SAFEX INTERNATIONAL
EST•1954

SAFEX International

Development and Application of Quantitative Risk Assessment Methodology

by

Lon Santis
(Explosives Risk Managers LLC)

Michael Swisdak and **John Tatom**
(APT Research, Inc)

SAFEX Topical Papers Series
Paper No. 09/15

SAFEX Topical Paper Series

The papers in SAFEX's Topical Paper Series acknowledges the work done by the SAFEX community in promoting better health, safety, security and environmental (HSSE) performance in the explosives industry. This community comprises representatives of Member companies, Associate Members and Expert Panel members. The papers can be based on presentations at events, published articles or even original work in the explosives HS&E field. The information in these papers should be topical and of interest to other SAFEX members. In keeping with its mission of exchanging relevant HSSE information among its members, SAFEX continually encourages members of its community to submit such papers for consideration as a Topical Paper.

Development and Application of Quantitative Risk Assessment Methodology

by

Lon Santis

(*Explosives Risk Managers LLC*)

Michael Swisdak and **John Tatom**

(*APT Research, Inc*)

with additional contributions by

Foreword: **Josephine Covino, PhD** (*US DoD Explosives Safety Board*)

Introduction: **Mike O'Lena** (*Explosives Program Manager, ATF*)

Conclusion: **Bill Evans** (*Chair, IMESAFR Subcommittee, IME*)

This is a collection of articles that appeared in the *QRA Corner* column of SAFEX Newsletters Nos. 39 to 51 during the period December 2011 to December 2014.

SAFEX Topical Papers Series
Paper No 09/2015
Published: May, 2015

About the Authors

Lon Santis holds a BS and MS in Mining Engineering. After working for the Ensign-Bickford Company and the Pittsburgh Research Laboratory of the US Bureau of Mines, he became the Manager of Technical Services at the Institute of Makers of Explosives (IME) in Washington, DC in 1998. In 2013, he started Explosives Risk Managers LLC, a consulting company providing services on all aspects of risk from industrial explosives related activities.

Michael Swisdak is a Senior Scientist in the Explosives Safety Group at APT Research Inc, headquartered in Huntsville, AL. He is retired from the Department of Defense after 45 years of service. His specialties include airblast, explosion-produced debris, and the effects of debris on explosive-safety quantity-distance. He is the author or co-author of over 150 technical publications in these fields and holds a Master of Science degree in Physics from the University of Florida.

John Tatom is the Manager for Explosives Safety at APT Research in Huntsville, AL. He serves as the algorithm coordinator for the SAFER project, participates in the DDESB Science Panel, and has developed original technical routines for use by SAFER. He has played a similar role in the development of IMESAFR. He is the author of numerous papers concerning explosives safety modeling and testing. He holds a Bachelor of Electrical Engineering degree.

Contact details:

Lon D. Santis, Explosives Risk Managers LLC, 11104 Innsbrook Way, Ijamsville, MD 21754, USA. Cell: 202-288-2029; E-mail: santis@ermanagers.com

Michael M. Swisdak, APT Research, Inc, 4950 Research Drive, Huntsville, AL 35805. Phone: +1-301-908-8272; FAX: +1-256-837-7786, E-mail: MSwisdak@APT-Research.com

John W. Tatom, APT Research, Inc, 4950 Research Drive, Huntsville, AL 35805. Phone: +1-256-327-3392; FAX: +1-256-837-7786, E-mail: JTatom@APT-Research.com

CONTENTS

GLOSSARY

≈	Approximation
ANFO	Ammonium nitrate fuel oil
ATD	American Table of Distances
ATF	US Bureau of Alcohol, Tobacco, Firearms and Explosives
B	Barricaded
BVN	Bi-Variant Normal
cm	centimetre
CMU	Concrete Masonry Units
DDESB	United States Department of Defense Explosives Safety Board
DoD	United States Department of Defense
EMRTC	Energetic Materials Research and Testing Center
ES	Exposed site
ESKIMO	Explosive Safety Knowledge IMprovement Operation
ESKIMORE	Explosive Safety Knowledge IMprovement Operation--REdux
ESRM	Explosives Safety Risk Management
FAA	Federal Aviation Administration
fps	feet per second
FRM	fast-running models
ft	feet
g	gram
GZ	ground zero
HD	Hazard Division
HE	high-explosive
IBD	inhabited building distance
IME	Institute of Makers of Explosives
IMESAFR	Institute of Makers of Explosives Safety Analysis for Risk
ISURF	Initially Sloping Upward Range Function
in	inch
ISO	International Organisation for Standardisation
KE	kinetic energy
kg	kilogram
ksi	kilopounds per square inch
lb	pound

m	metre
m/s	metres per second
mm	millimetre
MPa	Megapascal
NASA	United States National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organisation
NEW	net explosives weight
PDF	probability density functions
P_e	probability of an event occurring
PEMB	pre-engineered metal buildings
PES	Potential explosion site
P_f	probability of fatality
$P_{f\|e}$	Probability of fatality given an event occurs
psi	pounds per square inch
PTN	Pseudo-Trajectory Normal
Q-D	Quantity - Distance
QRA	Quantitative risk assessment
R/C	reinforced concrete
RBED	Risk-Based Evaluation Distance
RBESCT	Risk-Based Explosives Safety Criteria Team
RTC	Redstone Test Center
RTTC	Redstone Technical Test Center
S	South
SAFER	Safety Analysis for Explosives Risk
SPIDER	Science Panel Impact Data Evaluation and Review
SW	South-west
TNT	Trinitrotoluene
TP	Technical Paper
UB	Unbarricaded
USA	United States of America
USD	United States Dollar

Note: The values of the US Customary Units originally used are indicated in brackets. These have been converted to the equivalent International System of Units (SI) and rounded off accordingly.

PREFACE

The authors would like to express their gratitude to all those in the worldwide explosives safety community who are promoting quantitative risk assessment (QRA) and advancing the associated science and regulatory practices. In particular, the authors would like to thank the United States Department of Defense Explosives Safety Board (DDESB) for their sponsorship of the test programs described in Chapter 4 and both the DDESB and the Institute of Makers of Explosives (IME) for their continued support and guidance.

1. FOREWORD (Josephine Covino[1])

The DDESB, formerly called the Armed Forces Explosives Safety Board, was established in 1928 by the Seventieth Congress after a major disaster occurred at the Naval Ammunition Depot, Lake Denmark, New Jersey in 1926. The accident virtually destroyed the depot, causing heavy damage to adjacent Picatinny Arsenal and the surrounding communities, killing 21 people, and seriously injuring 53 others. The monetary loss to the Navy alone was USD 84 million. As a result of a full-scale Congressional investigation, Congress directed the establishment of the Board to provide oversight of the development, manufacture, testing, maintenance, demilitarization, handling, transportation and storage of explosives, including chemical agents on US Department of Defense (DoD) facilities worldwide. The DDESB mission is to provide objective advice to the Secretary of Defense and Service Secretaries on matters concerning explosives safety and to prevent hazardous conditions to life and property on and off DoD installations from the explosives and environmental effects of DoD titled munitions.

Since the 1928 establishment of the Board, Quantity-Distance (Q-D) criteria have been used as the primary means for the safe siting of facilities. Q-D

[1] Josephine Covino, PhD works for the Department of Defense (DoD) Explosives Safety Board, Suite 16E12 4800 Mark Center Drive, Alexandria, VA 22350-3606, USA. Her email address is Josephine.Covino.civ@mail.mil

criteria consider only explosives quantity, Hazard Division (HD), and facility type to determine a safe separation distance. During the past 30 years, safety professionals have recognized that Q-D could be improved by considering other factors in the safety analyses including type of activity, number of people, building construction, and environment to assess the overall risk of an operation.

The DDESB recognized the need to develop and adopt a risk-based approach for explosives safety analysis and decided to pioneer it in the USA on behalf of the explosives safety community. In 1997 it embarked on a comprehensive development of a risk-based tool that would be used to improve explosives safety at large and the Risk-Based Explosives Safety Criteria Team (RBESCT) was chartered to develop such an approach. The results of these efforts and the QRA methodologies are currently documented in Technical Paper (TP) 14 and TP-19. In 1999, the DDESB approved the Risk based approach for use in DoD safety analyses on a trial basis from 2002 through 2007.

In 2007 the DDESB adopted the methodologies of TP-14 and incorporated the risk-based explosives siting criteria into DoD 6055.09-STD (currently DODM- 6055.09 Vol 1-8 *DoD Ammunition and Explosives Safety Standards: Published date Varies by Volume*). TP-14 provides DDESB approved methodologies for calculating the risk associated with explosives operations and storage. The three elements of the methodology are the probability of event, probability of fatality given an event, and exposed personnel. TP-14 methodology incorporates a significant body of data from explosion effects testing and is being continually improved as new data and understanding is made available.

From 2002 to today significant improvements have been made to these risk analysis methodologies. Currently, the DDESB has multiple QRA tools of varied complexity and for different applications. Since 2002, significant efforts have been funded by the DDESB to improve the knowledge base of QRA in all areas of the risk equation:

Risk = Likelihood x Consequence x Exposure

Technology gaps in test data and need for improved consequence algorithms resulted in the establishment of a significant test program (see Chapter 4, Testing) which is still ongoing today.

In 2008 the DDESB published DODI 6055.16: *Explosives Safety Management Program: Published date 7/ 29/2008, Change 1 (12/ 8/2011) incorporating the* DoD Military Munitions Explosives and Chemical Agent Risk Stewardship (MMRS).

In 2009 the DDESB published TP-23: *Assessing Explosive Safety Risks, Deviations, and Consequences* which provides the DDESB six-step process for Explosives Safety Risk Management (ESRM).

In 2012 the DDESB published CJCSI 4360.01: *Explosives Safety and Munitions Risk Management for Joint Operations Planning, Training, and Execution: Published date 02/29/2012.*

Since 1997 the DDESB has been actively involved in the North Atlantic Treaty Organization (NATO) communities developing risk management approaches and joint documents.

The efforts of the DDESB in risk-assessment and management for munitions have been leveraged by organization to include: The IME, Federal Aviation Administration (FAA), NASA, and Department of Justice -The Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF).

More information is available on the DDESB website at *https://www.ddesb.pentagon.mil*

2. INTRODUCTION (Mike O'Lena[2])

In 1971, the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) adopted its first tables of distances requirements from the Institute of Makers of Explosives (IME). These Q-D standards were originally developed

[2] Mike O'Lena is Program Manager, Explosives Industry Programs Branch with the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF), 99 New York Avenue, NE, Room 6N-672, Washington, DC 20226 USA. His email address is Michael.J.O'Lena@usdoj.gov

for explosives storage in rural areas where there was typically a low exposure to individuals. Since the development of the Q-D standards, the explosives industry has generally seen an increase in use of less sensitive explosive materials, advances in the construction of explosives storage magazines and nearby inhabited buildings as well as significant improvements in explosives safety management processes. All these factors contribute to reduced risk to explosives personnel and individuals in the public.

However, traditional ATF Q-D requirements only account for the net explosives weight in the explosives storage magazines, their distances to exposed sites (e.g. highways and inhabited buildings), and, in some cases, proper barricading. Although the explosives industry has seen significant improvements in many aspects of explosives operations, the Q-D standards have remained constant and protected the public from magazine explosions, with risk to the public being generally the lowest.

It is important to remember that, even when explosives storage meets Q-D standards, there is some risk to the public. However, under a traditional Q-D regimen, the risk is difficult to quantify and industry members and regulators do not have the ability to evaluate and measure risk when changes are made at explosives storage sites. Explosives regulators and industry members alike should consider measures to reduce risk from explosives operations. Although explosives operators will never eliminate risk, they should consider a level that is as low as reasonably practicable. QRA can be a useful tool when evaluating and managing risk for explosives operations that are not covered by traditional Q-D or for operators who want to reduce risk at explosives storage sites even if they meet traditional Q-D standards.

During a time when many explosives operators are facing encroachment and struggling to sustain current operational levels, QRA can be a valuable tool if operational restructuring is necessary. QRA can be used to measure and compare risk from existing Q-D compliant explosives operations with risk from restructured operations that may not meet required Q-D standards. Industry members can then alter their explosives operations and use QRA to

compare the risk associated with the Q-D compliant and the altered explosives operations. Although risk comparison and implementation may require regulatory approval, QRA can effectively supplement traditional Q-D requirements in reducing risk to the public and explosives personnel from explosives operations.

3. APPLICATION (Lon Santis)

3.1. What do we mean by QRA?

What is QRA and how does it differ from traditional Q-D criteria?

QRA provides a numerical estimate of the risk of conducting a particular activity. The risk is usually expressed in units of fatalities per year, but can also be calculated for injuries or monetary loss per year. The mathematical formula for QRA is:

Risk = Probability of Event [P_e] x Consequence.

Consequence is then the factor of Damage from an Event times Exposure.

A big difference between QRA and Q-D is that QRA considers many additional factors before a “go/no-go” decision is made. This allows risk managers to make informed decisions about risk rather than be held to the rigid structure and limited options provided by Q-D. From a mathematical viewpoint, Q-D equates Risk to Consequence, assuming that the event will take place.

Why should we consider complicating our life with QRA since Q-D has worked so well?

Our life is already complicated by risk analysis even if we do not realize it. We make hundreds of decisions based on risk every day. For example, if we applied Q-D principles to the decision of whether to cross a busy street, we would never get to the other side. So QRA in explosives risk management is a natural extension of the digital age. Q-D standards have worked well, and when open space is readily available, there is little need for QRA. However, Q-D standards do not limit risk to zero, and in fact allow for a very wide range of risk to occur.

How can I use QRA?

QRA is best applied when space is at a premium or a Q-D standard does not exist for the activity to be undertaken. Additionally, QRA can help with compliance with risk-based regulatory procedures and can serve as justification for a variance from overly restrictive regulations. At a minimum, QRA provides an entity with a means of managing risk equally across many different activities or scenarios.

Isn't it possible to manipulate QRA to get the answer you want?

Yes, but the same could be said of any faulty engineering analysis. If QRA is performed by qualified individuals using appropriate models that accurately represent reality, then it can be used to manage risk very effectively.

Do the algorithms have any basis in actual test data?

Yes, a considerable amount of large scale testing has been performed, some of it designed specifically for use in QRA models. In a later chapter, some of this testing will be explained in more detail. Although test results commonly exist for all aspects of the models, the data are often described as anchor points. In other words, the head and tail of a data curve may be known from the data, but perhaps only one or even no mid points are known. Until tests can be performed to fill-in those data gaps, the models err on the side of conservativeness.

What do I do with the number that I get?

Perhaps the best question of all, for unlike the black and white "line in the sand" drawn by Q-D, QRA reveals the fact that risk is a continually changing shade of grey. So it is best to have a plan in place for the numerical criteria to be used with QRA. Fortunately, many government bodies have adopted numerical criteria for risk-based "go/no-go" decisions. In general, individual risk criteria centre around a value of about 1×10^{-6} fatalities per year. Individual risk is defined as the risk to any particular individual, either a worker, related person, or a member of the public. Group risk criteria are more diverse, but also exist. Group risk is defined as the sum of all significant individual risks within a group.

If you are new to QRA, we hope this section whets your appetite to learn more about the topic. If you are a veteran of QRA, this has all been familiar territory. In either case, we hope to get you thinking about the nearly boundless opportunities of QRA. These and other topics will be discussed in more detail in later chapters.

3.2. The Realities of QRA and Q-D

So far, this chapter has introduced QRA and some of the common questions about it, described the connection between testing and modelling, and discussed the necessary elements of a QRA model. This Section delves into the realities of what QRA and Q-D deliver to explosives risk managers.

First of all, QRA is really just an expansion of Q-D. It merely takes more factors into consideration. Q-D tables typically take into account factors such as the net explosive weight (NEW), the distance to the exposed site (ES), the type of explosive, the presence of barricades, the volume of traffic, the type of ES, the relation of the person to the explosives operation and others. A valid QRA takes all these things into account, plus many other factors not suitable for incorporation into a set of human-readable tables. Broken down to its individual parts, a QRA is just a complex set of many tables and formulae; and the magic of personal computers make it possible to extract information from those tables and make sophisticated computations with it. QRA is a complement to Q-D for explosives risk management and Q-D should be the first standard considered. But when the simple Q-D approach is not applicable, consider doing a QRA. If a QRA does not provide definitive guidance, more detailed modelling using finite element codes, fault-tree analyses, or subject matter experts may be required.

