Consequence Assessment for Weapon Impacts on Process Plant

Colin Rettie, Matthew Vickers and Douglas McKechnie, Abbott Risk Consulting Ltd., 11 Albyn Place, Edinburgh, EH2 4NG, UK

Historically, deliberate attack on Oil and Gas process facilities has been excluded from process safety assessments and the consequences of weapons impact are not frequently studied. It is noted however that consequence modelling techniques for weapons attack have been developed independently for buildings and structures protecting personnel. In the modern geopolitical and international security climate, facilities may be subject to attack with little warning. Additionally larger munitions, previously only associated with national forces, are more commonly held and used by insurgents. Plant operators and designers need to understand the hazards posed by such weapons when deciding on the mitigation required. Responses range from complete shutdown of a threatened facility to continued operation with risk reduction measures including plant and personnel protection, reduced manning, reduced inventory and operational restrictions. Abbott Risk Consulting (ARC) Ltd. has experience of applying munitions assessment to process plant situations and this paper presents the lessons learned in combining the, generally separate, disciplines of process plant hazard analysis and munitions effect analysis.

Munitions cause damage to structures and equipment by a number of mechanisms including: overpressure, fragmentation and kinetic penetration, with or without subsequent explosion. The paper discusses the general characteristics and hazards from commonly-available munition types, from small arms and hand held missiles to artillery shells and larger vehicle-mounted rocket systems.

Case studies are presented for the impact of munitions on a conceptual Liquefied Natural Gas (LNG) facility including process plant, full containment LNG tanks and manned buildings. The importance of assumptions regarding the damage mechanism, particularly between fragmentation and kinetic penetration, is demonstrated. Methodologies for combining such munitions studies with process safety techniques, including event tree analysis of the hazard frequency, are discussed such that a scenario-based risk assessment can be produced. “Conditional Risk”, the risk of undesired consequences given that an attack takes place, is proposed as the most appropriate risk measure for such studies since the greatest unknown is usually the probability of an attack.

Introduction

Attacks on Oil & Gas facilities are nothing new, and occur at both Onshore and Offshore facilities. There are frequent attacks on cross-country pipelines, but attacks such as the In Amenas hostage crisis in Algeria, where 39 foreign hostages were killed (along with an Algerian Security Guard and 29 militants), are becoming more common. Recent events include the takeover of many of Iraq’s Oilfields, including the biggest oil refinery in Iraq, by ISIS (Islamic State) militants. The nature and level of threat in many Oil and Gas producing countries has changed rapidly and significantly in recent years and, as such, the potential for disruptive attacks on facilities is increasing.

Typically the life span of an onshore facility is in excess of 25 years and, as can be seen, the face of terrorism is constantly changing. The threat assessment conducted at the commissioning stage may soon be outdated as terrorism evolves. This is where risk management is beneficial; not only from a personnel protection perspective, but also from an asset protection and continuous operation one. By assessing the potential consequences from external threats, facilities can try to mitigate the resulting consequences, loss of life and economic loss.

Historically, deliberate attacks on Oil and Gas process facilities have been excluded from process safety assessments and the consequences of weapons impact are not frequently studied. There have been many papers written on the subject of consequence modelling and the effects of loss of containment scenarios in the process industry, covering the differing approaches, methodologies, and backgrounds. This allows risk assessors to choose the ‘best fit’ methodology for a particular scenario. Consequence modelling techniques for weapons attack have however been developed independently for buildings and structures protecting personnel and there are many research papers for the security assessment of perimeters, and security specific areas, such as guardhouses. Currently there is little to tie both methodologies together; this is potentially useful area for development.

In the modern geopolitical and international security climate, facilities may be subject to attack with little warning. Additionally, larger munitions, previously only associated with national forces, are more commonly held and used by insurgents. Plant operators and designers need to understand the hazards posed by such weapons when deciding on the mitigation required. Responses range from complete shutdown of a threatened facility to continued operation with risk reduction measures including plant and personnel protection, reduced manning, reduced inventory and operational restrictions. Abbott Risk Consulting (ARC) Ltd. has experience of applying munitions assessment to process plant situations and this paper presents the lessons learned in combining the, generally separate, disciplines of process plant hazard analysis and weapons effect analysis.

Background

History

Although terrorism has been present in various guises since the 17th Century, there has been a changing attitude toward it in recent years, with more and more organised groups in every corner of the globe, with more sophisticated weapons.

As terrorism changes, so does the vast array of weaponry. If we look to the earlier days, such as Northern Ireland, the weapons of choice were improvised explosive devices (IEDs) such as nail bombs, and small arms, such as rocket propelled grenades (RPGs).

However, as terrorist groups become both more organised, and better funded, the available armament also increases. Taking organisations such as Islamic State of Iraq and al-Sham (ISIS) and Al-Qaeda in the Arabian Peninsula (AQAP) as some of the more recent examples, a far more powerful range of weapons are available. These groups now have access to long range weapons, such as GRAD rockets, and in some cases air-borne devices. This is a very important factor for both new and existing facilities when assessing the potential for external security threats. A prime example of the need to develop both philosophy, and design of facilities, was the attacks in the USA on September 11th 2001. The World Trade Centre design engineers did consider impact from aircraft. However, as the size of aircraft increased, the ability to withstand the impact reduced.

