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Quantitative modelling of the performance of potential Australian chemical, biological & radiological defence systems – A pilot study

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Abstract: Current Chemical, Biological and Radiological (CBR) defensive equipment used by the Australian Defence Force (ADF) was designed to meet threats involving large-scale usage of sophisticated CBR agents and delivery systems, and may not be best suited to meet the challenges of the current asymmetric threat. DSTO are investigating the performance of both current and potential new CBR equipment in support of Joint Project 2110, which will procure the next-generation CBR defence system for the ADF.

The response of the equipment is estimated quantitatively using the CBR Virtual Battlespace (CBR VB), a synthetic environment that is comprised of a range of mathematical models that have been developed for predicting the extent of CBR hazards and how that hazard impacts on potential CBR defence systems (a CBR defence system includes protective clothing, CBR sensors, medical countermeasures, decontamination equipment and an information system to communicate warning messages). The CBR VB co-ordinates the sending and receiving of data from various individual models and is used to assess the performance of the overall CBR defence system. This process is repeated for a range of environmental conditions, CBR releases and military operations over a large number of simulations.

The CBR threat is a key input to studies of this type, and in this case comes from careful selection of appropriate vignettes, which describe particular CBR weapons and their usage. These vignettes are overlaid on the context of ADF planning scenarios, which contain representative future military operations. In order to demonstrate the methodology of the study at an unclassified level, a pilot study was developed using a fictional military operation, CBR release and CBR defence system.

The number of CBR and heat strain casualties and the time delay for the operation were the two performance metrics used in the pilot study. This allowed for a comparison of the balance between the level of CBR protection required and its associated physiological burden.

Three sets of simulation 'runs' were undertaken, the first being a baseline case without a CBR defence system. This involved modelling a CBR release using the well-validated dispersion model in the CBR VB and using the exposure levels for various personnel to drive casualty predictions. A second run examined the performance of a simple CBR defence system and predicted the casualty levels and various delays to the operation (caused by encumbrance of protective equipment). The final run looked at the sensitivity of the performance to extreme choices for the warning and reporting component of the simple CBR defence system.

Results from the pilot study show locally severe CBR effects that are well mitigated by the CBR defence system being investigated. This must be balanced against the significant operational delays associated with the adoption of a CBR defensive posture. Following a review of the methodologies used in the pilot study, a broader study will look at a wider range of CBR threats across a number of high priority ADF operations.

Keywords: *Chemical, Biological & Radiological (CBR) Defence, Modelling & Simulation*

1. INTRODUCTION

Recent Australian Defence Force (ADF) deployments to Iraq and Afghanistan have predominantly involved combat against groups of insurgents rather than more traditional state-based forces, some of which have shown a willingness to obtain and use weapons involving Chemical, Biological and Radiological (CBR) materials. This represents a significant change in the CBR threat faced by the ADF, from the large scale usage of nuclear, biological and chemical weapons considered historically, to a more asymmetric threat involving improvised devices or accidental releases, particularly those involving toxic industrial materials.

The Defence Science & Technology Organisation (DSTO) provides advice to the ADF on the performance of current and potential new CBR defence systems by conducting Operations Research (OR) to quantitatively assess benefits associated with various equipment options. The equipment being assessed falls into one of five broad components that make up the CBR defence system, as per the ADF 2020 CBR Capability Model (developed at DSTO's 2020 CBR Capability Workshop, 2007):

- Physical Protection – includes Individual Protection Equipment (IPE) and collective protection,
- Medical Countermeasures – includes pre-exposure treatments such as vaccines and post-exposure treatments such as antibiotics,
- Detection, Identification and Monitoring – includes point and stand-off sensors for locating and identifying CBR hazards,
- Warning & Reporting – a system to take information from sensors to provide situational awareness for commanders and communicate warnings for appropriate personnel to take protective action,
- Hazard Management – includes decontaminants and corresponding application systems for removing and/or neutralising CBR contamination.