It can be difficult to determine when to take the next step with explosives risk management and conduct a QRA. In general, explosives risk managers should apply QRA when the limits of Q-D are being stretched. Typically, this involves scenarios where the probability of an event occurring (P_e) is much different than the activity for which the Q-D standard was designed. For example, it may be inappropriate to use a Q-D standard designed for

explosives storage for a safer activity like ammonium nitrate storage, or a riskier activity like explosives waste disposal. Q-D limits are also stretched when scenarios involve extremes in the variability of various parameters that affect risk. For example, Q-D may be less desirable than QRA when thousands of individuals are exposed to risk or when only one individual is exposed every few days. Recognizing these extremes is the key; therefore, one must understand the levels of risk allowed by Q-D standards.

Table 1 shows how Q-D standards allow the quantitative level of risk to vary through many orders of magnitude for different yet compliant PES-ES pairs (PES is the Potential Explosion Site and ES is the Exposed Site). The variations were determined using the QRA tool IMESAFR V1.0 and the American Table of Distances (ATD) Q-D standard. Scenarios were considered that isolated and maximized the effect of each variable as much as possible and appropriate ranges from the ATD were used for distances between the PES and ES. For example, to evaluate the effect of glass, scenarios where glass was the dominant hazard were modelled. The spread in risk for Q-D compliant scenarios was measured as the variable changed and is shown in Table 1.

***Table 1**: Variation of Level of Risk using Q-D*

VARIABLE	UPPER LEVEL OF RISK[3]	LOWER LEVEL OF RISK[3]	RANGE OF RISK[4]
P_e (per year)	1	1×10^{-8}	8
Size of ES	7.0×10^{-2}	3.3×10^{-9}	7
Type of crater ejecta	2.2×10^{-3}	3.3×10^{-9}	6
Type of ES	1.1×10^{-3}	6.4×10^{-9}	5

[3] predicted fatalities/year to a single occupant of the ES given that an event occurs, unless otherwise noted

[4] Range of Risk is given in orders of magnitude (powers of 10)

***Table 1 (cont)**: Variation of Level of Risk using Q-D*

VARIABLE	UPPER LEVEL OF RISK[5]*	LOWER LEVEL OF RISK[5]	RANGE OF RISK[6]
NEW	2.5×10^{-4}	1.5×10^{-8}	4
Type of Explosive	3.4×10^{-4}	7.4×10^{-8}	4
Barricades	2.3×10^{-5}	1.5×10^{-8}	3
Number of exposures (people)	1.0×10^{3}	1	3
Size of PES	1.8×10^{-3}	1.5×10^{-5}	2
Percent glass (90-1) in ES	3.0×10^{-3}	3.4×10^{-5}	2
Type of PES	2.9×10^{-4}	1.5×10^{-5}	1
Type of glass in ES	2.5×10^{-4}	5.1×10^{-6}	2

Figure 1 shows details on how one of these variables, crater ejecta, can change the consequence factor in a QRA. The scenario, modelled by IMESAFR V1.2 in Figure 1, is an open PES (explosives in cardboard boxes are sitting on the ground in the open) and the ES is a vehicle at the unbarricaded, low-volume highway distance in the ATD for that NEW. This puts the individual relatively close to the PES in a structure that provides good protection from overpressure but little protection from debris.

Risk managers can infer several things from Figure 1. Except for rock, risk increases as the NEW increases even though the distance between the PES and ES increases. This is because larger NEWs create more hazardous crater ejecta that reaches the Q-D arc for that NEW. Also, placing the magazine on rock or crushed stone results in higher risk at all NEWs because these materials allow more hazardous crater ejecta to reach the Q-D arc than loose soil or concrete for a given NEW.

---

[5] predicted fatalities/year to a single occupant of the ES given that an event occurs, unless otherwise noted

[6] Range of Risk is given in orders of magnitude (powers of 10)

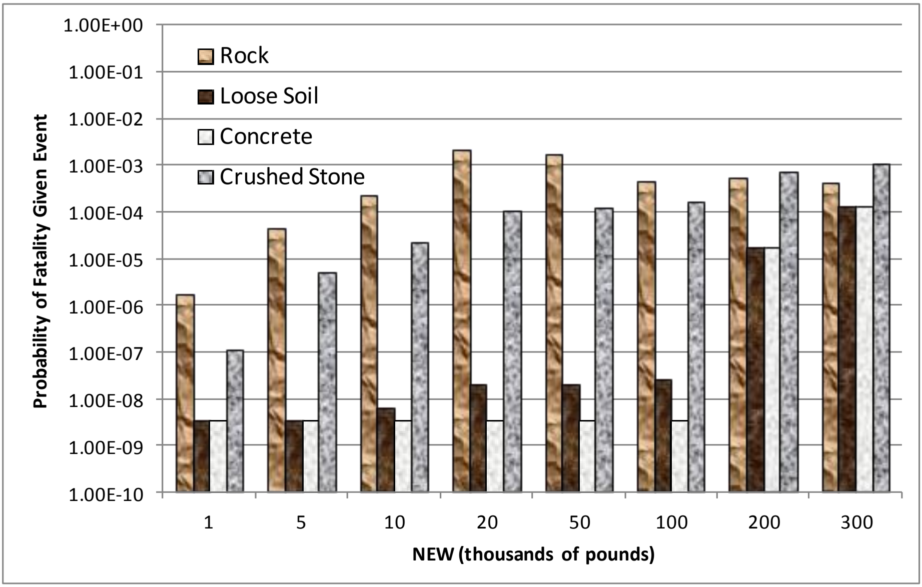

Figure 1: *Risk as a function of crater ejecta*

Risk managers can use this kind of information to make better decisions. For example, the reward for placing the PES on a concrete pad may be significant for NEWs up to 100,000 pounds (≈ 45,000 kg), but at 200,000 pounds (≈ 90,000 kg) and over, the risk rewards are much less. On the other hand, changes in NEW have little effect on risk from PES placed on rock.

In a particular scenario, it is impossible for all the variables in Table 1 to coincidentally fall on either the risky or safe side and produce an overall range of risk for Q-D equal to the sum of the rightmost column. Regardless of the probability of the event, Q-D standards are easily capable of allowing the risk of compliant scenarios to vary through 10 to 20 orders of magnitude or more. The goal of a good QRA should be to provide accuracy within one order of magnitude.

Risk ranging through the vast territory that Q-D allows makes risk managers nervous because the whole idea is to maintain a tolerable level of risk across all activities, thus providing a sustainable future for the overall endeavour.

QRA is far from perfect, but blindly following Q-D and allowing risk to be on either the extreme conservative or liberal side is ill-advised for the long-term. Extreme conservatism results in inefficiency and often causes increases and shifting of risk into other areas. Extreme liberalism creates excess liability and threatens long-term sustainability. Better knowledge of QRA principles helps minimize these extremes.

3.3. The Logistician and the Engineer

A logistician and an engineer were building bridges side-by-side across a river. The logistician asked the engineer, "Why are you building that bridge?" The engineer replied, "Because the people I work for want to connect both sides of the river. Boats cannot handle the traffic back and forth, which should not decrease in the foreseeable future." "How long is it going to take you?" asks the logistician? "About five years" says the engineer. The engineer then asks the logistician, "Why are you building that bridge?" The logistician says "You just answered that question."

So the logistician built his bridge in six months by copying a bridge that had stood for 100 years just down the river while the engineer toiled away. A year later, the engineer had still not broken ground when the logistician noticed he was packing up and moving up the river. "What's the matter, afraid to go up against my bridge, engineer?" mocked the logistician. "No," replied the engineer, "We determined this is not the best place to build a bridge, so we're going to build it upstream. Logistically, it is not as ideal a location as your bridge, but overall we like it better. Good luck with your bridge."

The logistician could not understand it. Why would the engineer delay his project another year and half and build his bridge upstream where the hills made getting to the banks of the river very difficult? Didn't the engineer understand that the bridge was just one link in the chain to get from A to B? The logistician was even more confused when seven years later the engineer opened the bridge, and it looked just like his bridge! What is wrong with the engineer, thought the logistician; it took him eight years longer than me to build a bridge just like mine in a place that is harder to get to. "I'll never

understand engineers," said the logistician.

A few years later a huge rainstorm swelled the river and washed away the river bank under the logistician's bridge. The logistician watched in horror as his bridge was swept downstream. Later he found out it smashed into the 100-year old bridge he copied and destroyed it, too. Sheepishly he approached the engineer. "I'd like to use your bridge to get from A to B, if that's ok?" "Sure," replied the engineer, "We're just lucky the water did not get a little higher, or we would have lost our bridge, too." The logistician could not help asking, "If you could have lost the bridge up here, too, why did you decide not to build the bridge where you started?"

The engineer replied, "We really wanted to build the bridge there, but after looking at all the geologic and weather data, we discovered that the cost to anchor the bridge abutments to the river bank was intolerable. And it would have taken three more years. So we moved upstream where bedrock is closer to the surface. We used 100-year flood data with a safety margin to figure how high above the water the bridge needed to be, and it was just enough. It cost us more to build and maintain, and everyone was disappointed in the delays, but we built this bridge to last 100 years so in the end, we were glad to know. Aren't you?"

The allegory to QRA and Q-D in the parable above comes from my experience with people's realization that QRA may not always allow relief from Q-D standards. The bridges represent risk from an explosives activity and the route from A to B represents risk from all things. The combined use of geology and meteorology data to look at one element of the explosive activity risk represents QRA and blindly copying what worked elsewhere represents Q-D. The role of the logistician and the engineer are played by themselves.

In most cases QRA will show that Q-D compliant situations are extremely low risk, with the risk of fatality less than 1 in 10 billion. But sometimes, QRA will show that the risk allowed by Q-D is above generally tolerable levels. Engineers tend to meet this realization with inquisitiveness, a desire to learn more about why the unintuitive is happening and take appropriate

action. Logisticians see many apple carts being overturned.

Being an engineer, I have difficulty understanding the "head-in-the-sand" reaction. Except of course if the intent is to make some quick cash and then close up shop like a roadside fireworks stand after the holiday. (A tradition in the U.S. around July 4th and I suppose at other times around the world.) I have nothing against these patriotic entrepreneurs but I do not think many of them are reading the SAFEX newsletter. I am sure that readers of the SAFEX newsletter are in this profession for the long haul and nothing screams UNSUSTAINABILITY like causing mass casualties while using century-old technology.

SAFEX readers want to know the truth, even if it is so-called "bad news;" because they know that ignoring "bad news" will eventually lead to "worse news." This is an essential SAFEX's founding principle; to suffer the consequences of sharing "bad news" about incidents so that similar incidents might be prevented elsewhere, even if it is at your competitors' operations. Are you the logistician or the engineer in the parable?

Other situations where Q-D might not provide the degree of protection we envision include large and relatively weak exposed buildings such as concrete tilt-ups near NEWs over about 50,000 kg, relatively unprotected exposed sites on the normal to donor walls that create large amounts of horizontal secondary debris, exposed sites with large amounts of glass, and exposed sites with a high density of people.

3.4. All I need is more distance, right?

Directional effects are often demonstrated by secondary debris; testing has demonstrated how various roof and wall constructions stop such debris. In this Section, we will discuss how we can use this information and what it gains us. Readers unfamiliar with directional secondary debris effects may find it beneficial to review Section 4.4 prior to reading this section.

Just as the roof protects against debris falling from the sky, an exposed structure's (ES) wall construction has a significant influence on horizontal, high velocity debris. It stands to reason that a reinforced concrete ES with a

thick concrete roof will protect occupants from all debris much better than a modular trailer. So in a scenario where debris is the primary hazard, we want any exposed people to be in concrete structures. This kind of scenario may involve an event with a moderate amount of explosive that generates lots of primary fragments, in a building that creates lots of secondary debris. The occupants of a robust ES are protected against the debris as much as possible, even if the ES is in a high debris density region.

On the other hand, in a scenario when the primary hazard is building collapse from overpressure, we would rather have people in an ES like a flimsy and flexible trailer. This kind of scenario may involve a large amount of explosive in the open that does not generate a lot of debris and an ES subjected to significant overpressure and impulse.

Now add directionality of the debris field to the equation, and we have some very powerful yet basic tools for risk management. Figure 2 shows a hypothetical scenario modelled in IMESAFR v2.0 with two types of ES at the same distance from a potential explosion site (PES). As in all the examples below, the ES meet the quantity-distance standards used in the U.S.

The PES is a medium sized concrete structure with 13,600 kg (30,000 lb) of metal cased explosives. The two ES are large pre-engineered metal buildings (PEMB), similar to those called “high-bays.” As in all the following examples, the ES have one occupant each and distances are shown in feet.

Figure 2 is a screenshot with annotations from the software and shows many of the critical inputs and outputs to the scenario. The various shaded areas are debris density contours.

A “Quick Report” for ES1 is shown in Figure 2 and displays certain key information about the relationship between ES1 and the PES. In this section, we will primarily discuss the bar charts at the bottom of the Quick Report. These show the probability of fatality given an event occurs ($P_{f|e}$) for each hazard mechanism. In this scenario, horizontal debris (the green bar) is the dominant hazard mechanism to occupants of the ES, followed by vertical debris (the dark grey bar).

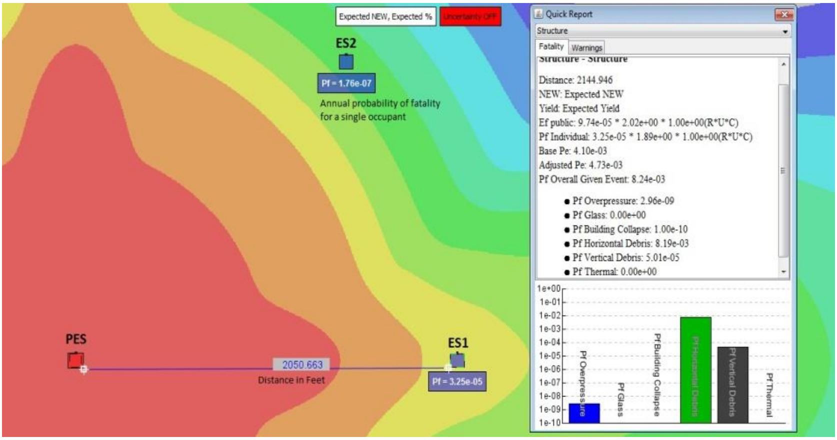

***Figure 2**: Debris sensitive ES around a debris generating*

Because ES1 is in a higher debris density area, over two orders of magnitude difference in risk exists between the two ES. The $P_{f|e}$ to a person in ES1 located off the normal to a side wall is 8.24 x 10^{-3} (1 in 121). In ES2, located on the corner, the $P_{f|e}$ is 4.47 x 10^{-5} (1 in 22,400). The only difference between the two ES is their orientation to the PES.

Figure 3 illustrates a hypothetical situation with two structures at the same distance from a PES that does not generate a lot of debris or show secondary debris directionality.

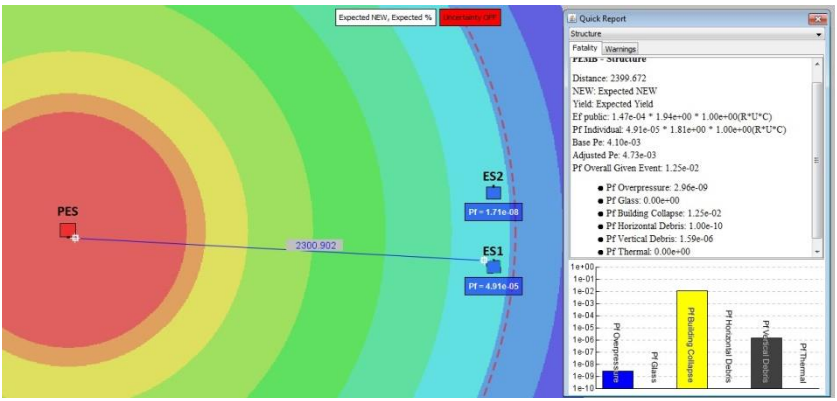

***Figure 3**: Overpressure and impulse sensitive ES around a PES with high NEW.*

This time, over three orders of magnitude difference in risk exist between the two ES at identical distances. The PES is 136,000 kg (300,000 lb) of boxed explosives in the open. ES1 is a large PEMB and ES2 is a small trailer. The Quick Report shows that the primary risk in the PEMB is from building collapse (the yellow bar). The $P_{f|e}$ to a person in ES1 is 1.25 x 10^{-2} (1 in 80). In ES2, the $P_{f|e}$ is 4.35 x 10^{-6} (1 in 230,000). The only difference between the two ES is the structure type. The large PEMB acts like a sail and "catches" the overpressure, leading to building collapse, while the trailer remains standing -- or presents less risk to occupants if it does collapse.

