



Office of the
Deputy Prime Minister

Creating sustainable communities

*Operational Physiological Capabilities
of Firefighters: Literature Review and
Research Recommendations*



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Deputy Prime Minister

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Operational Physiological Capabilities of Firefighters: Literature Review and Research Recommendations

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Optimal Performance Limited
on behalf of the
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The findings and recommendations in this report are those of the consultant authors and do not necessarily represent the views or proposed policies of the Office of the Deputy Prime Minister.

Following the reorganisation of the government in May 2002, the responsibilities of the former Department of the Environment, Transport and the Regions (DETR) and latterly Department for Transport, Local Government and the Regions (DTLR) in this area were transferred to the Office of the Deputy Prime Minister.

Office of the Deputy Prime Minister
Eland House
Bressenden Place
London SW1E 5DU
Tel: 020 7944 4400
Website: www.odpm.gov.uk

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Executive Summary

The Project Team were commissioned by the Fire Research Division of the Office of the Deputy Prime Minister to review the published literature on the physiological capability of firefighters to perform their wide-ranging operational duties, and to provide recommendations for further research to fill the knowledge gaps.

The drivers for this project emanated from two firefighter special interest groups – the Building Disaster Assessment Group (BDAG) and the New Dimensions Group (NDG). The intended outcomes for this review and any subsequent research are to:

- Reduce risk from work activity of firefighters
- Improve guidance for firefighter operational practices and training
- Improve planned and dynamic risk assessment
- Modify procedures for building design, approval and use
- Elicit improvements to the Building Regulations.

The first phase of the project identified, obtained, analysed, interpreted and reviewed all relevant published literature in a systematic, comprehensive and unbiased manner. Over 1300 references were identified during this phase from both fire-related and other sources. Following several sifting processes, hard copies of the full reports of the remaining references were obtained and the relevant subject matter expert undertook a review of each paper. The final reference list included over 170 journal articles and technical reports.

Modern firefighters constitute a highly skilled and professional service, with a wealth of experience and expertise in dealing with a wide range of incidents and hazardous situations. Firefighters and their Fire Officers have an understanding of what is feasible and safe, largely based on their experience. However, the role and function of the Fire Service is changing - the role is changing (to respond to terrorist threats); buildings and materials are changing (enabling taller and deeper buildings); clothing and equipment is changing (prolonging working durations); and personnel are changing (with an increasing number of women and ethnic minority firefighters).

Central to all these objectives is the need to know how long work can be sustained under a variety of operational conditions before performance deteriorates significantly. 'Performance' encompasses physical performance such as loss of strength, slowing of movement and loss of manual dexterity, but also impaired decision-making and risk assessment. In addition, consideration must be given to the possibility that the physical and environmental demands may present a risk to the health or safety of operational staff.

This review starts by summarising the legislative framework for the fire safety of buildings, their occupants and to the Fire Service provided by the DoE's Design Principles of Fire Safety (1996) and the DETR's Building Regulations (1991). While these documents cover most aspects of new buildings design and materials structure from the point of view of fire safety, the level of detail from a Human Factors

perspective is severely wanting, raising questions as to their appropriateness and relevance.

The roles and responsibilities of firefighters in the UK are broad and ill-defined from a Human Factors perspective. Although key firefighting tasks are reported widely, there is no consensus on duration, intensity, frequency, rest periods etc. – details that are crucial to determining workloads and their acceptability. The draft Worst Case Planning Scenarios (Thomas & Johnson, 2000) and the development of new Point of Entry Selection Tests (Rayson & Wilkinson, 2002) provide a start in the identification of a range of scenarios and tasks that encapsulate the requirements of firefighters. To date there has been a lack of consensus over operational requirements, both internationally and nationally, poor standardisation of task performance, and the lack of control over work rate. Genuine methodological difficulties in assessing the physiological and biomechanical demands of firefighting have further hampered attempts at quantifying these requirements.

Within safety constraints, firefighting tasks are often completed as quickly as possible to lessen the impact of fire-related damage to people and property. Most firefighting operational tasks are team-based and self-paced, usually performed at the highest sustainable pace tolerable by the group. This is largely dependant on their individual fitness - the work rate will be determined and limited largely by the least fit member of the team. Aerobic fitness, muscle strength and endurance, and body composition are known to be major determinants of firefighter performance and yet they are not formally assessed in job incumbents.

