Research

The development of a quick-running prediction tool for the assessment of human injury owing to terrorist attack within crowded metropolitan environments

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In the aftermath of the London ‘7/7’ attacks in 2005, UK government agencies required the development of a quick-running tool to predict the weapon and injury effects caused by the initiation of a person borne improvised explosive device (PBIED) within crowded metropolitan environments. This prediction tool, termed the HIP (human injury predictor) code, was intended to:

- assist the security services to encourage favourable crowd distributions and densities within scenarios of ‘sensitivity’;
- provide guidance to security engineers concerning the most effective location for protection systems;
- inform rescue services as to where, in the case of such an event, individuals with particular injuries will be located;
- assist in training medical personnel concerning the scope and types of injuries that would be sustained as a consequence of a particular attack;
- assist response planners in determining the types of medical specialists (burns, traumatic amputations, lungs, etc.) required and thus identify the appropriate hospitals to receive the various casualty types.

This document describes the algorithms used in the development of this tool, together with the pertinent underpinning physical processes. From its rudimentary beginnings as a simple spreadsheet, the HIP code now has a graphical user interface (GUI) that allows three-dimensional visualization of results and intuitive scenario set-up. The code is underpinned by algorithms that predict the pressure and momentum outputs produced by PBIEDs within open and confined environments, as well as the trajectories of shrapnel deliberately placed within the device to increase injurious effects. Further logic has been implemented to transpose these weapon effects into forms of human injury depending on where individuals are located relative to the PBIED. Each crowd member is subdivided into representative body parts, each of which is assigned an abbreviated injury score after a particular calculation cycle. The injury levels of each affected body part are then summated and a triage state assigned for each individual crowd member based on the criteria specified within the ‘injury scoring system’. To attain a comprehensive picture of a particular event, it is important that a number of simulations, using what is substantively the same scenario, are undertaken with natural variation being applied to the crowd distributions and the PBIED output. Accurate mathematical representation of such complex phenomena is challenging, particularly as the code must be quick-running to be of use to the stakeholder community. In addition to discussing the background and motivation for the algorithm and GUI development, this document also discusses the steps taken to validate the tool and the plans for further functionality implementation.

Keywords: quick-running; prediction; human injury; person borne; improvised explosive device (PBIED); crowded metropolitan environment

1. INTRODUCTION

(a) *Background*

The 7 July 2005 terrorist attacks on passengers using London’s transport infrastructure were a stark reminder of the vulnerability of everyday people to acts of

wanton, improvised aggression. Although London has previously been the recipient of explosive attacks by other terrorist organizations [1], the disregard of the perpetrators for their own lives, as well as the lives of their fellow citizens, increased the perceived potential scope for future terrorist acts.

There is no doubt that the courageous and skilled actions of the rescue and medical services during this period saved many lives [2]. However, since within the UK a device of this exact nature initiated within

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Figure 1. Hydrocode model showing blast pressure development within public transport infrastructure owing to improvised explosive device attack as well as the disruption to human occupants.

Figure 2. Calculation process associated with the human injury predictor (HIP) code.

these specific environments had not been observed before, a degree of uncertainty existed regarding the scope and extent of expected injuries. If in future the appropriate agencies have access to a method of estimating the injurious effects of these devices on the inhabitants of the UK, more effective proactive and reactive measures could be implemented in minimizing the ultimate consequences. It is well recognized that security and, to an even greater extent, political initiatives are the most comprehensive ways of eliminating terrorist events from our shores. However, in the unfortunate event of a future attack, an understanding of how best to distribute individuals within a crowded environment or how best to arrange physical mitigation measures would significantly reduce casualties.

(b) Requirement

To fulfil the requirements discussed above, the Centre for the Protection of National Infrastructure (CPNI) commissioned the Defence Science and Technology Laboratory (Dstl), an agency of the UK Ministry of Defence, to undertake a programme of work to:

- assist the security services to encourage favourable crowd distributions and densities within scenarios of ‘sensitivity’;
- provide guidance to security engineers concerning the most effective location for protection systems;
- inform rescue services as to where, in the case of such an event, individuals with particular injuries will be located;
- assist in training medical personnel concerning the scope and types of injuries that would be sustained as a consequence of a particular attack;

Figure 3. Generic person borne improvised explosive device.

- that assist response planners in determining the types of medical specialists (burns, traumatic amputations (TAs), lungs, etc.) required and thus identify the appropriate hospitals to receive the various casualty types.

Although the events of 7th July took place exclusively on public transport within London, it was recognized that many forms of crowded infrastructure across the whole of the UK could be targeted. As a consequence, prediction methods had to be developed to assess improvised explosive device (IED) attack within general crowded spaces, such as conference halls,

Figure 4. Representation of crowd within the HIP code. (a) Cylindrical representation of individual. (b) Random distribution of individuals with typical crowded scenario.

