Advances in Representing the Degradative Effects of Chemical and Biological Weapons in Conflict

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Abstract
Conventional simulation models and war-gaming tools make little or no allowance for the representation of chemical and biological warfare (CBW). It is generally accepted that the wearing of Integrated Protective Equipment (IPE) to protect against CBW leads to a degradation in the performance of troops. However, the level of degradation is complex, hard to quantify and is as much dominated by physiological and psychological factors as physical impedance factors. CBD Porton Down are attempting to develop simple degradation models which can be inserted into low level combat models to assess levels of degradation. A physiological model has been produced, based on the heat transfer between the man and the environment and the likely solar heat load incident upon a man at different times in different global locations. The model uses ideas and empirical data from more complex physiological models but is simple enough for inclusion in simulation models. The potential applications of the model are described and the difference in likely physiological degradation at different global locations is highlighted. The non-physiological contributions to degradation are mentioned and approaches to include their effects in models are discussed.

Introduction

The wearing of partial or full NBC protective clothing can lead to a degradation of human performance, resulting in tasks taking longer than would normally be the case. The degradation may arise from a number of contributory factors: physical, psychological, physiological and communicative. Presently, none of these factors are well represented within conventional simulation and wargaming tools. In the few models which possess any representation, a simple degradation factor is applied to all tasks, usually between 1.0 and 2.0. This factor cannot even start to represent the high complexities involved in degradation modelling, e.g. the wearing of a respirator virtually precludes the accurate use of some infantry weapons and the wearing of Integrated Protective Equipment (IPE) will cause severe chaos to high level command and control in hot weather. It is the aim of the analysts at DERA Porton Down to provide a degradation model valid for all common military tasks at all levels in all weather conditions. However, due to the limited trials and historical analysis data available this goal is a long way from being achieved[1]. The first element that has been tackled is the physiological degradation, the additional time that a task will take due to wearing IPE in unfavourable climatic conditions. In hot or humid weather this form of

[1] Currently all historical data available is from World War 1, which was fought in trenches with low mobility requirements, basic C^3I and in temperate conditions.

degradation is likely to dominate any impedance factors associated with the equipment.

Previous representations of physiological degradation

Previously physiological degradation estimates have been based upon work/rest cycles, a ratio of the time one could spend working without suffering heat exhaustion to the time one had to rest to recover. This ratio was predicted by a commander's guide sliderule developed from the guidance given in NATO AXP8. The parameters for the sliderule's calculation are based upon the IPE dress state, ambient temperature and level of intensity of work being undertaken. However other meteorological conditions such as humidity, windspeed and solar radiation are not taken into account. The sliderule was developed as a guide when conducting exercises in Northen European climates so average values for these parameters could be assumed. Present day operations can be conducted in any part of the world, therefore to provide an accurate representation within scenarios, different global locations need to be considered. Consequently for simulation and modelling purposes it was decided a model giving a better representation of physiological degradation, which included humidity, windspeed and solar radiation was needed.

Modelling approach taken

There is insufficient trials data available upon the performance levels people can sustain when wearing IPE to form the basis for a model. (It would be unacceptable to experiment with the duration people could undertake tasks before they became heat casualties). Human responses to heat stress are also likely to be distributed log-normally and a mean would be hard to obtain from a limited data set. It was decided that the human element should be taken out of the model and instead the physical limitations of the situation would determine the degradation level. Instead of the human psycho/physiological response to wearing IPE determining the extra duration that a task should take, the maximum physical ability of a man to maintain thermodynamic balance given his surroundings would determine the extra duration (this assumes that a man is covered in sweat and consequently maintains hydration). It was necessary that the model did not give a prescriptive degradation factor for a task, but could represent the difference in degradation that would occur in different locations at different times of the day and in different weather conditions.

A number of physiological models exist or are being developed which use physical heat transfer equations to evaluate the heat gain/loss to/from the body through clothing, these are then used to calculate the internal heat transfer in the body, either numerically or empirically, which facilitates an estimate of the core and skin temperatures in the body. These models provide a good estimate of work/rest cycles to undertake if the surrounding climate can be specified, e.g. the temperature, humidity, wind speed and surrounding radiation field. However, these models are computationally expensive and it would be unrealistic to include them in a simulation model when the environmental parameters are continually changing. The models also use the surrounding radiation field as an input and give no indication of how this might relate to the natural environment.

