Quantitative Risk Analysis in the Commercial Explosives Industry

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Abstract

Risk management has been, is, and always will be a required key competence for explosives companies. While the large/global commercial explosives companies have significant internal capabilities for risk management, smaller local companies and even medium-sized companies will generally have only limited capabilities. Since the larger companies recognize any accident in the industry will affect all companies, they are prepared to share their internal expertise and knowledge with the broader industry. This is generally done through industry associations, such as SAFEX International (SAFEX) and the Institute of Makers of Explosives (IME).

Risk management requires minimizing event frequencies and/or consequences. Explosives companies try to manage both, but the business adage is "what one can't measure, one can't manage." Explosives companies are generally good on the frequency side with a significant amount of historical data and standard methodologies, e.g., fault trees, to determine valid event frequencies and measure the effectiveness of various approaches to reduce them. Prior to the advent of Institute of Makers of Explosives Safety Analysis for Risk (IMESAFR), explosives companies had no effective way to measure the consequences or the effectiveness of various risk reduction approaches. IMESAFR has allowed explosives companies to move from Semi-Quantitative Risk Assessment (SQRA) to full Quantitative Risk Assessment (QRA).

1 Background to Risk Management in the Explosives Industry

When the author, Bill Evans, joined the world's largest commercial explosives in the late 1970s, the conversion to formalized risk and hazard review systems was just starting. The impetus was a series of significant explosives accidents globally and a growing realization that the approach to risk management needed to be more rigorous. Prior to this, risk management generally consisted of semiformal reviews by senior personnel and subject matter experts. Reviews would cover such things as Piping and Instrumentation Diagrams (P&IDs), Process Flow Diagrams (PFDs), project plans, and possibly use methodologies such as fault tree analysis to make the analysis at least semi-quantitative. This approach worked very well for many decades, mainly due to two factors:

1. The products manufactured and processes used had been evolving very slowly
2. Employees tended to be employees for life so senior employees really did understand their products and process at a fundamental level

However, starting in the late 1950s, the explosives technology started to evolve more rapidly and whole new technologies, e.g., ammonium nitrate/fuel oil (ANFO) and water-gels, were appearing. The other major change was in the mining industries, with a strong trend towards using very large open pit mines requiring very large amounts of explosives to operate efficiently. This trend towards large pits coupled with other trends in this new mining method, requirements simply could not be filled by the global availability of dynamites, which drove the original development of ANFO and water-gels.

These new products were, correctly, seen as much safer than the nitroglycerine (NG) products, which had long dominated the industry. But the requirement for very large quantities of explosives meant that new high-rate processes needed to be developed, and high-rate inevitably also meant high mechanical energy processes. This huge gap in sensitivity was undoubtedly true for ANFO and other dry blasting agents that would by any standard measurement be at least hundreds of times less sensitive than dynamites. However, water-gels, which always contain some nitro-organic sensitizer, might be an order of magnitude less sensitive than dynamites or maybe, for high water variants, two orders of magnitude less sensitive. The change of sensitivity was over-estimated and the difference in mechanical energy input of the new processes was underestimated. While the steady-state mechanical energy of the new processes was generally on the order of a magnitude higher than used in a dynamite plant, the catastrophic mechanical failure energy difference was much higher, mainly due to the very hard materials used for the manufacture of ANFO, water-gels and, later, emulsions versus the relatively soft materials used in dynamite processes. So, while the conversion to ANFO-type explosives was undoubtedly a quantum jump to a safer technology, this was not true for water-gels – or emulsions once they were invented, which was not recognized at the time. That is, while emulsions and water-gels are much less sensitive products than the dynamites they have been replacing over the past 5+ decades, emulsion and water-gel plants are not much safer than dynamite plants (at least on an annual basis; on a per unit weight basis, dynamite plants remain much more hazardous).

The other major issue was that companies had the people, knowledge, expertise, history, and limited methodologies needed to relatedly run dynamite plants safely. This was not true, on essentially any level, for the new technologies. The site the author worked at for 18 years in two stints is an excellent example of this. A world-scale dynamite plant (built by A. Nobel) opened outside Montreal in 1877 and closed in 1992, during which time there was not a single process explosion or process related fatality. However, that site had two serious accidents attributed to these “new” explosives: seven fatalities in the NI-1 water-gel plant in 1976 and four fatalities in the RE-20 emulsion pilot plant in 1988.

Therefore, hazards and risk management capabilities needed to evolve and become more sophisticated to match changes in these product and process technologies.

2 Evolution of Risk Management in the Commercial Explosives Industry

At the start of this evolution, the mentality was more “hazards management” than “risk management,” i.e., the goal was to reduce hazards to the lowest possible level rather than to operate the plant/site/company to a defined acceptable risk level. The discussion that follows will mostly pertain to Imperial Chemical Industries (ICI)/Orica, “the world’s largest provider of commercial explosives and blasting systems,”[1] which has an extensive R&D spend that includes a significant amount on hazards research, but will apply to the industry as a whole.

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[1] “Top 5 Companies Dominating the Explosives Manufacturing Sector,” https://www.spendedge.com/blogs/companies-explosives-manufacturing (July 13, 2018)

Hazards/risk management requires an understanding of three things:

1. How often the "bad thing" might happen
2. What the consequences will be
3. What is an acceptable level of frequency/consequences

The explosives industry understood frequency and consequences with the older technologies but had no baseline for the newer technologies and no history on which to base assessments. The old system of consensus expert opinion fails when new technology makes much expert opinion and historical data irrelevant. So, the industry transitioned to a more formal and rigorous approach. Before discussing some of approaches that were developed to manage "risk," it should be recognized this "management" was largely "hazards" management, not risk management as the focus was on reducing catastrophic event frequency with minimal capability to estimate consequences and therefore almost no capability to manage them. This management system consisted of: manning levels as low as operationally feasible, in-process quantities maintained as low to stay commercially viable, and separate people and sensitive materials greatest the degree possible. While these are sensible consequence mitigators with respect to fatalities, relying on quantity-distance (QD) was the only tool used to manage the risk to unrelated workers and the public. Another interesting mindset at that time was ICI only cared about fatalities and serious injuries; facilities can be rebuilt or replaced, but fatalities are final. With the advent of new explosives technologies, all the major/global explosives companies developed systems to manage these hazards, but the ICI system has been adopted widely across the global chemical and petrochemical industries as the "HAZOP" methodology – as well as being the one that the author can discuss authoritatively.

Acceptable level of fatalities induces queasiness in both the public and private sectors, but risk cannot really be managed unless there are pass/fail criteria. This is more difficult with limited capability to estimate potential consequences. ICI's approach was to set the risk criteria to be number of explosions per 100 million operating hours, with the assumption that each such explosion would result in at least one fatality.

2.1 Hazards Management Tools

ICI recognized that hazards occurred at three levels in explosives plants:

1. Process equipment specific, e.g., friction event in a high shear mixer
2. Process specific, e.g., no flow process condition
3. Plant generic, e.g., fire in plant

Consequently, the ICI Hazards Management System was designed to identify hazards at all three levels and then to manage/prevent/mitigate them. This was wrapped up into a six-step Hazard Study (HS) Process.

Hazard Study 1 (HS1): This was essentially the project design review step. Make sure all the company, regulatory, and project requirements are recognized and in place.