Attacks on facilities in recent months show just how damaging these can be.

Es Sider - Libya, December 2014

A rocket fired on December 25th by Fajr Libya (Libya Dawn), a coalition of fighters, ignited the first fire which then spread to six other tanks at Al-Sidra Oil Terminal. Total capacity of the 19 storage tanks is in excess of six million barrels.

Munitions Hazards

There are many types of munitions, each posing a different hazard depending upon the type and purpose of the projectile. The effect of the munition is primarily realised upon impact at the desired target location, and can be categorised into three main effects groups.

Firstly, the projectile may explode nearby to the desired location (i.e. early detonation, ricochet and detonation etc.). Following the nearby detonation, there are a number of resulting effects according to the type of munition and intended use. Early fragmentation results in large numbers of tiny objects being released from the projectile in all directions, resulting in damage to large areas. This may lead to damage to surrounding areas, but primarily impact is to personnel. In the case of rockets and larger projectiles, the fragments of the projectile itself are also of significant concern. These may be much larger than fragments produced by the warhead, and as such are likely to cause more significant damage to structures and equipment on impact.

Secondly, the projectile may explode on contact. In this instance, fragmentation is a lesser concern, as the purpose of this weapon is the explosive damage. Although the projectile may break-up into smaller fragments, this is not the primary function. In this instance, the impact energy alone may be the most significant problem. The energy generated by the mass of the object on impact is likely to be far worse than the impact of the resulting fragments.

With all explosive munitions, the explosion of the warhead will produce a hazard by blast. Even with a fragmentation projectile, there will be a resulting overpressure pulse or blast wave. This can be both damaging to structures and personnel. Plant buildings may be designed to withstand the external loadings of an explosion, but it is unlikely that administration buildings and the like are designed with this in mind.

Finally, the projectile may be designed with delayed ignition purposefully in mind. Or a fault in the detonation may cause the projectile not to explode. With the faulty detonation scenario, the kinetic impact energy is the overriding issue to the target. This will cause the most damage. However, for the delayed ignition projectile, there are further concerns. Should the projectile penetrate the target through kinetic impact energy, and then detonate, the consequences will be far worse.

The variety in size of the projectiles is largely dependent on the type of weaponry used, and the sophistication of the munition.

Small Arms and Artillery

Bullets and shells fired from small arms are common and occur in a range of sizes from the size of a rifle up to large shell and mortar launchers. As the size of the weapon increases, the size of the projectile increases. Munition size can range from 6mm (.22) in a small handgun, up to 203mm (8”), typically weighing 40g up to 50kg respectively.

To withstand the forces involved, the projectile is required to be strong, and typically has a low charge to weight ratio ranging from non-explosive kinetic rounds such as small arms bullets and armour-piercing types to mortars which have a significant explosive charge.

Such rounds are often shorter range than rocket types, and follow predictable ballistic trajectories.

In many rounds of ammunition such as those described above, there will be a limited explosive charge, limiting the potential for blast to damage large structures. However, there is potential for damage to structures such as tanks due to the high velocity of the projectiles alone. Similarly, it is important, as with all types of munitions, to consider the variety available, even for the same weapon there may be fragmentation and armour piercing types. Fragmentation rounds for small arms work in a similar way to large fragmentation projectiles. On impact, a fragmentation round breaks-up into numerous pieces in order to maximise the damage. This is particularly relevant for personnel. However, when considering attacks on Oil and Gas facilities, armour piercing rounds are of greater concern. With armour piercing rounds, the inner core of the round is made from a denser material, such as carbide or tungsten. As the round impacts, the nose flattens, and the inner penetrator continues forward into the target.

Rockets

Rocket artillery covers a wider range of weapon types ranging from shoulder-launched Rocket Propelled Grenades (RPGs) up to large vehicle-mounted launching systems. In general, the main types of rockets for consideration in these types of assessments are unguided types such as shoulder-launched RPGs, or vehicle-mounted GRADs, or guided types such as anti-tank rockets or wire-guided missiles.

The range of rocket rounds varies. RPGs are fired from relatively short stand-offs (900m), other types have ranges of many kilometres dependent upon the size of the rocket.

Much of the rocket mass is made from propellant, meaning that much of the total mass of the projectile at launch will burn before impact. Conversely the forces involved in launch are less than in a gun and therefore the warhead, which does make impact, does not require to be as strong, and can have a higher charge-to-weight ratio than a shell.

Due to the lower mass of the rockets, and lower strength of warheads, penetration effects are typically lower, unless specifically designed as armour-piercing rounds, as outlined above.

Heavy Weaponry

Heavy weaponry includes a variety of sophisticated munition types, complex long-range guided missiles, air-launched weapons and bombs. These can generally be excluded on the grounds of rarity and are typically not considered for assessment, as they are mainly only available to well-established national forces.

Process Hazards

In conventional weapon assessments, the target suffers damage from the munition directly. A guard house or barracks for example may be assessed for its ability to protect personnel within. For a process facility however, personnel may also be harmed by consequential effects of damage to process equipment.