Figure 5. 'Freidlander' pressure time history generated away from the explosive fireball within the free-field.

airport lounges, car parks, queues for tourist attractions, cafes and offices. In terms of the representation of the IED itself, it was decided that techniques to predict the blast and fragmentation effects of typical person borne improvised explosive devices (PBIEDs) should be developed. Work was also focused on predicting the effects of vehicle borne improvised explosive devices (VBIEDs), although discussion of this falls outside the scope of this document.

After considering various potential approaches, Dstl decided to address the above requirement by developing a user-friendly survivability computer code, termed the 'human injury predictor' (HIP) code. This document briefly discusses the physical phenomena associated with such attacks and presents the analytical philosophy adopted when generating the code. An outline description of the underpinning mathematical algorithms and the graphical user interface (GUI) is also provided.

2. ANALYTICAL APPROACH

There are many analytical methods that can be used to assist in the prediction of weapon effects on humans. These vary in their complexity from sophisticated hydrocode or finite element-based techniques [3–5] to far simpler empirical or semi-empirical methods [6].

The output from a typical hydrocode analysis, used to predict weapon effects on board public transport infrastructure is shown in figure 1. In simple terms, the scenario is separated spatially into a mesh of elements with algorithms, describing the material behaviour of the explosive and ambient air and human occupants, being assigned at the pertinent location within the mesh. The generation and action of the blast wave caused by initiation of the explosive are calculated by solving the conservation of momentum, energy and mass equations for all elements at a series of small sequential time steps. Such high-fidelity analysis can be used to shed light on the underpinning mechanisms of response as well as to determine response magnitudes at all locations within the scenario. The high spatial and temporal resolution associated with the analysis, however, means that relatively huge amounts of computational power are often required. Despite continual increases in computational parallelization and multi-processor technology, a single scenario can take many hours, if not days, to complete.

Owing to the inherent uncertainty associated with the nature of a terrorist attack coupled with the need to rapidly produce outputs for the purposes of planning and response, it was required that the HIP code be capable of analysing a broad range of potential scenarios within a short time-frame. A probabilistic

survivability modelling approach [7] was, therefore, adopted involving the development of quick-running 'engineering models'. These made use of empirical, semi-empirical or far less intensive numerical techniques, although the output from hydrocode analysis was used, in particular instances, for configuring and validating the algorithms.

The simplified calculation process associated with the HIP code is shown in figure 2. To address the inherent uncertainty associated with a particular event, many calculation cycles of the same general scenario can be undertaken with randomization algorithms being implemented to alter the input, within prescribed limits, between each cycle. The injury outputs from each cycle are accumulated so that statistical analysis can be performed on the whole dataset to determine the likelihood of sustaining a particular distribution, type or level of injury sustained within a particular environment.

With reference to figure 2, initially, the PBIED details, scenario type and population density for the overall analysis are set and an initial crowd distribution is generated randomly. In step 1, the blast and fragmentation effects on the crowd members based on their position relative to the device are calculated, while in step 2, these effects are translated into abbreviated injury scores (AISs) [8,9] for the body parts attributed to the crowd member. This process is described in §4. In step 3, the AIS scores are then accumulated using the injury scoring system (ISS) [10], which in turn is used to directly determine the triage level assigned to each crowd member in that particular calculation cycle. These data are stored to feed into the overall statistical assessment at the end of the analysis. In step 4, a different permutation of the crowd distribution and the weapon effects is generated for the next calculation cycle. The greater the number of calculation cycles, the more comprehensive the analysis; however, as discussed above, the significant challenge has been to develop faithful algorithms that run within a reasonable time frame.

3. SCOPE

(a) *Weapon effects*

Many forms of PBIED have been identified around the world (figure 3). It is convenient to categorize them into two forms:

- 'belt-type' devices that are attached to the terrorist's torso and initiated by him;
- 'satchel-type' devices that are carried by the terrorist and either manually initiated by him or left in place and initiated later remotely or by timer.

PBIEDs may consist of only plain explosive but could also contain objects such as nails, bolts or ball bearings (termed 'primary' fragmentation). The explosive forces generated upon detonation impart momentum to these bodies to form an array of high velocity fragments. With reference to step 1 of figure 2, and as discussed in §4b, algorithms have been incorporated within the HIP code to handle this fragment 'throw'. It is recognized that, in certain cases, blast loading on proximate objects (including

people) or structural components can also lead to the formation of 'secondary' fragmentation but this is currently beyond the scope of the code.

The blast effects of the device within a particular environment can depend heavily on the degree of confinement within that environment [11]. Two generic scenario types were considered:

- an 'open space' type scenario in which only the ground acts as a rigid, reflecting surface;
- a fully enclosed, parallelepiped, 'room' type scenario in which all walls were treated as fully rigid reflection surfaces.