Hazard Study 2 (HS2): This study looked at the major hazards, almost always explosions of inventories. There were three different study types that could be part of HS2.

1. Standard HS2: Uses guidewords, e.g., high temperature, to identify potential hazards in each section of a process and for the overall process and/or plant. The HS Team determined whether this condition was possible, how it could arise, and whether current safeguards were adequate to manage the hazard (i.e., reduce the frequency). If not, additional "safeties" would be added until the frequency was reduced to an acceptable level. This was at best a semi-quantitative system. If the review of the particular process required a deeper review and/or a more quantitative approach, there are two specialist HS2 methodologies available to be used. One of these, Hazard Evaluation and Risk Control (HERC), will be discussed next; the second, Hazard Identification, Risk Assessment and Control (HIRAC), was developed later and will be discussed in the Evolution to Risk Management section.
2. HERC is a highly detailed, very technical study on a single scenario, i.e., a specific product at a specific set of process conditions and equipment parameters. It looks at, mainly, friction and impact events inside a "machine," e.g., pump, mixer, etc. The study requires detailed knowledge of the friction, impact, and thermal response of a material: probit curves (initiation probability vs. rate of energy input in a friction or impact event) or material response curves (adiabatic time to detonation curves vs. temperature). Other product properties were also required such as Minimum Burning Pressure (MBP) vs. temperature and critical diameter vs. temperature and degree of confinement. The "machine" inputs were maximum component (generally tip) speeds, hardness of relevant components (e.g., rotor/stator), horse power (HP) (maximum rate of temperature generation in a no-flow condition) and degree of confinement available. Additionally, an event frequency was required that could be based on historical data, where enough existed or by using a standard technique such as fault tree analysis to derive one. The HERC equation is:

$$\mathbf{X_f = E_f \times C_p \times I_p \times S_p \times T_p}, \text{ where}$$

E_f = Frequency of Event

C_p = Prob. Material Present

I_p = Prob. of Initiation

S_p = Prob. of Sustained Burning

T_p = Prob. of Transition to Detonation

And X_f is the explosion frequency with the same units as E_f, normally per year. ICI considered a shift-year to be 2,000 hours, so a pass was less than one explosion per 50,000 years (100 million operating hours).

This analysis is for a single product at a single set of process conditions and equipment parameters. In general, look at the most sensitive material at normal operating conditions and, if this was a pass, then all less sensitive products were also a pass at standard operating parameters. If one wanted to, for example, make a more sensitive product or increase the rpm, then one had to extend the HERC analysis. Note that the method is very quantitative on the frequency side but fuzzy on the consequence side. The other critical point is this is an ICI/Orica specific study as it uses data that took a large number of person-years to generate. That said, there are a number of ICI/Orica trained "graduates" who are free to use the tool and have access to all the data.

Hazard Study 3 (HS3): Much like HS2 in that it is guideword, e.g., high/low/no-flow driven study but looks for operability issues rather than hazards. If HS3 finds some new/potential hazards not identified in HS2, the HS Study Team goes back to HS2 to cover them. Note that HS2 and HS3 were generally done sequentially by mostly the same team so this was not difficult. HS3 is the main component of what is also known as the "HAZOP" system, which ICI released for use by anyone and remains a standard risk management tool in the global chemical and petrochemical industries.

Hazard Studies 4 (HS4): Pre-commissioning and pre-startup looking at build vs. design and potential equipment/process issues.

Hazard Studies 5 (HS5): Addresses safety issues, e.g., hot surfaces, pinch points, etc., for operators.

Hazard Study 6 (HS6): A six month to one-year review of plant operating history vs. design to provide learning – good and bad – for the next project. This was only ever done on big projects.

The final component of the hazard management system was a formal change management system. One can use the safest processes and best designs but that can all be lost if one does not manage changes to products, equipment, and processes.

The ICI hazard study and change management system was a formal, comprehensive answer to the issues and gaps that were faced during the technology change from dynamites to "modern" explosives and provided a robust platform for hazards management. Other companies developed systems that did many of the same things in various ways. Everyone recognized that the world had changed and realized more formal systems needed to be used.

2.2 Evolution to Risk Management

The focus had been almost entirely on the prevention of accidental process explosions that would inevitably result in one or more fatalities, i.e., hazards management. But hazards management does not equal hazards prevention and two things became clear in the two decades following the advent of formalized hazards management:

1. Explosives accidents could not be prevented
2. Fatalities was not the only risk measurement that companies needed to be concerned about

Hazards management, especially when defined as minimizing event frequency is fairly straightforward; true risk management can be both much more complex and subtle.

Risk is generally defined as frequency times consequences with a third term – people present – being valid when looking at, e.g., fatalities to the public. Companies had become good at managing, i.e., minimizing, event frequency but the consequence side was little more than "bad thing happens, fatality occurs." To truly manage risk, especially taking more than just fatalities to related workers into consideration, requires more risk management capabilities than the explosives companies had. Consequently, it was slow evolution for companies to become more sophisticated in risk management and add risk management tools, expertise, and capabilities.

The first step in ICI/Orica's risk management was the addition of a new HS2 tool, the HIRAC, and with that, a risk matrix to determine whether the calculated risk was acceptable. As with all risk matrices, the approach is an SQRA as both frequency and consequences are quantified but are then matched to ranges on the risk matrix. The final section of this paper, Stockholm Syndrome, will cover the use of the Orica Risk Matrix in detail.

A HIRAC is used to review a specific hazard scenario with respect to causes, consequences, and base frequency. Hard and soft preventative factors are reviewed to determine whether the base frequency can be modified and, if so, by how much. Hard and soft mitigative controls are then reviewed to determine whether the consequences could be reduced and, if so, to what level. The modified event frequency and consequences are then used to determine which box in the risk matrix to use and thereby whether the risk is acceptable or not. Note that any risk criteria, e.g., financial loss, damage to corporate reputation, etc., can be used, not just fatalities.

The use of a risk matrix moved companies from hazards management to true risk management. However, companies still had limited capabilities to estimate some consequences, e.g., fatalities to members of the public and the use of the risk matrix limited risk management to a semi-quantitative level. That is, until the advent of IMESAFR.

3 IMESAFR

IMESAFR, a probabilistic risk assessment tool used to calculate risk to personnel from explosives facilities, has revolutionized risk management in the explosives industry. It provides a true QRA capability, i.e., both frequency and consequences are fully quantified and can be measured against internal or regulatory risk criteria. For information on how IMESAFR was developed and functions, refer to "NDIA 2018: IMESAFR Overview."[2]

Prior to the inception of IMESAFR, companies were able to easily calculate the cost to replace a building or to find alternate sources of product to retain customer satisfaction, in the event either were lost to an explosion, but had no way to determine off site effects such as fatalities to the public or damage to surrounding non-company structures. IMESAFR provides an effective way to assess this risk. IMESAFR allow companies to move from a risk matrix approach to a true pass/fail risk criterion. Most companies will use an individual risk criterion and a group risk criterion. The most broadly used are 1 E-06 (one in a million years) and 1 E-05 (10 in a million years) fatalities respectively, which are very standard criteria.