A number of studies from around the world, including some from the UK, have reported firefighter fitness, but these studies have many limitations when applying their findings to address this project's objectives. The studies indicate that UK firefighters appear to have aerobic fitness levels that are very similar to the general population. Many seem overweight and some are reportedly morbidly obese. Lack of physical strength does not appear to be an issue for male firefighters, but may be for some female firefighters. While the physical demands of the job appear to be insufficient to enhance or maintain role-specific fitness levels, physical training programmes engender large improvements in fitness, suggesting that physical training offers a cost-effective method of enhancing performance and improving health. Smoking hampers firefighter's performance and is a major risk factor in a number of fatal medical conditions.

In general terms, it is clear that for operational firefighting 'more fitness is better', i.e. the fitter and healthier the workforce, the harder and quicker they will be able to work, the more efficient they will be, and the quicker they will recover. This is particularly true when working in demanding thermal environments, especially when wearing PPE including SCBA. The national fitness profile of the current UK firefighting population is currently unknown and it is not possible to confirm that the UK firefighter health and fitness profile meets the requirements of the normal or occasionally more extreme demands of firefighting.

Although exposures to normal climatic factors are well known, the temperatures to which firefighters are exposed during actual firefighting and related activities are largely unknown, though some guide can be provided from studies of training environments. There is widespread evidence that during firefighter training, some firefighters attain body temperatures in excess of what would be considered a safe level. While firefighters require a degree of thermal tolerance to perform safely and

effectively in operational conditions, at present, thermal tolerance is not formally assessed. It is doubtful whether firefighters ever become heat acclimatised, due to their infrequent exposure to heat. Various strategies can be used to minimise the risk of heat injury, but the extent to which these strategies are in use by firefighters and indeed are beneficial to firefighters, is largely unknown.

Wearing modern firefighters' PPE results in an increase in energy cost of approximately 25-30%. The use of lighter composite cylinders may provide some benefit, but there is no evidence to favour any one style or make of clothing or SCBA. The addition of a cooling system to the PPE, via for example, cooled water or a cooled air supply (air-line) can significantly reduce the level of thermal stress over the SCBA-based unit and prolong performance. While the ways in which PPE can influence heat stress and consequent strain are well established in general terms, the level of knowledge concerning that worn by firefighters is best described as 'patchy'. Despite advances in fabric technology, standard firefighter clothing is heavy, deliberately highly insulative, and of limited vapour permeability, three factors known to influence significantly the level of thermal strain.

Respiratory protection is essential to firefighters operating in hazardous environments. It seems that UK firefighters wear SCBA less than once per week, probably too infrequently to develop tolerance to SCBA wear. The SCBA entry control tables are based on work done in the 1950s and would appear to be inadequate and in need of review. The wearing of SCBA may also impact on respiratory function by compressing the thoracic cavity and increasing the load placed on the respiratory muscles.

While there are many anecdotal reports of the influence of other factors (such as smoke and mental state) on the strain associated with firefighting tasks little evidence has been identified. Mental factors such as uncertainty and apprehension will undoubtedly influence physiological parameters but whether this, in turn, will adversely affect task physical performance, is unclear.

This report culminates in the identification and prioritisation of 14 research projects into primary, secondary and tertiary priorities. The proposed projects encompass all elements of firefighter performance reviewed in the earlier sections, including the identification and quantification of key firefighter tasks, improvements to the knowledge base about firefighter fitness and work performance capability, and the identification and modulation of factors that limit performance. The top priority has been defined as the need to 'Quantify the Physiological Requirements of Firefighter Key Tasks and Identify the Limiting Factors to Performance'. Devoting resources to addressing this issue initially should result in both direct and indirect payoffs. As well as addressing the main issue implicit in the title, the project should start to address many of the subsequent research questions concerning the modulation of performance under PPE and SCBA. The Fire Service faces changing threats and opportunities that require a greater understanding of the human element within the system. With this increased knowledge safety can be enhanced and operational effectiveness optimised.