The algorithms used to handle the blast loading in each scenario type are discussed in §4.

(b) *Human injury*

Many forms of human injury can result from the initiation of a PBIED in a crowded space. Although a certain degree of conjecture exists concerning the categorization of injurious events, for convenience it is common to subdivide injuries in line with the causal mechanism. As discussed in Elsayed & Atkins [12]: injuries resulting from interaction with blast waves are termed primary; penetrating fragment injuries are termed secondary; injuries owing to bodily displacement or collision are termed tertiary; and other physical injuries such as burns or those sustained within a toxic environment are quaternary.

As a starting point, the injuries considered during step 2 of figure 2 were those associated with the immediate 'output' of the device. As discussed in §4a, these included blast injuries to the ear and lung, as well as injuries associated with the process of TA. Injury owing to the penetration of primary fragments has also been addressed as described in §4b.

Steps are also being made to incorporate other potentially important forms of injury such as blunt trauma and burns. Currently, these are of insufficient maturity to be implemented within the HIP code.

(c) *Human representation and crowd distribution*

When transposing the weapon effects into injury effects, the human body requires some form of representative geometry within the code. Although other methods consider the human at the scale of individual organs [12], it was decided that to deal with the potentially many hundreds of individuals prospectively affected by an IED incident, a much coarser approach was required. As shown in figure 4a, for ease of mathematical analysis, the code represents the 'human' crowd member as a cylindrical volume which is divided into head, neck, chest, abdomen and leg components. At this stage, 'arm' components are not included, as it is felt that the increased fidelity does not outweigh the increased computational complexity. The manner in which the blast and fragmentation algorithms use the geometry when predicting injury is discussed in §4.

When spatially distributing a crowd of humans within a particular scenario, it is recognized that many factors such as familiarity, age and the particular scenario itself have a strong influence. Although

research is currently being undertaken to develop algorithms to cater for more realistic demography based on Saucier & Kash [13], within the current analytical framework purely random distributions of crowd members, each with common dimensions, are generated as shown in figure 4b.

4. WEAPON EFFECTS AND TRANSPOSITION TO INJURY

(a) *Blast component of loading*

As discussed in §3a, in addition to the mass and chemical make-up of the explosive charge, the degree of physical confinement within the scenario has a strong influence on the levels of blast loading experienced by a crowd exposed to PBIED attack.

(i) *Free-field prediction methods*

The sudden release of energy resulting from detonation within a plain high-explosive charge results in rapid compression of the exterior air, which in turn leads to the propagation of a blast wave (a form of shock wave) away from the point of detonation. Outside the fireball (the explosive products associated with the initiation process [14]), a blast wave, uninterrupted by obstacles or reflecting surfaces, has a 'Freidlander' type of temporal distribution [11]. As illustrated in figure 5, this is characterized by an abrupt pressure rise, associated with the shock front, followed by a reverse exponential decay associated with the subsequent particle flow or 'blast wind'. A negative phase is also observed since the inertia associated with the overdriven air particles results in the creation of a partial vacuum before the return to a state of equilibrium [14]. Although other parameters associated with the blast wave have importance,¹ in terms of loading predictions within the HIP code, the incident peak overpressure,² $p_{0\max}$, and positive incident-specific impulse, $i_{0\text{pos}}$ (the area under the curve), are primarily used to determine injury levels (§4a(iii)).

As the propagation occurs in three dimensions, the energy density of the overall event and the resulting peak overpressures diminish in line with the cube of the stand-off distance, R , from the explosive source. Since the energy within the explosive can be considered directly proportional to its mass, W , the concept of scaled distance, z , as shown in equation (4.1), can be used to relate blast wave parameters within a free-field environment [11]:

$$z = \frac{R}{(W^{1/3})}. \quad (4.1)$$

Kingery & Bulmash [15] developed a series of polynomial curves, of the basic form shown in equation (4.2), from which 'scaled' parameters, X , for a spherical, free-field explosive can be readily predicted, once the scaled distance has been determined:

$$\log X_{\text{scaled}} = A_0 + A_1(\log z) + A_2(\log z)^2 + \dots + A_n(\log z)^n, \quad (4.2)$$

$$p_{\text{actual}} = p_{\text{scaled}} \quad (4.3)$$

$$\text{and } i_{\text{actual}} = i_{\text{scaled}} W^{1/3}. \quad (4.4)$$

Within this system of similitude [16], the actual pressure-based parameters are equal to scaled overpressure values but time-related properties such as specific impulse have to undergo a further de-scaling process as shown in equation (4.4).

