Underground Storage of ANE in Urban Areas: A Risk Analysis Case Study

Summary

The EET (Explosives Expert Team) was asked to evaluate options for the storage of ANE near/underneath downtown Stockholm. The standard Orica Mining Services (OMS) risk analysis methodologies were inadequate in this case. This was due to the potential consequences being so catastrophic (potentially hundreds of fatalities and/or billions of dollars of liability) that the lowest event frequencies ‘allowed’ by OMS were not low enough for the potential consequence level to be acceptable. As well, OMS had no way to estimate the surface effects in an urban environment of a large explosion 20 – 30 metres underground.

The Technology Group in Watkins (Denver), CO used advanced modelling tools to estimate the surface effects of underground blasts then developed a novel conversion technique to translate the complex output of the model to Richter scale values. OMS ran iterative analyses to determine the maximum storage quantity/configuration that would generate an acceptable Richter scale value at the surface. This provided the key consequence factor for the risk matrix.

In parallel, the EET developed seven scenarios which covered the complete process (transport, storage, transfer and loading) and quantified the risk level (frequency and consequences) for each step of every scenario. The evaluation utilized the expanded risk matrix that the EET had been developing, which extended the standard OMS matrix both to greater (worse) consequences and to lower frequencies. This analysis showed that the original proposal did not meet OMS risk criteria: however, three of the scenarios did meet those criteria. The Nordics Business was given the option of using any of these scenarios to bid the various subcontracts for this project.

Background

Underground tunnelling is an important business application in the Nordics area and is a growing one in other areas as well. Starting 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 EET was asked for permission to store 30 te 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 our 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 EET, as well as the majority of the other OMS Expert Teams/Expert Panels (EP), was formed after the Lorena accident when it became obvious that the organization was failing badly at implementing/following/enforcing core systems and values. The initial remit of the EET was to act as the policeman for the explosives business – but a policeman with the power not only to enforce the rules, but to actually make them. The original remit has largely been completed, although of course it will never be completed as the organization will continues to evolve and so must the rules. During the rule making phase, the black and white areas were easily sorted and global standardization of must do’s and absolute don’ts implemented (e.g. Basis of Safety, Engineering Standards) and enforced (e.g. audits and action plans). There were, however, a rather surprising large number of grey areas.

These grey areas led directly to two initiatives driven by the EET. The first is the Joint Hazards Program with CERL, which most SAFEX members will be familiar with given the regular publication of results from that work by Dr. Phil Lightfoot of CERL in the SAFEX Newsletter. This initiative was started very soon after Lorena and has been of great value to OMS and, we hope, the commercial explosives business as a whole. This relationship with CERL has been augmented by a growing in-house hazards R&D capability. Discussions have also started with another major company in the industry over the potential to carry out a major joint program on pump safety, which will also be shared with the industry.

The other initiative that the EET undertook might better be described as a new direction, which was to start using risk analysis methodologies to move some of those grey areas into the black or white camps. Orica had ‘inherited’ some of this capability from ICI and had strengthened it in parts of the business, e.g. the AN EP was far advanced of the EET. The explosives industry has always been a consequence based one and moving towards a risk based one was a big step.

The basic change in the industry that allows the movement from consequence based to risk based is the much lower sensitivity of modern bulk explosives/ANEs. It is 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 Class 1.5 and Class 5 ANEs compared to Class 1.1 explosives. This approach was first formalized in the AEMSC Code, where credible evacuation was accepted as an alternative to full Q/D. Orica has adopted this approach globally, even where there is no formal requirement to have any Q/D around ANEs. The exception is countries, e.g. Canada, where ANEs are classified as 1.5 explosives and full Q/D is therefore required.

