Safe blast simulation: The potential to use radio frequencies to emulate blast effects

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Abstract: The paper provides a brief overview of the use of electromagnetic energy to emulate blast effects. The issue being addressed is: a safe method of emulating blast effects which demonstrates the distances at which injury and structural damage occurs without causing those effects. The ability to use electromagnetic transmissions combined with software to calibrate transmission to diminishing blast effects over distance has been demonstrated. Additional work on frequency selection has led to the development of a technology that emulates, to a reasonable degree, the effects of blast over distance. The safe indication of blast effects in a 'real time' and 'real world' environment will enhance training and hence safety.

Key words: blast, simulation, injury, replication, training, bomb disposal, emergency management, counter-terrorist exercises.

Context

The issue to be addressed is: a safe method of emulating blast effects; a method that demonstrates the distances at which injury and structural damage occurs without causing those effects. Safe indication of blast effects in a 'real time' and 'real world' environment will enhance training and hence safety.

The use of explosives in training is problematical in that.

- Participants training with explosives must be removed to safe distances well beyond the boundaries of physical injury. This separation, while providing safety, removes any possibility of understanding the effects of proximity to an explosion.
- Explosives can only be used in licenced range areas or under specific limited approvals if used during urban training. Range areas are under pressure to reduce charge sizes and usage.
- Explosives used in training are transported and stored within the provisions of dangerous goods legislation placing limitations on when, where and how they can be used[i].

Participants who require an understanding of blast effects include:

- bomb technicians, search personnel and incident commanders who need to understand and appreciate the distances at which blast effects occur;
- emergency services staff and commanders who require accurate guidance on the establishment of cordons, command posts, access routes and related planning factors;
- security and emergency managers who require reasonably accurate emulation of blast effects on people and buildings;
- emergency, security and others who advise on evacuation routes and safe distances for emergency assembly areas and related procedures; and

- structural, façade, safety and similar engineers who require an understand of the relationship between explosive charge weight, distance and damage.

Current situation

Emulating blast effects in real time in a manner that enables participants to identify if they are at risk from an explosion is difficult. The use of actual explosive charge weights in proximity to participants is not feasible as it would create an unsafe environment.

An indication that an explosion has occurred can be provide through the use of small pyrotechnics with a charge weight of grams, buzzers or other sound makers and flashes of lights or strobes. None of these represent blast effects over distance.

Laser systems can be used to simulate fragmentation effects but not blast effects.

In addition, often it is not possible to tell if the applied render safe procedures (RSP) for the practice improvised explosive device or explosive ordnance was effective in disrupting the firing system. A method of emulating the blast effects should the RSP fail would be of benefit. Currently small pyrotechnic charges and sound 'buzzers' are used to indicate if the firing system has activated. Because of the distance between the training item and observers it may not be clear if the firing circuit activated before, during or as a result of the RSP or if the item was successfully rendered safe.

Currently participants rely on 'non-direct' methods to indicate potential blast effects given nominated explosive charge weights and distances. These methods include the use of blast modelling, evacuation distance tables and 'Rule-of-Thumb'.

Blast Modelling

Lacking a physical indication of blast effects, participants rely on blast modelling to predict various injury and damage distances. Modelling represents the effects of an explosion in the specified locations. Modelling can create very accurate estimates of the expected results from a specified quantity of a particular energetic material at an exact pre-determined site.

Increases in technology, models and mobile computing power are improving the capability to conduct on-site, real-time prediction of blast effects. Viewing computer projections does not provide the visceral understanding to those deployed on the ground.

For detailed prediction of effects using finite element analysis, the measurements, drawings, charge weights and other information must be provided in advance to allow time for the calculations. This limits the ability to select the site of the explosion on the day or to modify it in relation to alterations in the training requirements.

Figure 1 shows modelling of injuries from a 5kg TNT charge. The distance for 50% eardrum rupture is ~ 10m.