There are no reflected surfaces within a truly free-field environment, but to be applicable within the HIP code at least reflections from the ground must be considered. As indicated in figure 5, the detonation of a hemispherical charge with its flat face in contact with a rigid surface also obeys the laws of similitude; Kingery & Bulmash [15] developed similar polynomial relationships for this scenario. There is an obvious analogy for a satchel PBIED detonated at ground level here (§3a). Predictions using this technique for crowd members near to a belt-type device, detonated at some distance above the ground, will obviously be less accurate, although, at larger stand-offs from the charge, discrepancies will become increasingly small.

In addition to the determination of 'incident' quantities, discussed above, similar relationships to those described in equation (4.2), are available for determining the loading (or reflected pressure) parameters developed when a blast wave interacts normal to an infinite reflecting surface. Blast wave interaction with a discrete obstacle, such as a human or a cylinder however, gives rise to additional complex processes such as drag and diffraction [11] that obviate rapid mathematical prediction (figure 6).

In the spirit of rapid calculation, it is convenient to 'transpose' the unobstructed, incident pressure and specific impulse values into the levels of human injury that would be sustained if an obstacle was in fact present. The veracity of this assumption becomes particularly threatened when dealing with high population densities, where the superposition of these accumulated perturbations causes significant deviation from free-field conditions (figure 7).

Numerical and experimental studies previously undertaken by Dstl [17] have indicated that, below population densities of two people per square metre, free-field conditions can be reasonably assumed for an engineering analysis.

(ii) *Prediction in enclosed environments*

When initiated within an enclosed environment, the blast waves reflect off the walls, floor and ceiling. As shown in figure 8, the waves coalesce with one another forming much more complex temporal pressure profiles compared with those observed within a free-field environment. Hydrocode techniques are conventionally used to determine pressure loadings within such an environment; however, as discussed in §2, performing a separate simulation for each permutation using this method would be prohibitively slow for survivability analysis.

Instead, within the HIP code, a blast wave superposition analysis is used to estimate these complex conditions with a fraction of the computation load. With reference to figure 9a, relationships for the spatial (indicated in red) and temporal distribution of

Figure 6. Spatial distribution of pressure around planar body as a consequence of interaction with a blast wave travelling from left to right.

the incident pressure and other thermodynamic quantities associated with a free-field, spherically expanding blast wave are stored within a tabulated dataset. In a manner similar to that explained in §5a(ii), simple scaling methods can be used to accommodate different charge sizes and stand-offs. When a reflecting face is encountered, a new ‘imaginary’ source can be located at a commensurate location on the other side of the face (figure 9b).

The pressure contributions from both sources can now be superimposed upon one another to simulate the process of blast wave coalescence and this can be repeated for other reflecting surfaces within the environment. In order to readily keep track of the reflection and superposition process, it is assumed that blast waves can be reasonably treated as acoustic sound waves in that the reflection angles are identical to the incident angles. It is also assumed that the pressure magnitudes associated with each contribution

Figure 7. Hydrocode analyses comparing specific impulse development within a free-field environment and an open environment containing a human crowd density (represented with rigid bodies). Belt-type PBIED detonation towards top left-hand corner of the environment. (a) Free-field environment; (b) environment containing crowd of five people per square metre.

Figure 8. Multiple peaks associated with blast trace recorded within an enclosed environment and ‘background’ quasi-static pressure (QSP) development.

Figure 9. Process associated with superposition analysis. (a) Explosive source, S , within enclosed structure; (b) imaginary sources used to predict reflections.

Figure 10. Comparison of (i) superposition method with (ii) hydrocode approach (taken from [19]). (a) Blast wave patterns produced at two sequential points in time (Mach stem not simulated with the superposition method); (b) comparison of typical pressure time histories. Gauge positions indicated above hydrocode analysis, dotted line; superposition analysis, continuous line.

can be superimposed in a linear fashion. In actual fact, the reflection angles of blast waves tend to be shallower than the incident angles and the superposition process is highly nonlinear. To account for this, the HIP code contains a superposition technique based on the LAMB (low altitude multiple burst) rule [18]. This was developed by Hillier [19].

As shown in figure 10a, the idealizations associated with the superposition method cause it to struggle when reproducing phenomena specific to blast wave propagation such as Mach stem formation [11]. Consequentially, when compared with hydrocode simulation, there is an increasing deviation in the

pressure time history record at increasing distances from the explosive source, as indicated in figure 10b. Despite this, the degree of discrepancy is well within the bounds of acceptability for the engineering analysis required for the HIP code.

In addition to the 'complex' reflected pressure loading component, the inability of energy to escape an enclosed system, can also lead to the development of a longer, lower magnitude build-up of background pressure, termed quasi-static pressure (QSP) [20] (figure 8). In addition to the energy release caused by detonation of the explosive, under sympathetic conditions, further 'secondary combustion' [21] of the

explosive constituents can also occur in the surrounding air resulting in higher blast loadings and temperatures. Dimensional analysis can be used to quickly estimate QSP development within these enclosed environments [14], although this has not been implemented within the code at this stage.