Glossary

CCBA	Closed-circuit Breathing Apparatus
CFBAC	Central Fire Brigades Advisory Council
CST	Chester Step Test – a sub-maximal effort field test of aerobic power
C-V	Cardio-vascular system
Def Stans	Ministry of Defence's (MoD) Human Factors for Designers of Equipment
DCOL	Dear Chief Officer Letter
F_C	Cardiac frequency (heart rate)
F_R	Respiratory frequency (breathing rate)
FSC	Fire Service College, Moreton-in-Marsh
FSRD	Fire Statistics and Research Division (formerly Fire Research & Development Group)
HSE	Health & Safety Executive
Lac	Lactate (lactic acid)
min	minutes
MSFT	MultiStage Fitness Test – a maximal effort field test of aerobic power
OCBA	Open-circuit Breathing Apparatus
PES	Point of Entry Selection
PPE	Personal Protective Equipment
ROPS	Response Options Planning Scenarios
RPE	Respiratory Protective Equipment
RPE _x	Ratings of Perceived Exertion
s	seconds
SCBA	Self-contained Breathing Apparatus
SD	Standard Deviation
WCPS	Worst Case Planning Scenarios
V_E	Minute ventilation
VO_2	Oxygen uptake
VO_{2max}	Maximal oxygen uptake

Contents

Executive Summary	3
Glossary	6
CHAPTER 1	
1. Introduction and Background	11
1.1 Participants	11
1.2 Building Regulations and Relevant British Standards	9
1.2.1 DoE: Design Principles of Fire Safety (1996 edition)	12
1.2.2 DETR Building Regulations 1991, Approved Document (2000 edition)	13
CHAPTER 2	
2. Methods and exclusion criteria	16
CHAPTER 3	
3. An Overview of the Key Tasks of UK Firefighters	19
3.1 Introduction	19
3.2 Firefighting Scenarios	20
3.3 Key Firefighting Elements	24
CHAPTER 4	
4. Modulating Influences on Firefighter Performance	25
4.1 Firefighter's Personal Protective Equipment (PPE)	25
4.1.1 Introduction	25
4.1.2 Effect of PPE on energy cost and consequent heat production	26
4.1.3 Thermal insulation of PPE	29
4.1.4 Effects of PPE on sweat evaporation	30
4.2 Thermal environments experienced by firefighters	31
4.2.1 Introduction	31
4.2.2 Heat Exposure	32
4.3 The Thermal Demands	36

4.3.1	Recorded body temperatures	36
4.3.2	Evaluative criteria	37
4.3.3	Body temperatures achieved by firefighters	37
4.4	Respiratory Demands	39
4.5	SCBA Entry Tables	40
4.6	The Respiratory Effects of SCBA Mass	41
4.7	Respiratory Factors and Firefighting Ensemble	43
4.7.1	General Physiological Effect	43
4.7.2	Lung Compliance	43
4.7.3	O ₂ Requirements of the Respiratory Muscles	43
4.7.4	Constant Positive Airways Pressure (CPAP)	44
4.7.5	Dead Space	44
4.7.6	Breathlessness (Dyspnoea) and SCBA wear.	45
4.8	Other factors	46

CHAPTER 5

5.	The Demands of Firefighting	48
5.1	Key Task Elements of Firefighting	48
5.1.1	Introduction	48
5.1.2	1970s	48
5.1.3	1980s	49
5.1.4	1990s	51
5.1.5	2000 and Onwards	58
5.2	Wildland Firefighting	60
5.3	Key Tasks of UK Firefighters	63
5.3.1	Practical Aptitude Tests for Fire Service recruits (David <i>et al.</i> , 1995)	64
5.3.2	The Physiological effects of wearing SCBA (Love <i>et al.</i> , 1996)	65
5.3.3	Lilleshall Report: A Fitness Standard for LFEPA (Brewer <i>et al.</i> , 1999).	66
5.3.4	The degree of Protection Afforded by Firefighters' Protective Clothing (Graveling <i>et al.</i> , 1999)	67
5.3.5	Physiological Monitoring of Firefighter Instructors (Eglin & Tipton, 2000)	69
5.3.6	The Physical Capabilities of Firefighter Instructors (Elgin and Tipton, 2002)	70