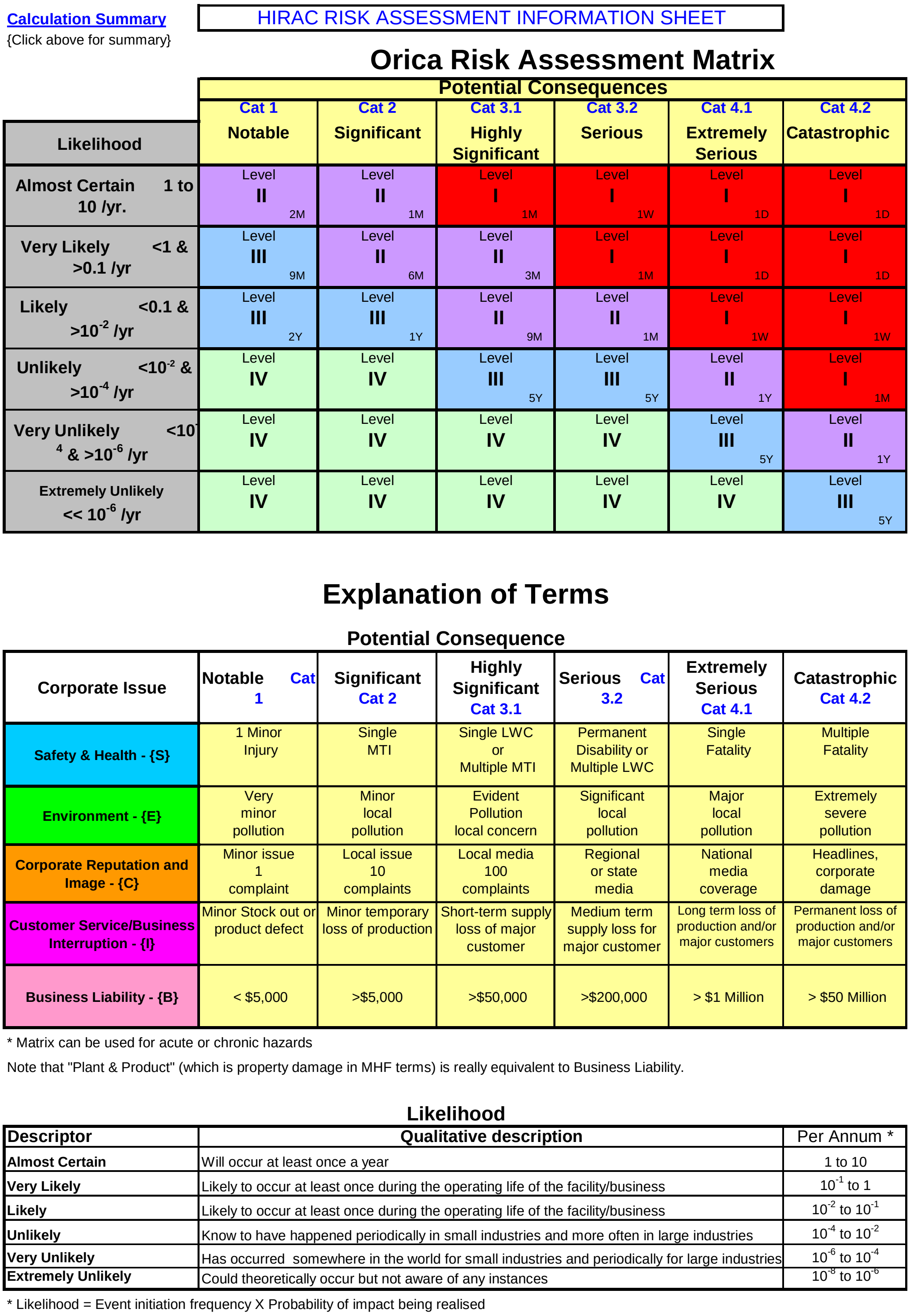
Therefore the EET had evolved to the point where a risk based approach to the storage of ANEs could be considered. The issue was that we lacked many of the tools to do a quantitative risk analysis (QRA) rigorously.