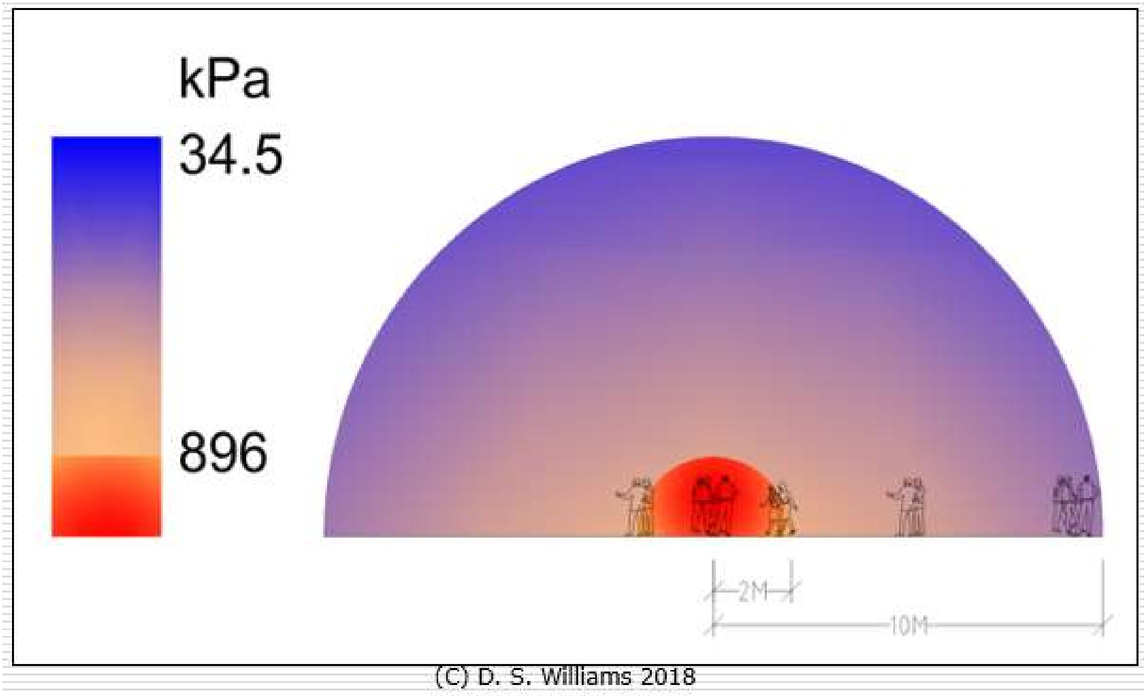

Figure 1 Modelling of injury from 5 kg TNT.

(Distances shown are 2m and 10m)

The use of modelling does not provide an immediate or visceral indication of the effects of an explosion.

Evacuation Distance Tables

Safety evacuation tables may be used as the basis for planning and operations (*citation*[ii]). The excessive distances issued by some agencies provide inaccurate guidance. The 1,135-metre evacuation distance for the public from a 2,500 gram pipe bomb[iii] is an example of overstated distances that reflect neither injury (threshold pressure for eardrum at 7.7 metres[iv]), damage (steel framed building damage at 6.4 metres[v]) or expected fragment range of <200 metres[vi].

Figure 2 shows the recommended evacuation distance for a 2,500 g pipe bomb[vii] within the Sydney central business distance. The distance does not, and is not intended to, provide a viable indication of explosive effects.

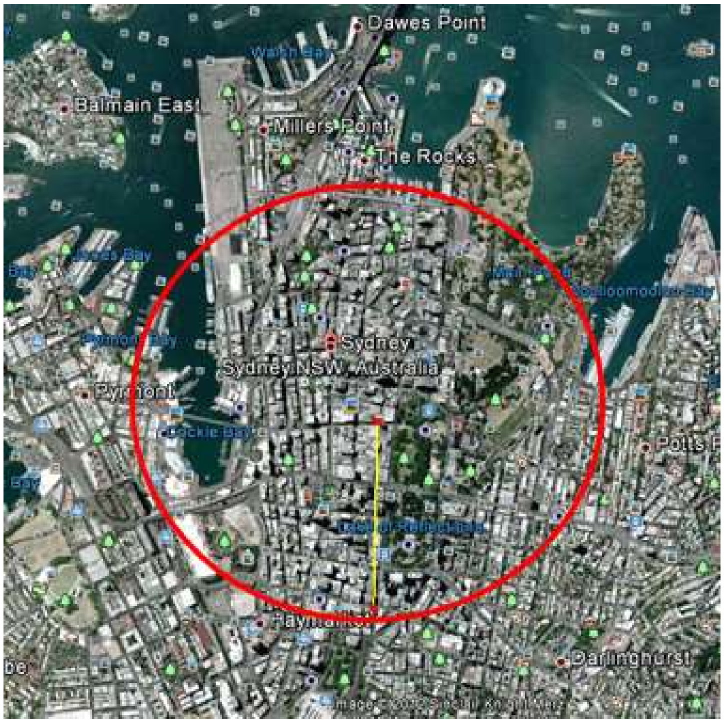

Figure 2 – ~1,135m evacuation distance for a 2,500 g pipe bomb in Sydney CBD

Distance tables are published to provide a high degree of safety and do not indicate the distances at which blast effects will be experienced.