CHAPTER 6

6.	The Fitness and Physiological Requirements of Firefighters	72
6.1	Introduction	72
6.2	Background: General Health of Firefighters	72
6.3	Firefighter Fitness (International)	73
6.4	The Fitness of UK Firefighters	75
6.4.1	The Chelsea College Report: Scott <i>et al.</i> (1988)	75
6.4.2	The Institute of Occupational Medicine: Love <i>et al.</i> (1996)	76
6.4.3	The Robens Institute Report: David <i>et al.</i> (1997)	76
6.4.4	Lilleshall Report: A fitness Standard for London Firefighters: Brewer <i>et al.</i> (1999)	77
6.4.5	Assessment methods for predicting Maximal Oxygen Uptake for LFEPA: Evetts <i>et al.</i> (2000)	77
6.4.6	Fit for Duty? Seeking a healthier Fire Service: HMFSI (2000)	78
6.4.7	Point of Entry Selection Tests: Rayson & Wilkinson, for ODPM (2002)	78
6.5	Thermal tolerance	81
6.5.1	Introduction	81
6.5.2	Heat acclimatisation	81
6.5.3	Aids to tolerating the heat	82

CHAPTER 7

7.	Summary Findings	83
7.1	Preamble	83
7.2	Fire Safety Legislation	84
7.3	Firefighter Key Tasks	85
7.4	The Fitness and Physiological Requirements of Firefighters	86
7.5	Thermal Environments, Demands and Tolerance	87
7.6	Personal Protective Equipment	88
7.7	Respiratory Demands and Effects	89
7.8	Other Factors	89

CHAPTER 8

8.	Research Priorities	91
8.1	Primary Research Priorities	91

8.2	Secondary Research Priorities	92
8.3	Tertiary Research Priorities	94

CHAPTER 9

9.	References	96
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ANNEX

Annex A.	MOD Standards 1997 – Human Factors for Designers of Equipment	107
Annex B.	Manual Handling Regulations	110
Annex C.	The Physical Fitness of International Firefighters	111

CHAPTER 1

Introduction and Background

1.1 PARTICIPANTS

The Project Team, led by Optimal Performance, were commissioned by the Fire Statistics and Research Division (FSRD) of the Office of the Deputy Prime Minister (ODPM) to review the published literature on the physiological capability of firefighters to perform their wide-ranging operational duties, and to provide recommendations for further research to fill the knowledge gaps. The drivers for this project emanated from two firefighter special interest groups – the Building Disaster Assessment Group (BDAG) and the New Dimensions Group (NDG). The BDAG needs to establish safe working durations to undertake Search and Rescue (S&R), environmental tenability to undertake S&R, and distances that could be penetrated into a building to undertake S&R activities safely. Approved Document B in the Building Regulations, while setting out the building design guidance for making suitable provisions for firefighters, has little physiological basis to it. The NDG are mainly concerned with defining the physiological performance of firefighters operating in confined areas, particularly while wearing Personal Protective Equipment (PPE) where metabolically generated heat may be more significant than environmental heat in limiting operational performance.

This project had two objectives carried out over two phases:

- To conduct an international review of literature and report on the extent of knowledge concerning the operational physiological capability of firefighters
- To make recommendations, and prioritise those recommendations for cost-effective research that would significantly improve this knowledge.

Ultimately, the desired outcomes of this review and any follow-up research included:

- Reduced risks from work activity of firefighters
- Improved guidance for firefighter operational practices and training
- Improved planned and dynamic risk assessment
- Modified procedures for building design, approval and use
- Improvements to the Building Regulations.

1.2 BUILDING REGULATIONS AND RELEVANT BRITISH STANDARDS

This section presents a review of some of the relevant legislation and guidelines and comments on whether they are useful protective tools for UK firefighters. Information from the Department of Environment, Transport and the Regions (DETR) Building Regulations (1991) and the Department of the Environment (DoE) Design Principles of

Fire Safety (1996) are included here. Relevant British and other International Standards are covered in Section 4. The relevant section of the Ministry of Defence's (MoD) Human Factors for Designers of Equipment (so-called Def Stans) is outlined in Annex A. Although not deemed directly relevant (the military have exemptions from some Health and Safety legislation for example) the Def Stans do provide performance capability data for strength and stamina for another public service. A brief overview of the Health and Safety Executive's Manual Handling Regulations (1992) is provided in Annex B.