If a weapon impact causes damage to process equipment, hazardous material can be released which can impact personnel directly by toxic effects, or where ignited, causing fire or explosion events. Targets can include process equipment, connecting pipelines, storage and loading facilities, as well as supporting utility systems such as power supplies and cooling systems.

The consequence modelling of process hazards is well-established and a process facility will normally have an assessment of credible process accident scenarios as part of a Quantitative Risk Assessment (QRA) or major accident risk assessment. Care should however be taken when extending the facility risk assessment to include munitions related events. Three main areas of potential difference should be considered: the extent of damage caused, the response time available, and the availability of emergency response systems.

Extent of Damage

The severity of a process event depends on the inventory released. Process plant assessments commonly use a credible maximum hole size to define the releases to be modelled. This may exclude some cases, such as rupture of a double wall tank, or simultaneous rupture of multiple lines, on the basis that such events are of such a low frequency that they can be discounted. In a weapon impact however, items which are functionally separate, and are thought of as independent safeguards, can fail if the area of damage is sufficient. It may therefore be necessary to model additional process consequence cases.

Response Time

Conventionally, a process hazard assessment considers that plant emergency response is triggered by detecting the process accident scenario by means such as fire and gas detection. All responses therefore occur after the event.

Response to weapons attack may however occur at different stages of the scenario development. If a threat is identified by intelligence or observation, for example the movement of hostile forces into a disputed area, then the plant response can start hours or even days before attack is possible. If the attack is not predicted, it can still be detected when it starts. It is likely that multiple attacks would be required to cause hits with the relatively simple weapons normally available.

Responses could include sheltering personnel, shutting down and depressurising plant, and removing inventory, for example an LNG carrier disconnecting and sailing away. Process plant can be shut down and depressurised relatively quickly, whereas substantial storage inventories may need a longer period of days or weeks to remove. The weapons impact consequence assessment should consider the likely state of the plant at the time of the attack. Sensitivity studies can be utilised to assess the effectiveness of various response strategies.

Response Measures

In a weapons attack, the protective systems used to control a process event, such as flare systems, firewater, and emergency power and cooling systems, may be damaged by the attack. The weapons impact consequence study should consider if active response systems are likely to be available and consider the impact on event outcomes very carefully, including where protective systems can be damaged by a common cause weapon effect.

Weapons Impact Consequence Assessment

History

Following the end of World War II, the US Army published TM5-855-1 (US Department of the Army, 1986) entitled "Fundamentals of Protective Design for Conventional Weapons" in 1949. This document was based on the experiences of structural damage during the war and described initial assessment methodologies against conventional weaponry.

Following this, the US Air Force did extensive research between the 1950s and 1970s and produced ESL-TR-87-57 (Drake, J.L., L.A. Twisdale, R.A. Frank, W.C. Dass, M.A. Rochefort, R.E. Walker, J.R. Britt, C.E. Murphy, T.R. Slawson, and R.H. Sues, 1989) which predominantly looked at the effects of nuclear weapons on structures. However, from this, important developments were made in the numerical modelling of many primary weapon effects. This included the dynamic response of aboveground and shallow-buried structures, airblast, blast-induced ground shock, cratering and ejecta, and the dynamic response to earth materials.

It was in the late 1980s that the US Defense Special Weapons Agency with the combined US Armed Services, initiated a Conventional Weapons Effects program, in order for them to address several technological deficiencies uncovered in the area of survivability and vulnerability of hardened structures. In response to the specific needs of the Combined Services, and North Atlantic Treaty Organisation (NATO), the program focused on key areas where the validated results of ongoing research could be integrated into a single design document. Extensive knowledge of nuclear phenomenology was combined with the laboratory and field experience brought by each of the Services in order to resolve gaps in knowledge, providing a better understanding of non-nuclear explosive phenomenology. Ultimately, the Joint Services Manual for the Design of Hardened Structures to Conventional Weapons Effects, UFC 3-340-01 (US Department of Defense, 2002) was produced.

The manual itself is orientated toward engineers with a working knowledge in weapons effects, structural dynamics, and the design of hardened, protective structures. Therefore much of the information presented is tailored toward occupied building protection, and munitions storage structures, however, the empirical codes are equally applicable to impact on other objects.

During development of UFC 3-340-01 (US Department of Defense, 2002), there were many hundreds of research documents produced in support of testing and field experience, however due to the nature of the subject, many of these documents are confidential. Those which are in the public domain have been referenced where applicable.

Effect Selection

There are varying effects from munitions and projectiles. However, for the purposes of weapons impact consequence assessment on Oil and Gas facilities, the effects of greatest concern blast, fragmentation and penetration.

If the weapon type is known, then the potential effects may be defined in the specifications of the weapon itself, for example a fragmentation round would be assumed to result in blast and fragment damage, an armour piercing type would be assessed primarily for penetration. However, if the type of weapon is unknown, then further assumptions must be made.

Firstly, assumptions must be made about the credible threat. Is the threat a small gun at relatively close range, or a large rocket from kilometres away?

