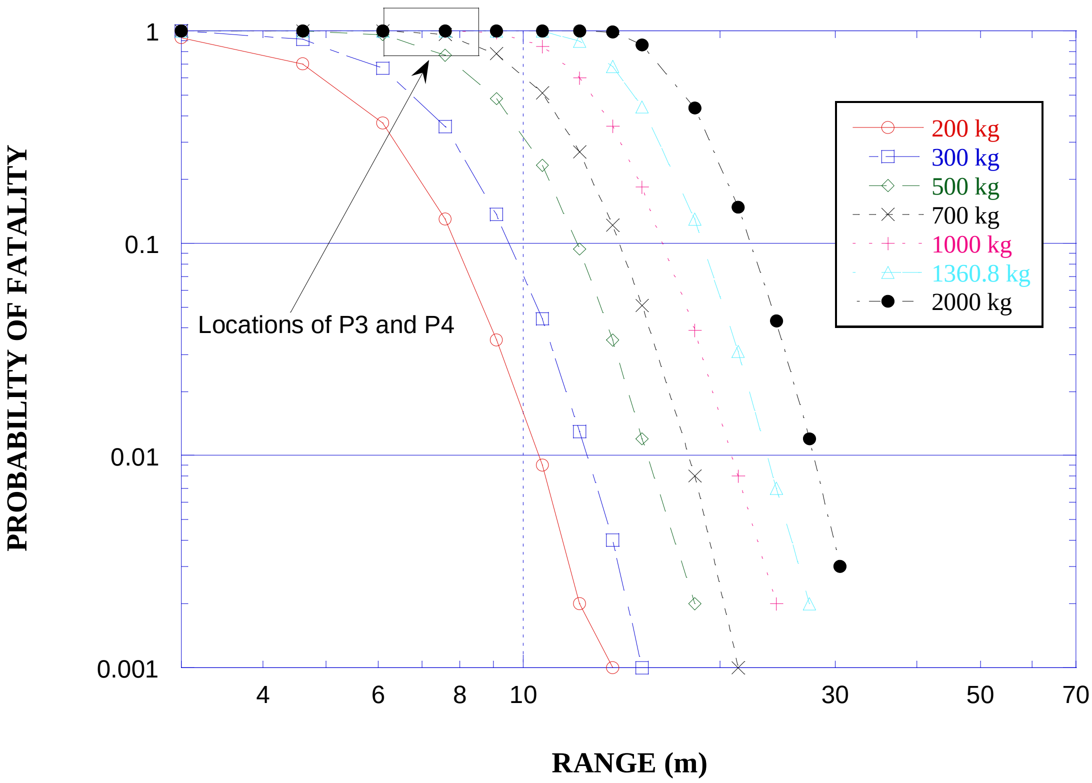

Figure 14. Probability of Fatality—Person in Open Behind Barricade—IMESAFR V1.2

3.3 DIRE Comparison

The consequence model DIRE was also used to simulate the Quin Site event. DIRE Version 1.2 does not consider barricades or their potential shielding effects. Therefore, its results would be expected to be conservative for P3 and P4. Table 12 summarizes the DIRE results. These are also shown in Figure 15 for a person in the open and Figure 16 for a person in an unreinforced masonry structure.

DIRE would estimate that with an NEQ of 1360 kg, P1 through P4 would have a probability of fatality of 1.0 for distances out to 23.8 meters. For P5, a fatality probability of 1 extends out to 14.9 meters.

Table 12. Summary of DIRE Results

NEQ	Range	Probability of Fatality		NEQ	Range	Probability of Fatality	
		Open	Unreinforced Masonry			Open	Unreinforced Masonry
(kg)	(m)			(kg)	(m)		
2268.0	18.3		1.000	453.6	6.0		1.000
	21.3		0.316		9.1		0.999
	24.4		0.221		10.7		0.247
	27.4	1.000			12.2		0.203
	30.5	0.948	0.212		13.7	1.000	0.201
	36.6	0.071			15.2	0.987	0.198
	45.7	0.059			18.3	0.039	
	61.0	0.039	0.189		21.3	0.035	
1360.8	13.7		1.000		24.4	0.031	
	15.2		0.994		27.4	0.028	
	18.3		0.217		30.5	0.024	0.185
	21.3	1.000			36.6	0.017	
	24.4	0.971	0.207		45.7	0.008	
	27.4	0.079			61.0		
	30.5	0.058	0.200	226.8	1.5		0.197
	36.6	0.050			9.1	1.000	0.195
	45.7	0.038	0.190		10.7	0.513	0.192
	61.0	0.020	0.176		12.2	0.029	0.19
907.2	12.2		1.000		13.7	0.027	0.188
	13.7		0.653		15.2	0.024	0.185
	15.2		0.212		18.3	0.020	0.184
	18.3	1.000	0.207		21.3	0.017	0.175
	21.3	0.760	0.203		24.4	0.013	0.174
	24.4	0.051	0.196		27.4		0.17
	27.4	0.047			30.5		
	30.5	0.044	0.193		36.6		
	36.6	0.036			45.7		
	45.7	0.024	0.184		61.0		
	61.0	0.010					