IMESAFR is used both as an internal risk management tool by explosives companies and to support QRAs for requests for variances from regulators. The ability to use true risk calculations to make decisions on siting, inventories, separation distances is highly valuable to explosives companies. Note that all the other methodologies used to design safe processes and minimize event frequencies remain valid for risk or hazard reduction. What IMESAFR provides to

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[2] Tatom, J., Hoffman, J, Fritz, C., Evans, B., Duncan, M., Robinson, M., *NDIA 2018: IMESAFR Overview*, Minutes of International Explosives Safety Symposium & Exposition 2018, NDIA Paper No. 20720

explosives companies is the capability to ensure that the external effects of accidental explosives are acceptable. As IMESAFR gains traction with regulators, companies will be able to do things that QD either forbids or limits, certainly without compromising safety and possibly occasionally reducing risk. Risk management is evolving to a system where companies can do smart things and either make more money or spend less money, without compromising employee or public safety.

4 Sharing the Wealth

In the days when dynamite was king, there were major financial barriers to entry to the explosives business. Most explosives companies were themselves very large, or part of an even bigger chemical or oil/petrochemical companies. The industrial associations to which these explosives companies belonged were mostly focused on safety and sharing safety lessons. The companies were all technically sophisticated and made similar products on very similar equipment. Thus, lessons learned would spread rapidly across the industry.

As the technology evolved to modern explosives, the barriers to entry disappeared and small companies became more and more common, especially in the U.S. These new companies were generally technically unsophisticated and had limited risk management capabilities. They also tended to have more accidents and near misses than the big companies, which concerned industry regulators. In general, regulators did not care who was having the accidents/near misses just that regulations needed to be tightened, i.e., industry risk management by regulatory mandate. This added regulation inevitably added costs and limited flexibility for all companies. Therefore, it became sensible for the big industry associations to evolve into organizations aimed at managing hazards/risks and regulators. Participation with these organizations allowed the free sharing of knowledge and expertise on process safety across all the companies in the industry, invariably from the big companies to the small companies.

The main method used for this sharing of risk management was the development of publications covering specific hazards, risks and/or safety concerns, such as, IME's Safety Library Publications (SLP) or Good Practice Guidelines (GPGs) from SAFEX. SAFEX also has a formal group of technical experts, to whom any member company may obtain expert advice on a safety or hazard concern. The development of IMESAFR is an example of a tool, funded and supported by IME, which any member or non-member company can use to better manage risks.

There are four key such associations covering the world's major explosives markets regions: Australian Explosives Industry and Safety Group, Inc. (AEISG) in Australia, Canadian Explosives Industry Association (CEAEC) in Canada, Federation of European Explosives Manufacturers (FEEM) in Europe, and the IME in the U.S. One global organization, SAFEX, has close ties to all the regional associations. Additionally, SAFEX has a remit to spread the expertise and capabilities mostly based in the large companies in the four regional associations globally, especially to those regions/companies with much lower internal capabilities and, therefore, a greater need of such assistance. Since accidents hurt everyone, preventing them is good for everyone. This makes associations very valuable in reducing process hazards/risks across the industry.

5 A Risk Management Case Study: The Stockholm Syndrome

This work has been presented at both a Chief Inspectors of Explosives (CIE) Conference (Ref 1) and a SAFEX Congress (Ref 2) and this section is largely taken from the SAFEX paper.

Underground tunneling is an important business application in the Nordics area and is a growing one in other areas as well. In 2010, Orica Nordics was very interested in being the explosives subcontractor for the major expansion of the Stockholm rail/subway system. Initial product volumes were small but would ramp up significantly. The Explosives Expert Team (EET) of Orica was asked for permission to store 30 te (30 metric tonnes = 33 tons/66000 lb) of ANE directly under the central rail station in downtown Stockholm. This proposal met Swedish regulatory requirements.

However, the EET found this proposal to be unacceptable due to the potentially catastrophic consequences in the event of the worst-case explosion, which were estimated to be tens or even hundreds of fatalities and billions of dollars of liability, as well as the “destruction” of Orica’s corporate image and reputation. The issue that the Nordics business faced after the initial refusal was that a) what they had proposed met all regulatory requirements, and b) their competitors were under no such corporate constraint. They would therefore be unable to compete effectively for such contracts as Orica was not allowing the most cost-effective approach to servicing such work. Therefore, the EMEA (Europe, Middle East, and Africa) business, of which the Nordics area was a part, appealed to the EET to reconsider the original decision – at least to the extent of determining what would be possible.

The main remit of the EET following Lorena was to make and enforce the rules, but there were areas identified where mandatory standards seemed to be overkill or too limiting. The EET therefore started using risk analysis methodologies to cover the grey areas. Orica had “inherited” some risk management capability from ICI and had strengthened it in parts of the business. The explosives industry had always been consequence-based, if largely on the event prevention side, so moving towards a risk-based focus was a big step.

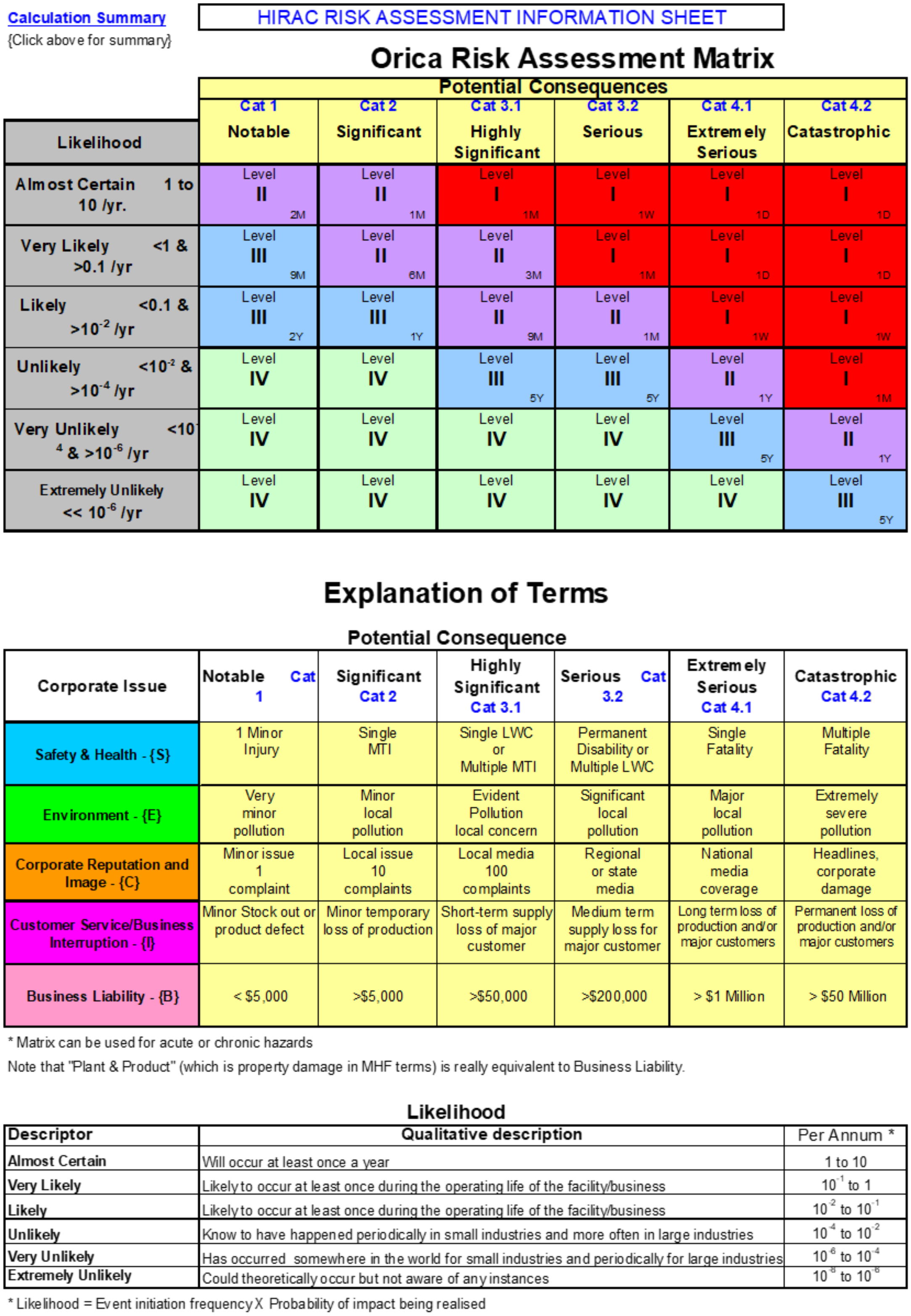
The basic change in the industry that allowed the movement from consequence-based to risk-based was the much lower sensitivity of modern bulk explosives/ANEs. It was accepted that a dynamite plant can blow up, essentially regardless of the standard to which it is run. That explosion will be without warning and the only way to protect personnel, other inventories, and other buildings is through distance. The same is generally not true for ANE inventories, especially after the manufacturing process. It is not that they won’t/can’t explode in some scenarios (e.g., fire engulfment); it is that there will be a warning and time can be used instead of distance to protect personnel. Nor is an explosion certain or even the most likely outcome, which is the other significant enabler for moving from a consequence only to a risk-based approach. There is a very large drop in frequency for accidental explosions of HD 1.5 and 5.1 ANEs compared to HD 1.1 explosives. This approach was first formalized in the AEMSC (Australia) Code, where credible evacuation was accepted as an alternative to full QD. Orica had adopted this approach globally, even where there was no formal requirement to have any QD around ANEs. The exception was countries, e.g., Canada, where ANEs were classified as 1.5 explosives and full QD is therefore required.