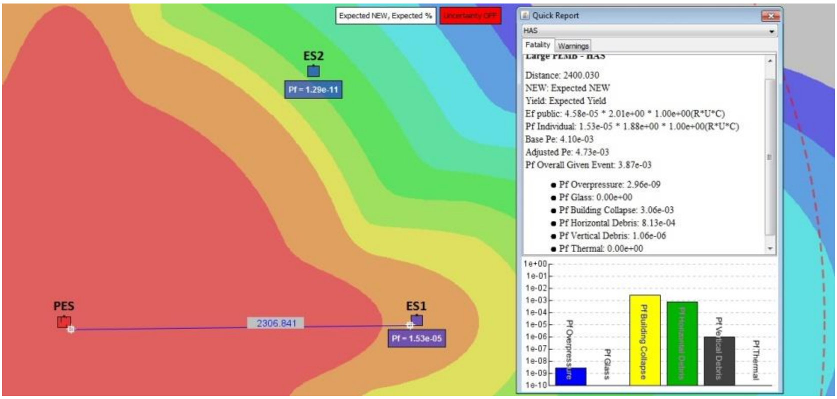

Figure 4. *An extreme example of differences in risk at the same distance from a PES*

Figure 4 shows how these two phenomena can combine for an even greater effect. The PES is 136,000 kg (300,000 lbs) of explosives in a large unreinforced concrete structure. ES1 is a large PEMB and ES2 is a small reinforced concrete bunker with a 36 cm (14 in) thick concrete roof. Except for the building type and azimuth relative to the PES, all other aspects of the two ES are identical.

The explosives event at the PES would create significant debris and overpressure. The thin metal skin and large surface area of the PEMB makes it susceptible to both hazards. The small bunker, on the other hand, is hardened against both hazards. The difference in risk at the two ES is astounding: over six orders of magnitude. The $P_{f|e}$ to a person in the PEMB

is 3.91 x 10^{-3} (1 in 256). In the bunker, the $P_{f|e}$ is 3.26 x 10^{-9} (1 in 307 million). The only differences between the two ES are the orientation to the PES and the structure type.

By most Q-D standards, both ES are acceptable, but outside that context, it would be hard to justify allowing such vast differences in risk at the two ES. When still in the planning stages, many options exist, including distance, to even-out the risk at the two ES. Even when faced with an existing situation like this, there are options to mitigate the risk at ES1.

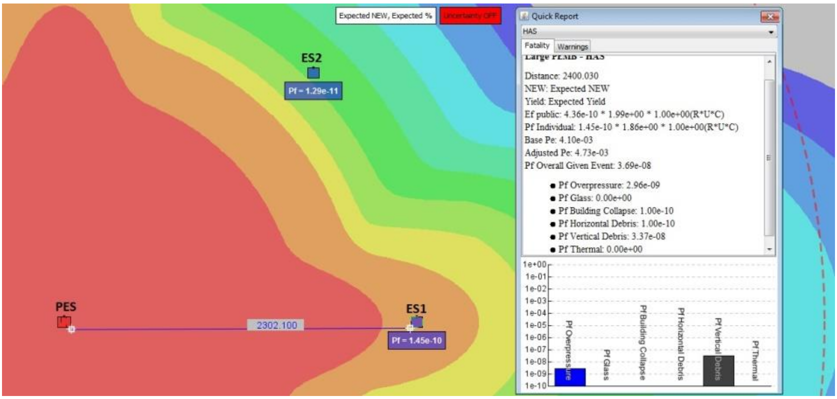

Figure 5. *Same scenario as Figure 4 but with risk mitigating measures.*

Figure 5 shows the same scenario as Figure 4, with three changes: (1) the installation of a barricade to shield ES1 from overpressure; (2) changing ES1's structure type from a large PEMB to a large tilt-up concrete structure to simulate installation of a brick or concrete facade on the side of the PEMB facing the PES; and (3) replacing the sheet metal roof of ES1 with a 10 cm (4 in) reinforced concrete roof. (Note: Large PEMB and large tilt-up concrete structures respond similarly to overpressure and impulse.)

Each of these changes addresses one of the three primary hazards at the PEMB. The overpressure barricade eliminates the threat of building collapse, the brick facade stops all horizontal debris and the protection added to the roof greatly reduces the threat of vertical debris. The risk at

both ES is now only an order of magnitude different.

This series of modelling scenarios shows how changes to just a couple of variables can have profound effects on risk. When all the variables that can increase and decrease risk are considered, the differences can be astronomical. Distance is still a factor, but clearly it can be overridden by PES orientation and ES construction. The key is to avoid building new sites with unintentionally high risks and to recognize risk imbalances at existing sites; then taking intelligent action to mitigate the risks.

3.5. A Quantitative Snapshot of the American Table of Distances' (ATD) Inhabited Building Distances

We have discussed how quantity-distance (Q-D) standards allow a wide range of risk depending on the specific circumstances. For example, one of the most obvious circumstances is exposure. Most Q-D standards make no distinction on how many individuals can be exposed beyond a certain distance. Yet based on exposure alone, the risk to the group can easily range through several orders of magnitude. The exposed structure(s) (ES) could be a single dwelling or an apartment complex.

We have also discussed how the pairing of certain types of ES with a certain types of potential explosion sites (PES) can lead to wide swings in risk. For example, it is undesirable to pair an ES that is vulnerable to debris with a PES that throws a lot of debris at the ES. On the other hand, an ES that is resistant to debris hazards in the exact same circumstances may be tolerable. In this article we conduct a QRA of a specific ES-PES pair by determining the annual probability of fatality [P_f] at the various distances provided by the Institute of Makers of Explosives' Metric American Table of Distances (ATD) using IMESAFR V2.0.464.

The PES structure used in the model was a steel magazine with exterior construction of 0.63 cm [0.25 in] steel lined with 7.6 cm (3 in) of hardwood. As the net explosive weight (NEW) in the model increased, the size of the steel PES increased accordingly as shown in Table 2.

Table 2: *Description of the PES structure used in QRA modelling*

Type of Steel PES	Minimum NEW		Maximum NEW		Volume		Length / Width		Height	
	kg	lb	kg	lb	m^3	ft^3	m	ft	m	ft
Very Small	0	0	1,100	2,400	13	450	2.4	8	2.1	7
Small	1,100	2,400	10,000	22,000	28	1,000	3.7	12	2.1	7
Med.	10,000	22,000	75,000	170,000	140	5,000	7.6	25	2.4	8
Large	75,000	170,000	135,000	300,000	310	11,000	10	33	3.0	10

The magazine was modelled sitting on crushed stone with the activity being explosives in long-term commercial storage for 8,760 hours per year. The explosives were Division 1.1D with no primary fragments. No environmental factors (conditions that would increase or decrease the probability of event from the default value) were applied in the model. Entering these data into IMESAFR produced an annual probability of an explosives event of 2.99×10^{-5}.

IMESAFR requires entry of a maximum and expected NEW, and allows the user to model the debris as varying by azimuth (or angle) from the PES or not. The same NEW was entered as the maximum and the expected NEW to minimize the effect differences in these two numbers can have. Debris density was set to vary with azimuth from the PES in the model, replicating the expected debris pattern from explosives stored near the centre of a square steel magazine.

Several ES properties must be entered into the IMESAFR model. The ES structure was a small, wood frame stud wall building with 10 percent of the surface area consisting of dual pane glass. The roof was modelled as plywood/wood joists (5 cm x 10 cm on 40 cm centres) and the ES was assumed to always be intact for all low angle fragments (this setting allows a damaged ES to protect occupants from horizontal debris but not from vertical debris). One person was assumed to be inside the ES for 6,000 hours a year. When modelling at the barricaded Q-D distance, a barricade

capable of stopping high-velocity horizontal debris was entered into the model. The barricade could be any size or construction capable of doing that.

The average NEW amount within the range specified in one row of the Institute of Makers of Explosives' American Table of Distances (ATD) was used as the NEW in the model, and the distance to the ES was the inhabited building distance (IBD) listed in the table for that NEW. For example, for the scenarios modelled using the highlighted row in Table 3, the NEW was 7.5 kg and the distance to the ES was 34 m in the barricaded scenario and 68.9 m in the unbarricaded scenarios.

***Table 3**: The first five rows of the IME Metric ATD for inhabited buildings.*

Quantity of Explosive Materials		**Distances from Inhabited Buildings (m)**	
kg Over	kg Not Over	Barricaded	Unbarricaded
0	3	21.3	46.6
3	5	29.4	56.1
5	10	34.0	68.9
10	15	39.0	79.0
15	20	43.6	87.8

The P_f to the individual in the ES for each row above 100 kg in the metric version of the ATD as calculated by IMESAFR is shown in Figure 6. The blue symbols show the P_f at the unbarricaded distance 180 degrees from the front of the PES. Since the PES is square and has equal mass in each wall, this represents the risk normal to any of the PES walls. The red symbols show the P_f at the unbarricaded distance 135 degrees from the front of the PES. This represents the risk directly off any corner of the PES. The green symbols show the P_f at the barricaded distance 180 degrees from the front of the PES. Keep in mind that the distance in the barricaded (green) scenarios is about ½ of the distance in the unbarricaded (blue and red) scenarios for the same NEW. The various symbol shapes correspond to the factor(s) driving the risk in those circumstances and shown in the legend of the charts.

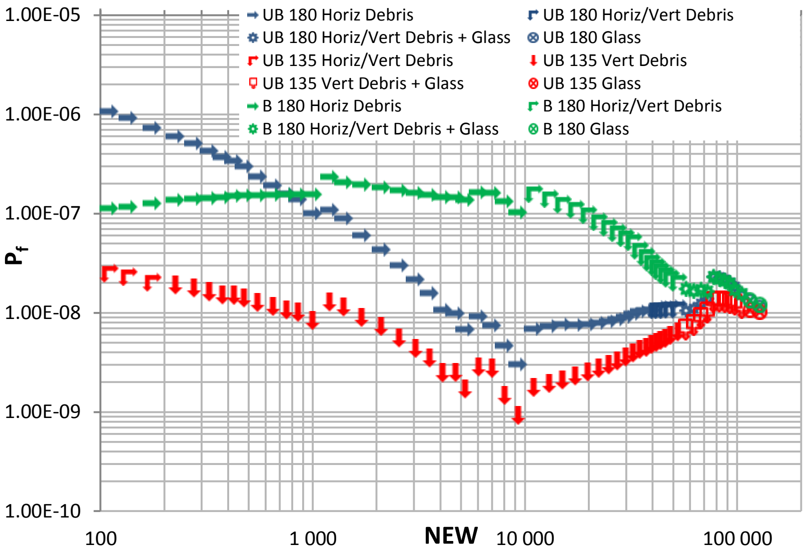

Figure 6: *P_f versus NEW at the distance specified in the Metric ATD above 100 kg*

As expected, the P_f heavily depends on the NEW, distance, azimuth to the ES and presence of a barricade; ranging over three orders of magnitude in this particular scenario. Also evident is how different hazards (horizontal debris, vertical debris, and broken glass) control the risk in different circumstances.

Figure 7 shows only the unbarricaded trends from Figure 6. The difference between the blue and red symbols at any particular NEW is entirely caused by the azimuth from the PES to the ES. As one might expect, horizontal debris is the primary hazard normal to the walls up to about 40,000 kg, while vertical debris is the primary hazard off the corners. But as the NEW increases above 40,000 kg, vertical debris and glass become more of a concern regardless of azimuth.

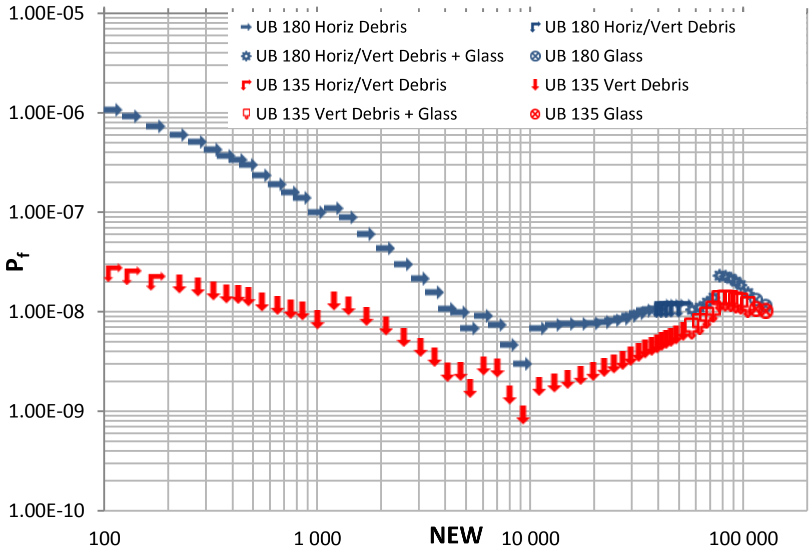

Figure 7: *Risk normal to the magazine wall (blue) as compared to risk off the corner (red)*

The effect of the increased PES mass when the model switched to the next larger PES is evident in the upticks in all three scenarios at about 1,000 and 10,000 kg and circled in Figure 8. But the effect is not as prevalent at the switch around 75,000 kg, especially in the unbarricaded scenario off the corner, because debris alone is no longer driving the risk; risk from broken glass is now a factor. Notice how the switch to a medium steel magazine at 10,000 kg elevates vertical debris risk to equal hazard status as horizontal debris risk for the barricaded scenarios from 10,000 to 40,000 kg.

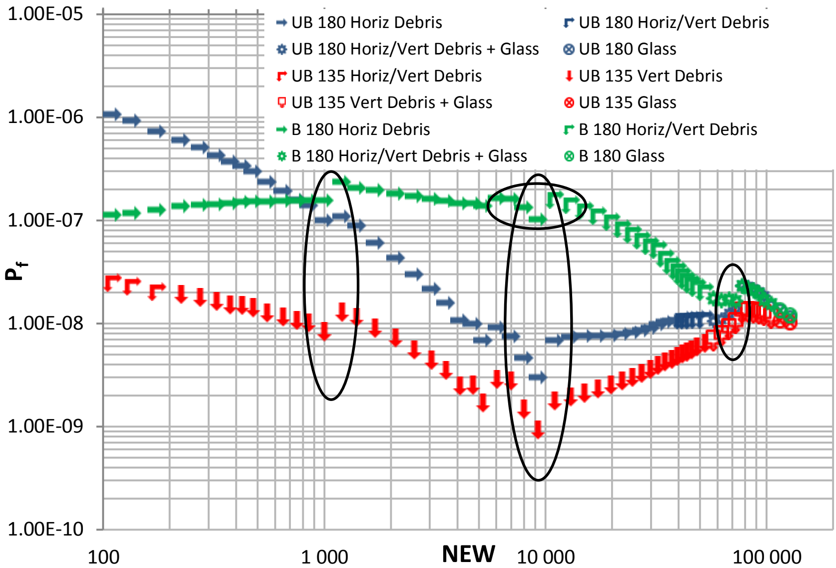

***Figure 8**: Upticks in P_f when magazine switched to next largest size*

The ATD has a section from 10,000 to 80,000 kg NEW where the unbarricaded distance remains constant at 610 m. This section is shown in Figure 9 P_f increases as NEW increases in this region, but perhaps not as much as one would expect, especially off the wall normals as compared to off the corners. Although NEW increases eight times within this range, P_f off the normal only increases three times while P_f off the corners increased over seven times. The differences in horizontal and vertical debris densities at this distance and these NEW are the cause. Simply put, vertical debris density increases more rapidly compared to horizontal debris density as NEW increases within this range of NEW.

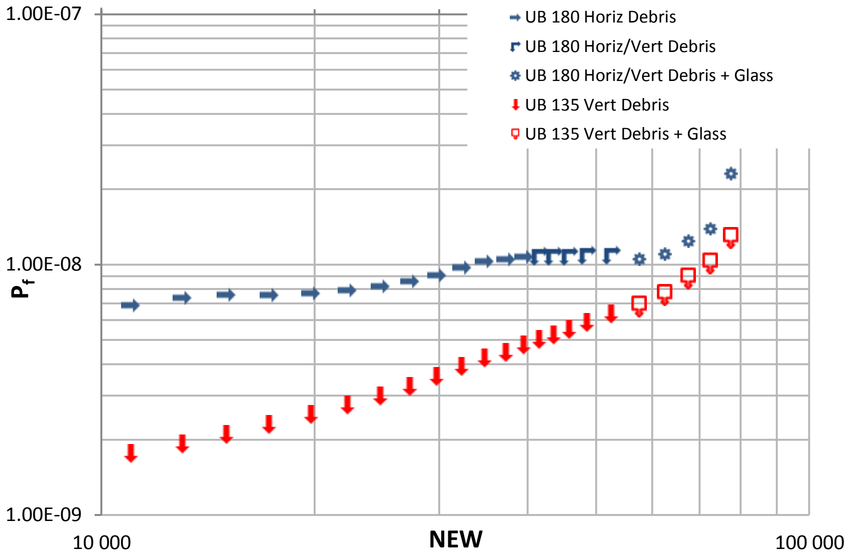

Figure 9: P_f *through the "plateau" region of the metric ATD*

Figure 10 shows that the barricaded P_f is from one to two orders of magnitude higher than unbarricaded P_f at the same NEW around 10,000 kg. This difference would be greater if the trends established from 1,000 to 5,000 kg continued to 10,000 kg. For some reason, the IBD decreases as NEW increases in the metric ATD from 4,900-5,550 to 5,600-6,500 kg. As NEW increases to about 10,000 kg, the trend continues, creating saw tooth patterns in the three scenarios.