It is important to note that when referring to performance guidelines and standards of the type covered in this section and in Annexes A and B the difference between physical capabilities (i.e. an individual's maximum performance potential), population norms (that vary for different populations) and general safety guidelines (e.g. the HSE's Manual Handling Regulations) that are geared towards the prevention of acute and chronic injuries. These are three very different criteria that need to be clearly distinguished.

1.2.1 DoE: Design Principles of Fire Safety (1996 edition)¹

This document has 13 chapters that include the science of fire, the legislative framework, means of escape, internal and external fire spread and fire safety engineering. It offers a good review of the science of fire and includes an explanation of heat transfer, a formula to predict the temperature rise of an object, ignition temperature, the movement gases and its effect etc. Other chapters include a review of the legislative framework, a review of the fire certificate, and local and national legislation. Two relevant chapters of this document are reviewed and critiqued below.

Chapter 3: Means of escape in case of fire. This is an apparently comprehensive review of requirements for the means of escape, and includes details on the width and height of emergency exits, flow rates of people evacuating from a building, and places an important emphasis on other human factors related to the building's occupants such as:

- Awareness – are the occupants awake or asleep?
- Familiarity - are the occupants familiar with the building?
- Ability – can the occupants respond quickly to evacuation requirements?
(particularly relevant to care homes and hospitals)

Within the rather extensive pages of chapter 3 are numerous diagrams and figures that describe the design and placement of evacuation routes in various buildings. However, no mathematical models are presented to allow the emergency egress of occupants to be predicted in a quantitative way. Nor is any assessment test proposed that enables a building design to be verified for either emergency evacuation or firefighting access.

Chapter 7: Access and facilities for the Fire Service. This is the most relevant chapter to the current review and it includes sections on vehicular access to the building, location and number of firefighting shafts, fire mains and landing valves, firefighting lobbies and smoke venting of basements. In the subsection on vehicular access to the building, it suggests that access should limit the distance a firefighter has to carry equipment before he (sic) can commence firefighting activities. "If the distance is too great there would be delay and reduced effectiveness" (pg. 195). This suggests that

¹ Department of the Environment (1996), Design principles of fire safety, Bickerdike Allen Partners, London: HMSO, ISBN 0-11-753045X

some account was taken of the physiological elements of the firefighting role (e.g. fitness, strength and stamina) when these recommendations were set.

This chapter describes three different levels of provision for access of firefighting equipment. The first relates to small buildings below an undefined ‘stated height’, and the second applies to larger buildings but where an internal firefighting lift is not needed. For these two levels of provision, internal mains water and other internal firefighting facilities are not required and access for firefighting vehicles needs to be from an access road close to the facade. The third level relates to all other buildings (e.g. high-rise buildings) where firefighting facilities are required. For this level of provision there should be access for a pumping appliance to within a limited distance of each fire main connecting point, and these access points should be readily visible. Figure 68 offers simple line drawings for vehicular access for each of these levels of provision (pg. 196).

An interesting example of the lack of adequate detail provided in this document is seen in the section in chapter 7 on “Location and number of firefighting shafts”. It states “the hose length criterion alone could be considered as sufficient to provide for a satisfactory number of shafts, particularly since it is based on a practical performance limit, rather than an arbitrary area limit” (pg. 197-198). The actual performance limits are not presented. Whether the ‘performance limit’ in question is that of the range and effective function of the equipment, or of the performance of the firefighter, is not evident. Clearly, the effective performance of a firefighter is dependent on a number of factors, including the firefighting equipment used, the ambient conditions, the physical cost of the PPE worn and, of course the firefighter’s individual health and fitness profile.

In summary, while chapter 7 offers a superficial indication of the requirements of access for firefighting vehicles and personnel, it offers little in the way of specific quantifiable detail. It offers only the briefest description of the access points for firefighting vehicles to each of the stated levels of provision, and it uses phrases such as buildings “that are below a stated height’ and “a given percentage of the building perimeter should be accessible”, yet it does not offer either the dimensions or any specific information against which these standards may be verified.