Therefore, the EET had evolved to the point where a risk-based approach to the storage of ANEs could be considered. The issue was that many of the tools to do a QRA rigorously were lacking.

6 Quantitative Risk Analysis

In 2010, Orica had many risk assessment tools: the hazard study process inherited from ICI, the HERC process developed by CIL (the ICI subsidiary in Canada), HIRACs, fault tree analyses, Level of Protection Analysis (LOPA), etc. There were also risk targets for both internal and external consequences, especially fatalities. These methodologies/tools provided outputs on frequencies and consequences that were plotted on a risk matrix (see Fig 1). The first issue encountered was that this matrix was a) more geared towards internal events in some of the risk categories, particularly injuries and fatalities, and b) did not cover the type of potentially catastrophic consequences possible with transporting/storing large quantities of ANEs underneath major capital cities.

Orica had adopted the general United Kingdom (UK) public risk target of 1E-06, which is a widely accepted risk used also by Department of Expense Explosives Safety Board (DDESB), with the additional proviso that as the consequence increases by an order of magnitude, the frequency must drop by the same amount. Thus, an accident that could kill hundreds or thousands of members of the public is only an acceptable risk if the frequency is very low and may be deemed to be unacceptable at any frequency. The consequence and frequency axes of the standard Orica Risk Matrix clearly did not extend far enough for an event such as this. Fortunately, the EET had already recognized this limitation and had started the development of an expanded risk matrix (see Fig. 2).



Calculation Summary
{Click above for summary}

HIRAC RISK ASSESSMENT INFORMATION SHEET

Orica Risk Assessment Matrix

	Potential Consequences					
Likelihood	Cat 1 Notable	Cat 2 Significant	Cat 3.1 Highly Significant	Cat 3.2 Serious	Cat 4.1 Extremely Serious	Cat 4.2 Catastrophic
Almost Certain 1 to 10 /yr.	Level II 2M	Level II 1M	Level I 1M	Level I 1W	Level I 1D	Level I 1D
Very Likely <1 & >0.1 /yr	Level III 9M	Level II 6M	Level II 3M	Level I 1M	Level I 1D	Level I 1D
Likely <0.1 & $>10^{-2}$ /yr	Level III 2Y	Level III 1Y	Level II 9M	Level II 1M	Level I 1W	Level I 1W
Unlikely $<10^{-2}$ & $>10^{-4}$ /yr	Level IV	Level IV	Level III 5Y	Level III 5Y	Level II 1Y	Level I 1M
Very Unlikely <10 ^{4} & $>10^{-6}$ /yr	Level IV	Level IV	Level IV	Level IV	Level III 5Y	Level II 1Y
Extremely Unlikely $<< 10^{-6}$ /yr	Level IV	Level IV	Level IV	Level IV	Level IV	Level III 5Y

Explanation of Terms

Potential Consequence

Corporate Issue	Notable Cat 1	Significant Cat 2	Highly Significant Cat 3.1	Serious Cat 3.2	Extremely Serious Cat 4.1	Catastrophic Cat 4.2
Safety & Health - {S}	1 Minor Injury	Single MTI	Single LWC or Multiple MTI	Permanent Disability or Multiple LWC	Single Fatality	Multiple Fatality
Environment - {E}	Very minor pollution	Minor local pollution	Evident Pollution local concern	Significant local pollution	Major local pollution	Extremely severe pollution
Corporate Reputation and Image - {C}	Minor issue 1 complaint	Local issue 10 complaints	Local media 100 complaints	Regional or state media	National media coverage	Headlines, corporate damage
Customer Service/Business Interruption - {I}	Minor Stock out or product defect	Minor temporary loss of production	Short-term supply loss of major customer	Medium term supply loss for major customer	Long term loss of production and/or major customers	Permanent loss of production and/or major customers
Business Liability - {B}	< $5,000	>$5,000	>$50,000	>$200,000	> $1 Million	> $50 Million