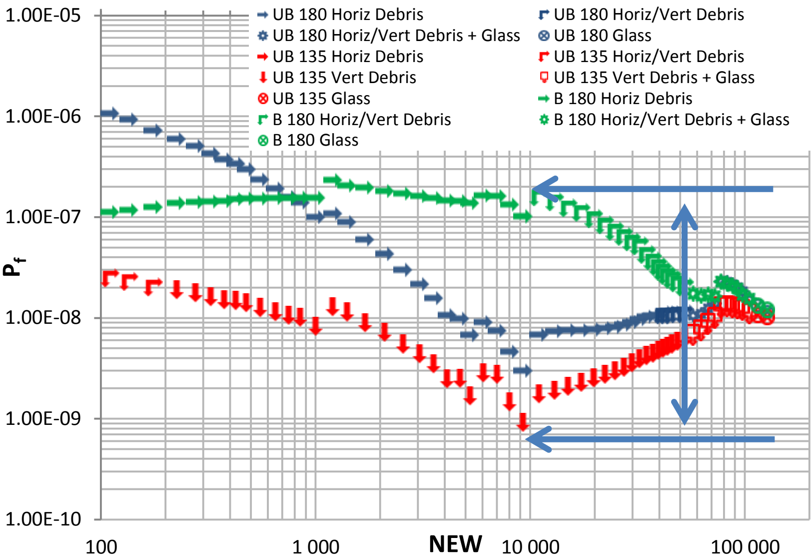

***Figure 10**: Extreme differences in risk between barricaded and unbarricaded scenarios at the same NEW*

As shown in Figure 11, the P_f in all three scenarios comes together at around 1 x 10-8 above about 50,000 kg. But depending on azimuth, risk is being driven by different sources until the NEW gets a bit over 100,000 kg. At 180 degrees, all three hazards are about equal while only glass and vertical debris drive risk at 135 degrees. Above 100,000 kg, glass takes over as the dominant hazard in all three scenarios.

Readers may wonder why horizontal debris is a driving factor in the barricaded scenario. The reason is that barricades are generally only effective against high-velocity horizontal debris. In the IMESAFR model, as in real life, a significant amount of horizontal debris can fly over barricades and still hazard ES occupants.

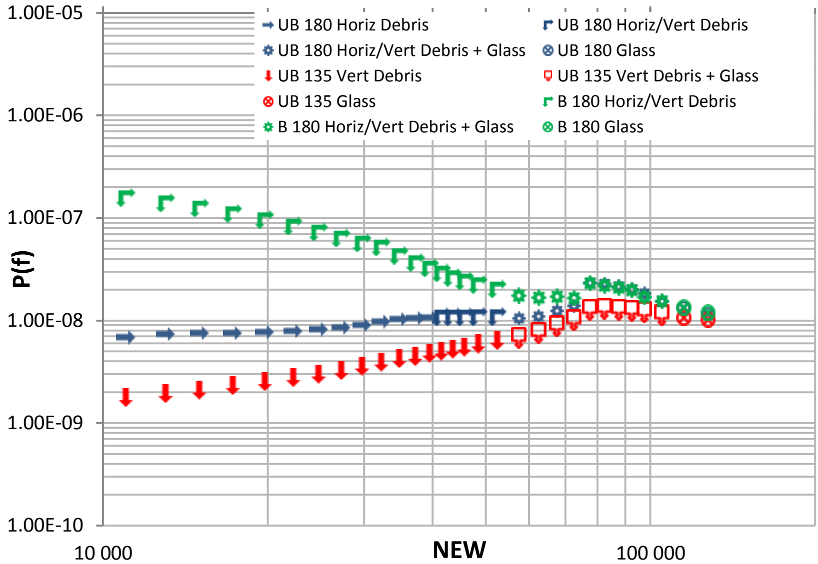

Figure 11: *Convergence of P_f in the 3 scenarios*

The discussion above shows how Q-D standards allow risk to roam through wide ranges rather arbitrarily and how QRA identifies the different actions needed to address specific circumstances. For example, building a barricade in this scenario would have virtually no effect on P_f in an ES off the corner of the PES or if the NEW went above 40,000 kg. Although Q-D keeps risk below generally considered tolerable levels, QRA can identify easy ways to make significant improvements in risk.

Changing parameters such as the type of PES or ES structure in the scenarios may result in a chart very different in appearance than Figure 6. For example, if an ES structure susceptible to collapse from overpressure was used, we would see that hazard introduced into the mix and the shapes of the trends in Figure 6 would change. If the PES was changed to a structure type that generates more debris than steel structures, then we would see increased debris hazards across the board. In some situations, the risk may be above generally accepted tolerable levels.

4. TESTING (Michael Swisdak)

4.1. Large scale testing for QRA in the last decade

The year is 2002 and Version 2.0 of the DoD quantitative risk assessment software SAFER has just been released. The DoD's Risk Based Explosive Safety Criteria Team (RBESCT) has spent ten years and over four million dollars developing a state-of-the-art, semi-empirical QRA model. The observations and experiments upon which the model is based come from the existing literature. Largely, this includes U.S. DoD as well as international testing on explosive safety and human response. Where data were lacking or incomplete, the RBESCT made conservative assumptions in the SAFER algorithms.

Seeing a need to fill in some of the gaps but also recognizing that obtaining all the data they wanted was impractical, the RBESCT asks its technical advisory group, the U.S. DDESB Science Panel, for assistance. The Science Panel is asked to assess the maturity of the science behind the software and to propose a testing program that would address areas of conservatism introduced by a lack of established test data. In order to create a testing program that would fill in the gaps that most severely limited the development of algorithms (yet were feasible to address with testing), the Science Panel identified the following three most important issues:

- ISSUE 1: Secondary or donor (PES) debris generation and density versus distance,
- ISSUE 2: Target building (ES) response to blast loading, and
- ISSUE 3: Target building (ES) protection against debris afforded to occupants.

Two series of tests were proposed to address these issues, with the SciPan program addressing ISSUE 1 and ISSUE 2, and the SPIDER (Science Panel Impact Data Evaluation and Review) program addressing ISSUE 3. Because of the manner in which these programs were structured, the results would benefit both the Q-D community and the risk assessment community. Planning for both the SciPan and SPIDER testing began immediately. Moving forward to the present, the SciPan program is nearing completion while the

SPIDER program is about halfway done.

The SciPan program derives its name from an abbreviation for the DDESB Science Panel and is in no way affiliated with the city/island of Saipan in the Northern Marianas Islands. The SciPan test series is structured to examine the break-up and debris generation of reinforced concrete and masonry structures exposed to internal detonations of varying sizes. Where feasible, various types of structures would be exposed to the air overpressure produced by these detonations in order to ascertain their behaviour under blast loading. SciPan 1 and SciPan 2 were conducted in 2003. SciPan 1 involved the detonation of 12,249 kg (27,000 lb) of flaked TNT inside the test structure and also examined the blast response of a nearby, large tilt-up concrete panel structures. SciPan 2 provided a blast-only environment for the large tilt-up reinforced concrete structure tested as an ES on SciPan 1 by detonating a 2,270 kg (5,000 lb) hemisphere of TNT external to the ES structure. SciPan 3 was conducted in 2005. It involved the detonation of 27,200 kg (60,000 lb) of flaked TNT inside the test structure and also studied the blast response of brick and concrete masonry structures exposed to the airblast produced by the detonation. Figure 12 shows a SciPan PES, the SciPan explosive charge, and the debris cataloguing after the event.

SciPan PES ***SciPan 5 Charge*** ***SciPan Debris Cataloguing***

Figure 12. *Scipan Testing*

One of the major sources of uncertainty in the performance of risk-based explosives safety analyses is the amount of protection that is provided by an exposed site. The SPIDER program was designed to address this issue. Specifically, this program examines two key questions:

1. How are material type, mass, and velocity of debris used to predict

perforation of and damage to specific roof and wall types?

2. What is the resultant hazard to occupants posed by fragment perforation and damage?

SPIDER 1, which looked at debris impact effects on typical roofing materials, was conducted in 2004. Figure 13 shows typical SPIDER testing.

Figure 13. *SPIDER Testing*

Figure 14. *ISO Container Detonation*

Around 2005, with military operations intensifying in the Middle East, questions were being raised about the effects of detonations inside ISO containers. A third testing branch was designed and the first test on ISO

containers (ISO-1) was conducted in May 2006. It involved the detonation of 1,054 kg (2,324 lb) of ANFO inside an ISO container located on the back of a truck. Figure 14 shows the fireball from one of the ISO container tests.

Based on the initial success of these programs (SciPan, SPIDER, and ISO), the DDESB asked the Science Panel to prepare a formal testing effort that would include those test series already underway as well as to propose additional work in other explosive safety areas. The program was formalized in February 2007 as a ten-year effort with testing proposed in the following areas:

- SciPan,
- SPIDER,
- ISO Container,
- Modelling of exposed structure behaviour under blast and debris impact,
- General debris physics experiments, and
- Earth-covered magazine (ECM) debris

This effort was viewed as a continuation of an earlier DDESB testing program known as Project ESKIMO conducted between 1971 and 1985. ESKIMO was an acronym for Explosive Safety Knowledge IMprovement Operation. The goal of this program was to determine more accurately the minimum safe separation distance between earth covered magazines storing high explosives. This new program, designed to continue the successful ESKIMO work, is known as Project ESKIMORE (Explosive Safety Knowledge IMprovement Operation--REdux).

Since its formalization in 2007, Project ESKIMORE testing has continued:

- SciPan 4 was conducted in August 2008. It examined the effects of a 1,000 kg detonation of flaked TNT inside the structure.
- SciPan 5 was conducted in June 2011. It examined the effects of a 3,000 kg detonation of flaked TNT inside the structure.
- SPIDER 2 was conducted in the summer of 2009. It examined the effects of impact on typical wall materials.
- ISO-2 was conducted in March 2007. It involved the detonation of

4,000 kg of ANFO inside an ISO container that was sitting on a truck.

- ISO-3 was conducted in March 2009. It involved the detonation of 1,000 kg of high explosive projectiles inside an ISO container that was sitting on the ground.
- ISO-4 was conducted in September 2010. It involved the detonation of 1,000 kg of Composition C-4 plastic explosive inside an ISO container sitting on the ground.
- ISO-4 Retest was conducted in December 2010. It again involved the detonation of 1,000 kg of Composition C-4 plastic explosive inside an ISO container sitting on the ground.

In addition to ESKIMORE, other allied nations have conducted and collaborated on large-scale explosives tests in the last 10 years. These include but are not limited to the United Kingdom, Belgium, Netherlands, Canada, and the KLOTZ group (a consortium of nations made up of the United States, Germany, Netherlands, Norway, Singapore, Sweden, Switzerland, and the United Kingdom).

4.2. SciPan – A test series to determine the response of reinforced concrete and masonry structures to blast loading

Accurate QRA models depend on debris hazard prediction methods that are validated against full scale tests. When the effects of gravity are important, tests conducted at a reduced scale may not provide reliable data. The SciPan test program, which was planned as testing at full scale, was designed to help fill these data needs.

The SciPan test series has been structured to examine the break-up and debris generation of reinforced concrete and masonry structures exposed to internal detonations of varying sizes. In addition, where feasible, various types of target structures have been exposed to the air overpressure produced by these detonations in order to ascertain their behavior under blast loading.

The PES dimensions and building materials were chosen to represent those of typical operating buildings. The building designs included a floor slab and foundation as well as reinforced concrete and masonry walls and a reinforced concrete roof. The PES was designed for normal dead plus live loads (in other words, the PES was not a hardened structure). Figure 15 shows the nominal PES configuration for a 1000 kg detonation, which corresponds to the fourth test in the series, SciPan 4.

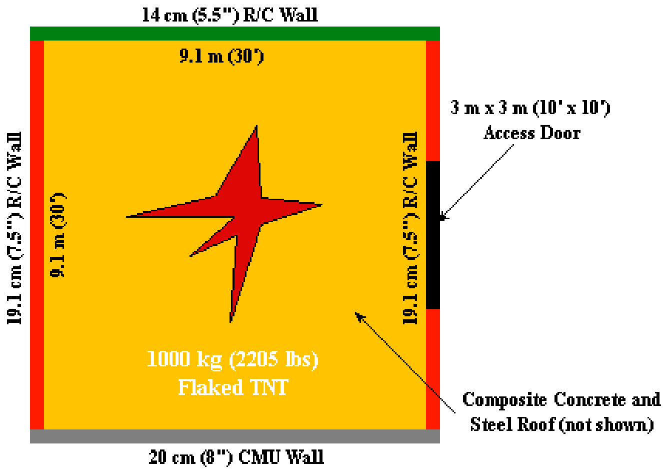

Figure 15 *SciPan 4 PES Nominal Configuration*

As depicted in Figure 15, three different PES wall cross-sections were included in each test:

- 14 cm thick reinforced concrete (R/C) with a grid of no. 15 (Metric) rebar spaced @40 cm centre-to-centre (40 cm centres)
- 20 cm R/C, and with a grid of no. 15 rebar @ 40 cm centres
- Fully-grouted, reinforced 20 cm Concrete Masonry Units (CMU) with a grid of no. 15 rebar vertical @ 40 cm centres and No. 15 rebar horizontal @ 80 cm centres

In each test, the roof was a composite section, as shown notionally in Figure 16; it had a corrugated metal deck with an R/C fill, and a grid of no. 10 rebar @ 40 cm centers. The average thickness of the R/C was about 11 cm. The roof was supported with steel beams spanning the length of the structure. Similar to the roof, the floor slab on each test was 10 cm thick R/C with No. 10 rebar @ 40 cm centers each way.

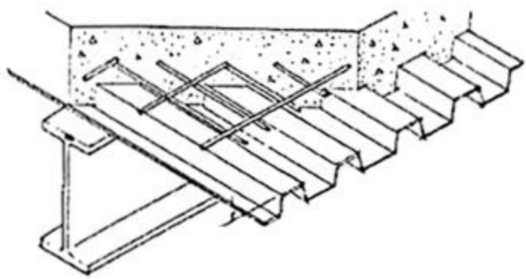

***Figure 16**: Composite Roof Cross-*

Table 4 provides a brief summary of the tests that have been conducted thus far during the SciPan test program.

***Table 4**: SciPan Program Summary*

Test	Date	NEQ** (kg)	Loading Density*** (kg/m^3)	PES Volume (m^3)	PES Dimensions	Exposed Site (ES) Description
SciPan 1	4/19/2003	12,249	11.74	1,043.9	14.6 m x 14.6 m x 4.9 m	(1) 139.7 mm Tilt-up RC Wall/Wood Roof (2) 190.5 mm Tilt-up RC Wall/Wood Roof
SciPan 2*	7/9/2003	2,270	NA	NA	N/A	(1) 139.7 mm Tilt-up RC Wall/Wood Roof (2) 190.5 mm Tilt-up RC Wall/Wood Roof
SciPan 3	4/6/2005	27,218	106.79	254.9	9.1 m x 9.1 m x 3.0 m	(1) 203 mm Unreinforced CMU/Wood Roof (2) 203 mm Double Wythe Brick Wall/Wood Roof (3) Concertainer Barricade****
SciPan 4	8/27/2008	1,000	3.92	254.9	9.1 m x 9.1 m x 3.0 m	(1) Concertainer Barricade****
SciPan 5	6/8/2011	2,991	11.74	254.9	9.1 m x 9.1 m x 3.0 m	(1) Concertainer Barricade****

* No PES
**Flaked TNT used as explosive on each test
***Explosive Weight/Structure Volume

****The concertainer barricade design provides a cellular structure using a welded mesh framework with a geotextile lining. It can be filled with local material such as sand or soil.

Figure 17 shows three views of the SciPan 4 PES. The photo on the left shows the intersection of the 20 cm CMU wall with the 20 cm wall with the opening into the structure. The center photo shows the 14 cm wall and the concertainer-type barricade. The photo on the right shows the intersection of the 20 cm R/C wall with the 14 cm R/C wall.