Site or local intelligence is likely to understand what type of threat is credible, even if not the exact weapon type. There are various methods of finding out detailed weapon information, primarily from ammunition literature from manufacturers and military documentation.

Alternatively, specialist publications such as the "Janes" series and even the internet can be a source for detailed munition data. It is imperative that threat selection is undertaken by a suitably qualified and competent person, with an in-depth knowledge of weapon characteristics and their respective effects.

For an assessment where the exact weapon type is unknown, from a conservative point of view, it is better to include too many effect calculations rather than not enough. Therefore, in this situation the projectile should be assessed from both a fragmentation and penetration effects. The primary difference is the assumption of detonation; whether the projectile detonates on impact (fragmentation), or is delayed (penetration).

Blast

The blast overpressure effects of Vapour Cloud Explosions (VCEs) within process plants have long been estimated by a methodology based on analogy with the explosive effects of TNT in the "TNT Equivalent" model. This is convenient as weapon impacts can be modelled using the TNT Equivalent model in standard process consequence analysis packages such as DNV's PHAST consequence modelling software.

Several decades of research (including war-time data) have produced well-established models of the severity of explosive detonations (Mannan, 2012). The variation of overpressure with distance for TNT explosions is well defined (HSC, 1979).

PHAST's TNT Equivalent model calculates overpressure using an approximation of the Kingery and Bulmarsh curves published in Lee's Loss Prevention (Mannan, 2012).

The procedure to estimate the damage associated with an explosion using the TNT Equivalent method is as follows:

1. Determine the total quantity of explosive material involved in the explosion. Calculate the equivalent mass of TNT;

2. Define the explosion efficiency; this is the fraction of the combustion energy contained in the explosive material that will be converted to explosion energy;
3. Define if the blast is located at ground or in the air, as this allows the effects of ground reflection to be taken in to account;
4. Calculate peak side-on overpressure using model; and,
5. Use overpressure results and industry data to estimate the damage for common structures and process equipment (van den Bosch and Weterings, 2005).

Penetration

Penetration relies on the impact kinetic energy of the projectile and not on the explosive charge. The factors governing the penetration effect of the projectile fall generically into three categories:

- Characteristics of the projectile;
- Impact attitude; and,
- Characteristics of the target.

There are many variables that affect the penetration behaviour of the projectile, and the main parameters that govern this are the mass, shape and structural integrity. A small, heavy projectile with a low charge to weight ratio (typical of an artillery shell) will be very efficient at penetration and will be unlikely to break up on impact. A projectile of the same mass but larger with a wider cross section will spread its kinetic energy over a wider impact area and will thus penetrate less deeply. A projectile with a high charge-to-weight ratio (such as a thin-skinned rocket) may break up on impact which will both dissipate energy in the deformation of the projectile and will further spread the impact area.

The next consideration is the impact attitude of the projectile. This is governed by the trajectory of the projectile, and the shape of the target. The figure below shows a summary of the geometry of impact.

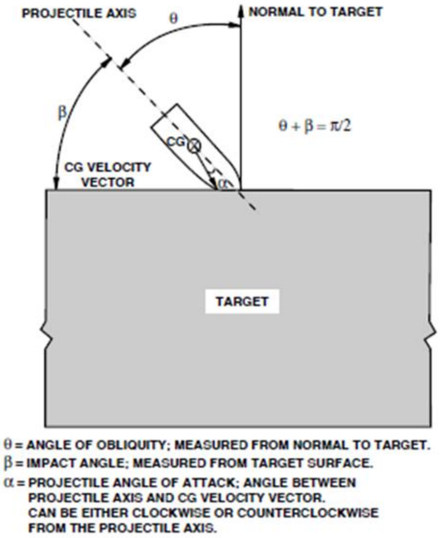

Figure -1 - Geometry of Projectile Impact (UFC-3-340-1)

The final category is the characteristics of the target. This includes some very complex structural factors, such as compressive and tensile strengths, material densities, ductility, porosities and surface geometry.

There are a significant number of parameters for consideration, and equally a variety of responses. Depending on the combination of variables, and the interaction of all these, the resulting penetration cases are considered:

- Breakup - this is a failure of the munition and is likely to cause minor damage to the target, but nothing significant;
- Ricochet - this is also likely to cause external surface damage to the target, with the potential secondary consequence of damage to surrounding targets;
- Broach - similar to ricochet with a loss of velocity/momentum on the exit of the primary target;
- Penetration - enters the target and becomes stuck; and,
- Perforation - enters the target and exits through the other side. This is the worst case for a protected structure.

The below diagram gives a brief illustration of the various types of projectile response detailed above.

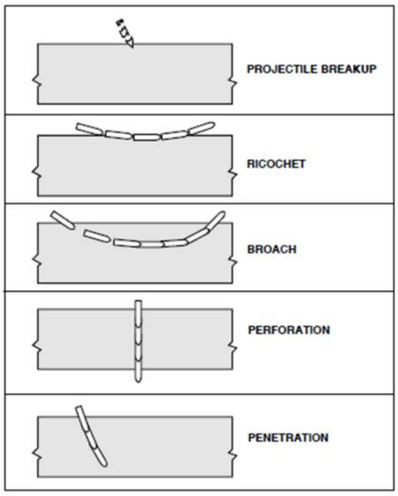

Figure -2 - Types of Projectile Response

Prediction Techniques

Penetration

There are four main prediction techniques associated with projectile penetration; the empirical approach, the assumed force law approach, the analytical approach, and the numerical first principle analysis. The advantages and disadvantages of these approaches is considered below.