1.2.2 DETR Building Regulations 1991, Approved Document (2000 edition)³

In general this document covers all aspects of building regulations and is broken down into the following 5 parts:

- B1: Means of warning and escape
- B2: Internal fire spread (linings)
- B3: Internal fire spread (structure)
- B4: External fire spread
- B5: Access and facilities for the Fire Service.

The majority of the parts relates to building materials and other technical specifications specifically relevant to architects and builders and therefore falls outside the scope of

² The actual distance is not specified within this document.

³ DETR, The Building Regulations (1991), Fire Safety, Approved document B, 2000 Edition, ISBN 1-85113-1-2, UK

the present review. Parts B1 and B5 are of some interest as they cover aspects of escape from buildings and Fire Service access to the buildings.

Part B1 Section 4 - Design from horizontal escape - buildings other than dwellings, states that the principle for escape from a building is that “any person confronted by an outbreak of fire within a building can turn away from it and make a safe escape” (pg. 35). To prevent occupants from being trapped by fire or smoke there should be alternative escape routes from all parts of the building except when the buildings are of limited size and occupancy (60 persons). Table 3 on page 36 of the document identifies the limitations on travel distance for an escape route. This is a considerable improvement on the information contained in the DoE document as it offers quantifiable data for assessment and validations purposes, although the data on which these recommendations are based are not fully referenced.

Part B1 Section 5 - Design from vertical escape - buildings other than dwellings, states that an important aspect of escape from a multi-storey building is the availability of adequately sized and protected escape stairs. This section includes recommendations on the number, design, position and size of escape stairs, and includes the requirement of simultaneous evacuation of all floors of the building. The section also includes worked examples with the formulae needed to calculate the safety staircase requirements. Table 7 for example (pg. 44) describes the capacity of a stairway for the basement and for simultaneous evacuation of the building, and presents data on the maximum number of people that can be serviced by stairs of various widths. The section also deals with the protection of and exits from stairways.

Part B5: General - Access and facilities for the Fire Service. To meet the requirement of this part of the document each new building requires a means of external access so that fire appliances can be brought near the building, sufficient means of access into the building for firefighting personnel, sufficient access to internal or external mains water supplies, and adequate means for venting heat and smoke from a basement fire. For small buildings not fitted with water mains, there should be adequate vehicle access for a pump appliance. The actual dimensions, position and spacing of these facilities for different building size, configuration and utility are specified in the document (e.g. Diagram 51: Provision of Firefighting Shafts, pg. 105). If these recommendations have been verified for their effectiveness from a Human Factors perspective, no reference has been cited in this document.

The size of the building will determine the facilities needed by the Fire Service. The larger and taller the building, the greater are the demands for access and internal firefighting services. Of specific interest to the current review is the need to provide facilities for internal firefighting where Fire Service personnel need to gain access to fires both below and above ground level.

Part B5 Section 17: Vehicle Access. Table 20 (pg. 101) presents data on Fire Service vehicle access to buildings not fitted with fire mains. The table includes data on the size of building in m², the percentage of the perimeter of the building that needs to be accessed by the Fire Service vehicle, the height of the top storey above ground, and the type of appliance in attendance.

Part B5 Section 18: Access to buildings for firefighting personnel. Of most relevance to the present review is the part of this section that deals with firefighter access to internal fires in high-rise buildings. The regulations suggest that in smaller buildings, the provisions for emergency egress provisions would provide firefighters with adequate access to fight internal fires in the shape of firefighting shafts.

High-rise buildings will be equipped with firefighting lifts, firefighting stairs and firefighting lobbies, “which are combined in a protected shaft known as the firefighting shaft” (DETR: 1991, Diagram 51, pg. 105). Special-case buildings are defined as those with upper storeys more than 18m above, and those with basement storeys more than 10m below the Fire Service vehicle access level. Other buildings having special purposes or occupancy will also fall under the special-cases regulations. Firefighting shafts may or may not require firefighting lifts, depending on the building status (see Diagram 51, pg. 105). The minimum number of firefighting shafts required in a building is also governed by the largest qualifying floor area (m²).