The SciPan test series has produced several kinds of unique information.

Figure 17 *SciPan 4 PES*

This information has significantly contributed to the science of both explosive-safety quantity-distance (ESQ-D) and QRA. These data sets include, but are not limited to, the following:

- Effect of concertainer-type barricades on debris density,
- Mass distributions (debris sizes) for R/C of various thicknesses as a function of loading density,
- Quantification of both the range and angular dependence for the debris density from R/C and masonry structures (quantification of the cruciform debris pattern),
- Initial velocities, launch angles, and uncertainty for the debris produced by explosions inside R/C and masonry structures
- Better estimates of the range at which the density of hazardous fragments falls below a value of 1 hazardous fragment per 56 m^2 (1 per 600 ft^2) for R/C structures.

As an introduction to these topics, this Section provides a summary of one of these results—the effect of concertainer-type barricades on debris density.

As indicated in Table 4 the effects of concertainer-type barricades on debris density were examined on three of the SciPan events. Figure 18 shows the

measured debris density (number of debris strikes per square meter) as a function of range for both the barricaded and unbarricaded direction for the SciPan 3 event. As can be seen in this figure, the barricade has the effect of reducing the total number of debris strikes out to a range of about 700 m from ground zero. Figure 19 shows the remains of the barricade after the detonation. The portion of the barricade that was located directly in front of the opening in the 20 cm wall was completely obliterated, while the rest of the barricade remained standing, albeit after sustaining massive damage.

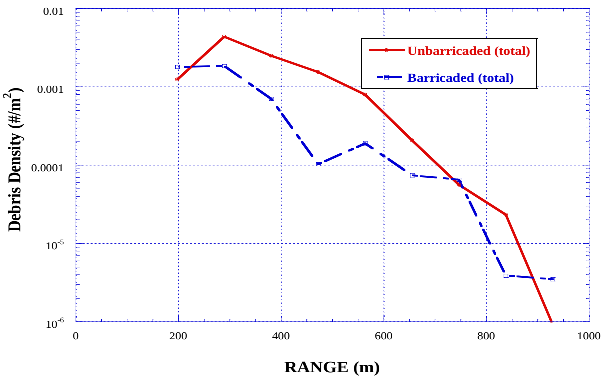

Figure 18: *Barricade Effect on Debris Density*

Figure 19*: Barricade Remains—Post Detonation*

This section has provided an introduction to the SciPan testing program which was designed to provide much-needed information in two areas:

- Secondary or donor (PES) debris generation and density versus distance, and
- Target building (ES) response to blast loading.

4.3. SPIDER—A Test Series to Determine the Response of Typical Roof and Wall Materials to Debris Impact

In order to differentiate between exposures in the open and in different types of buildings, explosive QRA models rely on being able to accurately predict the likelihood of debris penetrating or perforating the roofs and walls of exposed sites (ES). Assuming the structure does not collapse, no other factor has as much effect on the risk to occupants of an ES as the nature of its construction. In 2004, the SPIDER program was established as part of the DDESB Project ESKIMORE to determine the degree of protection that is provided by an ES for typical construction practices in the United States. Specifically, this program was designed to examine two key questions:

1. How are the material shape, type, mass, and velocity of debris used to predict perforation of and damage to specific roof and wall types?
2. What is the resultant hazard to occupants of an ES posed by fragment perforation and damage?

Prior to the start of the program, it was decided that one of the variables, impactor shape, would not be initially addressed and that a single shape would be employed for both the roof and wall tests. To ensure that debris orientation did not affect the results and to enhance the ability to model the events (since most predictive models have a difficult time handling more realistic debris shapes) it was decided that spherical impactors would be utilized. Except for cannon balls, it is doubtful that any debris would actually be spherical; however, as a first step, this minimizes variables coming from the impactor and allows better comparison of the construction of various

wall and roof types. As will be explained, the results show how important the shape of the impactor is with constructions such as sheet metal.

On both the roof and wall tests, two types of material, representing the most common types of explosion-produced debris, were utilized for the impactors—steel and concrete. The steel impactors used in the tests were commercially available, while the concrete impactors were prepared by the testing organization. A minimum compressive strength of at least 20.7 MPa (3,000 psi) was specified for the concrete.

On all tests, a distinction is made between perforation and penetration. The term perforation is used to indicate that the entire impactor passed through the target, whereas penetration refers to the impactor breaking the surface plane of the front face of the target (but not exiting through the rear face of the target).

On SPIDER 1, which examined roof impacts, it was further assumed that the only way that debris could reach a roof was via a trajectory with a high launch angle. Such material would have an impact velocity no greater than the terminal velocity of the material, which in all cases would be less than about 100 m/s. SPIDER 2, which investigated wall impacts, did not have this velocity restriction. The impacts considered on these tests could reach significantly higher velocities.

The following information was collected on each test: (1) impactor mass; (2) impact velocity; (3) perforation (yes/no); (4) if perforation occurred, the residual velocity of the impactor; and (5) characterization any spall that might have occurred. Prior to the start of the program, it was decided to characterize each impact in terms of the kinetic energy of the impactor. The goal was to try and determine the minimum kinetic energy at which perforation occurred. The kinetic energy was changed by varying either the impactor mass, velocity, or both.

SPIDER 1 was conducted in 2004 at the Energetic Materials Research and Testing Center (EMRTC), in Socorro, New Mexico (USA). All impactors were launched from a breechless powder gun. The test series examined impacts on typical roofing materials. The targets were:

- 100 mm (4 in) Reinforced Concrete – 100 mm (4in) thick, one-way, simply supported 2.44m x 2.44m (8ft x 8ft) reinforced concrete slab constructed with 20.7 MPa (3000 psi) concrete and #3 rebar – 60 ksi (USA specification)/#10 rebar – 414 MPa (Metric specification) on 254 mm (10 in) centres, each way, with 19 mm (0.75 in) bottom cover.
- Plywood Panel – 2.4 m x 2.4 m section with 13 mm (0.5 in) exterior plywood sheathing on 50 mm x 150 mm (2 in x 6 in) wood joists at 610 mm (24 in) spacing. Minimum 100 mm x 200 mm (4in x 8in) beams support the roof joists. Typical nailing, steel connectors, and built-up roofing materials were used.
- 0.71 mm (22 gauge) Corrugated Metal Panel – 0.9 m x 3.7 m (3 ft x 12 ft) steel panels spanned one way over typical 200 mm x 64 mm x 2 mm (8 in x 2.5 in x 14 gauge) steel channels at 1.5 m (5 ft) (nominal) spacing. The valleys of the corrugated steel panel were bolted to the flange of each of the three supports.

Figures 20, 21, and 22 show photographs of the three types of targets.

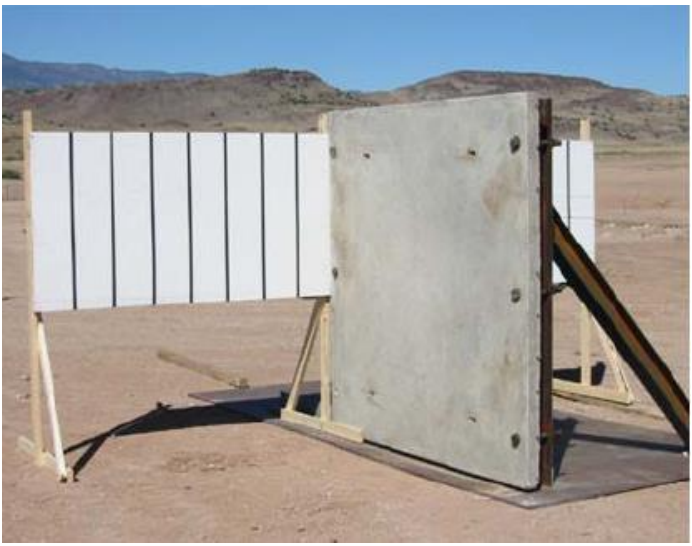

Figure 20: *Concrete target*

***Figure 21**: Panelized plywood target*

***Figure 22**: Corrugated metal panel target*

SPIDER 2 was conducted in 2009 at the Redstone Technical Test Center (RTTC) (now Redstone Test Center (RTC)), in Huntsville, Alabama (USA). All impactors were launched from an air gun. This test series examined impacts on typical wall materials. The targets were:

- 140 mm (5.5 in) Reinforced Concrete – Nominal 2.7 m x 2.7 m (9 ft x 9 ft), 140 mm (5.5 in) thick, one-way simply supported reinforced concrete slab, with 27.6 MPa (4000 psi) concrete constructed with #5 rebar – 60 ksi (USA specification)/# 16 rebar – 414 MPa (Metric specification) on 400 mm (16 in) centres, each way, centred within the slab depth. The rebar began 150 mm (6 in) from the edges (free edge and edge of channel support, top and bottom) and provided 36 – 400 mm x 400 mm (16 in x 16 in) square targets framed by the rebar.
- 0.71 mm (22 gauge) Corrugated Metal Panel – 0.9 m x 3.7 m (3 ft x 12 ft) steel panels spanned one way over typical 200 mm x 64 mm x 2.11 mm (8 in x 2.5 in x 14 gauge) steel channels at 1.5 m (5 ft) (nominal) spacing. The valleys of the corrugated steel panel were bolted to the flange of each of the three supports.
- Unreinforced Concrete Masonry Unit (CMU) – 203 mm x 203 mm x 406 mm (8 in x 8 in x 16 in) standard lightweight CMU in a running bond, with #13 – 414 MPa (#4 – 60ksi) vertical rebar @ 610mm (24 in) (every third cell). The wall was 2 m (6 ft 8 in) wide x 2.4 m (8 ft) high with the outside vertical cores reinforced. Figure 22 shows both an unreinforced as well as a reinforced CMU panel.
- 203.2mm (8in) Reinforced CMU – 203.2mm x 203.2mm x 406.4mm (8in x 8in x 16in) standard lightweight CMU in a running bond, with #13 – 414 MPa (#4 – 60ksi) vertical rebar @ 400 mm (16 in) (every other cell). The wall is 2.4 m (8ft) wide x 2.4 m (8 ft) high with the outside vertical cores reinforced. Figure 23 shows both an unreinforced as well as a reinforced CMU panel.

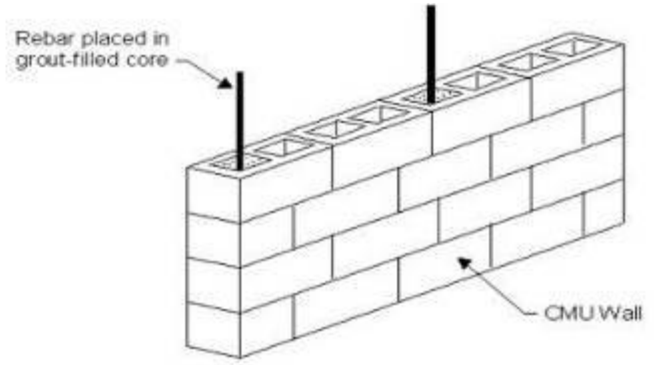

***Figure 23**: CMU Wall*

Note: test wall used #13 @ 610mm (#4 rebar @ 24in) or 406mm (#4 rebar @ 16in) on centre as discussed on the previous page

Table 5 summarizes the results that were obtained on the SPIDER 1 and SPIDER 2 test series. The Minimum Perforation Kinetic Energy (KE) is the highest KE that did not result in perforation of the target. The Maximum perforation KE is the lowest KE that did result in a perforation. Another way of saying this is that the maximum KE that was deflected by the target in any of the tests becomes the minimum KE deflection capacity for the target, while the minimum KE that perforated the target in any test becomes maximum KE deflection capacity for the target. Any debris with a kinetic energy greater than the Maximum perforation KE will perforate the target and hazard interior spaces. Similarly, debris with kinetic energy less than the Minimum perforation KE will not be able to perforate the target and will not pose a hazard to the interior. Between these two levels, there may or may not be perforation.

Table 5: SPIDER Threshold Perforation Energy Results

Target Type	Target Material	Impactor Material	Perforation Kinetic Energy	
			Minimum (Joules)	Maximum (Joules)
Roof	Reinforced Concrete (101.6mm thick)	Concrete	12,326	28,242*
		Steel	9,355	11,832*
	Plywood Panel	Concrete	184	305
		Steel	54	156
	Corrugated Steel (22 gauge (0.711mm)	Concrete	3,064	4,848*
		Steel	1,356	1,647
Wall	Reinforced Concrete (139.7mm thick)	Concrete	99,309	110,205
		Steel	33,466	34,787
	Corrugated Steel (22 gauge (0.711mm)	Concrete	6,294	1,564
		Steel	3,650	1,300
	Unreinforced CMU	Concrete	5,866	6,951
		Steel	2,772	2,498
	Reinforced CMU	Concrete	25,539	28,408*
		Steel	18,998	20,710

*Threshold performation obtained (entire impactor did not pass through target)

The corrugated steel panels were much more resistant to perforation than pre-test predictions indicated. Looking at the structural response of these panels, it appears that they undergo a membrane action type of response with very large deflections, thus allowing the panel to resist perforation, given that a tear in the panel is not initiated (see Figure 24). However, in some tests the impactor perforated the panel at a much smaller KE and the damage was very localized. This seemed to be dependent on where the impactor struck the panel along the corrugation pattern (valley, ridge or transition region) and where the impactor struck the panel with respect to the support. If a tear in the panel was initiated, the impactor would perforate cleanly with minimal reduction in velocity.

It must be noted, however, that all of these results are for spherical impactors; cylindrical or other shapes with sharp edges may have

significantly different and variable results. Planning is already underway for SPIDER 3, which will examine the effect of impactor shape on the results that have been obtained thus far. One of the ultimate goals of this testing is to eventually develop perforation prediction models based on either unit kinetic energy or as a function of mass and velocity as independent variables.

***Figure 24*: Front and Back of Corrugated Metal Panel (Post-Impact)**

This section has drawn heavily on the report prepared by Dr. Michelle Crull[7] of the U.S. Army Corps of Engineers in Huntsville, AL (USA), that described and summarized the SPIDER 1 and SPIDER 2 testing.

4.4. ISO — A Test Series to Determine the Consequences of an Explosion Inside an ISO Container

ISO containers are steel shipping containers used around the world. Their standard design specifications ensure their compatibility with handling equipment, storage areas, and replacement parts in almost any country. ISO containers used for explosives are usually 2.4 m (8 ft) wide, 2.4 m (8 ft) high and 6 m (20 ft) long (external dimensions), although 12 m (40 ft) long containers are also available. The top, bottom, and sidewalls of the

[7] Crull, Michelle, "Science Panel Impact Debris Evaluation and Review (SPIDER) Test Program: SPIDER 1 and SPIDER 2," CEHNC-EDS-O-11-03, November 2011

containers are made of corrugated steel panels 1.5 mm thick, joined to steel structural members at the panel intersections. Double-leaf steel panel doors are usually located at one end of the container. Many other configurations and customized designs are available worldwide, but the ones described in this paragraph are the most common. It should be pointed out that the ISO containers tested are not the same as tanktainers, which are tanks, usually built on an ISO container frame, used for transporting liquids.

In 2005, US military operations were intensifying in multiple conflict regions. With this increased tempo, in addition to their being used for shipment, ISO containers were increasingly being used to store and protect explosives. As a result, questions were being raised about the effects of detonations inside these containers. A test series known as ISO was designed and implemented to address these issues. Specifically, the test series attempted to address the following questions:

- How much debris is produced?
- What is the mass distribution of the debris (i.e., what sizes of debris are produced)?
- How far does the debris get thrown?
- What is the azimuthal distribution of the debris?
- How much airblast attenuation is provided by the ISO container?

As the testing progressed, additional questions were raised:

- What is the source of each piece of debris that is catalogued? Specifically, where on the ISO container does each piece of debris originate?
- What are the effects on the structural break-up of the ISO container when using energetic materials with differing TNT equivalences and brisance?
- What is the effect of loading density (explosive weight/volume of container) on debris generation and airblast attenuation?
- Are there differences in the debris distribution/characteristics produced by a detonation of a typical explosive load inside a standard ISO container that has no interaction with other structures

(such as a truck) or no effects from primary fragments (i.e., using bare charges)?