To produce a simulation model which includes physiological degradation, it is only necessary to evaluate the heat build-up within an individual. The transfer of heat by conduction, convection and evaporation can be determined physically and is represented in the model in a similar manner to the existing physiological models. However, the conventional dry heat transfer terms only represent the radiative heat transfer between the man and a characteristic ambient temperature. In the open-air the sun has a dominant effect upon the surrounding radiative field, adding an additional directional heat load. It was thought necessary to provide the most likely representation of the solar radiation at different times of the day, at different times of the year and at different locations, and to include its effect within the heat balance equations. Although the contribution to the overall heat gain from solar radiation is not dominant, it is often the sensitive factor which produces the additional heat gain, leading to heat exhaustion. (It often feels pleasant on a hot cloudy day but it becomes immediately uncomfortable, once the clouds are penetrated.)

Method for calculating heat production within the body

Heat is produced within the body all the time, at a rate of 105 Watts when resting, increasing in comparison to the exertion level required to conduct the task. For each task undertaken a representative average work rate can be associated with it. The net metabolic heat produced is the heat produced within the body minus the energy potential overcome to complete the task. For the body temperature to remain in thermal equilibrium this heat gain has to be dissipated to the environment. The methods of heat exchange between the body are conduction, convection, evaporation and radiation, hence:

Heat storage = Heat produced by metabolism ± Dry heat exchange - Heat lost by evaporation + Solar heat load.

The dry heat exchange represents the heat transfer due to conduction, convection and radiation between the skin and the environment at its characteristic ambient temperature (this does not include the additional heat load generated by solar radiation). For heat to be lost from the body it needs to be transferred through the clothing and through the surrounding air boundary layer. The total insulation, I_T, provided by the clothing and air layer has been determined experimentally at a number of different windspeeds for the various IPE dress states, by personnel at CHS. From which, a functional relationship has been used to relate the windspeed and the insulation provided. The subjects within the physiological model are assumed to have an average body surface area of 1.8 m^2 and an evaporative sweat rate lower than that required to keep their skin temperature in the comfortable range, but are not on the verge of becoming heat casualties. Consequently, a characteristic skin temperature of 36°C has been applied in the model. The following equation has been used in the model to represent the dry heat exchange:

$$H_s = 1.8 \times \frac{1}{I_T}(36 - T_a)$$

H_s = Heat loss from body to atmosphere
I_T = Total clothing insulation

T_a = Surrounding ambient temperature.

The main mechanism for heat loss from the body is through heat loss due to the evaporation of sweat. The rate of heat loss is determined by the difference in the saturated vapour pressure of water at skin temperature and the vapour pressure of the surrounding air. The evaporative capacity is also dependent upon the material properties of the clothing; it is inversely proportional to the insulation factor, I_T, and proportional to the permeability of the clothing, I_m. I_m has also been determined experimentally at a number of different windspeeds for the various IPE dress states. The rate of maximum evaporative heat loss that is physically possible is used in the model, this is:

$$E_{\max} = LR \times \frac{I_m}{I_t} \times 1.8 \times \left(P_{sk} - \frac{RH}{100} P_a \right)$$

E_{max} = Maximum evaporative capacity

LR = Lewis relation = 2.2 °C/Torr

(Equivalent temperature difference per unit difference of pressure)

I_m/I_t = Evaporative capacity of material (Water vapour permeability / Insulation)

P_{sk} = Saturated vapour pressure at the skin

= 44.6 Torr, for a skin temperature of 36 °C

RH = Relative Humidity (%)

P_a = Saturated vapour pressure at atmospheric temperature

Contribution to heat production from solar radiation

The solar heat load model has two important and distinct parts: the intensity and direction of the solar radiation surrounding a man and the proportion of that power which is absorbed by the body.

The radiation intensity surrounding a man depends upon the time of day, time of year, location, terrain, altitude, shade and cloud cover. The incident radiation is a combination of the direct radiation from the sun, the diffuse radiation from collision with atmospheric molecules and the reflected radiation from the ground. On a clear day the intensity of the direct radiation depends on the angle of the sun from the ground, as this detemines the air mass the rays must pass through. This parameter can be calculated from the time of day, time of year and location. The direct intensity is reduced exponentially with the air mass. The diffuse radiation and its horizontal component can also be determined as a function of the solar angle. The type of the ground determines the amount of radiation which is absorbed and hence the quantity of reflected radiation. Modifiers are inserted into the code to reduce the radiation intensity when it is cloudy and when there is partial shade.