Of immense practical importance to the physical capacity of firefighters to perform their function is the requirement for each firefighting shaft to be located such that “every part of every storey, other than the Fire Service access level, is no more than 60m from the fire main outlet, measured on a route suitable for laying hose” (pg. 106). Given that some firefighting shafts are not required to include a firefighting lift, the firefighter may be required to climb a number of flights of stairs before reaching a fire floor. No physiological test data are provided in the document to support this requirement, nor to ensure that the average UK firefighter is capable of completing such a task during real fire emergencies.

Part B5 Section 19: Venting of heat and smoke from basements. Smoke and heat build-up can adversely affect the performance of firefighters when working in basements. Smoke outlets (or vents) can be either natural or mechanical and their effectiveness may be enhanced by firefighter intervention (by opening and closing of connecting doors). The physiological effects of smoke and heat on firefighters are dealt with in Section 4, but are an important consideration in the safe design of buildings.

CHAPTER 2

Methods and exclusion criteria

The first phase of the project identified, obtained, analysed, interpreted and reviewed all relevant published literature in a systematic, comprehensive and unbiased manner. As a first step, database searches were conducted. From this search, apparently relevant papers were identified primarily from fire-related research. However, the initial search was expanded to encompass other non-Fire Service industries including mine rescue, navy firefighting and other military sources. Industrial reports have also been included where it was felt that the quality of the material was suitable.

A summary of the output from the initial main searches conducted are presented in Table 2.1 together with an approximate count of the number of potentially relevant citations found during the initial search. During the on-line searches keywords were used to identify potentially relevant papers from information contained in the title and abstract. In total over 1300 references were identified during this phase.

Table 2.1. Initial literature search			
Site	Database	Location	Number of references
National Institute of Standards and Technology (NIST):	Buildings and Fire Research Laboratory (BFRL), Fire Research Information Services (FRIS)	On-line database	~600
National Library of Medicine (NLM):	The National Centre for Human Genome Research (NCIB)	Pubmed on-line database	~350
ODPM Fire Research & Development Group at Moreton-in-Marsh:	Fire Research Technical Reports and Memoranda 1971 - 2001	On-line database	~230
The Ministry of Defence (MoD)	Held by the Defence Science and Technology Laboratories (DSTL)	On-line database	~25
The literature resources of the members of the literature review team	Including those of Optimal Performance Ltd, Human Vertex, and the Institute of Occupational Medicine	Hard copy library	~200

Members of the Steering Group furnished various other documents for consideration. These documents included the DETR Building Regulations 1991 (Fire Safety), DoE

Design Principles for Fire Safety 1996, the Response Options Planning Scenarios from the Central Fire Brigades Advisory Council, and others.

Given the huge number of references in the published and unpublished literature that related in some part to the research questions in hand the review team had to make some clear decisions on the inclusion policy. Citations were removed from the list if they met any of the following criteria:

- the reference that had been printed in a publication that did not have a clear peer-review policy. Such periodicals included 'Fire', 'Firehouse', 'Fire Chief' and the 'American Fire Journal'
- the paper was not in English. No translation facility was available to the Review Team
- the paper did not contain any new data, unless it was itself a relevant review of the literature
- the paper comprised an epidemiological report and / or review of specific PPE and RPE ensembles
- the paper was a duplication of one already identified. Conducting a keyword search of different databases will inevitably elicit duplicates
- the material was deemed irrelevant to the tasking.

Emphasis was placed on those papers that presented original research or otherwise advanced scientific knowledge and understanding, rather than those that presented opinions or theories. Where possible, recent review papers were taken as the basis of knowledge and understanding at the time of preparation. However, some checks on source material were conducted to ensure that the review had been conducted in an adequately stringent and unbiased manner. After filtering out irrelevant citations, an archive file of all candidate paper titles identified was formed - this served as a core database. The articles for consideration including full citation and abstract (where available) were collated into discrete tables and assigned according to the following review topics (see separate CD-ROM: Reference Tables V4 Sections 1, 3, 5 and 6).