Rule-of-Thumb

Another method used for determining an appropriate distance from an explosive device is 'rule-of-thumb' based on experience or expediency. While the selected distance and location may be appropriate it could be hard to justify.

Requirement

The requirement is for a tool that enables those without formal training, experience and qualifications in explosive engineering to gain an understanding of the distances at which explosive effects can reasonably be expected. Such a tool would also enable experienced practitioners to demonstrate and validate their advice.

The challenge was to identify a means of demonstrating the distances at which injury and damage from blast effects would be experienced in a non-hazardous manner. The criteria for the 'blast emulation system was determined as:

- able to be scaled in some manner to indicate blast injury and structural damage at various distances related to selected explosive charge weights;
- be omni-directional;
- penetrate thin walls and materials;
- be reflected by strong walls and materials;
- preferably be reflected around corners;
- ideally flow over and around items using the principles of hydrodynamics;
- operate out to distances equivalent to the injury distances for (say) 100 kilograms of TNT (trinitrotoluene);

- be simple to operate;
- be non-hazardous to store, transport and operate;
- be deployable in a wide range of physical environments;
- be easily transportable across jurisdictions; and
- have a low cost of procurement and maintenance.

Consideration of Electromagnetic Properties

The use of electromagnetic transmission was considered. Specific electromagnetic transmissions were expected to meet many of the stated requirements. Radio frequency *(RF)* signals travels in an omnidirectional manner. Through selection of appropriate frequency and strength the signal can pass through thin materials, be reflected by solid ones and reflect around corners. The RF signal from a transmitter (Tx) can be scaled using frequency, power or software to provide indication at receivers (Rx) at specified distances. It was considered feasible to relate the transmissions to selected explosive charge weights and have these trigger Rx at predetermined distances.

The International Telecommunication Union[viii] – Radio Waves produced an authoritative paper on the "Effects of Building Materials and Structures on Radio wave propagation above 100 Mhz". The designers reviewed frequencies between 300 Mhz to 3 Ghz to find a frequency best suited to the defined requirements. Another ITU paper[ix] addresses the absorption of RF in various building materials and was referenced to support the selection of a frequency to determine the feasibility of the concept[x].

While RF offered some advantages there are significant differences between the electromagnetic energy and the hydrodynamic properties of blast. These are summarised as:

- Radio waves travel in straight lines and do not flow around objects. Electromagnetic waves dissipate based on a square root basis; blast on a cube root basis.
- The effects of an explosion are dependent upon the amount, type and confinement of the energetic material. The effects of a radio transmission are dependent on the strength and frequency of the signal.
- Electromagnetic signals travel at the speed of light, blast travels at a greatly reduced speed through the medium. Given the distances at which blast damage will be observed from specified explosive charge weights the practical differences in time will not be observable by the operator[xi].
- Electromagnetic signals reflect immediately and do not build up an increased pressure against a surface in the manner of a blast wave. As a result, there is no simulation of peak reflected pressure.
- The ability for an electromagnetic wave to penetrate a wall does not represent structural damage or failure that would result from impact of a blast wave.
- There is no replication with an electromagnetic wave of the shock front that precedes the blast wave. The shock wave does specific damage to people and structures.
- An electromagnetic signal has no propulsive effect and can not simulate the effects of fragmentation.
- Nor can an electromagnetic signal simulate the manner in which a human body can be accelerated and projected resulting in impact-related injuries.

Initial Design Concept

The concept proposed was to use some form of electromagnetic signal to provide readings to indicate blast effects. The design concept was to place a transmitter at the desired location of the simulated explosive event and one or more receivers to be placed at locations where estimations of explosive force are required.

It was not intended that the system be an analysis tool, rather it was conceived as a training system that provides an indication of damage over distance from blast effects, in a safe manner.

The electromagnetic signal to be scaled using changes in frequency or strength of signal at the transmitter or through the adjustment of the signal at the receiver. By calibrating the signal against peak incident and/or peak reflected pressures it was expected that a reasonable approximation could be achieved.