Both the empirical and assumed force law methodologies are relatively simplistic approaches, based on fitting mathematical models, equations and algorithms, linked to existing databases. The limiting factor in these cases are that everything is based on datasets and databases that are already existing. However, it should be noted that the data available for these models is extensive and, as such, the resulting models are accurate and linked to validated tests (Forrestal, Altman, Cargile and Hanchak, 1993). The force law approach has been used successfully to develop trajectory codes for non-normal impact and penetration into complex layered targets (i.e. soil and rock) (Creighton, 1982).

For the analytical approach, constitutive laws are established for a particular material type. From these laws, equations can be established for the impact of the force on the projectile nose. This force can then be assumed to be the resisting force on the projectile during the impact event, for a specific material and projectile combination. Unlike the previous two methodologies, the analytical approach does not tend to rely on parameters that must be confirmed experimentally, it is however less clearly linked to past experimental data and requires more complex analysis (Rohani, 1979).

The final approach is the most comprehensive, and utilises either finite element or finite wave propagation methodologies (Durrett and Matuska, 1978). This is much more detailed than the other methods, and allows for assessment of both the impact area and the deformation of the projectile to be considered dynamically.

None of these approaches can fully evaluate projectile penetration, although they do provide a realistic engineering solution for the majority of penetration issues. Selection of an appropriate methodology is somewhat complex, with variables including weapon type and characteristics.

Each target material requires a different approach. For the purposes of this paper, reinforced concrete (such as a large oil or LNG tank wall) is used as an example. Other materials are assessed in a similar way but the factors used will differ depending on the properties of the material.

Concrete is a composite material and therefore there are further parameters that require consideration to characterise the behaviour of the target. Concrete behaviour depends on a number of factors including:

- Gravel size;
- Concrete age (although past a certain point this becomes irrelevant); and,
- Concrete strength; Reinforcing steel bar is used to increase the tensile strength of concrete. Concrete is very strong in compression, but weak in tension, therefore the addition of steel bars at specific separations improves the tensile capacity of the concrete. This has a positive effect on penetration, increasing the penetration resistance of the concrete.

Gravel size refers directly to the size of the gravel used to produce the concrete. It has been observed that the greater the gravel size, the smaller the penetration depth of a projectile.

Concrete age is only a concern for high strength concrete, or new concrete. As a rule of thumb, concrete usually reaches its full strength after 28 days of curing, however, for high strength mixes, this could be as long as 91 days. Therefore, it can be assumed that for existing concrete structures, the age will not impact the penetration depth.

The typical unconfined compressive strength of concrete is usually around 35MPa. This is what many of the experiments for empirical variables have considered. More recent tests on high strength concrete (>100MPa) found that although it would be expected that the higher strength concrete would positively influence the penetration depth, this is not always the case. Therefore, concrete strength is an important variable in the case of high strength concrete.

The breakup velocity of the projectile is also a key factor. While it does not form part of the calculation, if a projectile impacts at greater than the breakup velocity, then penetration is significantly reduced because the energy is dissipated widely. For a projectile which can exceed its breakup velocity, it is appropriate to take the break up velocity as the maximum velocity for penetration. This value is usually taken from experimental data, but is a complex function of many different variables, including the charge-to-mass ratio and impact attitude. If data is not available, the breakup velocity can be estimated as a function of the charge-to-mass ratio of the weapon.

Although the impact surface may be different, the general methodology remains the same. Looking at reinforced concrete as outlined earlier, there are two recommended methodologies for calculating the depth of penetration (Luk and Forrestal, 1987).

The first method is based on work completed by the National Defense Research Committee (NDRC), and is the simpler of the two methods. For the purposes of illustration in this paper, this method will be considered.

Note: the second methodology is based on the 'S-Number' also known as the penetrability factor.

As with all complex methodologies, there are a number of variables which dominate the penetration depth of a projectile. Similarly, the NDRC equation has been refined for both small and large calibre projectiles. The penetration equations are detailed below:

For P >2D

$$P = \frac{56.6\left(\frac{m}{D^3}\right)^{0.075} \bar{N} m V^{1.8}}{\left(D^2 \left(f_c'\right)^{0.5}\right)} \left(\frac{D}{c}\right)^{0.15} f_{age} + D \tag{1}$$

And for P ≤ 2D

$$P = \frac{15.1\left(\frac{m}{D^3}\right)^{0.038} V^{0.9}}{\left(D^2 \left(f_c'\right)^{0.25}\right)} \left(\frac{D}{c}\right)^{0.075} \left(\frac{\bar{N} m}{D} f_{age}\right)^{0.5} \tag{2}$$

Where:

P - penetration depth (mm)

f_{age} - concrete age factor (Table 1)

f'_c - unconfined compressive strength of concrete (MPa)

$\bar{N}$ - nose performance coefficient (eq. 3)

m - projectile mass (kg)

D - projectile diameter (mm)

c - maximum gravel size (mm)

V - impact velocity (m/s)

And the nose performance coefficient is given by:

$$\bar{N} = 0.72 + 0.25 \frac{L_n}{D} \tag{3}$$

Where:

L_n - nose length (m)

D - penetrator diameter at the base of nose (m)

f_{age}	Concrete Age (days)
1.0	≥ 360
1.01	180
1.02	66
1.05	≤ 28

Table - 1 - Concrete Age Factor (UFC-3-340-1)

It must be noted however that this simplified equation set neglects the explosive impact of the projectile, and only assesses the penetration of the impact.