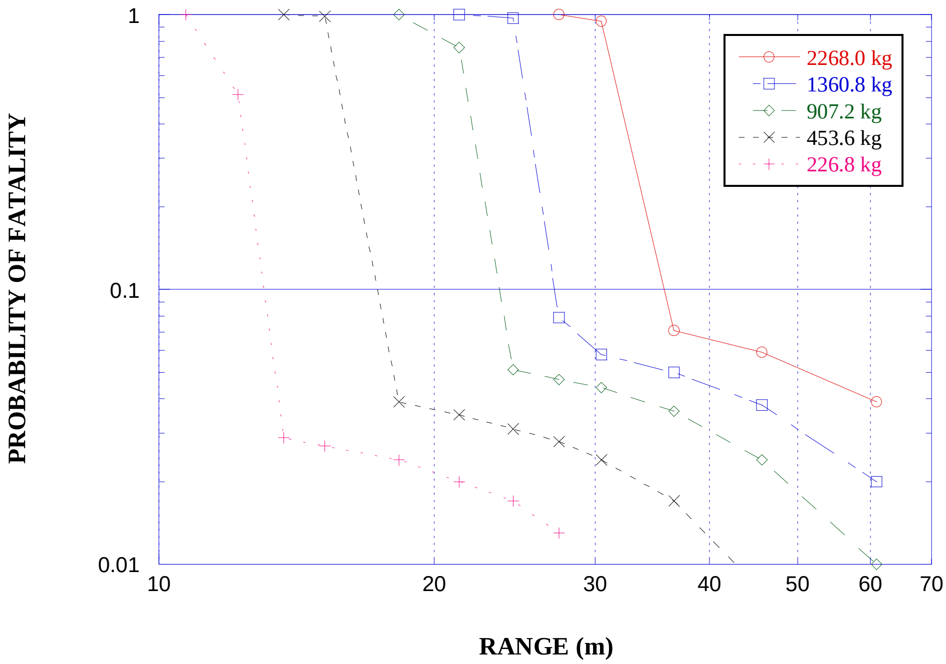

Figure 15. Probability of Fatality–Person in Open–DIRE

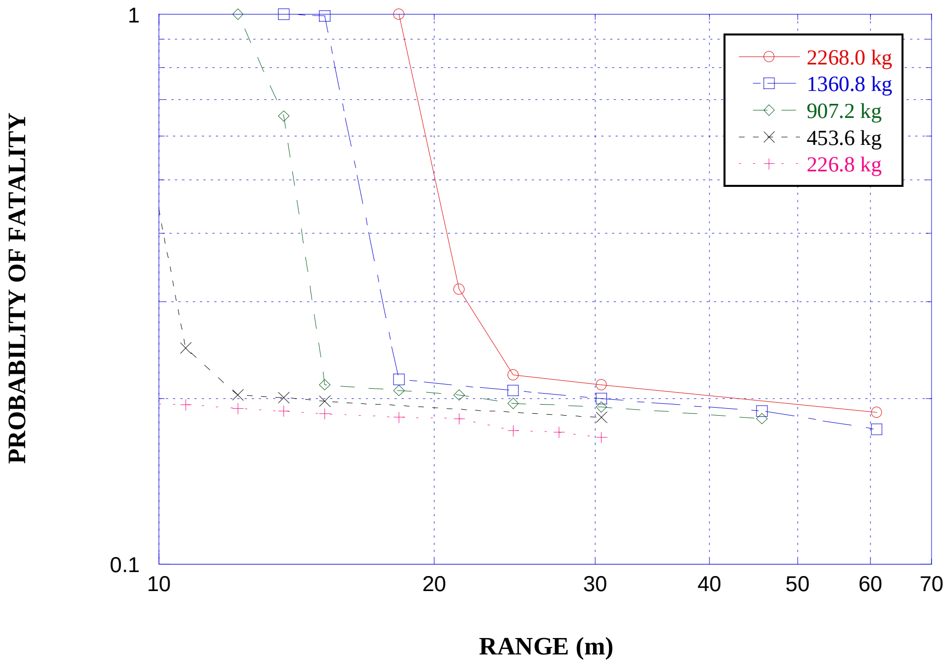

Figure 16. Probability of Fatality–Person in Unreinforced Masonry–DIRE

3.3.1 Discussion

As pointed out earlier, P3 and P4 survived the event and recovered. Both versions of IMESAFR and DIRE predict that these two people would be expected to receive fatal consequences from the event. A known conservatism that is built into IMESAFR is its treatment of debris at close ranges, as discussed throughout Section 2.0. The code assumes a bi-variant normal distribution for the debris. Test data have shown that this assumption tends to over-emphasize the importance of such debris close to the explosion source. It is planned that a future version of the code will address this, but to this point the program sponsors (for both SAFER and IMESAFR) have been willing to “err on the side of caution” in these predictions.

4.0 CONCLUSION

QRA models (such as IMESAFR) and consequence models (such as DIRE) have been in use in the explosives safety community for many years and these models have been compared against test results, accident data, terrorist events and other available models. The algorithms have improved over time and undoubtedly will continue to be updated. As shown in the Assheton data comparisons, the trend for the models is conservative; they over-predict the actual expected results, especially at close ranges.

The tragic events at the Quin Site in 2006 have been assessed with IMESAFR and DIRE. The results, as expected, show conservative predictions by the models when compared to actual experience. The exact details of the accident (precise determination of event size, personnel placement, etc.) can be questioned, but it appears that the models are firmly conservative when predicting fatalities at such close ranges.

Some of the over-prediction is due to assumptions about the debris density distribution, which is a recognized flaw in the algorithms. However, this error applies mostly to very close ranges and is not optimistic, so the program sponsors are not necessarily rushing to correct this problem. Nevertheless, it is important to note this discrepancy and plan to address the issue in time.

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