* Matrix can be used for acute or chronic hazards

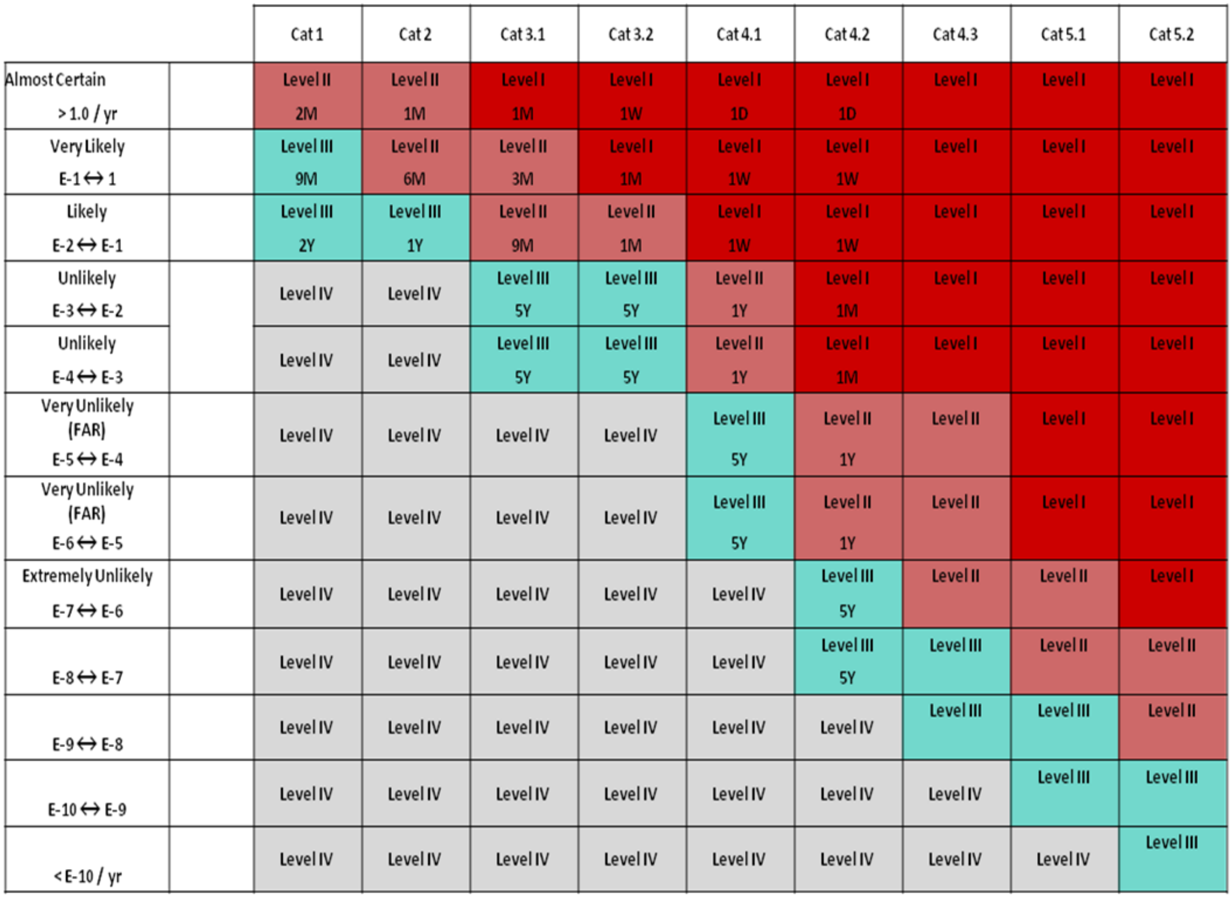
Note that "Plant & Product" (which is property damage in MHF terms) is really equivalent to Business Liability.

Likelihood

Descriptor	Qualitative description	Per Annum *
Almost Certain	Will occur at least once a year	1 to 10
Very Likely	Likely to occur at least once during the operating life of the facility/business	10^{-1} to 1
Likely	Likely to occur at least once during the operating life of the facility/business	10^{-2} to 10^{-1}
Unlikely	Know to have happened periodically in small industries and more often in large industries	10^{-4} to 10^{-2}
Very Unlikely	Has occurred somewhere in the world for small industries and periodically for large industries	10^{-6} to 10^{-4}
Extremely Unlikely	Could theoretically occur but not aware of any instances	10^{-8} to 10^{-6}

* Likelihood = Event initiation frequency X Probability of impact being realised

Figure 1: Standard Orica Risk Matrix



		Cat 1	Cat 2	Cat 3.1	Cat 3.2	Cat 4.1	Cat 4.2	Cat 4.3	Cat 5.1	Cat 5.2
Almost Certain > 1.0 / yr		Level II 2M	Level II 1M	Level I 1M	Level I 1W	Level I 1D	Level I 1D	Level I	Level I	Level I
Very Likely E-1 ↔ 1		Level III 9M	Level II 6M	Level II 3M	Level I 1M	Level I 1W	Level I 1W	Level I	Level I	Level I
Likely E-2 ↔ E-1		Level III 2Y	Level III 1Y	Level II 9M	Level II 1M	Level I 1W	Level I 1W	Level I	Level I	Level I
Unlikely E-3 ↔ E-2		Level IV	Level IV	Level III 5Y	Level III 5Y	Level II 1Y	Level I 1M	Level I	Level I	Level I
Unlikely E-4 ↔ E-3		Level IV	Level IV	Level III 5Y	Level III 5Y	Level II 1Y	Level I 1M	Level I	Level I	Level I
Very Unlikely (FAR) E-5 ↔ E-4		Level IV	Level IV	Level IV	Level IV	Level III 5Y	Level II 1Y	Level II	Level I	Level I
Very Unlikely (FAR) E-6 ↔ E-5		Level IV	Level IV	Level IV	Level IV	Level III 5Y	Level II 1Y	Level II	Level I	Level I
Extremely Unlikely E-7 ↔ E-6		Level IV	Level IV	Level IV	Level IV	Level IV	Level III 5Y	Level II	Level II	Level I
E-8 ↔ E-7		Level IV	Level IV	Level IV	Level IV	Level IV	Level III 5Y	Level III	Level II	Level II
E-9 ↔ E-8		Level IV	Level IV	Level IV	Level IV	Level IV	Level IV	Level III	Level III	Level II
E-10 ↔ E-9		Level IV	Level IV	Level IV	Level IV	Level IV	Level IV	Level IV	Level III	Level III
< E-10 / yr		Level IV	Level IV	Level IV	Level IV	Level IV	Level IV	Level IV	Level IV	Level III

Figure 2: The Expanded EET Risk Matrix

The standard risk matrix had the lowest frequency row as << E-06. The issues with this were a) where did << E-06 start, and b) how did one treat anything between E-06 and << E-06. This lower limit was placed because it was felt that historical data would not support lower frequencies. Certainly, this was true for some events but there are many events, e.g., cartridges clipped, prills augered, pump rotations, where the historical data would allow much lower frequencies to be calculated. The consequence column only goes to Category 4.2, e.g., ‘multiple’ fatalities (and this was then a recent change from 2-3 fatalities) or >$50M in business liability. The potential consequences of a major explosion below Stockholm (or any urban environment) could be two orders of magnitude or greater worse for both fatalities and liability. Four fatalities and $60M in liability are not equivalent to 800 fatalities and $3,000M in liability.

The expanded risk matrix had added five rows, most to lower frequencies but some added definition to the standard matrix as well, and three columns, all for more severe consequences. This remained a draft document, used only in the EET and the values for the additional three consequence columns were never finalized. The worst event was assigned the draft values of 100+ fatalities, $2 billion+ liability and potentially irreversible damage to the corporate reputation. These were the only risk categories that could have worse consequences than the standard 4.2 limit, given Orica’s scope of operations. For the draft version, 4.3 was considered to be roughly three times worse, 5.1 10 times worse, and 5.2 40 times worse, all compared to 4.2.

While the EET now possessed the necessary tool to determine the acceptability of the risk, neither the frequency nor consequence data was available for making that determination. For the frequency side, the EET was confident that the necessary data could be generated, building on previous work. The EET was also confident that some of the consequence data was known and most of the rest could be generated. The exception was critical: Orica did not know how to evaluate the consequences of a large blast just below the surface of an urban area. Fortunately, Orica possessed some very clever modelers who were able to do just that. A team was formed to carry out a QRA for this process and provide Orica Mining Services (OMS) with recommendations on how such a project could be carried out at acceptable risk to the local population.