A specification of the intensity and direction of the three components of radiation allows the proportion of radiation incident upon a man to be calculated. The quantity of radiation incident upon a man depends upon his posture and the directionality of the radiation. In the model it was assumed that the man was standing. Expressions were used to determine the surface area of a man: exposed to the direct radiation, facing the horizon, and facing the sky. This surface area is modified by the additional bulk added by the clothing worn. This determines the intensity of radiation deposited on the clothing. The proportion of this energy that is transferred to the body is given by the emissivity of the clothing and the efficiency factor. The efficiency factor is the ratio of the insulation afforded by the surrounding air boundary layer to the insulation afforded by the clothing. Hence, the following expression was used to model the rate of solar energy absorbed by the body:

$$E = \varepsilon U\left[f_a A_p I \ + 1.8 \times f_{acl}\left(\gamma_z D_h + \gamma_h D_n / 2 + \gamma_h R_h / 2\right)\right]$$

ε	= emissivity of clothing (assumed to be equal to 0.8)
U	= efficiency factor
I	= direct radiation intensity normal to the incident rays
D_n	= diffuse radiation intensity normal to the direct incident rays
D_h	= diffuse radiation intensity parallel to ground
R_h	= reflected radiation intensity parallel to ground
f_a	= ratio of presented surface area to the direct rays when clothed compared to naked
f_{acl}	= ratio of overall surface area when clothed compared to naked
A_p	= naked surface area presented to direct radiation
γ_z	= Proportion of body surface area facing zenith
γ_h	= Proportion of body surface area facing horizon

Use of the model

The model has been designed so that when: environmental parameters, time, location, metabolic rate, and usual task duration are specified, the model will output the minimum actual time required to do the task in various NBC dress states. This time makes no account of the psychological or impedance degradation that the subject will also suffer. The model can also be linked with representative diurnal meteorological data from the area that is being considered. This provides the likely degradation times that can be used in simulations within Studies, Assumptions Group (SAG) scenarios.

When representative temperate conditions during summer days in Northern Europe were used in the model, it provided similar guidance to the commander's guide

sliderule and to the advice contained in military Standard Operating Procedures (SOPs). However, when conditions were entered which represented extreme hot dry, wet hot, or humid hot coastal conditions the degradation was much more severe[2]. In some situations heat could not be lost even when resting. It is likely that future operations will be conducted in these types of areas. These levels of severe degradation need to be encapsulated within studies to show the likely problems if CB operations are conducted in a similar manner to conventional operations. To provide support to the armed forces survive to operate policy it is essential that simulations are carried out which represent whole operations. In some operations there is enough time to rest between tasks to counteract physiological degradation, however, it may be necessary to re-schedule the order of tasks, provide cooling facilities, conduct more tasks when it is cooler or make allowances for the additional time the operation will take. The model will also give an indication of the level of water required to keep people hydrated, based upon empirical equations used in a US model. The quantity is quite often huge, consequently the feasibility of the logistic support that an operation may require must also be considered.

The military are interested in finding out if operations are sustainable in a CB environment, an example of a study currently in progress is the feasibility of conducting amphibious operations in a CB environment. Traditionally, this type of study has concentrated on the likely casualties that may be suffered and simple degradation encumbrance factors. However, it is now possible to examine the increased degradation that could be suffered in some of the hotter scenarios. It will also be used in future studies to look at the impact of artillery fire when the operators are wearing IPE. This gives the ideal opportunity to optimise the highest achievable firing patterns when in hot conditions wearing IPE.

The Complete Degradation Picture.

The aim is to have a full representation of degradation. Attempts to include performance degradation factors into OA studies have mostly failed. It was previously thought that one model, based upon empirical results, could be created encompassing, physical impedance, psychological effects and command and control degradation. However, the scarcity and unsuitability of the performance data available made this an almost impossible task. It was decided the way ahead would concentrate on looking at each type of degradation separately, with a view to studying their non-linear interaction at a later date. A task is on-going to collect all available international trials data, which measure the additional duration of common tasks while wearing IPE. This should facilitate the development of an empirical model based on the abilities and skills required to complete the task. Command and control representations are being examined at a high level. Human factors personnel who have been involved in trials which examine the effects of IPE on C^3I in brigade headquarters will provide advice of how to represent these factors in a model. More speculatively, it is hoped that a representation of psychological degradation can be obtained by using the performance shaping factors for 'soft' human effects within a fuzzy logic model based on expert

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[2] This is especially true in conditions which have very high humidity. The high humidity prohibits heat loss by evaporation and is likely to lead to dehydration, although this effect is not accounted for in the model.

opinion. Eventually, it is intended that these effects, along with physiological degradation and CB casualties, can be implemented into a unit combat model to provide a full CB representation in the model.