In order to align the dissipation of RF with the much faster dissipation of blast effects the design incorporated software in the Tx and Rx to equate the RF output over distance to the required blast effects.

By selecting an appropriate frequency or signal strength it was considered that the ability to penetrate thin walls and reflect from solid ones could be replicated to a reasonable degree.

Initial concept demonstration

The concept demonstrator was designed and constructed as a Tx linked to a number of Rx. The Rx could be worn by participants or placed at specific sites. The Tx would be adjustable to represent various (TNT) explosive charge weights. The Rx had a series of lights used to indicate if the pre-programmed blast peak pressures had been received.

A concept demonstrator was constructed. A transmitter released a signal which could be received by receivers and indicated a point at which selected pressures would be exceeded. The system was trialled using peak reflected pressures of ~5 and ~35 kPa, equating to “minor damage to some buildings or break glass distance”[xii] and threshold eardrum damage[xiii].

The proof of concept was demonstrated using the 151 to 174 MHz band.

The Tx could be used as a stand-alone item initiated by the exercise controller or the Tx could be linked to a firing system built into a training improvised explosive device (IED) , booby trap or item representing unexploded ordnance. For the demonstrator a triggering system required an electric firing circuit. If the circuit closed due to a timer, command detonation or due to a render-safe procedure the Tx would trigger the Rx within the specified blast injury radius.

The initial system was tested in open field environments and at a cultural venue which offered a range of building and façade materials. The system provided reasonable indication of blast effects at specified distances for selected explosive charge weights.

The Rx did receive signals at the appropriate distances to provide an indication of immediate injury or damage.

The signal did pass through thin walls and reflect from solid walls and the signal reflected around corners. It did not, nor was it expected to, ‘roll’ over and around structures as per the hydrodynamic nature of blast.

The concept demonstrator raised issues over ease of use, manufacturing costs and transportability across jurisdictions. An issue was that the selected frequencies may not be readily available in all countries.

A review of published data demonstrated differences between a number of the available blast/damage tables (but within allowable margins). Published blast/damage tables[xiv] err on the side of caution by adding safety margins. These margins are added as the tables are normally used as guides for those planning safety distances for potential explosive events and a conservative figure is desirable.

Therefore, the first task in the development of a blast simulation system was to review existing data and generate a table that is as accurate as possible i.e. without a conservative (safety) bias.

The following distances and pressure effects were used as the basis for the emulation and show the selectable 'charge weights' used on the concept demonstrator. Figures are approximations for use in real-world environment.

Dial Setting (in Kg of TNT)	"Break Glass" Distance (5 kPa)	Slight chance of Eardrum Rupture (35 kPa)
5.0 kg	**40m**	**10m**
20 kg	**65m**	**17m (say 15m)**
50 kg	**85m**	**23m (say 20m)**
100 kg	**110m**	**29m (say 30m)**

Table 1 – Programmed distance against specified blast effects.

As expected, when using the electromagnetic forces to replicate blast effects there was not a complete match. The following differences were observed:

- the Rx could only indicate either peak incident or peak reflected pressures, the tests were calibrated to peak incident;
- the RF signal does not 'roll' around structures in the manner of blast;
- the ability to penetrate thin walls and reflect from solid walls is not closely aligned to blast effects;
- orientation of a person towards the Tx altered the ability of the Rx to receive the signal, for example if the Rx is worn on the chest and the person's back is towards the Tx the signal may be blocked or diffused; and
- there were variations in Rx at the same distances from the Tx depending on location and reflective surfaces.

In relation to the variances between RF and blast it is noted that blast effects are subject to a wide range of effects that alter the observed performance from the modelled predictions. Minor variations in the Rx indications reflect the reality of practical experience. Modelling assumes perfectly manufactured and detonated explosives, with flawless containment, ideal gasses and perfect reflecting surfaces. The reality is that blast can and does vary in its effects.

If the person is facing away from the seat of the explosion and whether the person is breathing in or out at the time will alter the injuries received particularly ear, lung and other soft tissue damage.

Additional development

A redesigned, preproduction system has been designed, developed and undergone initial field tests. A new frequency band has been selected that better represents the penetrative and reflective nature of blast. In addition, advances in computing capability and miniaturisation since the concept demonstrator was built have improved the design of the Tx and Rx.