Rather than consider the options for each component of the CBR defence system individually, DSTO is planning to use a detailed modelling and simulation tool known as the CBR Virtual Battlespace (CBR VB) to investigate the performance of potential CBR defence systems for JP2110. Developed by the Defence Science & Technology Laboratory (DSTL) in the UK, the CBR VB is currently being enhanced as part of a joint DSTO/DSTL collaborative effort. It contains mathematical models of each of the above components as well as models to predict how material spreads following a CBR release. The CBR VB is being used to overlay the effects from a range of CBR threats on representations of ADF operations. As this is a computer-based simulation, the performance of a large number of potential systems can be estimated relatively quickly.

This paper outlines a modelling and simulation pilot study that has been conducted as a proof of principle for this type of investigation and also to allow development and testing of scripts and analysis methods.

2. PILOT STUDY DESCRIPTION

2.1. Operational Context

The pilot study involved overlaying the effects of a single CBR release onto a representation of an operation and investigating the performance of a simple CBR defence system. It should be noted that the operation was developed for testing purposes only and is not intended to be an accurate depiction of an actual military operation. However, the authors believe that it provides an unclassified demonstration of the methodologies that will be used in the full study and insight into the performance of CBR defence systems in general.

The operation involves a coalition (blue) force consisting of two companies, each consisting of three troops (denoted Troop A through F). Troop A is an artillery troop consisting of six vehicles, each towing a field artillery unit. Each vehicle has a driver, a gunner and six personnel to operate the artillery unit. Troops B - F are motorised infantry units consisting of five vehicles, each manned by a driver, a gunner and seven infantry (in the rear of the vehicle). They face an enemy (red) force consisting of three disparately located troops (Troops X, Y & Z) of 50 dismounted infantry each.

The operation for this pilot study was dubbed Operation CATWALKER and involves the blue forces invading the Bellarine Peninsula in Victoria, attacking each of the enemy troops in turn. The operation begins at 2200 UTC (0900 local time) on a hot summer day.

2.2. CBR Threat

A single incident that results in the release of a CBR material is considered in this pilot study, but as noted previously, it is important in the full study to overlay a variety of threats to properly investigate the performance of any defence system. DSTO uses source-term models from widely used tools such as HPAC (Hazard Prediction & Assessment Capability) (US DTRA, 2007) to estimate the effect of a particular incident in terms of the mass of material that is initially aerosolised, spilled, burnt, etc (this is calculated outside the CBR VB). Due to classification issues associated with the output of these models from a particular incident, the release in this pilot study is illustrative only.

The release occurs when artillery fire from Troop A targeting Troop X hits a building that is being used to store 10,000 kg of the chemical warfare agent sarin (a highly toxic nerve agent), as shown in Figure 2. This occurs approximately 70 minutes after the initial landing by Company 1 and results in the following:

- A release of 1,000 kg of the agent in the form of a liquid aerosol with a droplet mass mean diameter of 50 µm (droplet sizes modelled using a lognormal distribution)
- A spill of 5,000 kg onto the ground as a liquid pool which evaporates over the next 75 minutes
- The destruction of 4,000 kg of agent which is burnt in the explosion

2.3. Performance Metrics

Before the effects of the above release are overlaid on Operation CATWALKER, performance metrics for comparing CBR defence systems need to be determined. The authors believe that there are two distinct levels of performance metrics when considering CBR defence:

- Level 1 metrics – measure performance of the CBR defence system
- Level 2 metrics – measure the impact of CBR environments on ADF operations, missions and campaigns.

This study is looking at level 1 metrics only, as this is more readily quantifiable with modelling and simulation tools like the CBR VB. The impacts on operational outcomes are better determined from qualitative studies and will not be addressed here.

Ideally the level 1 metrics used in the CBR VB study would be extracted from the broader level 2 metrics, but unfortunately these don't exist in the ADF as CBR OR is still in its infancy in Australia. It was for this reason that the metrics used in this pilot study were extracted from the UK level 2 metrics of 'Survive' (measure of casualties) and 'Sustain' (measure of time delays) (Hill, 2007). The interpretations of the Survive and Sustain metrics used here are:

- Metric 1 – Proportion of force that are CBR or heat strain casualties
- Metric 2 – Operational delay due to encumbrance of CBR defence system

2.4. The CBR VB Modelling System

The units in Operation CATWALKER were scripted into the CBR Virtual Battlespace using a custom built spreadsheet-based tool, as shown in Figure 1, which shows the starting points and paths followed by each vehicle throughout the simulation. When the simulation was run without a CBR release, the operation was completed after approximately 6.5 hours. Environmental conditions were extrapolated from Bureau of