The team, assisted by detailed current and proposed operating procedures provided by the Nordics business, put together seven scenarios covering possible ways of supplying this type of market. Each scenario covered transportation from the initial factory or magazine site, transfer operations, surface and/or underground storage, and loading.

7 Hazards Description

Risk requires both a frequency and consequence that are non-negligible. In this case, most people would accept that a large explosion just beneath a major city would be likely to have potentially catastrophic consequences. This was in fact borne out by the modelling results, which are discussed in the next section. The discussion for this analysis centered on the frequency side. As this practice was allowed in the Nordics business area, one can assume that the regulators believe this practice to be adequately safe. Orica did not necessarily share that view and always had the philosophy that Orica will operate to the higher of the Orica and regulatory standards. Because of the potentially catastrophic consequences should there be a large explosion under Stockholm, Orica was unwilling to proceed without carrying out a complete QRA to measure the various scenarios against OMS risk criteria and standards and would allow only those practices that met OMS internal standards (given the near absence of regulatory restrictions for this practice, anything meeting OMS standards would be an allowed practice in the Nordics area). The hazards OMS was concerned about included:

- Transportation: vehicle fires from accidents/rollovers, tire fires, electrical fires, engine fires leading to an explosion on the vehicle. This was a hazard recognized by regulatory agencies, although, as far as OMS can determine, it had never occurred with ANEs. In the Nordics area, transportation in aluminum (“aluminum” in Canada and the U.S.; “aluminium” everywhere else) tanks is mandated as the authorities believe that aluminum tanks greatly decrease (potentially eliminates) the possibility of an explosion in a fire scenario. OMS accepted that there would be a significant reduction in the risk but did not believe this was an intrinsically safe option. The reason for this was quite simple. While the melting point of aluminum is well below that of steel, it is also hundreds of degrees above the auto-decomposition and auto-explosion temperatures of AN and AN-based products. While the testing to date does show an improvement with aluminum, the number of tests is far too low to prove intrinsic safety. OMS did accept that the use of low melting plastics for the storage and/or transportation of ANEs would probably be intrinsically safe.

- Transfer: vehicle fires (same causes) or transfer pump explosions which propagates to large inventories (vehicle and/or storage tank). The choice of pump critically effected the frequency of the latter cause.
- Storage: fires in the storage area. All the arguments on container type covered in “Transportation” applied here as well.
- Loading: the loading of packaged product in this application can be intrinsically safe from the perspective of surface effects. The largest potential event would not be noticed on the surface. For the loading of bulk products, vehicle fires (standard causes) and pump explosions were the key risks.

8 Development of the Surface Damage Model

A full description of the development of a model to predict surface damage from an underground explosion is beyond the scope of this paper. The executive summary is that a 2D model was used to generate, e.g., vibration amplitude, frequency and duration at the surface from an underground explosion. The first run was for the initial 30 te proposal. The output indicated that although the blast would not quite reach the surface, it would come close enough to breach the basements/parking garages of the high-rise buildings within 50 meters of the epicenter. The expert opinion was that this was likely to compromise foundation stability enough that some of those buildings would likely collapse. Significant vibration damage would extend at least another 50 meters, probably resulting in, for example, breakage of many windows, with glass fragments falling into the streets below. The EET felt that such catastrophic damage was unacceptable at any frequency and requested further modelling be done to determine whether there was an amount that could be stored underground that was small enough to do no more than an acceptable level of damage and that would allow the Nordics business to be competitive in this market.

The output of the modeling was extremely complex and hard to interpret, so it was converted to a pseudo-Richter Scale with a very high decay rate from the center of the blast. Various storage quantities were run to find an amount that would be large enough for commercial viability and small enough to generate only acceptable damage, which was defined to be below a Richter Scale conversion value of 4.0. For transient activities, e.g., reloading of the ANE storage bins, a value of 4.5 was defined as acceptable. This was the standard risk tradeoff: lower frequency for higher consequences.

The model was run at various maximum explosion sizes. The results indicated that the 5.6 tes generated a Richter 4.0 event directly above the explosion and 11 tes generated a Richter 4.5 event directly above the explosion.

Working with the Nordics business and the contractor, Orica was able to find a storage configuration that allowed three 5.6 te bins to be placed in the designated area with adequate separation to ensure no propagation between bins. Thus roughly 17 tes could be stored directly below downtown Stockholm with no risk of a catastrophic event. The Nordics business also felt that this level of storage plus the larger amount that could be brought in to refill bins would allow them to be efficient enough to be competitive in this market.

9 Determination of Event Frequencies

9.1 Determination of Transport Event Frequencies

The Event Frequency of interest was an explosion during the transportation of product from the originating site to the storage location at the job site. Transport accident frequencies were from UK transportation data. This data included baseline accident rates (per million vehicle-km), broken down into the three major causes: accidents/rollovers, tire fires, and mechanical/electrical/engine fires. Data was also available on how often each of these causes resulted in a major truck fire. Explosives industry historical data was used to estimate the probability of a major fire would result in an explosion of the load; the probabilities were different for each of the initiating causes.

The EET Transport Subgroup carried out a HIRAC and identified 20 plus factors that could reduce the frequency/probability of a catastrophic accident. This analysis was then extended to the transportation of Class 5.1 materials (AN, ANS, ANEs). Both ANS and ANEs were assigned much lower explosion probabilities (there were no identified occurrences in countries where OMS could be relatively sure of both the standards and reporting accuracy); AN and explosives turned out to have similar frequencies. The vehicles to be used were rated with respect to the number of preventative/mitigative factors in place and an event frequency was determined for vehicle accidents leading to major explosions. One of the mitigative factors allowed was credible evacuation, which varied as to whether the accident/fire occurred in a rural, suburban or urban location. The frequency data did not demonstrate any difference in the event frequencies down to this level, but the consequences could differ immensely. The number of people at risk in a fire -> explosion scenario depended on a) getting nearby people away, and b) preventing others from getting close. All historical data indicated a window of 30-45 minutes to accomplish this. Evacuation was highly credible in low population and traffic density areas where there were good emergency response capabilities. This has been demonstrated in Canada and Australia. At some population/traffic density, a full evacuation in this scenario is not credible given the limited timeframe. The analysis used the simple assumption that the rural/suburban/urban risk levels (frequency) would be proportional to the relative distance travelled through each.

9.2 Determination of Transfer Explosion Frequencies

Transfer accident rates are strongly pump dependent: Wilden pumps are considered to be intrinsically safe whereas PC pumps have a recognized potential for explosions resulting from no flow pumping events. The analysis assumed the standard OMS pump protection system for PC pumps, which reduced the baseline no-flow event frequency by up to three orders of magnitude. A pump explosion by itself would not be a hazard to people as the quantities are so (relatively) small. As the products in this analysis were unsensitized, it was relatively easy to minimize the probability of a knock-on event to external inventories by using small diameter hoses (below the critical diameter) and minimizing direct line of site. Direct propagation to the inventory being transferred (from) cannot be eliminated, although it was not certain, and this is the event that is evaluated in the QRA.