Quantitative Risk Analysis

Orica has many risk assessment tools: the hazard study process inherited from ICI, the HERC process developed by CIL, HIRACs, fault tree analyses, LOPA, etc. We also have risk targets for both internal and external consequences, especially fatalities. These methodologies/tools provide outputs on frequencies and consequences which are plotted on a risk matrix (see Fig 1). The first issue we hit was that this matrix is a) more geared towards internal events in some of the risk categories, particularly injuries and fatalities and b) does not cover the type of potentially catastrophic consequences possible with transporting/storing large quantities of ANEs underneath major capital cities. Orica follows the general UK (and widely accepted) public risk target of 1E-06, 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 is capable of killing hundreds or a thousand 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 or frequency axes of the standard Orica Risk Matrix clearly do 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).

The standard risk matrix has the lowest frequency row as << E-06. The issues with this are a) where does << E-06 start and b) how does 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 is 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 is 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.

Figure 1: Standard Orica Risk Matrix



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

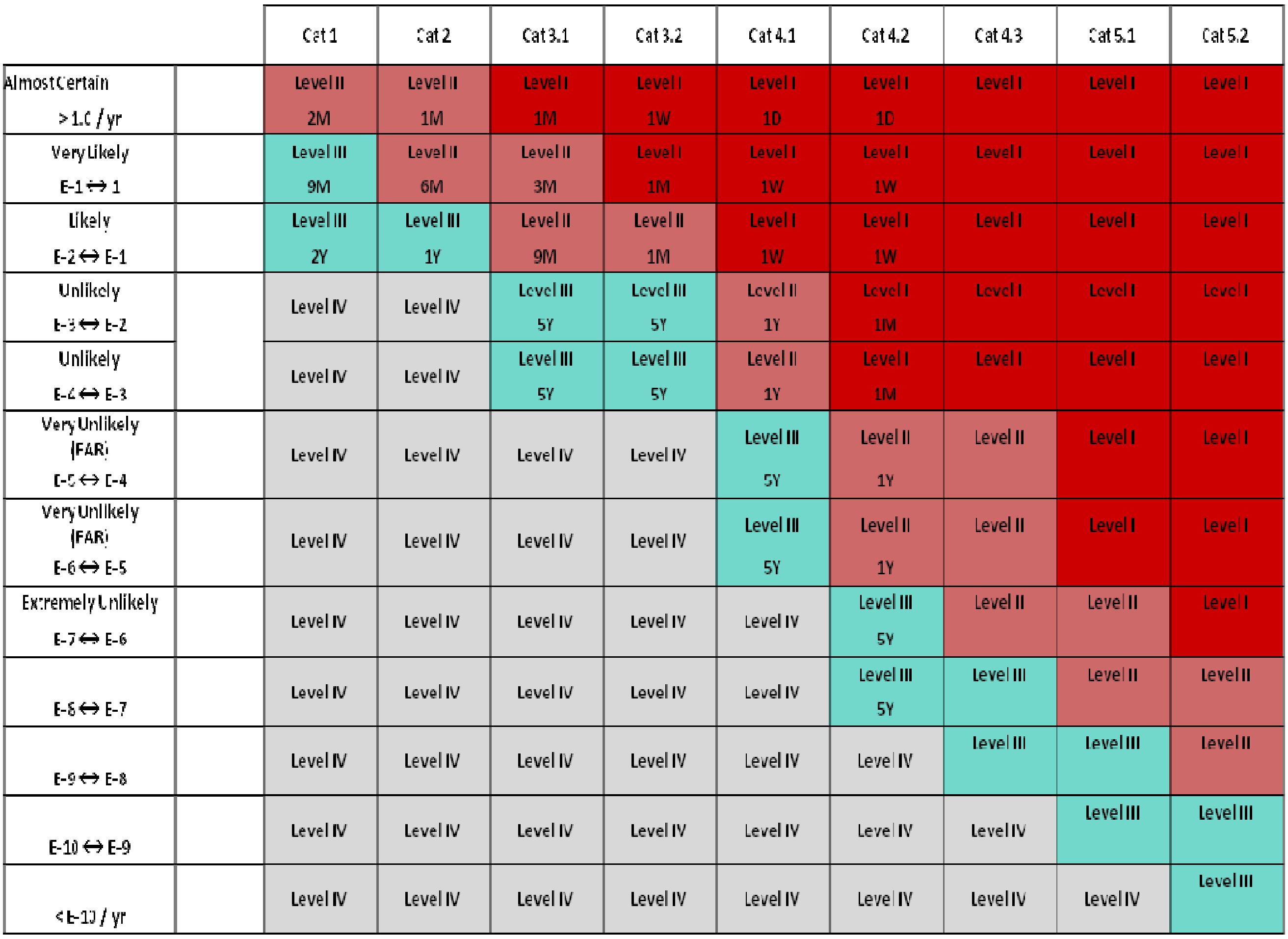
Note that "Plant & Product" (which is property damage in MHF terms) is really equivalent to Business Liability.