Thus far, there have been five test series that have examined the effects of detonations inside ISO containers. Four were sponsored by the DDESB and one was sponsored by the Klotz Group, an international body of explosives safety experts whose main objective is to improve the knowledge of and to reduce the risk associated with the storage, processing and transport of ammunition and explosives for both the military and the civilian community. Table 6 provides a summary of these ISO container test series. The ISO-4 series was composed of two events—ISO-4 and ISO-4 Retest. The retest detonation was conducted to obtain high speed photography missed on the ISO-4 event. A limited debris recovery effort was conducted on the retest. The Klotz Group series, although considered a single test, consisted of three separate detonations inside ISO containers; only the container orientation was changed on each test. An extensive debris recovery was conducted on Test 1, while on Tests 2 and 3, only selected sectors were catalogued

Table 6: *ISO Container Testing Summary*

Test Series	Test Name	Test Date	Primary Sponsor	Explosive Weight/Type	Test Description
ISO-1	ISO-1	May 2006	US DDESB	1,054kg ANFO	ISO container on truck
ISO-2	ISO-2	May 2007	US DDESB	4,000kg ANFO	ISO container on truck
ISO-3	ISO-3	March 2009	US DDESB	1,054kg Projectiles and Propellant	ISO container on ground
ISO-4	ISO-4	September 2010	US DDESB	1,000kg C4 Plastic Explosive	ISO container on ground
	ISO-4 Retest	December 2010	US DDESB	1,000kg C4 Plastic Explosive	ISO container on ground
ISO Klotz	ISO Klotz Test 1	August 2011	Klotz Group	100kg Plastic Explosive	ISO container on ground
	ISO Klotz Test 2	August 2011	Klotz Group	100kg Plastic Explosive	ISO container on ground
	ISO Klotz Test 3	September 2011	Klotz Group	100kg Plastic Explosive	ISO container on ground

Figure 25 shows the truck/ISO container just prior to the detonation of the ISO-1 event. Superimposed on this figure is an outline of the explosive charge that was used. Figures 26, 27 and 28 show the remains of the truck and other debris located within 100 meters of ground zero (GZ).

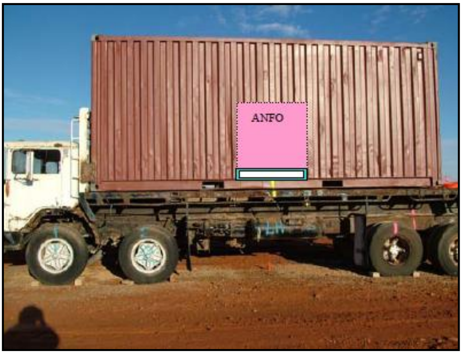

Figure 25: *ISO Container on Truck*

Figure 26: *Crater*

Figure 27*: Near-Field Truck Debris*

Figure 28: *More Near-Field Truck Debris*

As an example of the types of information collected during this test series, consider these results for the ISO-4 event. Over 9,500 pieces of debris were located and catalogued during the recovery effort. Each piece of debris that was collected was identified as either originating from the skin of the container, from the bracing of the container or from the floor of the container. A total of 20 pieces of debris traveled beyond 500 m. Of these 20 pieces, 11 were door bracing, which tend to form dense, compact debris that have low drag properties, four were other brace components, and five were skin pieces. Despite the preponderance of brace pieces beyond 500 m, the furthest fragment recovered was actually a piece of skin found at 663 m from GZ. This piece only had a mass of 47 g and was heavily scrutinized to

ensure that it was indeed a valid piece. The smallest piece of debris to travel beyond 500 m was also a piece of skin that weighed only 16 g. At the time of the test, the wind was coming from the S/SW direction at 1.9 m/s, which would have aided the travel of these two pieces.

The ISO-4 debris data are displayed over an aerial photograph of the test range in Figure 29. The colors correspond to the source of the debris (when identifiable), while light gray data points were debris with no color identified. The three circles evident in this figure represent 100-m (red), 300-m (orange) and 500-m (yellow) radii circles from GZ.

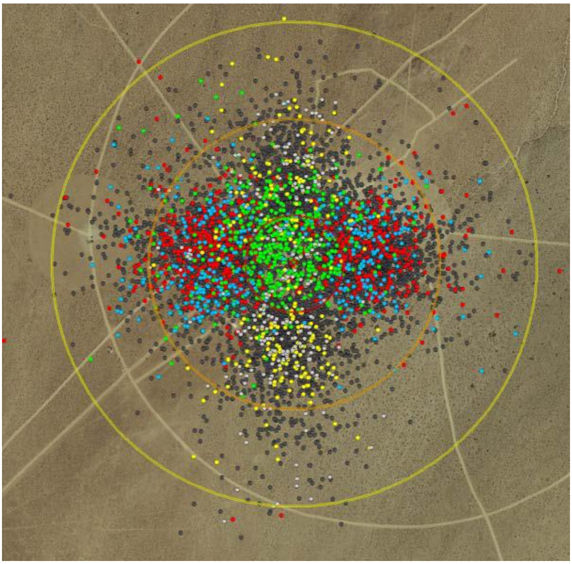

Figure 29: *Scatter Plot of ISO-4 Debris*

Figure 30 shows the debris density generated on the ISO-4 event out to a radius of 300 m. It uses an incremental angle of 1° and an incremental depth of 5 m to display the debris densities. The manner in which plots such as this are constructed is highly dependent upon the desired fidelity. If less fidelity is desired, larger incremental angles and depths could be chosen.

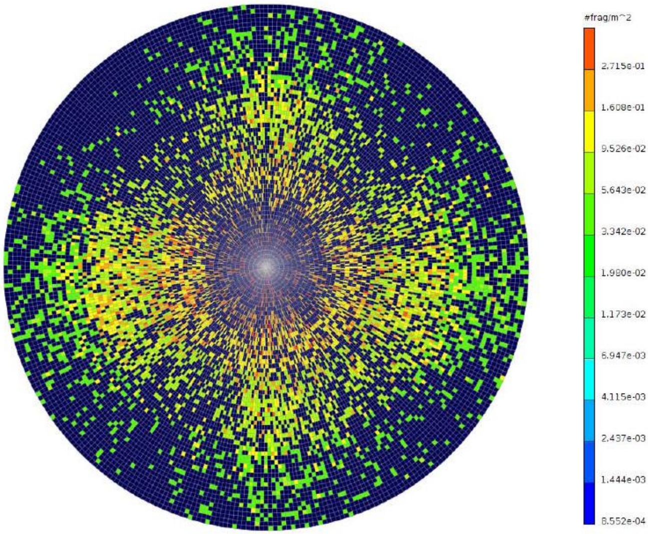

Figure 30: *ISO-4 Debris Density Visualization*

Another example of the types of information that are being generated by this test series is the determination of the Pseudo-Trajectory Normal (PTN) Debris Inhabited Building Distance as a function of azimuth. The PTN debris density is defined as all debris in or passing through a given zone divided by the area of that zone. The PTN debris IBD is defined as the range at which the PTN density of hazardous fragments falls below a value of 1 per 56 m^2, where a hazardous fragment is defined as a fragment with an impact kinetic energy of at least 79 Joules. Figure 31 shows such a plot generated for the ISO container debris on the ISO-3 event.

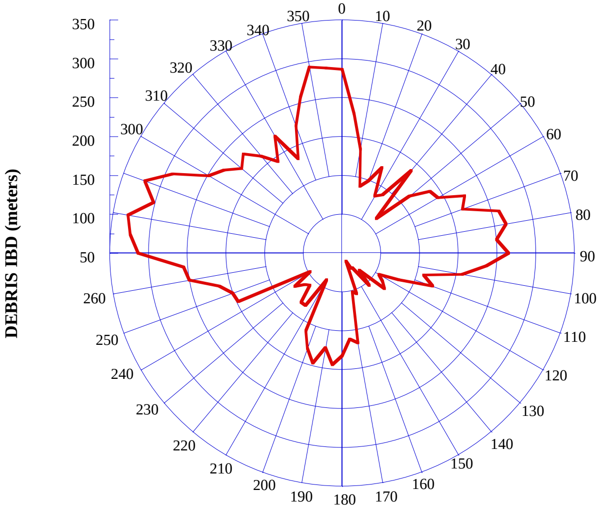

Figure 31: *Container Debris Inhabited Building Distance—ISO 3 Event*

One feature that is common to Figures 29, 30 and 31 is a well-defined cruciform pattern, such as those that been observed on other high explosive tests.

The information generated by the entire ISO test series represents a start to the ongoing task of understanding and modeling the debris and airblast produced by explosions inside ISO containers. It has been used to update and improve existing quantitative risk assessments tools such as IMESAFR. It can also be used to better assess existing Explosive-Safety Quantity-Distance regulations and enhance the state-of-the-art in other debris prediction models.

5. ALGORITHMS (John Tatom)

5.1. The Science of Quantitative Risk Assessment for Explosives Safety

QRA tools, as described in Section 2, can only be considered valid if the real-world situation can be modelled accurately. For explosives safety, the model must be able to represent the effects produced by the detonation of the donor and the consequences on the target. The science that goes into such a model must be carefully thought-out and based on as much data as possible.

In a high-explosive (HE) event, the effects that must be considered are the blast wave, the debris, and the thermal environment created by the donor item (material, article, or weapon). The consequences to the target, which is normally a human but could also be other vulnerable assets, include not only the direct results of the HE effects, but also the response of the structure where the target is located. Glass hazard and building collapse are key facets of this structural response.

The algorithms that form a model of an HE event are based on physics, certainly, but are anchored whenever possible by test and/or accident data. Although a wealth of test data already exists, new test programs are underway that will supply important information for use in models. This was described in Section 3. The data from a test or accident can also be used to check the predictions of the model and point out areas for improvement.

There are generally three types of models: (1) physics-based, (2) empirical, and (3) semi-empirical. Although physics-based models can be developed to model explosives safety scenarios, they are, by necessity, quite complex and therefore expensive to develop. Empirical models, which report only data points available from tests and accidents, are by their nature limited in scope. Semi-empirical models, which use anchor points from available data but “fill in the gaps” with physics-based algorithms, may offer the best compromise between development cost, capabilities, and acceptance of results.

In a semi-empirical QRA model, conservatism is inversely related to the amount of available data. That is, if there are very few (or no) data points available to anchor an algorithm, the model must err on the side of caution. However, when an algorithm can be readily corroborated by test and/or accident data, the model does not need to include conservatism. This is important because the inclusion of conservatism would prevent model results from comparing well with the empirical data anchor points (i.e., reality).

This chapter intends to provide an overview of the explosives safety effects and consequences models that should be employed by QRA tools. Subsequent sections will provide more detail (and references) on individual areas.

Effects and Consequences

To determine the effects and consequences of an explosive incident, the effective yield of the event must be determined. This is accomplished by adjusting the free-field results to account for the explosive's immediate container (if present), the explosive type, and the attenuation of the blast wave caused by the presence of the donor structure (if applicable).

For modelling purposes, the effects of an explosive incident are the changes in the environment created by the blast outside the donor structure (if one is present). Such effects include overpressure and impulse, debris, and thermal. It should be noted that ground shock is not normally considered when concerned with fatality or injury.

The consequences of a blast are the results on the target structure (if one is present), including glass and structural failure.

These effects and consequences, as depicted in Figure 32, can then be used to determine the target (usually a human) vulnerability. The target vulnerability should be considered separately for each applicable effect and consequence and then summed.

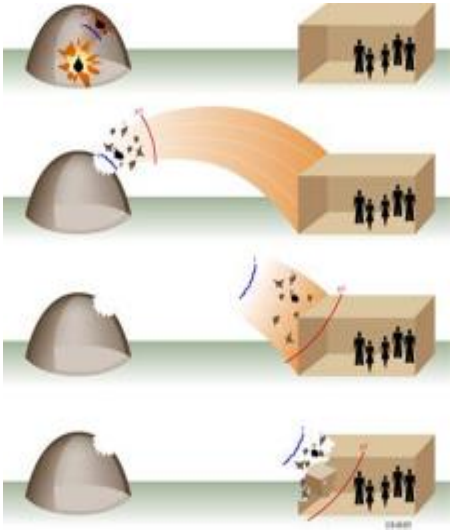

Figure 32: *Blast Effects and Consequences*

Yield

The explosive yield can be determined through the algorithms and procedures in the DDESB Blast Effects Computer, as documented in the DDESB TP-17. Equations for a hemispherical TNT surface burst are used as the "basic airblast engine" to generate the various airblast parameters. For situations other than a hemispherical TNT surface burst, including various types of charges in the open or detonations inside a donor structure, effective TNT yields are computed and used. These yields are functions of the scaled distance (distance divided by the cube root of the explosive weight) from the center of the event and the type of donor item and/or structure selected. The calculated effective yields are used in conjunction with the hemispherical TNT surface burst curves to generate the appropriate airblast parameters.

Pressure and Impulse

Once an effective yield has been calculated, the airblast algorithms from the Blast Effects Computer can be used to generate the pressure and impulse at the target structure. The pressures and impulses computed in this manner

have been compared to all available test data and have been found to be in good agreement.

Structural Response

When the target building is "hit" by the blast wave, the structure may provide its occupants with some protection. However, as the building breaks up – the worst case being total collapse – the occupants are exposed to the additional hazards produced by the building itself.

Glass

Extensive research has been conducted, especially by the physical security community, on glazing targets to determine their response to blast loading. A "broader brush" program can use the output of these more detailed models in combination with accident data to generate results suitable for a QRA. It is important to note that while glass is a serious hazard to personnel in a building with windows, anecdotal evidence suggests that it is rare that fatalities are caused by glass in an explosives event.

Ongoing testing efforts will eventually supply enough data to expand the list of input options for QRA purposes. Safety retrofitting of existing windows is now a relatively common occurrence; consequently, more work must be done on the glass models to allow such modifications to be taken into account.

Building Failure

A great deal of testing has been conducted on the blast response of structures. However, actually determining the hazard to the building occupants is another matter. The results of accidental (or terrorist) events can be studied, but it is not always easy to reconstruct the scenario, i.e., the exact location and amount of explosives and the precise position of the people within the building.

Clearly, the first step is to understand the response of the target building to the blast load. This allows for the development of pressure-impulse (P-I) diagrams, which are then used to predict damage to a specific structure (or structural component) based on the blast load. Given the damage, the

hazard to the occupants can then be predicted. These types of predictions have been compared between models and to the limited real-world data available, with encouraging results.

Debris

The debris created by the blast can be divided into three categories: primary fragments (the casing and/or immediate packaging of the donor item), secondary debris (the pieces of the donor structure), and crater ejecta (the debris from the crater formed in the ground and/or foundation of a donor structure).

Primary Fragments

The primary fragment characteristics that should be modelled (initial velocity, number of fragments, size distribution, and maximum range) are consistent with information and procedures contained in DoD literature, such as DDESB TP 16, Methodologies for Calculating Primary Fragment Characteristics. However, commercial explosives normally do not have a dominant primary fragment hazard.

Secondary Debris

Predicting the size, shape, initial velocity and angle, and maximum throw range of debris coming from the donor building is a particularly challenging task. Even if a given model can accurately predict the debris characteristics of a single event, it is still quite possible that the same model will be inaccurate for other events. This is the reason why it is highly desirable to have multiple data points (usually at different loading densities) for the same building type.

Crater Ejecta

Characterization of crater ejecta should be based on the type of soil around the donor structure; crater ejecta prediction algorithms can be based on available models and data.

Thermal

For QRA, thermal effects are usually only considered for Hazard Division (HD) 1.3 materials (mass fire). It is assumed that thermal effects from a high-explosives event would be insignificant (compared to other effects) if 1.3 items were not present. This assumption is based on the fact that, compared to other blast effects, thermal effects are extremely short ranged; i.e., the hazardous consequences from blast and fragmentation extend to significantly greater distances than do thermal effects.

Thermal models have not been developed to the level of maturity of the other algorithms discussed. However, the models are based on available data and literature, and have been compared to each other within NATO.

Vulnerability

Predictions involving the probability of fatality (or injury) for a person exposed to a given hazard are always difficult to corroborate, but some good work has been done in this area. For the human response to direct blast loading (skull fracture, lung rupture, and whole-body displacement), American and European research led to the development of probit functions to estimate the conditions required for lethality. This type of probit function has been expanded and extended for inclusion in QRA models and is widely accepted.

The range (missile launch) safety community has developed and issued standards for determining the vulnerability of people to debris impacts. This standard provides a series of "S-Curves" relating the probability of fatality to the kinetic energy of the fragment.

Models

Each scenario that can be considered by software tools must have a model for the elements that will affect the results. These elements are the donor item type, the donor structure (or PES, the Potential Explosives Site), the target structure (or ES, the Exposed Site), and any natural or man-made barricades. To the extent possible, these models are based on test data.

5.2. Anchoring Models to Test Results

As mentioned in Section 3.3, accurate QRA models depend on algorithms that are validated against full scale tests. Also previously mentioned was the concept that a semi-empirical model has to “err on the side of caution” for scenarios without such supporting data. Therefore, for efficient operation it is critically important to incorporate all available test results that are pertinent to the QRA model.