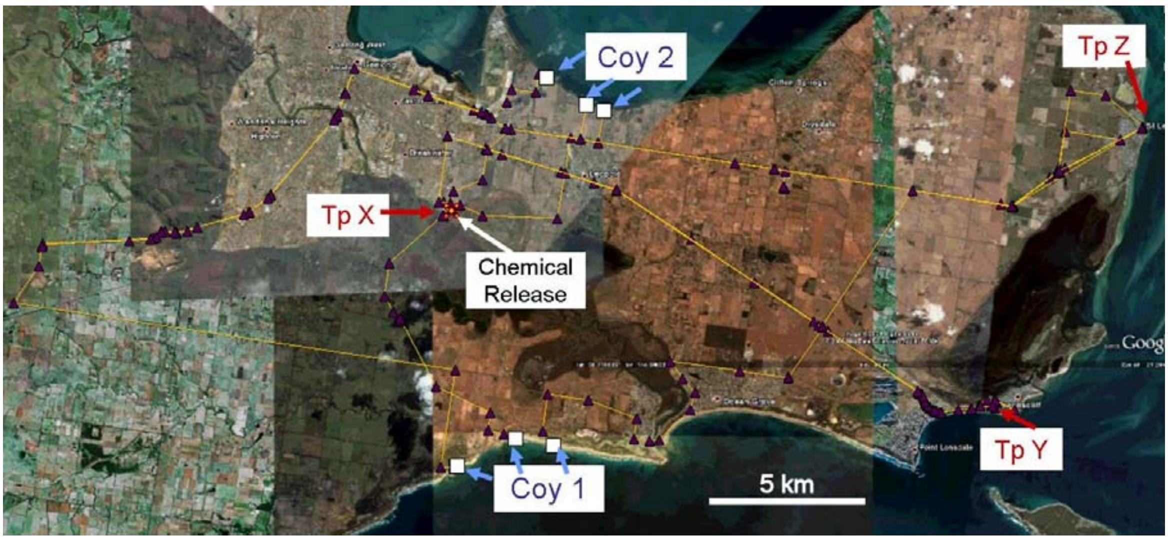

Figure 1. Pilot study "Operation CATWALKER" in the CBR Virtual Battlespace – Bellarine Peninsula, Victoria (imagery from Google Earth).

Meteorology climatology data for the area. An ambient temperature range of 25 – 35 ^{o}C and a relative humidity range of 30% to 80% were used over the course of the operation. Winds were from the west at an average speed of 5 kph and atmospheric stability conditions were neutral (no temperature change with height).

The modelling chain for the CBR VB is shown in Figure 2, and shows the flow of information between models (shaded blue) and the outputs (shaded white) provided by the system. The data inputs to the system are shaded grey and include the details of the movement of vehicles, the chemical release parameters described in Section 2.2 and various static data (such as the environmental parameters described above and toxicological information regarding the agent). The first model in the chain calculates the airborne transport and dispersion of the chemical agent, in this case a cloud and pool of sarin. The dispersion model used in this study is known as SCIPUFF (Sykes, et al 2004) which was developed in the US and widely used in tools such as the HPAC. SCIPUFF calculates grids of the mean concentration time series, which is used by the CBR VB to determine concentration time series for moving units and detectors.

When a CBR detection capability is available in the defence system being modelled, the SCIPUFF output is passed to models of the detectors to determine when they would alarm. The chemical detector model used in this study is a simple empirical model based on experimental work previously carried out at DSTO (Tilley et al., 1995). It estimates the time taken for the detector to alarm for a given concentration time series and also the time for the detector to clear down and be ready to detect again.