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 2: The Expanded EET 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

The expanded Risk Matrix has 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 remains a draft document and the values for the additional three consequence columns have not been finalized. The worst event was assigned the draft values of 100+ fatalities, $2,000,000,000+ 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 ten times worse and 5.2 forty 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: we did not know how to evaluate the consequences of a large blast just below the surface of an urban area. Fortunately, Orica possesses some very clever\ modellers who were able to do just that for us. A team was formed to carry out a QRA for this process and provide OMS with recommendations on how such a project could be carried out an unacceptable risk to the local population.

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This team, assisted by the 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.

Scenario Descriptions

Keys: Gyt = Gyttorp, main plant/magazine complex in Sweden
UV = Uplands Vasby, magazine complex just outside Stockholm
NCC = Job Site

Scenario 1: Packaged products, Gyt to UV to NCC, **No** local surface or u/g storage at NCC

Scenario 2: ANE, Gyt to NCC, surface storage (7 tonne plastic IBCs) and transfer to mini-SSEs

Scenario 3: As Scenario 2, 2 x 8 tonne storage in aluminium tanks

Scenario 4: ANE, Gyt to NCC, u/g storage (3 x 5.6 tonne separated stores in aluminium) and transfer to mini-SSEs

Scenario 5: As Scenario 4, storage in plastic bins

Scenario 6: As Scenario 5, u/g transportation and storage in plastic

Scenario 7: Original scenario (as Scenario 4 but 30 tonne storage in single aluminium tank u/g)

Bulk is shipped from Gyttorp in 11 tonne tankers. Transportation risk is broken into rural, suburban and urban components (evacuation probable, possible and impossible respectively). These tankers will go u/g to transfer product to the storage bins. The analysis assumes that the maximum quantity between the tank being filled and the tanker is 11.5 tonne. Transport of PE is by 1 te pallets (single pallet loads), taken directly to the face and manually loaded.

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 centred on the frequency side. As this practice is 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 operates under 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 our a complete QRA to measure the various scenarios against OMS risk criteria and standards and would allow only those practices that met our 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). What were the hazards that OMS was concerned about:

Transportation: vehicle fires from accidents/rollovers, tire fires, electrical fires, engine fires leading to an explosion on the vehicle. This is a hazard recognized by regulatory agencies, although, as far as OMS can determine, it has never occurred with ANEs. In the Nordics area, transportation in aluminium tanks is mandated as the authorities believe that aluminium tanks greatly decreases (potentially eliminates) the possibility of an explosion in a fire scenario. OMS accepts that there will be a significant reduction in the risk but does not believe this is an intrinsically safe option. The reason for this is quite simple, while the melting point of aluminium is well below that of steel, it is also hundreds of degrees above the autodecomposition and autoexplosion temperatures of AN and AN based products. While the testing to date does show an improvement with aluminium, the number of tests is far too low to prove intrinsic safety. OMS does accept that the use of low melting plastics for the storage and/or transportation of ANEs is probably intrinsically safe and plans to carry out a test program to demonstrate this.

Transfer: vehicle fires (same causes) or transfer pump explosions which propagate to large inventories (vehicle and/or storage tank). The choice of pump will critically effect (or eliminate) the frequency of the latter cause.

Storage: fires in the storage area. All the arguments on container type covered in ‘Transportation’ apply here as well.