This section will begin to introduce the idea of how tests can be designed to produce results that can be used to anchor the elements of a QRA model. It is important to note that, although the test results “are what they are” (they shouldn’t be ignored or manipulated for some non-technical ulterior motive), the tests themselves can be designed with the goal of supporting model needs.

DEFINITIONS OF EFFECTS AND CONSEQUENCES

As defined in Section 4.1, for modeling purposes, the effects of an explosive incident are the changes in the environment created by the blast outside the donor structure (if one is present). Such effects include overpressure and impulse, debris, and thermal. The consequences of a blast are the results on the target structure (if one is present), including glass and structural failure, and any exposed people. The vulnerability of the people must also be modeled. This model is depicted in Figure 33. How then are test results used to corroborate or anchor the models?

Yield: Before any other blast-related effects and consequences can be considered, the size or strength of the event must be established. The “yield” of an event can be thought of “if this much stuff of that sort in this type of packaging in that sort of building were to explode, what amount of TNT in the open would create an equivalent overpressure?” (roughly speaking). The yield can be determined from test results with simple and relatively inexpensive pressure gauges; when there is only one variable (e.g., introduction of a concrete structure as a PES, containing an unpackaged TNT charge), the effect of that variable on yield is easy to characterize. In order

to limit the variation to one parameter, a "calibration shot" is sometimes conducted to characterize the explosive articles to be used in the test.

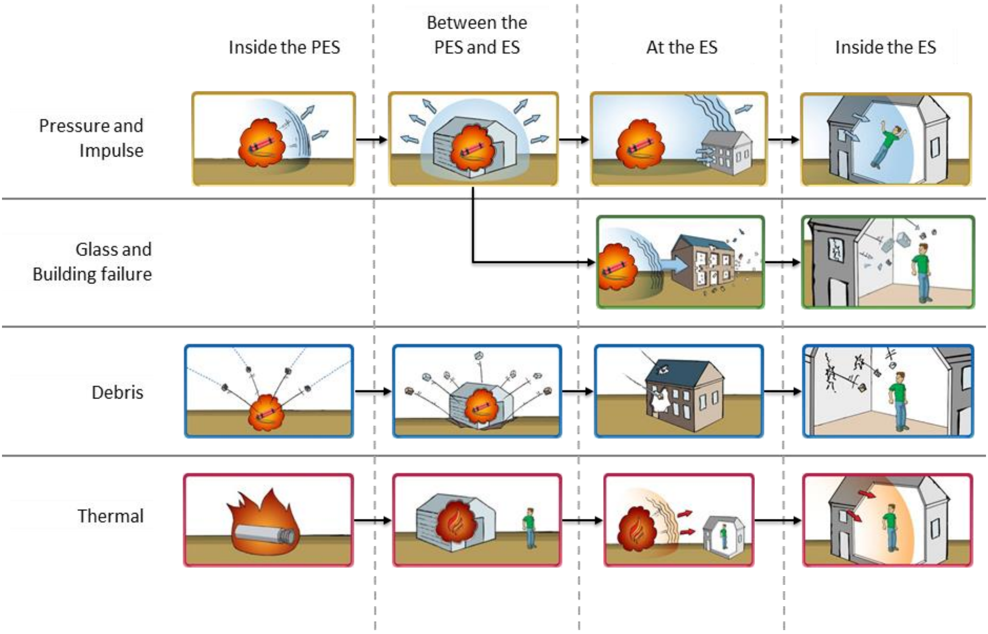

***Figure 33**: Blast Effects and Consequences*

Pressure and Impulse: Of course the gauge readings are also used to characterize the pressure and impulse at different locations, including the "blast load" at the face of any target structure experiments. Simple displacement gauges may also be used on targets to estimate loads. Depending on the location and purpose of the gauge, the readings may be for peak incident values or for reflected values – or even shielded values behind a barricade or inside a target structure. Measuring pressures and impulse inside a donor structure is more challenging, but is generally possible.

Structural Response: Given the establishment of yield and blast load parameters, the response of any target structure (or glass) experiments can be characterized. For QRA tools interested in consequences to exposed personnel, these structural response findings are then translated to expected human vulnerability. Of course, not all tests have target experiments, as they may actually interfere with the debris results.

Glass: Glazing targets can be stand-alone experiments or included as part of a target structure. The first question is whether the glass breaks, then whether it will become a hazard (versus staying in the frame or falling out with little chance of harming a person), and finally how significant the hazard would be. Breakage is relatively easy to determine, and the distance the glass shards have traveled can be measured after the event without much trouble. High-speed cameras can also be used to determine the velocity of the shards, as well as to tell more about the behavior of the glass before, during, and after breakage. The most difficult aspect is of course the human vulnerability; while gelatin targets can be used to simulate human flesh, it is difficult to model the human reaction and the timing of the glass interaction with the occupant. This consequence mechanism is considered by many to be well-characterized up to the point of human response, and poorly understood thereafter.

Building Failure: As mentioned, the response of the target building can be measured in terms of wall displacement or number of failed panels or such, but much of the information gained in this area is through interpretation of damage by structural experts (example shown in Figure 34). The task is to establish a level of damage that can be translated into a consequence level for occupants. Critical determinations, such as whether the roof failed or not, establish key anchor points for the models.

Debris: Using test results to create a debris model can be tricky. The first decision is to physically capture the debris in some way (e.g., having the fragments strike a "soft catch" system) or to allow them to translate naturally. The advantage of a capture system is that information about the mass distribution and velocity can be obtained relatively quickly and without the need for a lot of land, but the downside is that the debris density as a

function of range and azimuth cannot be observed (although it could be predicted). It may also be costly to devise an adequate capture system, and

Figure 34 *Sample Test Results (Damage Interpretation)*

it may only be feasible for small charge weights. The natural translation option allows for the determination of all of the information (with some complications, of course) when using a combination of high-speed cameras and a debris recovery crew, and can be done for any charge weight. However, this requires a large test range, and is very demanding in terms of time and effort (thus, money).

Primary Fragments: The fragments created by the casing or packaging of the explosives articles are typically not a dominant hazard for commercial explosives. If testing material other than bulk explosives, these primary fragments can be distinguished from other debris such that models can be created to represent their behavior.

It is important to note that in testing, all the explosives articles may be forced to initiate, rather than allowing natural communication. This is done in order to know the exact size of the event (i.e., the yield) and to minimize the danger of having unexploded articles thrown around the test range.

However, this may create an unrealistic set of primary fragmentation results.

Secondary Debris: On a full scale test debris recovery effort, the "big job" is to characterize all of the donor structure debris. For a concrete donor, this type of recovery effort can take a crew of 50 people several weeks to complete. Additionally, concrete or masonry debris may shatter on initial impact, so the results have to be interpreted before use in the model. Further complicating the problem is the "bounce-skid-roll" aspect of the debris; after the test, it may be difficult or impossible to recreate the complete trajectory history, knowing only the final resting place. This problem applies to all material types of debris, and is to some extent dependent on the range conditions (which may match typical real-world conditions).

To help determine the starting point of a particular piece of debris, the different elements of the donor structure can be dyed or marked in some way that will survive the event. An example of this was shown in Section 3.2.

Crater Ejecta: This category can range from massive clay "clods" to shattered elements of the floor slab under the donor structure. The slab concrete can also be dyed to distinguish it from the walls or roof of a concrete donor. The earthen debris is readily identifiable as ejecta, unless there is earth-cover on the donor, or some sort of earth-filled barricade between the donor and the recovery area. Shatter is typically a serious issue with ejecta, as the pieces tend to be falling at a sharp angle and are often in a brittle condition (post-event).

Thermal: Video review and simple inspection are often adequate for determination of the fireball radius from an event (which also must be considered when placing cameras, such that the desired information is not obscured by the fireball). Thermocouples or more advanced heat flux measurement equipment can be used, but may be beyond the level of detail required for the QRA model.

Vulnerability: With all of the hazard mechanisms, the most difficult part of the final answer is the human element. Tests do not include actual humans,

of course, and substitute targets may not be as reliable as desired for determining human response. This leads modelers to review accident or terrorist event data to try to supplement test results, but then the controlled circumstances of the test are lost.

5.3. Considering Accuracy and Conservatism in Debris Modelling[8]

When modelling debris generated by an explosives event, the behavior and hazards associated with the debris can be addressed with differing levels of complexity. The most complex of models would look at each debris element and track its behavior from origin to final resting place, considering the time-history of all debris in order to characterize the hazard. This thorough approach may provide the most accurate representation of the event, but is extremely difficult to design for a particular event, the predictions are not applicable to other situations, and would require computation power beyond the reach of most users. The simplest approach would be to devise some rudimentary tables that provide the general idea of the debris hazard, without the ability to provide any details within the predictions, and with very limited ability to distinguish between scenarios.

These limitations of the modelling extremes have led to the development of better routines for fast-running models (FRMs). These debris models rely on probability density functions (PDFs) to characterize the debris behavior. These PDFs are created for different categories of debris, and are ideally based on test results, but should also be in agreement with physics-based predictions. A complete debris density PDF must consider the downrange prediction (how the density varies as a function of the distance from the origin) and the cross-range prediction (how the density varies with angle, or azimuth, in relation to the origin, if applicable).

The focus of this section will not be on the overall merits of using PDFs for FRMs, nor on the cross-range aspects of a PDF, but only on the downrange

[8] Tyler Ross, John Tatom, Bob Baker and Mike Swisdak, "Advanced Debris Probability Density Functions," Proceedings of the ISIEMS 2013 Conference

component.

Thinking of a plan view of a facility, a function that behaves like a normal distribution (or a "bell curve") in X and Y (or North-South and East-West), is often referred to as a Bi-Variant Normal (BVN) phenomenon. That is, the function "varies normally" along both axes. With no azimuthal variation, a BVN PDF forms an "anthill" shape, as shown in Figure 35, with the amplitude representing debris density.

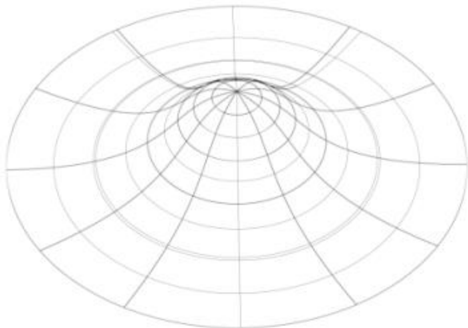

***Figure 35**: BVN PDF ("Anthill")*

Using a BVN model to predict debris density works well for debris elements such as the roof of a donor structure, or the crater ejecta (debris) thrown from the event, or any other material that is expected to move vertically from the origin with no expectation of azimuthal variation. From an explosives safety perspective, a BVN model also seems appropriate in the sense that the answer is the highest/worst near the donor, and gets lower/better as the distance increases.

However, when predicting the behavior of debris that is expected to have a mostly horizontal trajectory (e.g., material coming from the walls of a donor building), a BVN will almost certainly not accurately represent the expected pattern. It is intuitive that the debris from the wall will travel some distance before stopping, therefore the peak of the density cannot be at the origin. This is consistent with what has been seen in tests where the wall material

has been differentiated from the roof.

Assuming the peak density to be at some distance away from the origin, and disregarding any azimuthal variation, produces a PDF with a toroid or "volcano cone" type shape, as shown in Figure 36.

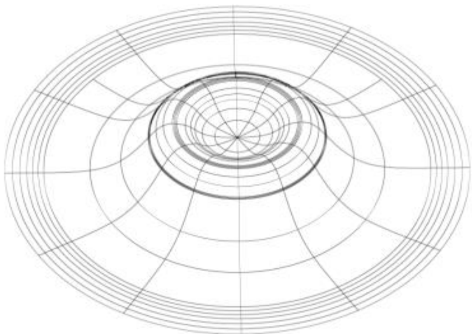

Figure 36: *Toroid PDF ("Volcano Cone")*

An example of this type of downrange prediction is the ISURF model in IMESAFR 2.0, as described in a recent published paper [1]. This particular toroid-type function is characterized as shown in Figure 37.

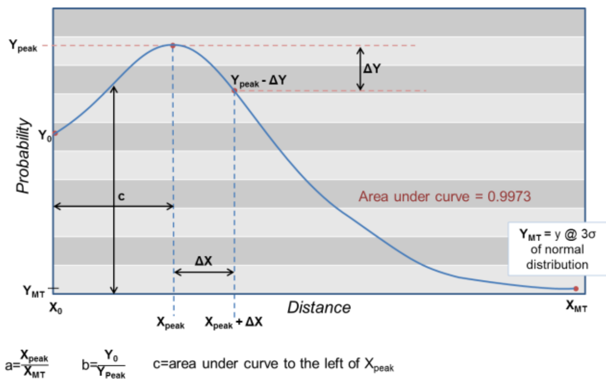

Figure 37*: ISURF Model*

The attraction of this model is two-fold: first, the model is simple enough to be characterized by a few parameters; second, these parameters can be anchored to test results. It should be noted that modelling the debris density is not the same thing as predicting the hazard associated with the debris, so Figure 36 should not be viewed as a representation of debris hazard, but merely density (i.e., where the debris would be found on the ground after an event).

The negative connotation associated with a toroid-type prediction is that it might provide non-conservative results. It may seem problematic to have a debris prediction showing a lower answer at a closer distance, but further scrutiny shows this is not an issue. To illustrate this, Figure 38 shows a comparison of a BVN and a toroidal downrange debris density prediction. Although the values for the density and the distance are not shown, it is intended that the area under each curve is equal.

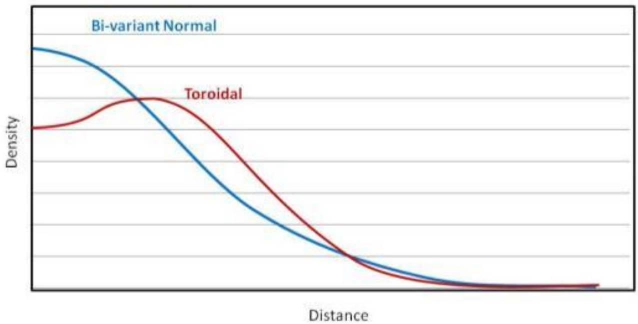

***Figure 38**: Comparison of Downrange Debris Density Prediction Techniques*

This comparison shows that the BVN curve predicts a lower debris density at some ranges, and these ranges may well be the region of interest for explosives safety scenarios. In the close-in region where the BVN prediction is higher than the toroidal curve, there are probably many other consequence mechanisms that would cause lethality. It is also critical to keep in mind that the density predictions are not hazard predictions; the toroidal curve will be treated with something like a PTN technique, which

considers the hazard associated with all distances associated with the debris trajectory.

Therefore, the toroidal prediction for debris density is actually more conservative, in addition to being more accurate than a BVN prediction, when considering horizontal debris trajectories and the associated hazards.

5.4. Evaluating Debris Hazards

Most Q-D systems are based, directly or indirectly, on some form of cube-root scaling. This means that in order to keep the same pressure level, the required distance increases proportional to the cube-root of the charge weight. In general, this produces consistent results for pressure (and impulse) considerations, but what about the debris produced from an explosion? The answer is quite different: certainly the quantity of explosives and the distance to the “target” affect the results, but the cube-root scaling does not apply, and there are many other factors to consider as mentioned in Section 2.4. When studying the problem, it becomes clear that a “cookie cutter” solution may not be available.

QRA models, as previously discussed, must consider these additional factors, and can use the test results to generate more realistic debris density predictions (also discussed previously). But is this just an academic exercise? How safe are people from debris hazards when they are far enough away, according to Q-D? Let us consider a series of tests to examine this issue, rather than discussing it hypothetically.

If we look at several different tests with approximately the same explosives quantity, we can look at Q-D and debris patterns to make a general comparison, and also consider how differences in the test parameters affect the debris results. Since we have several tests at approximately 1000 kg, each with comprehensive debris catalogs, let’s look at Q-D and debris at that charge weight. The tests are from the US DoD’s Project ESKIMORE series: ISO-3, ISO-4, and SciPan 4, as described in Section 3.7. We’ll use the American Table of Distances (ATD) to determine the Q-D arcs.