The system has acknowledged limitations which stem from the use of one form of physics to simulate, to a reasonable degree, another form of physical behaviour:

- It can only indicate peak incident pressure or peak reflected pressure.
- The performance of the energy passing through surfaces is not the same as the effects of blast causing a surface to fail, but it does indicate the ability for blast to penetrate certain materials.
- It does not simulate fragmentation but alignment with a laser-based system would enable high velocity/low trajectory fragmentation to be represented.
- There may be places where it is inappropriate to use the system, such as in hospitals or near sensitive electronic equipment.

The company behind the design and development of the system, Layer 3 Services (L3S), continues to develop the system under international patent and copyright with the intent of providing a safe and reasonably accurate method of emulating blast for those who need to plan for and respond to explosive incidents.

Conclusion

Field test a have demonstrated that the electromagnetic forces can be used to replicate blast effects to a degree of accuracy suitable to enable safe training that indicates injury and structural damage.

While the capability is expected to be available in early 2020; L3S will continue to fund research and development into the use of radio frequency transmissions to emulate blast effects.

Assumptions.

The following have been assumed:

- An impulse time of 4 milliseconds.
- Glass Break over pressure for non-laminated 5mm sheet glass is ~ 1 psi (7 kPa) this also equates to the FEMA 428 range for damage to most buildings.
- Blast over pressure for slight chance of Eardrum Rupture is ~5 psi (35 kPa),
- Blast over pressure for slight chance of Blast Lung damage is ~35 psi (241 kPa),

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Company funding the research and developing the capability:

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Endnotes:

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[i] UN Economic and Social Council (ECOSOC) Committee of Experts on the Transport of Dangerous Goods (TDG) Transport of Dangerous Goods – Recommendations of Experts on the Transport of Dangerous Goods (The UN Orange Book) (2005), 14th revised edition, New York and Geneva.

[ii] xxx

[iii] Australia-New Zealand Counter-Terrorism Committee (ANZCTC) "Improvised Explosive Device (IED) Guidelines For Places Of Mass Gathering" April 2016.

[iv] Based on 34.5 kPa (using TNT as explosive material) as per Figure 1-3 of United States Unified Facilities Criteria Department of Defense Structures to Resist the Effects of Accidental Explosions (UFC 3-340-02) 5 Dec 08.

[v] Based on 48 kPa (using TNT as explosive material) which is given as the upper threshold for "severe damage to steel framed buildings" in Table 4.3 of US Department of Homeland Security FEMA-428 (2003) Primer to design Safe Schools Projects in Case of Terrorist Attacks.

[vi] Based on equivalent 81mm mortar and assuming a similar charge weight to casing weight ratio and noting that military ordnance is designed to fragment in an effective manner as opposed to improvised devices.

[vii] Australia-New Zealand Counter-Terrorism Committee (ANZCTC) "Improvised Explosive Device (IED) Guidelines For Places Of Mass Gathering" April 2016.

[viii] International Telecommunication Union – Radio Waves ITU – R P.2040 – 1 "Effects of Building Materials and Structures on Radio wave propagation above 100 Mhz" 2015

[ix] International Telecommunication Union – Radio Waves ITU – R P. 2346 – 1 "Compilation of measurement data relating to building entry loss" 2019

[x] See also, B Alexander 802.11 Wireless Network Site Surveying and installation. Cisco Press 2004.

[xi] For example, for a 100 kg at 30 m (using TNT as explosive material), the approximate distance for ear damage, the time of arrival of the blast is ~56 msec; calculated using CONWEP.

[xii] US Federal Emergency Management Agency FEMA 428 Table 4.3

[xiii] US Unified Facilities Criteria UFC 3-340-02 Table 1.3

[xiv] Ryan, J.M.; Rich, N.M.; Dale, R.F.; Morgans, B.T.; Cooper, G.J., Ballistic Trauma: Clinical Relevance in Peace and War, p57, Arnold, London, 1997. Montanaro, P.E. (formerly Indian Head Division/Naval Surface Warfare Center); Swisdak, M.M. Jr. (Indian Head Division/Naval Surface Warfare Center); Ward, J.M. (Department of Defense Explosives Safety Board), The DDESB Blast Effects Computer -- From Circular Slide Rule to Excel Spreadsheet, 2000. White, C.S., The scope of blast and shock biology and problem areas in relating physical and biological parameters. Annals of the New York Academy of Sciences, 1968, 152: p. 98. Noon R. Engineering analysis of fires and explosions. Boca Raton: CRC Press, 1995 (page 191). CONWEP US Corps of Engineers Waterways Experimental Station