Loading: the loading of packaged product in this application can be considered to be intrinsically safe from the perspective of surface effects. The largest potential event will not be noticed on the surface. For the loading of bulk products, vehicle fires (standard causes) and pump explosions are the key risks.

Development of the Surface Damage Model

Dale Preece and Ayman Tawadrous were approached as to whether they could use one of Orica’s computer models to predict the surface damage from a shallow underground blast. Their response was that this could readily be done. Readily in the sense that they had a standard 2D model that could be used for this application. Not readily in the sense that the data would be easy to generate using the code. Setting it up for each run was time consuming, the actual runs required roughly a day of high end computer time and the data then had to be analysed and converted to a format that we could understand and use.

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 metres of the epicentre. 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 metres, probably resulting in, e.g., 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 which was small enough to do an acceptable level of damage and allow the Nordics business to be competitive in this market.

The Nordics business was able to provide all the required data on rock type and properties, as well as data on where emulsion could be stored. This allowed the modellers to maximize the accuracy of their predictions. The issue for most of the team was that the output of the model did not lend itself to easy interpretation of what the effects on Stockholm would be. The second breakthrough that the modellers made was to convert the output to a Richter Scale value. Vibration frequencies, amplitudes and durations are all very different between a small underground explosion and an earthquake. Therefore this is not an exact equivalent to the Richter Scale but it should be an accurate predictor of damage levels equivalent to that Richter Scale value. The major difference is that earthquakes can cause major damage over very wide areas whereas the decay rate for shallow underground explosions is much faster.

The team decided that given the uncertainties in the model’s predictions and non-exact conversion to a Richter Scale value, a conservative maximum Richter Scale Value would be chosen. Therefore a maximum value of Richter 4.0 was chosen for ‘permanent risks’, e.g. storage and Richter 4.5 for transient risks, e.g. transfer/refilling operations. 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, we were 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 1 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.

OMS will be extending this methodology to develop a matrix for maximum quantities that can be stored underground without the possibility of unacceptable results if the worst possible event occurs. Rock type/properties and depth will be the two key parameters driving the results.

Determination of Event Frequencies

1, Determination of Transport Event Frequencies

The Event Frequency of interest is an explosion during the transportation of product from the originating site (Gyttorp or Uplands Vasby for the scenarios under consideration to the storage location at the job site. OMS has gathered the best transport data (baseline and explosives industry) that was available following the accident/fire/explosion in Mexico. The purpose was to determine, as best we could, our current level of risk versus standard OMS risk targets, as well as determining methods of reducing that risk. 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 identified twenty plus factors that could reduce the frequency/probability of a catastrophic accident. These factors could work at any step, i.e. prevention of the initial event (e.g. accident, tire fire,…), prevention or mitigation of fire/fire effects, prevention/reduction of the probability of a significant fire causing an explosion and elimination/reduction of fatalities if an explosion did occur. In the original analysis, the Transport Subgroup differentiated these factors by four levels of implementation: baseline, current OMS (somewhat better than baseline), OMS BoS level (determined at the end of the analysis), full implementation of all factors. Each of the factors was also assigned an effectiveness rating, which also varied across the four implementation levels (baseline was defined as a risk reduction factor of ‘0’). The hazards levels calculated from this analysis are not directly comparable to the standard OMS values but they can be modified to make a semi-quantitative comparison. For explosives, both the baseline and current OMS status ‘failed’ this comparison and a number of cost effective changes were mandated. This became the BoS level and is being implemented globally – or at least in those areas where OMS is able to exercise some control/ influence.

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 turn out to have similar frequencies. The same modifying factors were considered and the same four levels identified. The evaluation indicates that the transport of ANE meets OMS requirements with little improvement from the baseline case. OMS is currently developing the BoS for the transportation of these materials which, following the ALARP approach, will have mandated cost effective improvements compared to the baseline case.

For this analysis, the accident/fire causes are summed and transition to explosion factors are weighted average of the transition factors for the three causes. The modifying factors weighting reflect current norms (good) in the Nordics area and there is one additional factor applied, as was discussed previously. Transportation (and storage) in aluminium tanks provides a 75% reduction in the probability of an explosion; the use of plastic provides a 90% reduction.