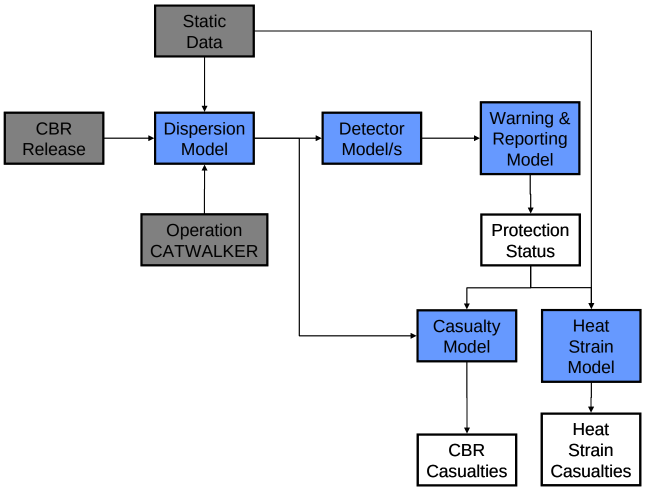

Figure 2. The CBR VB modelling chain used in the pilot study. The system inputs and outputs are coloured grey and white respectively, and the component models are coloured blue.

Once a detector has alarmed, the location and time of this alarm is passed to a heuristic-based Warning and Reporting (W&R) model which predicts the times at which at-risk units are warned of the hazard in order to don protective equipment (essentially a protection status time-series).

The SCIPUFF output for each vehicle is passed to the CBR casualty model in the CBR VB (Fish & Lanning, 2007), which relates exposure over time to probability of CBR effects using a range of published toxicological data (e.g. US Army, 2005). The level of exposure is reduced by matching the level of protection associated with each unit as a result of the warning and reporting system.

Heat strain casualties are predicted in the CBR VB in a separate 'strand' of the modelling chain. The biggest contributing factor to heat strain in a CBR context comes from the heavy and relatively impermeable protective clothing. In order to calculate the heat strain, the protection status time series is passed to the heat strain model along with static data detailing work rates, breathing rates, etc. The number of heat strain casualties is estimated by overlaying the core temperature output from the METHS heat strain model (Cooper, 2008) on probability of heat exhaustion curves (US Army & Air Force HQ, 2003).

The time delays in the second metric were calculated from estimates of the level of encumbrance associated with conducting various tasks in IPE and were taken from Army doctrine (Australian Army, 2005). Time delays from the employment of ADF work/rest tables could also be considered in the full CBR VB study for appropriate operations. This calculation took place outside the CBR VB software.

All individual models used in the CBR VB have undergone various levels of validation against available experimental data, although the extent of this validation is dependent on data availability. This validation work forms part of the ongoing joint UK and Australian development of the CBR VB.

3. RESULTS

3.1. Run 1 – No CBR Defence System

The first simulation run was a baseline where no CBR defence system was used, and casualties from heat strain and chemical exposure were calculated. The predicted individual core temperatures for all blue units in Operation CATWALKER were calculated assuming all personnel were wearing a standard combat uniform and showed a profile consistent with their changing work rates. The probability of each person becoming a heat strain casualty was determined by comparing peak core temperatures with the heat strain prediction curves discussed above; an example of this is shown in Figure 3. On average a single person out of the total force of 273 is expected to suffer from heat strain. This indicates that the environmental conditions and personnel behaviour in Operation CATWALKER are reasonable, as significant heat strain casualties aren't seen in the vast majority of ADF operations.

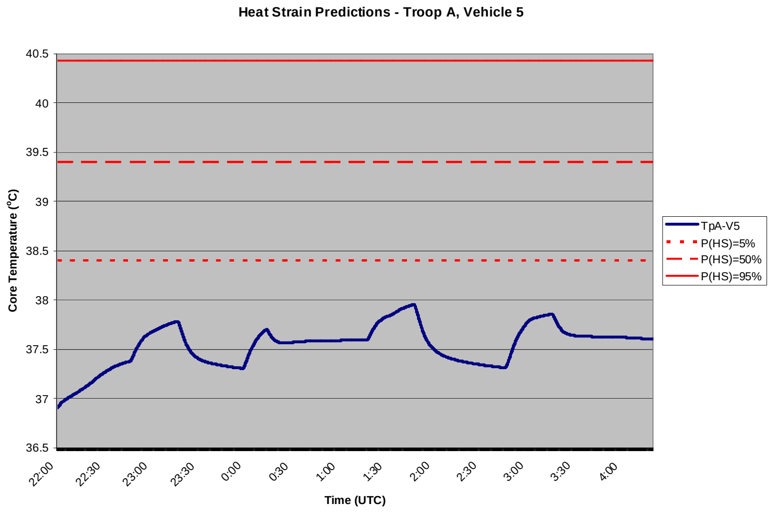

Figure 3. Example output from the CBR VB heat strain model showing core temperatures and probability of heat strain for part of Troop A (blue line) and 5%, 50% & 95% probability of heat strain (red lines)