9.3 Determination of Storage Event Frequencies

The best public storage event frequency data came from the IME. This data was used, unmodified, for the baseline event frequencies. This was conservative as some event initiating mechanisms, e.g., lightning strikes, were not possible for underground storage sites. The event of concern was fire engulfment leading to an explosion. OMS believed that outside of a vessel, i.e., on the ground, there was no risk of an ANE explosion in a fire scenario. Therefore, if the vessel under fire engulfment lost structural integrity, the risk of an explosion became zero. OMS has assigned different probabilities that this will happen for steel, aluminum and plastic vessels (0, 75%, and 90% reduction respectively).

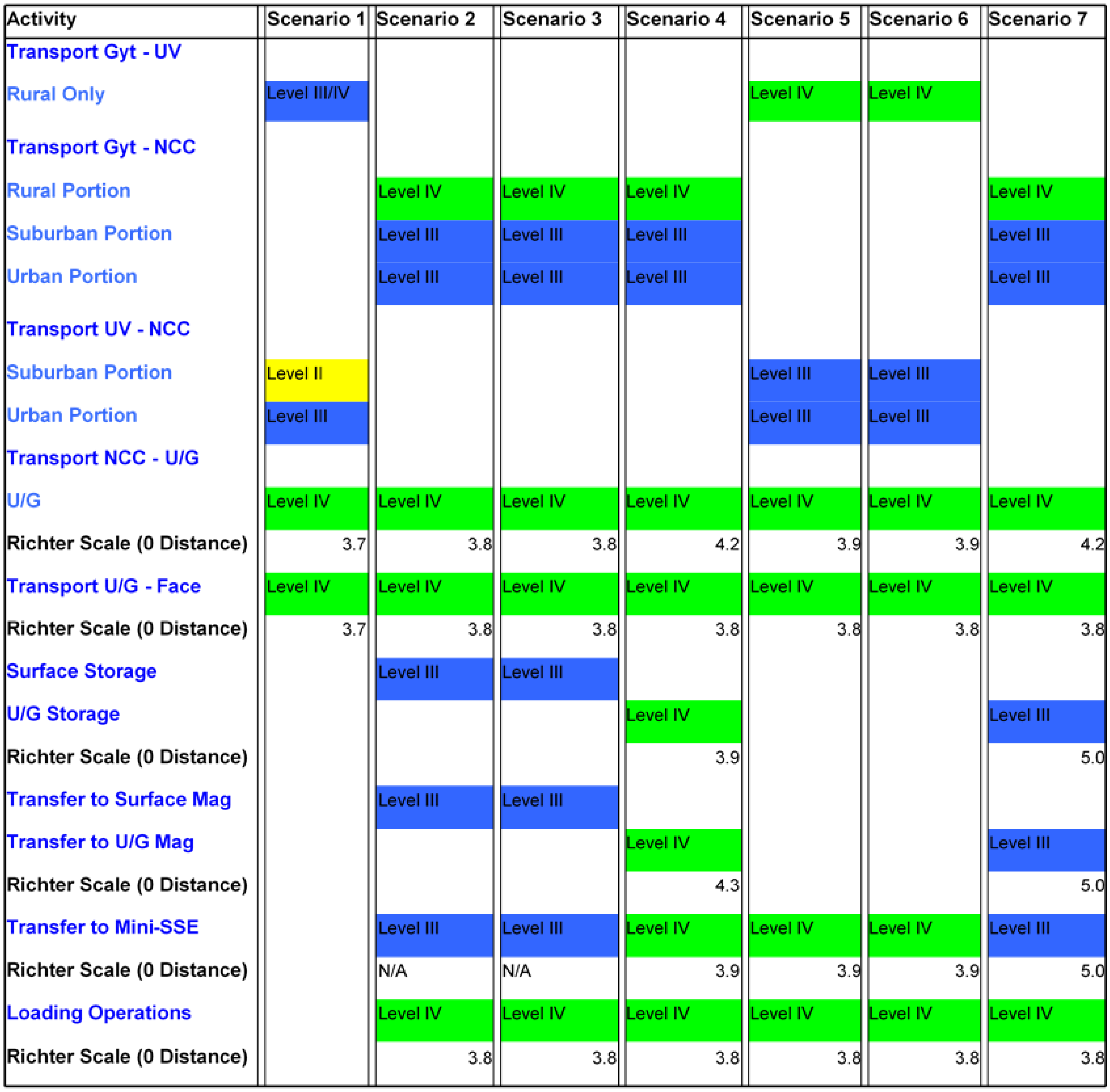
9.4 Determination of Consequences

The initial concern for the Risk Assessment Team was the potentially catastrophic event of a large explosion directly below the middle of Stockholm. However, the development of the surface damage model allowed OMS to define parameters that ensured that the worst possible event would not be a catastrophic one. However, surface storage still had the potential for catastrophic events, as did the transportation of Class 1 or Class 5 through built-up areas. These events did have some potential for evacuation and it was very difficult to work out what the fatality circles would be. Using tools such as IMESAFR indicated that fatality rates were likely to be significantly lower than might be expected at any significant distance from the explosion, but damage levels would still be potentially catastrophic. After internal discussion, it was decided to largely remove fatalities from the consequence model and focus on liability and damage to corporate reputation. While that may seem to be a flawed choice, it should be remembered that any event that might kill large numbers of people was certainly going to result in huge liabilities and damage to the corporate reputation. The QRA methodology assumes that one will select the risk category with the highest consequence when analyzing an event. Therefore, Orica decided to use the consequences of fatalities, rather than the number of fatalities directly as the latter would be difficult or impossible to estimate.

Therefore, for each step in each scenario, the worst possible event was determined. In every case, this was simply the largest amount of explosives that could explode in an initial event plus any direct knock-on effects. The consequences of each of these events were then quantified, using whichever risk category provided the worst result.