(iii) *Prediction of blast injury within the human injury predictor code*

Both the simple scaled distance approach (§4a(i)) and the superposition method (§4a(ii)) can be used within the HIP code to assign the blast-loading parameters that affect the crowd members.

With the very rapid scaled distance approach which is most appropriately used in an open environment, the following calculation sequence is made:

- a line-of-sight (or stand-off, R) between the charge and the body part of the individual of interest;
- the scaled distance, z , based on equation (4.1);
- values for peak overpressure and specific impulse using equations (4.2)–(4.4).

These values are then fed into a ‘pressure-specific impulse (PI)’ envelope to determine whether, for a particular body part, a particular threshold of injury is exceeded. The PI concept is a highly convenient and rapid way of attributing a blast loading to an AIS score. As shown in figure 11, within the HIP code, combinations of incident pressure and specific impulse above and to the right of a particular curve result in attributing the AIS score for that injury type. The curve can be described by:

$$p_{0\max} = C_1 + \frac{C_2}{i_{0\text{pos}} - C_3}, \quad (4.5)$$

where the C coefficients are derived empirically. If the criterion is based purely on the peak pressure, only the C_1 coefficient has to be established such that:

$$p_{0\max} = C_1. \quad (4.6)$$

Work to relate blast-loading parameters to blast injury has been undertaken for many years [22,23], although a certain degree of conjecture exists as to the appropriateness of the data used to derive the coefficients. With respect to the injury requirements of the HIP code (§3b), the TM5-1300 design manual [6] contains PI relationships for lung and ear damage (based on incident parameters), which are used as defaults within the HIP code. Further work is required to develop truly reliable relationships for TA, but values based on limited anecdotal evidence are currently used.

The great flexibility of the superposition method makes it most suitable for dealing with enclosed environments. Although far less computationally intensive than hydrocode analysis, conducting a separate calculation for each population distribution within a series of calculation cycles (figure 2) would result in significantly longer run times than when using the simple scaled distance method. Instead, within the HIP code, a single calculation is undertaken for a given room size, charge size and charge location.

This produces a series of peak pressure and specific impulse maps at various planes within the room which can be used to linearly interpolate values of each body part as shown in figure 12.

When transposing loading to human injury, the PI approach has a serious limitation within an enclosed environment as the loading is assumed to have a simple temporal distribution, such as the Freidlander function shown in figure 5. The many peaks and indefinite duration (and hence specific impulse) associated with a complex trace (figure 8) clearly deviates from this behaviour. Currently within the HIP code, a cut-off time can be set after which no further specific impulse is recorded. A superior approach would be to represent the response of each body part using a single degree of freedom system or multi-degree of freedom system [22]. Although issues would remain concerning the rapid prediction of the blast loading in this instance, and the technique carries a much greater computational load than the PI method, the approach does allow a force full time history to be applied to each body part. An implementation for lung injury has been developed by Axelsson & Yelverton [23] and future research is planned to incorporate a generic approach of this type, for all body parts, into the HIP code.

(b) *Fragmentation prediction*

As discussed in §3a, the presence of primary fragmentation within a PBIED can drastically alter the nature and amount of injury sustained within a crowded environment. When located at the front of an explosive charge, the pressures developed as a consequence of the rapid energy release, can drive discrete objects away from the explosive source at velocities far in excess of the speed of sound in the surrounding ambient air [24].

Once the explosive driving forces have been expended, retardation of the fragments occurs owing to drag forces developed in the surrounding air. When more substantial bodies, such as human crowd members, are contacted and subsequently penetrated, additional forces developed as a consequence of material strength and friction can also contribute to the retardation process. ‘Efficient’ primary fragmentation can readily penetrate more than one individual and the heterogeneous nature of the human form can result in very complex fragment trajectories during the penetration process. In uninterrupted flight, gravitational forces are usually of less influence when considering fragments expelled from PBIEDs as they generally possess very high initial velocities. However, in very sparsely populated areas where fragments can travel a long way, or when dealing with larger, slower, less aerodynamic fragments, such as those resulting from VBIED initiation, gravity can be significant.

As shown in figure 13, relatively sophisticated numerical modelling techniques can be used to simulate the initial throw-out velocity and spatial distribution of fragmentation as well as the subsequent trajectory alterations and penetrations owing to

fragment collision with other bodies. In the spirit of quick-running prediction, however, the HIP code uses a range of less computationally intensive analytical approaches to make the consequent human injury predictions.

The code contains algorithms that handle the fragment throw-out and subsequent fragment trajectory separately.

(i) Initial fragment throw-out

Fragment throw can be treated in a partially coupled or decoupled manner. With the decoupled approach, numerical or experimental techniques can be adopted to determine the fragment pattern empirically.