The atmospheric transport and dispersion of the cloud and pool of sarin were calculated in the CBR Virtual Battlespace and overlaid on the troop locations specified in Operation CATWALKER. Accumulated doses were calculated from the concentration time series experienced by each person as they moved through the battlefield and passed to the CBR casualty model, which uses a probabilistic approach to determine health effects. There are a number of levels of effects for exposure to chemical agents like sarin, including minor injury (e.g. miosis), incapacitation and death. Part of the blue force was located extremely close to the release point and suffered 45 deaths, with 6 others receiving minor injuries. For the purposes of this study it was assumed that those personnel who are incapacitated or killed are considered casualties, but not those experiencing minor effects.

As no personnel are wearing protective equipment, there is no delay to the operation due to encumbrance. It is important to note that the chemical casualties themselves are likely to result in a significant delay or even failure of the operation, but are unable to be quantified in the CBR VB; these effects are best investigated using qualitative OR techniques.

3.2. Run 2 – Simple CBR Defence System

A simple CBR defence system was modelled in the pilot study and consisted of the following:

- Physical Protection – all personnel have access to a protective overgarment, including gloves and boots (MkIV) and a respirator (S10 with an AMF-12 canister),
- Detection, Identification and Monitoring – a CAM chemical detector is mounted externally on the command vehicle in each troop,
- Warning & Reporting – Nearby personnel masked up within one minute of alarm and were fully protected after eight minutes. If a second sensor alarms, all personnel begin taking protective measures after 5 minutes. The order to unmask is given 15 minutes after all detectors have stopped alarming and are ready for use again (i.e. have cleared down),
- Hazard Management & Medical Countermeasures – no capability available.

The concentration time series for each detector was passed to the detector model to predict the times at which a detector alarmed and the time it took post-exposure to clear down and be ready for use again, as shown in Figure 4. It shows that Troop B's detector receives such a high level of exposure that it takes many hours for it to clear down, and this results in all personnel remaining in their IPE for the remainder of the operation. This causes a time delay of more than 2 ½ hours (or 42% of the duration of the original operation), as infantry tasks such as engaging enemy troops take significantly longer when in a protective posture.

Unit	Alarm	Clear Down
Coy 1, Tp A	No Alarm	N/A
Coy 1, Tp B	2343 – 2359	After 0700
Coy 1, Tp C	No Alarm	N/A
Coy 2, Tp D	2314 – 0024	0025
Coy 2, Tp E	No Alarm	N/A
Coy 2, Tp F	No Alarm	N/A

Figure 4. Simple CBR defence system alarm table (all times in UTC)

The protective equipment used in this pilot study was designed to withstand high levels of CBR exposure, and since it was donned promptly after an alarm, there were no chemical casualties in the second run of the pilot study. However, the protective equipment is heavy and not made from breathable materials and as it was worn for long periods, there were significant heat strain casualties (117).

This means that the number of casualties has increased by the application of this warning and reporting system. However, in this instance chemical deaths have been exchanged for a greater number of people with heat-related injuries, many of whom will eventually recover (note that in extreme cases heat strain can result in long term incapacitations and death). Changes in the sensor characteristics or the warning and reporting system implemented in this simple CBR defence system can be investigated readily using the CBR VB. For example, if each troop had a second clean detector and used it to confirm that the first detector was just clearing down and no agent was present, then personnel would not spend nearly as long in protective suits and respirators. By using the CBR VB in this way the costs of procuring these extra sensors can be compared with a quantified measure of the benefits, and repeated across a range of threats and operations.