Previous analyses have all been completing generic; in this case we have seven specific scenarios. Therefore one more level was added to the analysis: rural, suburban and urban transportation routes. The frequency data does 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 depends on a) getting nearby people away and b) preventing others from getting close. All historical data indicates a window of 30-45 minutes to accomplish this. This is highly credible in low population and traffic density areas where there are good emergency response capabilities. This has been demonstrated in, e.g., Canada and Australia. At some population/traffic density, a full evacuation in this scenario is not credible given the limited timeframe. The analysis uses the simple assumption that the rural/suburban/urban risk levels (frequency) would be proportional to the relative distance travelled through each.

2. Determination of Transfer Explosion Frequencies

Transfer accident rates are strongly pump dependent: Wildens are considered to be intrinsically safe whereas PC pumps have a recognized potential for explosions resulting from no flow pumping events. The analysis assumes the standard OMS pump protection system for PC pumps, which will reduce the baseline no flow events by up to three orders of magnitude. A pump explosion by itself is not a hazard to people as the quantities are so (relatively) small. As the products in this analysis are unsensitized, it is 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 is not certain, and this is the event that is evaluated in the QRA.

3. Determination of Storage Event Frequencies

The best public storage event frequency data comes from the IME. This data was used, unmodified, for the baseline event frequencies. This will probably be conservative as some event initiating mechanisms, e.g. lightning strikes, are not possible for underground storage site. The event of concern is fire engulfment leading to an explosion. OMS believes that outside of a vessel, i.e. on the ground, there is no risk of an ANE exploding. Therefore, if the vessel under fire engulfment losses structural integrity, the risk of an explosion becomes zero. As has been previously discussed, OMS has assigned different probabilities that this will happen for steel, aluminium and plastic vessels (0, 75% and 90% reduction respectively).

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 has the potential for catastrophic events, as does the transportation of Class 1 or Class 5 through built up areas. These events do have some potential for evacuation and it is very difficult to work out what the fatality circles would be. Using tools such as IMESAFR indicates that fatality rates are 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 is 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 analysing an event. Therefore we can use the consequences of fatalities, the number of which will be difficult or impossible to estimate, rather than the number of fatalities directly.

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.

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 will occur in every scenario. The results are shown in summary form in Figures 3 and 4.

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 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

Level I: Unacceptable risk; must be dealt with in time indicated on Risk matrix
Level II: Acceptable only for defined time periods, risk must be reduced following ALARP Principles
Level III: Broadly acceptable, review against ALARP principles
Level IV: Acceptable; already in ALARP region

Figure 4: QRA Summary, EET Expanded 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

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 conclusions drawn from the QRA:

1. The expanded risk matrix is a required tool when dealing with low probability/high consequence events (which is a major part of the remit of the Expert Teams in OMS).

2. It was necessary to extend the standard risk matrix to **both** worse consequences **and** lower frequencies. Doing only one will result in incorrect rating of risks.

3. For any quantity of explosives or ANEs, underground storage and transfer are preferable to surface storage/transfer in an urban environment.

4. For some quantity (and less) of underground storage, the surface consequences of the worst possible event will be acceptable. This will be true only for very small amounts of surface storage.

5. The high risks assigned to surface storage and transfer operations were driven by the very high consequences. Even with very low frequencies, these were marginal or unacceptable risks.

6. The next highest risk was the transportation of Class 1 and Class 5 through urban environments. This only met OMS risk criteria because of the very low event frequency, which in turn is driven by the very low proportion of transport time spent in urban areas. The BoS for transportation will raise the standards for OMS and OMS contractors to further reduce this risk.

7. Three scenarios were identified that fully met OMS risk criteria (only Level III and IV risks). The Nordics business was given the option of bidding contracts using any of these three scenarios.

8. OMS has used this analysis/methodology to evaluate other proposals.

9. OMS is using the modelling capability developed during this process to underpin a BoS for the underground storage and handling of explosives and ANEs.

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March 2011