Based on radiographs such as that shown in figure 14, the velocity vectors associated with a fragment array can be fitted to a Gaussian-type function as follows:

$$P(\theta_x, \theta_y) = \frac{1}{2\pi\sigma_x\sigma_y} e^{-1/2((\theta_x^2/\sigma_x^2) + (\theta_y^2/\sigma_y^2))}. \quad (4.7)$$

Although in reality the fragments have an initial spatial distribution within the device, for simplicity a 'point source' ejection is assumed. With reference to figure 13a, P is the probability density function associated with each fragment trajectory angle, θ , in the x and y direction relative to the origin, O . The σ variables determine the degree of potential angular 'spread' in each direction. Although somewhat randomized to cope with the requisite variability from calculation cycle to calculation cycle, in line with the numerical and experimental observations, there is a strong bias for low values of θ_x and θ_y to be selected.

Once the trajectory angles have been determined, the accompanying velocity, v , required to complete the fragment trajectory vector is determined from the following function.

$$v(\theta_x, \theta_y) = v_{\max} - (v_{\max} - v_{\min}) \times \sqrt{\frac{(\theta_x/\theta_{x\max})^2 + (\theta_y/\theta_{y\max})^2}{2}}. \quad (4.8)$$

As indicated in figure 13a, the fragment velocity is a function of the trajectory angle in each direction, and varies linearly from a pre-selected maximum velocity $v_{\max}$ at low angles to a minimum velocity $v_{\min}$ at high angles.

The main disadvantage with this approach is that the fragment pattern is only truly pertinent for particular configurations and cannot be readily transposed to PBIEDs containing different fragment types or possessing different explosive output. As a consequence, a partially coupled approach is also implemented within the code which uses the principles developed by Gurney [24]. Conventionally, these analyses have been used to model the break up of military munitions and metal pushing problems, a simple example of which is shown schematically in figure 15 by an 'asymmetric sandwich' construction. This has an explosive charge of mass C , sandwiched between a tamping element of mass N and a metal-pushing element (to

be driven in the downward direction by the explosive force) of mass M .

By making several engineering assumptions, such as one-dimensional movement and a simple velocity distribution across all constituent weapon components, the initial velocity of the metal pushing element, v_M , can be estimated using the following dimensionless relationship:

$$\frac{v_M}{\sqrt{2E}} = \left[\frac{1+A^3}{3(1+A)} + \frac{N}{C}A^3 + \frac{M}{C} \right]^{-1/2}, \quad (4.9)$$

where

$$A = \left[\frac{1+2(M/C)}{1+2(N/C)} \right]. \quad (4.10)$$

E is termed the specific Gurney energy and is derived for many common explosives via carefully controlled experiments [25].

With reference to figure 15, within the HIP code an analogy is drawn between this sandwich construction and a typical PBIED configuration, with parameter adjustments being made for different fragment types such as nails, ball bearings and bolts. Since this model is one-dimensional in nature, the analysis is linked to an equation similar in form to equation (4.7) to cater for the three-dimensional spread which would occur in reality (figure 14). Although in its infancy, more sophisticated numerical techniques such as those shown in figure 13 are being used to calibrate the equations to better reflect reality.

Currently, both HIP code fragment throw-out algorithms do not account for the presence of fragmentation when predicting the blast output of the PBIED. The net explosive quantity (NEQ) associated with all charges is purely based on a plain spherical or hemispherical charge as described in §4a.

(ii) Trajectory calculation

Once the initial fragment pattern has been established, the trajectory of the projected fragments within the surrounding environment, and the consequent injury, has to be considered. The HIP code can handle this process with either a relatively computationally intensive 'ballistic' trajectory method or a simple 'line-of-sight' approach.

In general terms, if no further 'driving' energy is imparted to the fragment, the retarding forces acting on it, with the exception of gravity, can be described by the following equation of motion [26]:

$$-m \frac{dv}{dt} = A(v^2) + B(v) + C. \quad (4.11)$$

The A , B and C terms, respectively, represent drag, frictional and material strength phenomena. The relative magnitude of each term depends heavily on the nature of the medium through which the fragment is travelling. For the crowded space scenarios handled by the HIP code, these media are the ambient air and the crowd members, which, for simplicity in the

Figure 11. Pressure-specific impulse diagram.

current implementation, are considered to be formed of gelatin.

With the ballistic approach, the above equation is solved for a series of discrete time steps using the Runge–Kutta numerical method [27]. The size of the time step is adaptive such that finer values can be used when greater rates of trajectory change are encountered (for example, when a fragment travelling in air begins to penetrate a gelatin crowd member). Reasonable fragment flight predictions depend on proper characterization of the terms in equation (4.10). The requisite drag parameters, which dominate the behaviour of simple fragments in air, are well documented [28], including the differing behaviour observed when considering supersonic and subsonic conditions. Although *a priori* information existed concerning penetration into gelatin [29], for characterization within the HIP code a series of bespoke experiments were conducted (figure 16), which were used to calibrate equation (4.10).