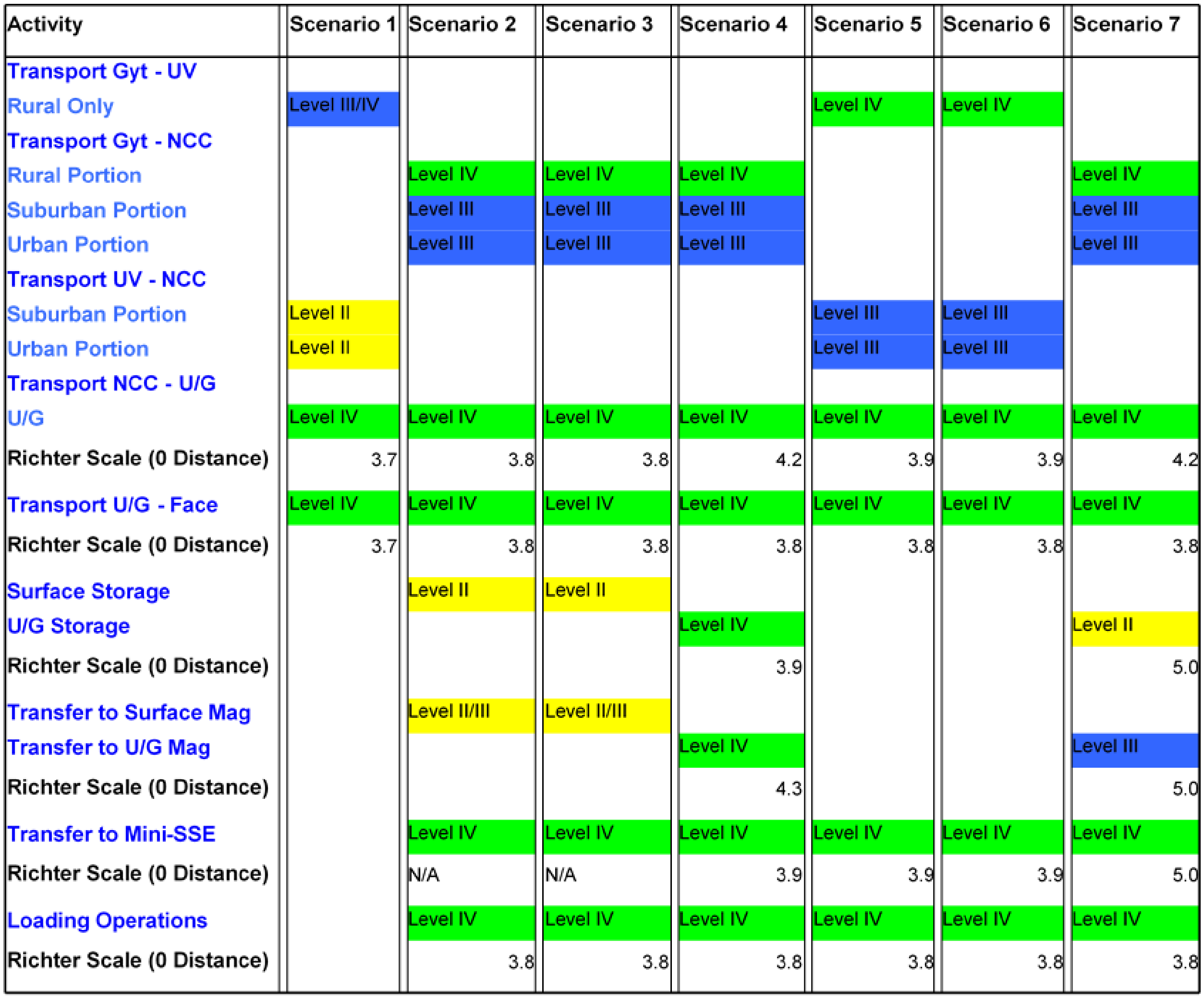
10 QRA Output

The frequencies and consequences were determined for each step of each scenario and the risk level then determined on both the Standard and Expanded EET Risk Matrices. Note that not each step occurs in every scenario. The results are shown in summary form in Figure 3 and Figure 4.



Activity	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7
Transport Gyt - UV							
Rural Only	Level III/IV				Level IV	Level IV	
Transport Gyt - NCC							
Rural Portion		Level IV	Level IV	Level IV			Level IV
Suburban Portion		Level III	Level III	Level III			Level III
Urban Portion		Level III	Level III	Level III			Level III
Transport UV - NCC							
Suburban Portion	Level II				Level III	Level III	
Urban Portion	Level III				Level III	Level III	
Transport NCC - U/G							
U/G	Level IV	Level IV	Level IV	Level IV	Level IV	Level IV	Level IV
Richter Scale (0 Distance)	3.7	3.8	3.8	4.2	3.9	3.9	4.2
Transport U/G - Face	Level IV	Level IV	Level IV	Level IV	Level IV	Level IV	Level IV
Richter Scale (0 Distance)	3.7	3.8	3.8	3.8	3.8	3.8	3.8
Surface Storage		Level III	Level III				
U/G Storage				Level IV			Level III
Richter Scale (0 Distance)				3.9			5.0
Transfer to Surface Mag		Level III	Level III				
Transfer to U/G Mag				Level IV			Level III
Richter Scale (0 Distance)				4.3			5.0
Transfer to Mini-SSE		Level III	Level III	Level IV	Level IV	Level IV	Level III
Richter Scale (0 Distance)		N/A	N/A	3.9	3.9	3.9	5.0
Loading Operations		Level IV	Level IV	Level IV	Level IV	Level IV	Level IV
Richter Scale (0 Distance)		3.8	3.8	3.8	3.8	3.8	3.8

Figure 3: QRA Summary, Standard Risk Matrix



Activity	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7
Transport Gyt - UV							
Rural Only	Level III/IV				Level IV	Level IV	
Transport Gyt - NCC							
Rural Portion		Level IV	Level IV	Level IV			Level IV
Suburban Portion		Level III	Level III	Level III			Level III
Urban Portion		Level III	Level III	Level III			Level III
Transport UV - NCC							
Suburban Portion	Level II				Level III	Level III	
Urban Portion	Level II				Level III	Level III	
Transport NCC - U/G							
U/G	Level IV	Level IV	Level IV	Level IV	Level IV	Level IV	Level IV
Richter Scale (0 Distance)	3.7	3.8	3.8	4.2	3.9	3.9	4.2
Transport U/G - Face	Level IV	Level IV	Level IV	Level IV	Level IV	Level IV	Level IV
Richter Scale (0 Distance)	3.7	3.8	3.8	3.8	3.8	3.8	3.8
Surface Storage		Level II	Level II				
U/G Storage				Level IV			Level II
Richter Scale (0 Distance)				3.9			5.0
Transfer to Surface Mag		Level II/III	Level II/III				
Transfer to U/G Mag				Level IV			Level III
Richter Scale (0 Distance)				4.3			5.0
Transfer to Mini-SSE		Level IV	Level IV	Level IV	Level IV	Level IV	Level IV
Richter Scale (0 Distance)		N/A	N/A	3.9	3.9	3.9	5.0
Loading Operations		Level IV	Level IV	Level IV	Level IV	Level IV	Level IV
Richter Scale (0 Distance)		3.8	3.8	3.8	3.8	3.8	3.8

Figure 4: QRA Summary, EET Expanded Risk Matrix

The expanded risk matrix did indeed provide “higher resolution” in the QRA. While six of the seven scenarios passed (i.e., only Level III and IV risks) using the standard risk matrix, only three passed using the expanded version. The most surprising difference is in the analysis of the original proposal (30 te beneath downtown Stockholm). In this instance, the acceptance of this risk was based on the “failure” of the consequence axis to cover the potentially catastrophic results should such a large inventory explode under an urban area. For many of the “points” on the standard risk matrix, the QRA moved the consequence to the right (worse) when using the expanded matrix, but also moved the frequency down (better). In a very large number of cases, this resulted in the same risk level, even though the position on the relative positions on the risk matrices was very different. This will not always be the case so the EET believes that this analysis actually understates the benefits of converting to the expanded risk matrix.

Conclusions

The explosives industry has evolved from risk management being a consensus of experts to a sophisticated approach using formal risk management systems and advanced computer capabilities in less than 50 years, with much of that change happening in the last 15 years. This paper outlines this evolution and presents a case study that demonstrates just how advanced these capabilities can be – and are needed to be. IMESAFR has become an invaluable and irreplaceable risk management tool for large explosives companies and is gaining traction with both smaller companies and regulators.

References

1. W.B. Evans, Orica Mining Services, “The Evolution of Risk Management in Orica Mining Services”; A Case Study Chief Inspectors of Explosives Conference, Salt Lake City, May 2011.
2. W.B. Evans, Orica Mining Services, “Case Study – Application of Risk Methodology for U/G Tunneling Project in Stockholm”, SAFEX Congress, Istanbul, May 2011.