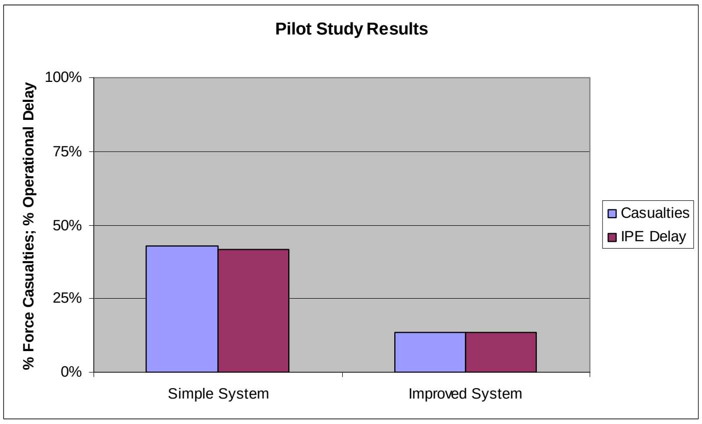

Figure 5. Comparison of performance for simple and improved CBR defence systems

This 'improved' CBR defence system was modelled for the specific threat and operation considered in the pilot study. This resulted in a reduction in the number of casualties to 37, and a reduction in the time delay to around 50 minutes (~13%). Figure 5 shows the comparison of the simple and improved CBR defence systems against two performance metrics used in this study.

3.3. Run 3 – Sensitivity to Changes in the Warning & Reporting System

Investigation into the sensitivity of changes to particular components of various CBR defence system options is a key aspect of studies of this type. As an example, two extreme warning and reporting systems were considered in the pilot study. In the first case, no warning and reporting system was used and units were in a protective posture at all times. The other extreme was a perfect warning

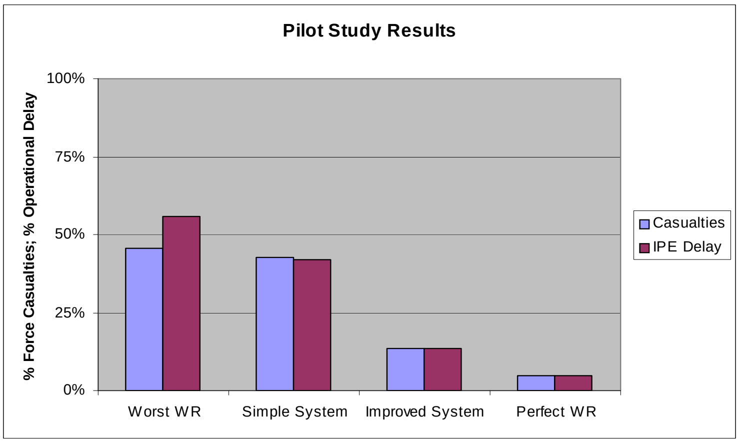

Figure 6. Sensitivity of performance for simple and improved CBR defence systems to Warning & Reporting component

and reporting system in which units only took protective action when the model predicted they would be exposed to dangerous levels of the agent and unmasked immediately after the hazard had passed.

There are significant heat strain casualties (125) and long delays (~56%) if personnel operate in their protective equipment for the duration of the operation, as the protective equipment considered provides a high level of protection and a high physiological burden. If in the full study a protective ensemble with lower CBR protection and physiological burden is considered, then the impact on these metrics would be reduced.

The perfect warning and reporting system results in the lowest number of casualties (13) and the shortest delay (~5%). A comparison of the performance of the simple and improved CBR defence systems to the performance of the perfect warning and reporting system shows that for this example further investment in this component could significantly improve the overall system (Figure 6).

4. DISCUSSION & CONCLUSIONS

The methodology used in this pilot study appears to provide reasonable, consistent results and could be used in a more detailed study that would look at a range of CBR threat and ADF operation combinations. The sensitivity of potential Australian CBR defence system options to any particular component can be easily investigated, providing valuable information to those involved in the capability development process. The CBR Virtual Battlespace is an ideal tool for this type of quantitative CBR Operations Research study.

While it is difficult to draw conclusions based on the single threat/operation combination used in the pilot study, it appears that:

- Extremely hot conditions and existing high CBR protective ensembles are likely to result in very few CBR casualties, but large numbers of heat strain casualties.
- It would be possible to reduce the level of heat strain casualties by reducing operational tempo when operating in CBR protective equipment. This however would result in increases to the total time taken to complete the operation, which causes a decrease in performance against the high-level 'Sustain' metric.
- Multiple simulation runs over a range of CBR threats and ADF operations are essential if conclusions from the full study are to be reliable.

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