The ballistic method has great flexibility when reproducing trajectory behaviour, as temporal discretization allows highly nonlinear phenomena to be represented. With reference to figure 17a, separate equations of motion, in the vertical and horizontal direction, can be concurrently solved to handle gravitational effects. Also with appropriate characterization, the more complex in flight phenomena associated with irregularly shaped natural fragmentation from VBIEDs can be tackled. As the method carries a considerable computational tariff, particularly when dealing with the potentially thousands of fragments acting against thousands of crowd members, the HIP code also incorporates the far less computationally intensive line-of-sight method.

Here, as indicated by the plan and elevation views in figure 17b, the fragments leaving the explosive source continue to be projected along their original throw-out vector until external forces developed in the air and within the crowd members bring them to rest. Although gravitational effects cannot readily be included in such an approach, the perforation of two crowd members, for example, can be handled with just a four-stage calculation ($O-A$, $A-B$, $B-C$, $C-D$) before the fragment is brought to rest. To ensure representative behaviour, the challenge is to develop equations that properly capture the velocity reduction during each stage.

Figure 12. Blast parameter maps and interpolation method. (a) Three-dimensional representation; (b) peak overpressure map for interpolation.

Although other methods exist [30], it was determined that for the purposes of the HIP code calculations, a more appropriate degree of generality would be achieved by using an equation of the following form to relate the initial velocity, v , to the distance travelled in the propagation medium, d :

$$d = C_1 \left(\frac{(v - C_2)}{C_3} \right)^{C_4}. \quad (4.12)$$

In terms of fragment impact of gelatin, a very powerful relationship was developed [31] in which variables C_3 and C_4 were used to define the overall shape of the penetration function while variable C_2 defined the minimum impact velocity to initially penetrate the gelatin, as a function of the fragments presented area, A , and mass, m . Variable C_1 was used to determine the depth penetrated for a given impact velocity as a function of target density, ρ , presented area, fragment mass, fragment drag coefficient, C_d and an empirical target material

Figure 13. Numerical modelling of fragmentation throw-out and penetration. (a) Idealized weapon configuration; (b) coupled finite element-hydrocode model used to determine fragment throw-out; (c) lagrange/particle simulation of PBIED fragments penetrating object.

Figure 14. Experiment to study fragment throw-out from typical PBIED. (a) PBIED detonated against witness screen (water container used to replicate the effect of human carrier); (b) two radiographic images showing evolving throw-out pattern after initiation of the PBIED (b: courtesy of Institute of Saint Louis, FRA, GER).

Figure 15. Adaptation of Gurney analysis to handle fragment throw-out.

Figure 16. Experimental assessment of fragment penetration into gelatin cylinder.

strength constant (set to 0.011). This resulted in the following relationship:

$$d = \frac{0.011 \times 2 \times m^{0.95}}{\rho A C_d} \left(\frac{V - ((80 \times A)/m^{1.3})}{400} \right)^{0.55} \quad (4.13)$$

Through appropriate selection of the variable magnitudes, the US Army Core [31] also demonstrated

that the expression was of sufficient generality to model penetrations of various fragmentation shapes and successfully validated the output obtained from experiment and other, higher fidelity analytical prediction approaches.

If the fragment has sufficient velocity to pass through the medium, equation (4.11) can be rewritten to calculate the residual velocity upon exit, which is then used as the initial velocity for the adjacent medium.

Figure 17. Trajectory calculations conducted within the HIP code. (a) Line-of-sight versus ballistic method; (b) trajectory and velocity profile associated with the line-of-sight method.

(iii) Validation

Extensive validation of the algorithms that underpin the HIP code is vital to attain confidence in its usefulness. Significant efforts are being made to use the limited anecdotal data attained from the 7/7 events [2] and previous terrorist incidents [1] for validation purposes, but there is significant degree of uncertainty concerning the exact nature of the PBIED and the exact location of the affected crowd members. To complement this anecdotal validation process, a number of 'engineering' experiments have been conducted to assess the veracity of the fragmentation aspect of the HIP code. A series of trials have been conducted using a typical fragmenting PBIED (strapped to a water cylinder to represent the carrier as in figure 14) to load a population of surrogate humans represented by stacked water containers (figure 18).

In each case, the surrogates were placed in predetermined, 'random' positions on a 5×5 m grid. For each test, 25 surrogates were used, giving a population density of one person per square metre. After each test, the number of penetrations into (and out of) each surrogate were counted and compared with the line-of-sight HIP code output, an example of which is shown in figure 19. Considering the inherent variability of the device and the relatively simple treatment of fragmentation trajectory simulation within the HIP code, there was an excellent qualitative and good quantitative correlation.