ISO-3 had 1054 kg of munitions inside a 20’ ISO container on the ground (not on a truck, like ISO-1 and ISO-2), with no barricades involved. Using IMESAFR 2.0 with an ISO-3 debris scatter plot as a background image, we can look at Q-D and the debris pattern. Figure 39 shows this, looking at only the debris from the ISO container (no primary fragments from the munitions), with

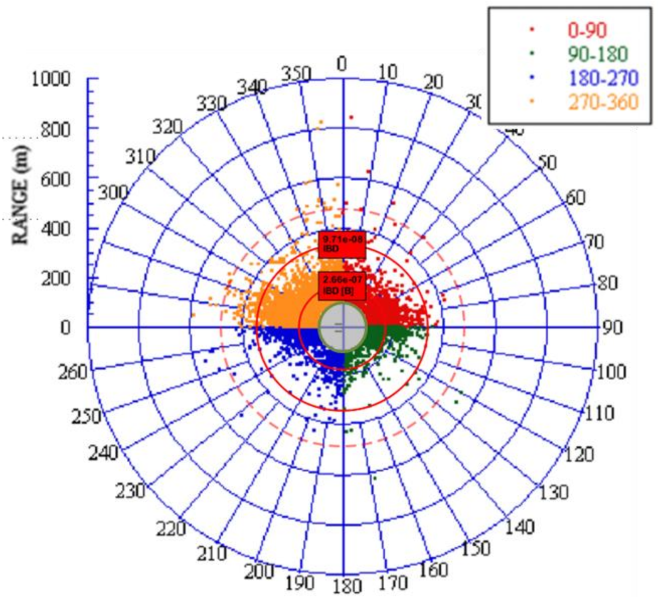

Figure 39: *ISO-3 (ISO container debris only) Debris Scatter Plot*

both regular Inhabited Building Distance (IBD) and the barricaded value (IBD [B]) shown. In this figure, the different colors merely represent the different debris recovery quadrants. IBD in this case is 329m. The dashed red circle represents the Risk-Based Evaluation Distance (RBED), which is an indication of the distance beyond which IMESAFR predicts negligible risk, regardless of angle. In this case, the RBED is 478m.

Note the numerical values in the red label boxes represents the highest risk that IMESAFR calculates at the IBD arcs. These values depend on the input assumptions and are not the focus of this article.

Looking at Figure 39 we see that some debris goes beyond IBD – some well

beyond it, to 800m or so. This should disprove the misconception that Q-D is a “force field” that prevents debris from escaping. But perhaps there isn’t that much debris beyond Q-D, depending on what angle you look at. It’s unclear if there is a cruciform pattern to the debris, because the relatively strong wind at the test seems to have skewed everything to the “northwest” in this plot.

Figure 40 again shows the ISO-3 test results, but this time plotting only the primary fragments from the munitions, versus the same IBD arcs. Note that the introduction of primary fragments has increased the RBED (again shown as the dashed red circle) to 493m, though IBD is still 329m.

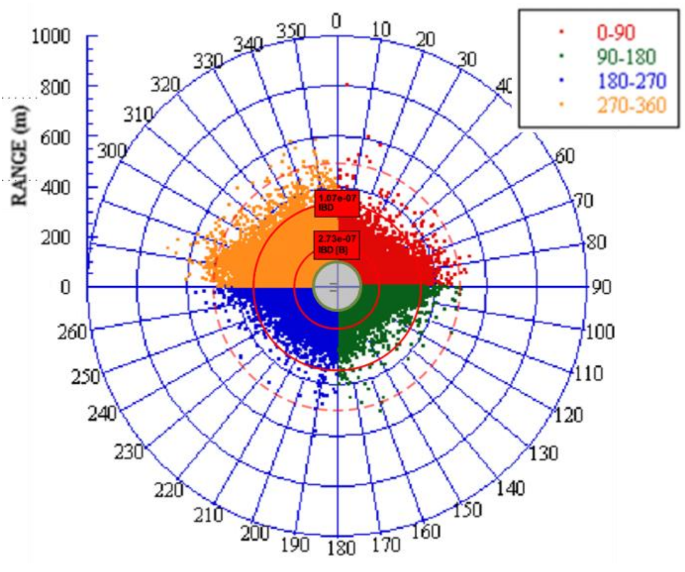

Figure 40: ISO-3 (primary fragments only) Debris Scatter Plot

Now we see quite a lot of debris beyond IBD, especially in the 270-360° quadrant. Also, although there does not seem to be a pronounced cruciform pattern to the debris, there does seem to be a “long axis” for the debris, along the 270-90° line.

Normally, however, typical commercial explosives will not have this primary

fragment concern, at least not to this degree, so let's consider another test.

ISO-4 had 1000 kg of bulk explosives (no primary fragments) inside a 20' ISO container on the ground, with no barricades involved. There was only a slight wind to the "northwest" in this test. Using IMESAFR 2.0 with an ISO-4 debris scatter plot as a background image, we can plot the same Q-D arcs again, as shown in Figure 41. Now the RBED is 478m.

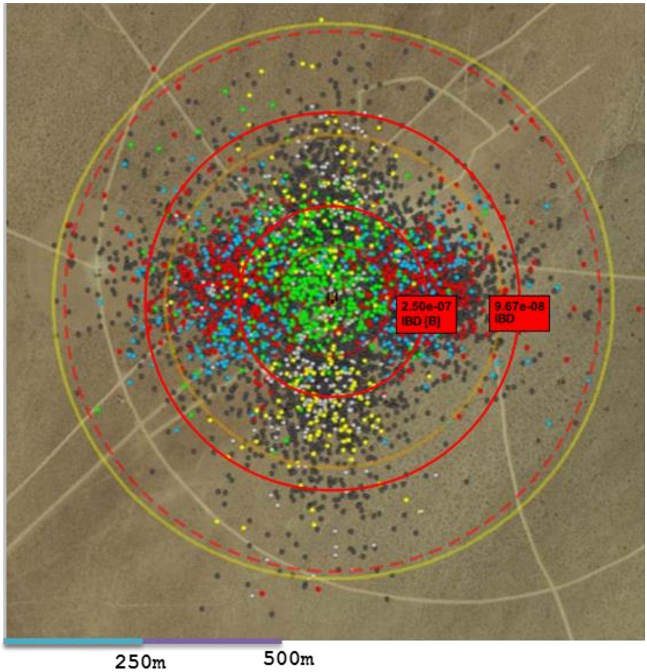

Figure 41: *ISO-4 Debris Scatter Plot with Q-*

In this plot, the color of the point represents the origin of the debris (in terms of the part of the ISO container), when known, as described in Section 4.4. The solid rings without labels are 100m (red), 300m (orange), and 500m (yellow). As with ISO-3, debris is found well outside the IBD arc (329m). Without a significant wind, a cruciform pattern is evident in this scatter plot, but it not particularly pronounced.

Changing from an ISO container to an aboveground concrete structure (with no earth-cover), but staying at 1000 kg, we can now view the same sort of plot for SciPan 4. Figure 42 shows the concrete debris beyond IBD (still 329m), and has a distinct cruciform pattern. In this case, it is not just a question of a few pieces here or there exceeding IBD – there are thousands of pieces beyond 329m along each of the wall normals. Because of the anticipated increase in debris hazard, IMESAFR has generated a much larger RBED (866m).

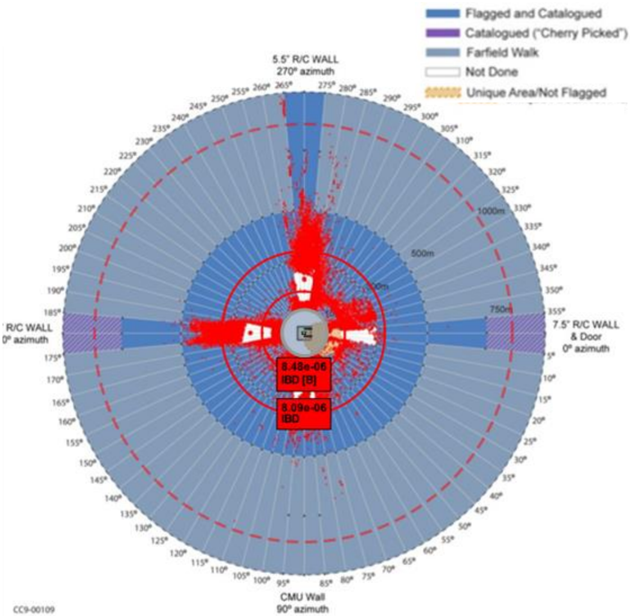

Figure 42: *SciPan 4 Debris Scatter Plot with Q-D*

It is evident at this point that there is some debris hazard beyond IBD. The question then becomes how this can be addressed (or how well this can be addressed) by a QRA model. Using the ISURF downrange debris prediction model, as described in Section 4.3, and a presumption of Gaussian cross-range debris density decay, IMESAFR 2.0 produces the debris density prediction shown in Figure 43 (overlaid on the same scatter plot, without

the Q-D arcs). An overview is shown in the top part of the Figure and a zoom-in on the high density areas is shown at the bottom.

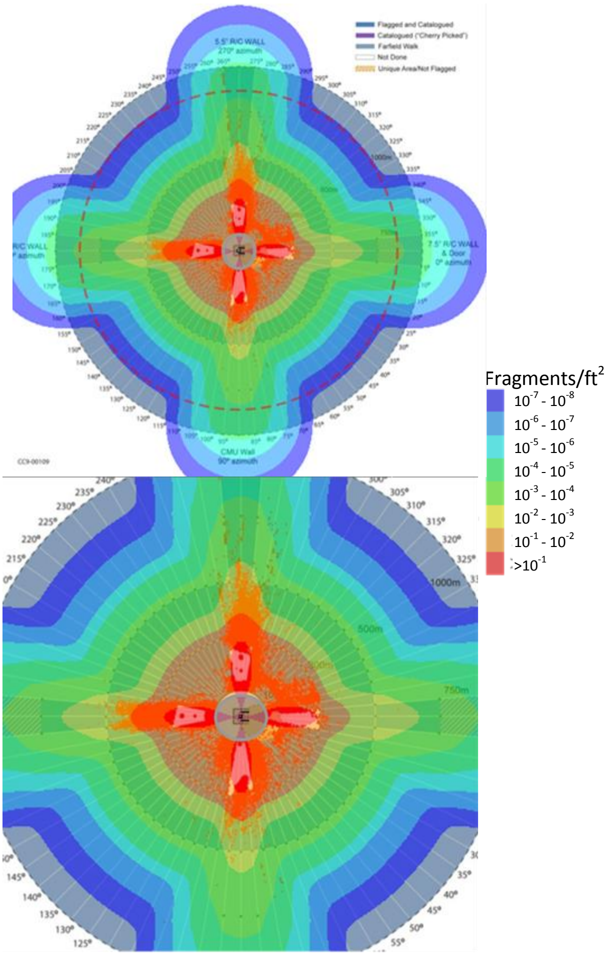

Figure 43 *QRA Debris Density Model vs SciPan 4 Debris Scatter*

As the scatter plot and the debris density contours indicate, the debris hazard is different at various angles for a given distance. If a siting standard provides only a single distance for a certain NEW (i.e., a Q-D arc), there is no easy way to establish that distance without resorting to a very conservative approach that works for all angles. And how does one account for the debris variations observed between different types of structures? Would there be a different distance for each type of structure? Whereas these complexities are hard to address with Q-D, they are inherent to a QRA model.

6. CONCLUSION (Bill Evans[9])

This publication, built on a series of articles in the SAFEX Newsletter is intended to demonstrate that while Q-D may still be king, we are moving towards a system where QRA will have a prominent seat at the table. The publication has attempted to demonstrate three key points:

- QRA will never be the easier option (to Q-D) but it will often be the better one (Section 3)
- The best QRA approaches need to be grounded with real data (Section 4)
- IMESAFR 2 is a highly sophisticated model, grounded wherever possible in real data and using the most sophisticated algorithms available to generate the best consequence/risk estimates for explosion scenarios (Section 5)

An important thing to note is that IMESAFR and QRA are not synonyms. IMESAFR is a tool – arguably the best, most sophisticated, accurate and precise tool available – to underpin a quantitative risk analysis, whether for internal company use or to support a request to a Regulator.

The key question is why one would consider QRA when Q-D apparently works so well, at least based on historical accident data. This question would be particularly relevant to Regulators who aren't paid to be risk takers.

[9] Bill Evans is the Chair of the IMESAFR Subcommittee of the Institute of Makers of Explosives, 1120 Nineteenth St NW, Suite 310, Washington, DC 20036-3605, USA. His email address is bill.evans@orica.com

One part of the answer is that there have been so few accidents that the apparent success of Q-D is not statistically significant. For companies, the answer is pretty obvious: a QRA approach will generally give you a 'better' answer than Q-D - i.e. the inventory can be increased, the distance can be smaller, etc. - but not always. And that is where the Regulators get a win. This Paper has shown how Q-D compliant situations can have a level of risk that is orders of magnitude higher than a non-compliant situation for the same site. If one of the key responsibilities of Regulators is to ensure an acceptable level of safety (risk) to the public, then QRA actually does a better job than Q-D. This point can be highlighted at the hand of two questions:

- Would you rather be in a glass building near a concrete explosives building or in a concrete building near a glass explosives building?
- Would you want that explosives building to be a dynamite manufacturing plant or an ANFO manufacturing building?

Regulations treat those situations identically but the risk-levels are hugely different. The first question highlights that ES and PES structures have huge effects on the consequence component of the risk – several orders of magnitude even at IBD in this example. The second question emphasises both the frequency and consequence sides of risk. For consequence, the effective energy of, for example, 1000 kg of an average dynamite will release about 50% more energy than the same weight of ANFO. So blast overpressures will be higher, debris will be more energetic/travel farther, etc. in the dynamite scenario. On the frequency side, dynamite plants are known to explode pretty regularly and the plants are set up with that expectation. No ANFO plant has ever blown up 'spontaneously' and it is generally accepted that an explosion in an ANFO Plant without warning is hardly credible. So for the ANFO plant, there is an additional safety/risk reduction factor of being able to evacuate – a very good idea if you are in that glass house, not nearly as necessary in your concrete bunker.

Q-D makes little or no distinction between any of these scenarios but both companies and Regulators should care about this. QRA is the tool that

allows both to do so and IMESAFR is the key component of the QRA tool to credibly calculate that risk.

7. ACKNOWLEDGMENTS

SAFEX would like to acknowledge the work of the IMESAFR Subcommittee Chaired by Bill Evans and in particular the following organisations and individuals without whom this valuable tool would not be available:

- **IME**: Chris Ronay, former President of the IME, who obtained the support for this project. Lon Santis, who was the IME presence on the Development Team and Subcommittee from the start of the project until the release of IMESAFR 2. Also thanks to Deb Satkowiak, current President of the IME for continuing that strong support which will allow IMESAFR to become an even better tool in the future.
- **APT Research**: John Tatom and his group have done all the real work on the development of IMESAFR and have always been prepared to go above and beyond during this process.
- **US DoD ESB/Science Panel**: It is entirely appropriate that Dr Josephine (Jo) Covino wrote the Introduction to this SAFEX publication. The parent of IMESAFR is SAFER and IMESAFR would not have been possible if the US DoD did not allow the IME to use the SAFER code as the basis for IMESAFR. Jo and her colleagues on the DDESB and Science Panel have been members of the Development Team since the start and have made many valuable contributions.
- **Regulators**: One of the best features of the IMESAFR Development Team has been the participation of people from relevant regulatory agencies. They have made major contributions to the project, have ensured all assumptions/decisions were reasonable and have occasionally reined in approaches that were too conservative. In particular, thanks to Mike O'Lena (ATF), John Buszard (ERD) and Bert von Rosen (CERL).
- **David Leidl**, recently retired from Halliburton and the original chair of the Development Team and Subcommittee who contributed so much to the success of this project.

About SAFEX International

SAFEX International is a global organisation with the fundamental objective of improving the safety of explosives operations and their impact on people and the environment. Operations cover the development, manufacture, storage, and transport of commercial explosives, military explosives and pyrotechnic products throughout the world. The term “explosives” includes initiating devices, propellants, industrial and military powders as well as the raw and intermediate materials associated with the explosives industry.

Current membership of **SAFEX** is almost 250 companies from all the continents in the world and operating in more than 45 different countries.

SAFEX is a non-profit association of manufacturers of explosives and was founded in 1954 with the aim of exchanging experiences within the explosives industry. The way **SAFEX** works is to exchange health, safety, and environmental (HS&E) information about major accidents, serious incidents, and near-events. The objective is to help other manufacturers prevent the same or similar events from occurring. In this way **SAFEX** contributes to improve the health and safety of operations within the explosives business as well as the reputation of the explosives industry. As a voluntary organisation, **SAFEX** is not organised for the financial gain of any of its members or associates.

SAFEX International is registered in Switzerland as an international non-profit association

Registered Office:
c/o Modoux Services Sárl, Route du Village 13, CH-1807 BLONAY, Switzerland
Tel: +41 21 943 0101; Fax: +41 21 943 0109;
Web: www.safex-international.org

Please direct all communication to the Secretary General
Tel/Fax +27 11 704 1743

e-Mail: secretariat@safex-international.org