Fragmentation

Fragmentation munitions are those that, when the explosive charge within the munition detonates, rupture into a large number of fragments. These fragments are then accelerated further by the expanding detonation products. The fragments usually vary significantly in size and detailed fragmentation assessment is much more difficult empirically.

Due to the complexity of fragmentation methodologies, this paper does not present a full methodology. The main approaches and considerations are discussed below.

Empirical calculations allow calculation of typical characteristics, such as the mass, velocity and shape of the fragments. More rigorous, first-principle calculations can be used for calculating fragmentation effects. However, it should be noted that the present state-of-the-art methodologies cannot sufficiently predict detailed fragment size, velocity, or response for brittle materials. This is primarily due to a lack of accurate failure models for the corresponding impact medium.

There are two main types of fragmenting warheads that are of concern:

- Controlled; and,
- Natural

Controlled fragmentation refers to warheads with pre-formed fragments within the casing, of a specified size or mass, such that, upon detonation, the fragments will maintain size and shape. The casing itself deforms and fragments randomly, with respect to the dynamic loading imposed on it.

Natural fragmentation occurs when no controls are imposed on the warhead, and so the projectile fractures in an unpredictable manner. For a natural fragmentation, the shape, velocity and spatial distributions of the fragments is probabilistic, due to the nature of the shockwave produced from the detonation.

For the assessment of hardened structures against fragmentation, the main consideration is that of steel fragments impacting on structures. This is due to the availability of information. Although there is information available for materials such as lead, aluminium, titanium and tungsten, the equations presented relate to steel.

Process Hazard Consequences

In order to tie this type of assessment into process consequence and risk assessments, further modelling is required. There are many established consequence models for process hazards, this paper will not consider these in detail but will focus on the specific differences between conventional, process based causes, and munitions causes.

The sections below discuss some of the major considerations and the assumptions to be made; it is beyond the scope of this paper to provide guidance on modelling all the potential permutations. It can be seen that there are more variables than in a standard process consequence model and therefore the selection of assumptions which are both appropriate to the situation expected, and sufficiently conservative to address uncertainties, is vital to the methodology. As in any modelling, appropriate sensitivity studies should be used to understand the effect of assumptions and uncertainty on the results. A team approach using modellers experienced in both munitions effects, and process plant hazard consequences will be required to define and validate assumptions.

Hole Sizes

For a standard process model, the release size is normally the starting point. Hole sizes are selected based on plant characteristics and historical data to represent typical releases. In weapons impact however, the munition hits a defined target and leads to loss of process containment. Although the exact size of the penetration hole from the projectile is unlikely to be known, assumptions can be used based on the likely physics of the situation.

Vessels under significant pressure may fail catastrophically if subject to major damage, the failure being aided by the pressure stress. This can be modelled using a rupture or instantaneous release model. Consequences would then be dispersion of process fluids leading to toxic effects, flash fire, pool fire, jet fire or VCE hazards, or spill of liquids. Similarly pipework should be assumed to fail, leading to a full bore release. This type of model would be appropriate where blast or fragmentation models show extensive damage to process equipment. In the case of multiple inventories within a congested area, allowance must be made for common cause damage to multiple inventories. Conventional sectionalisation by valves may not be effective if mechanical damage affects multiple isolated sections. Rupture models have the benefit of being dependent primarily on the inventory present and not the detail of the release and thus do not require detailed assessment of the impact.

If, however, a vessel is not under pressure stress, particularly large, low pressure storage tanks, the size of hole will be related to the size and behaviour of the munition. It is important to make reasonable assumptions in this case as assuming rupture may lead to unrealistic consequences. In the case of penetration, the hole will be closely related to the size of the projectile. Steel will deform and then puncture leaving roughly circular holes similar in size to the projectile. Concrete typically fails along angled planes, leading to roughly conical cratering. The thicker the concrete, the more energy is absorbed and the further cracks will propagate around the impact site. The hole size is therefore potentially greater in thicker concrete, but the type of failure will depend on the details of construction.

It should be noted that explosive effects on impact are generally less significant than kinetic energy in penetration effects. Certain, more sophisticated, weapons have the potential to withstand impact intact and explode with a delay. This could increase the consequences either by explosion within the tank leading to overpressure, or partial penetration of a thick wall followed by explosion which would increase the crater size.