(iv) Transposition to human injury

As discussed, various methods exist that can be used to calculate injuries from high velocity projectiles [31]. These include:

- depth of penetration (DOP) in a person [32];
- DOP in individual organs of a person [33];
- wound volume or wound path diameter in a person [34];
- wound volume or wound path diameter in individual organs of a person [33];
- total energy of the projectile [35]:
 - (i) Total energy of the projectile deposited in the person.
 - (ii) Total energy of the projectile deposited in individual organs of a person.

Although it is intended that a more sophisticated approach be implemented, currently the injury in the HIP code is based purely on DOP. As a further simplification and as shown in figures 4a and 17, this is undertaken as a probabilistic assessment at the resolution of a given body region, rather than at discrete organs level.

In line with figure 2 (step 2), the penetration depth into a particular body region is assigned an AIS score from 0 to 6.

Figure 18. Surrogate field testing used to validate the HIP code event (courtesy of the Metropolitan Police Service). (a) Pre-test view; (b) post-test view; (c) still from high-speed video of event.

Figure 19. Comparison of the HIP code and surrogate field test. (a) Experiment; (b) the HIP code.

5. GRAPHICAL USER INTERFACE DEVELOPMENT

(a) Requirement

The previous sections have presented quick-running algorithms suitable for predicting the weapon and injury effects sustained owing to IED attack within a crowded environment. These were originally implemented within a *Microsoft EXCEL* spreadsheet (using the Visual Basic computer language), but it was soon realized that, in order to allow the user to readily generate scenarios and interrogate the output after running the HIP code, a bespoke GUI had to

be generated. This was done using the C++ computer language operating on the 'QT' platform [35].

(b) Key forms of output

With reference to figure 2, output is generated in two general forms:

- three-dimensional 'injury map' images from each calculation cycle;
- graphs from the cumulative (multi-cycle) output from the HIP code.

Figure 20. Single cycle output from the HIP code; single cycle prediction plotting 'triage state' for an IED attack within an open environment (trajectory lines of fragments are shown in black).

Figure 21. Typical cumulative output from the HIP code. Cumulative plot indicating the statistical spread of blast injury: the output here is from 1000 cycles arranged in ascending order.

As shown in figure 20, the injury maps, which can be manipulated in three dimensions, show the position of crowd members (represented with cylinders) with a particular injury type or level. The maps are colour-coded to indicate the severity of the injury. Blast injuries (§4a(iii)) and fragmentation injuries (§4b(iv)) (along with fragment trajectory lines) can be shown in isolation, or the distribution of the combined injury sustained by crowd members in the form of a triage state can also be displayed (§2). The GUI contains other viewing windows that present the overall injury information for the calculation cycle, and by 'clicking' each crowd member the individual injuries can be scrutinized.

Figure 21 shows the cumulative injury for all calculation cycles in graphical form. The number of injuries and triage details from each calculation cycle are

brought together and placed in ascending order, such that further statistical analysis can be undertaken to determine the likelihood of a particular distribution of casualties within a given environment owing to initiation of a particular PBIED threat.

The HIP code can also plot human injuries as a function of population density so that favourable crowd distributions for a given threat can be determined.

6. FUTURE CODE DEVELOPMENT

The HIP code is now widely used for planning, security and survivability analysis. The users have provided recommendations concerning the adaptation of the GUI to better reflect their operational requirements and, in addition, have requested additional

functionality to be implemented within the code. Dstl also have aspirations to improve the fidelity of the code, in order to represent the more comprehensive underpinning weapon effects and human injury phenomena without incurring prohibitively long simulation times. In terms of the enhancement of blast prediction, algorithms are currently under development to cater for the effect of obstructions within the flow field as described in §4a(i). A method of predicting the parameters associated with the thermal output of the device is also being investigated so that burn-related injuries can also be addressed. Although not discussed in this document, an approach for predicting the complex fragmentation output from VBIEDs is being generated, together with a similar method for predicting the secondary fragmentation produced when blast waves interact with ‘deformable’ or ‘frangible’ building components such as glazing (§3a).

It is recognized that the injury algorithms used with in the HIP code are relatively simple and there is a strong intention within Dstl to work with internal and external experts in the field to represent these responses more comprehensively. In addition to the surrogate testing procedures (figures 18 and 20), the anecdotal data from 7/7 will also be used for the purpose of code validation, where appropriate permission is granted.

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ENDNOTES

¹In figure 5a, t_a is the arrival time of the blast wave and t_d is the positive phase duration of the pulse.

²The term ‘overpressure’ indicates the value of pressure above the ambient atmospheric pressure (generally approx. 1 bar). ‘Incident’ or ‘static’ quantities are those developed in the free field in the absence of any flow-field obstruction.

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