Consequence Types

It would seem logical to assume that a munition explosion will cause ignition of any process fluids. This is not, however, necessarily the case. The explosion may occur before impact, if there is no pre-existing leak then the source of ignition is over before the leak occurs. Conversely if the explosion is delayed, the release may have become fuel rich and will not ignite. On at least one occasion a rocket munition penetrated an LPG carrier leading to a spill of LPG to the sea but no fire.

It is therefore necessary to consider the full range of potential effects including immediate ignition, delayed ignition and no ignition effects.

Response Action

In modelling the process consequences, it is important to consider the potential state of the plant at the time of impact. Assessing the difference in consequence if the plant has been, for example shut down and depressurised, or if storage inventory has been reduced, can be helpful in comparing the effectiveness of different response strategies.

Conversely, the plant may suffer multiple simultaneous effects which would not be considered in a conventional assessment. Common cause loss of power, cooling water or other utilities may increase the potential for process hazards to be realised. The potential for external support to be disrupted should also be considered. A HAZID or What If study could be used to define scenarios for consideration, and to improve response plans.

Frequency

Although it is almost impossible to assess the actual hit probability of the rocket, assumptions can be made from previous data, and based on the size of the critical targets.

Company security or local intelligence can provide information on historical attacks as well as intelligence on potential unrest and attacks in the surrounding area. This enables a more accurate assessment of potential threats to a facility.

Similarly, the probability of impact can be estimated relatively accurately based on the layout of the plant. For example, should the layout of the plant be such that the most critical areas are both large in area, and height, then it is more likely that this area is vulnerable to projectile impact. Equally, if the critical plant is condensed in a small area, then the probability of impact is much lower.

This can also be effective for probability estimation based on munition type. A wire-guided missile, although previously excluded, is far more accurate than a mortar round from distance.

Taking these into account, a relatively accurate approximation of the probability of impact can be made.

Case Study

In order to put the various methodologies into perspective, it is important to look at them in the context of potential projectiles, and targets. Taking the BM Grad 21 rocket as an example and a large reinforced concrete storage tank as the target, the following shows the uncertainties in modelling, and their use in consequence modelling.

The Soviet BM-21 Grad has a range of up to 45km. The major advantage of this type of artillery is that a total of 40 rockets can be fired in as little as 20 seconds. This improves the probability of a ‘positive’ impact, but due to the range of the rockets, reaction time increases at the target location (should it be detected).

It is not only important to understand the type of projectile that is the threat, but also the variation on type. The Soviet BM-21 has a number of variations that should be considered, and although the rockets have similar properties, the effects can be significantly different.

As discussed earlier, the difference between the consequences of impact from a penetration projectile and a fragmentation projectile can be significant. However it is not only the munition characteristics that have variance. Depending on the purpose of the weapon, the resulting mass and velocity can be significantly affected. For the purposes of conservatism, if the exact munition type is unknown, then it is better to conduct the assessment based on the highest muzzle velocity and mass.

When assessing a specific impact area, such as an Oil & Gas facility, the sensitivity to launch angle on a probabilistic assessment is extremely significant.

Assuming that the muzzle velocity of the projectile is 660 m/s, resolving projectile equations for the launch angle shows the that maximum horizontal distance can range from approximately 1500m at a launch angle of 1° to approximately 44000m at 45°. So it can be seen that the sensitivity to launch angle is significant.

As discussed earlier, for conservatism, and when the exact weapon type is unknown, it is best practice to model all potential scenarios; penetration, fragmentation and munition overpressure. Therefore, in this case study all three effect models have been assessed.

The impact targets of greatest concern in this example are the large concrete storage tanks and the accommodation area. Assessments were based on the reinforced concrete protection protecting both targets.

Due to confidentiality, the exact parameters of this assessment cannot be publicised here, however the assessment was carried out based on the following generic parameters:

- Compressive Strength - 28 MPa
- Concrete Age - 360 days
- Aggregate Size – 20 mm
- Concrete Depth – 800 mm pre stressed reinforced concrete

Based on these parameters, the following indicative results were calculated for penetration, fragmentation and blast overpressure.

Total penetration depth into the mass concrete was determined to be 3609mm, with a minimum thickness requirement of 4609mm.

Fragmentation penetration depth in the mass concrete was determined to be negligible. However, the assessment was also undertaken for the steel tank shells (assuming 10mm thick mild steel). From this it can be concluded that for the weapon type assessed, the minimum thickness of steel required is approximately 19mm to withstand fragments from close range.

Finally, based on the assumption that the warhead contains 18kg of explosive charge, the source overpressure is catastrophic to the surrounding area (in excess of 6800 kPa), but reduces rapidly with distance, to 20 kPa within 20m.

In assessing the probability of the consequences, it is important to understand the targeting of the weapon. The Grad system is unguided and relies purely on launch angle and direction. The distribution of impacts is therefore quite wide and dependent on the skill and experience of the users. If historical attacks have taken place on the facility, they can be used to assess the accuracy of the weapon. For example if in three attacks, with single projectiles, one has landed within the plant area, it can be assumed that rocket hits on the facility are 1 in 3.

The footprint of the target area is taken to be the whole site area, in this case 3km x 1km = 3,000,000m^2. Conservatively it is assumed that the rockets are fired along the long axis of the plant area because error in range is typically greater than error in direction.

Conservatively, it is assumed that the impact occurs over a footprint that is twice that of the relevant target. This accounts for the height of equipment and buildings. For distributed targets such as camp areas, with low height relative to the footprint, this correction would not be applied.

Based on the footprint of the target area above, the probability of impact can be estimated using the footprint of critical targets. The footprint of the LPG Tanks is 20,000m^2 (based on tank area of 100m x 100m), and the footprint of the Accommodation is 720,000m^2 (based on accommodation area of 600m x 600m).

Therefore the conservative probability that a rocket, randomly landing in the plant area, will impact on a critical target can be taken as:

- Tanks - 6.67E-03 per tank [2.22E-03]
- Accommodation - 1.20E-01 [4.00E-02]

It should be noted that these values are the probabilities per rocket strike. These could potentially be reduced by 1/3 (to the values in brackets) if a historical hit probability were to be considered to represent probability per rocket launch.

Due to commercial confidentiality, the consequence model outputs cannot be documented here, however, a brief summary of the results are given below.

The consequence modelling was carried out using DNV PHAST (v 7.1), with the hole size assumed to be large, based on the concrete storage tank being a pressurised vessel. The modelling was conducted for typical metocean data for the area, for a number of weather conditions.

Early Pool Fire

Pool Diameter	164 m
Flame Length	200 m
Flame Emissive Power	220 kW/m^2
Distance to 37.5kW/m^2	313 m
Distance to 12.5 kW/m^2	441 m
Distance to 4 kW/m^2	639 m
Burn Rate	2,974 kg/s
Fire Duration	~5.5 hours

Late Pool Fire (Bunded)

Pool Diameter	273 m
Flame Length	283 m
Flame Emissive Power	220 kW/m^2
Distance to 37.5kW/m^2	419 m
Distance to 12.5 kW/m^2	610 m
Distance to 4 kW/m^2	907 m
Burn Rate	8,247 kg/s
Fire Duration	~2 hours

Dispersion - Bunded

Distance to Lower Flammability Limit (LFL)	1,695 m (2/F)
	493 m (5/D)

As the results show, the methodology for the consequence modelling produces results that would be as expected from a typical consequence assessment. These results can then be combined with the probability of impact as discussed earlier, to produce an estimated risk profile for the impact of a projectile on process plant. The risk profile can be further refined when taking into account the probability of the attack taking place. This should have a significant effect on reducing the risk.

Risk Reduction

There are many types of risk reduction that can be designed for this type of situation for an Oil and Gas facility. However there is no 'one-size fits all' solution. The mitigation options can only reduce the impacts of an attack, and not prevent it from happening.

It is unlikely that significant design changes can be made to an existing facility, the options to reduce the risk can therefore be grouped;

- Prevent or reduce the frequency of attacks;
- Protect plant and equipment;
- Reduce hazardous inventories; and,
- Reduce personnel exposure.

The simplest measures to implement are solutions external to the plant to reduce the likelihood of attack. Protecting the boundary, and controlling approach to the area, requires effective security which is outside the scope of this paper. It should be noted however that some munitions considered have a range of several kilometres and therefore it is hard to prevent attacks completely, although short range munitions can be excluded by perimeter stand-off distance.

For longer range weaponry, consideration could be given to a radar system. Although this is an expensive solution, it does not protect the site, only increases the early reaction time by warning of an incoming projectile. Further to this, protective habitats would be required to muster on alert.

Protection of plant and equipment is possible, local barriers are frequently used to protect smaller targets such as manned control rooms and personnel shelters, however protecting large tanks or process plant areas by means of structural barriers would be very expensive and time-consuming. For a large tank the barrier would need to exceed the height of the tank. A further option for explosive munitions would be a net or grid type system. This is intended to initiate detonation by triggering the fuse of the munition at a standoff distance. Penetration is prevented and fragmentation and blast effects are reduced due to the distance. This option is somewhat munition specific as fusing types vary, delayed fuses may be unaffected.

If the risk is not acceptable, then it can be reduced by restricting operations so that the process consequences are reduced. For example in a tank farm the outermost tanks, which are most exposed to attack, could be left empty and the stored plant inventory reduced. Process plant inventories can generally be reduced quickly, by Emergency Shutdown (ESD) and Emergency Depressurisation (EDP), in the event of intelligence suggesting a higher level of threat. Stored inventories however cannot be reduced quickly. It is important therefore to understand the nature of the threat to each element of the site.

Finally, personnel are exposed directly to the munitions effects with or without additional process hazards. Manning reduction is a significant risk reduction tool, and essential manned buildings can be protected.

Conclusions

It is not common for Oil & Gas facility assessments to consider malicious attacks, however given the current terrorism climate, this is something that cannot be ignored. Both the effects to personnel and asset from such incidents are of major concern.

There are a variety of weapon types that have the potential to be used in malice and as discussed, each weapon type can have significantly different effects, dependant on its purpose/use.

Although some of the calculation data is available such that these assessments can be carried out, it is important that they are conducted by suitably qualified and competent engineers with experience of this type of assessment. With the varied weapon effects available, and such a large number of variables for consideration, inaccuracies in assessment could prove fatal.

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