V.4 Section 1:	Background (n = 11)
V.4 Section 3:	Key Tasks (n = 36)
V.4 Section 5:	Energy Demands of firefighting, PPE including RPE (n = 116)
V.4 Section 6:	Firefighter fitness (n = 45).

The Reference Tables (V4) were distributed to members of the review team to identify first, which references would be included, and second, whether hard-copies of the full reports were already held or would be needed. The final list was collated into Reference Tables V5 (see separate CD-ROM).

V.5 Section 1:	Background (n = 10)
V.5 Section 3:	Key Tasks (n = 34)
V.5 Section 5:	Energy Demands of firefighting, PPE and RPE (n = 102)
V.5 Section 6:	Firefighter fitness (n = 44).

Hard copies of the full reports of the remaining references were obtained and the relevant subject matter expert undertook a thorough review of each paper. The final reference list included over 170 journal articles and technical reports.

The initial trawl for candidate review articles included technical reports from Canada and the US, including articles from the US National Institute of Science and Technology (NIST). A number of these papers were considered for inclusion in the review but were ultimately excluded. The specific exclusion criteria for these reports included the following: the technical or operational content fell outside the remit of the review; descriptions of firefighting technique were considered to be beyond the expertise of the review panel or not relevant to UK firefighting; and many of the most relevant reports had been rewritten for external consumption and published in the general literature.

The format of this review is as follows.

Section 3 - presents a top-level overview of the tasks undertaken by Fire Services in the UK.

Section 4 - presents a top-level discussion of the factors that modulate and influence the physical workload of firefighters, most notably the thermal environment and the effects of PPE (including RPE), but also the effects of smoke.

Section 5 - discusses the demands of firefighting, including identifying and quantifying key firefighting tasks.

Section 6 - reviews the literature on the fitness and physiological requirements of firefighters from the UK and overseas.

Section 7 - summarises what is and what is not known about the physiological capabilities of firefighters.

Section 8 - provides a priority listing of the research projects accompanied by a brief description of the objectives and estimated costs.

CHAPTER 3

An Overview of the Key Tasks of UK Firefighters

3.1 INTRODUCTION

Apart from a detailed report recently presented to the Central Fire Brigades Advisory Council (CFBAC see below), there has been little consensus on the key tasks required of UK firefighters. For the purposes of clarity, the present section provides a broad, top level description of general Firefighting Scenarios as presented to the CFBAC and under consideration by Fire Services, and will attempt to identify the key 'Task Elements' of the role that place a significant physiological or metabolic load on operational firefighter.

It is widely recognised that the tasks performed by UK firefighters are many and varied and go far beyond the 'simple' role of extinguishing fires. These tasks range from activities of moderately low intensity but extended duration (e.g. Road Traffic Accidents, extended Search and Rescue operations, chemical spillages, rail disasters), to high intensity operations of short duration either in the heat or the cold (e.g. hot rescues in full turn-out gear and SCBA).

The recent catastrophic events of 11th September 2001 in New York, and the role played by the Emergency Services during major disasters and terrorist events, has undergone serious scrutiny and review recently and the development of guidelines for the Fire Service response to these large-scale events is ongoing. The efficiency of Standard Operating Procedures and current safety equipment (including Personal Protective Equipment – PPE) during events of this type has been called into question. An overhaul of current Standard Operational Procedures and PPE is ongoing.

Jackson *et al.* (2002) prepared a review of a conference documenting the experience of emergency responders to recent large-scale catastrophic events (e.g. World Trade Centre, Pentagon, Oklahoma City). Delegates reported that where it was available, "PPE generally worked well for its designed purpose in the initial response." However, the equipment was not designed for continuous use; these incidents involved days and weeks of constant work after the initial rush to respond. Some responders reported that basic problems such as wet garments and blistered feet hampered their ability to work. PPE ensembles were not designed to protect against the multitude of hazards that were present at these events, which included rubble and debris, airborne fine particles, and other hazardous materials (e.g. ammonia, Freon, and battery acids).

Delegates reported that the PPE impeded their ability to work and in particular, the clothing was heavy and inflexible, the RPE hampered breathing and the eye protection failed to protect against the dust at the World Trade Centre. The consensus was that SCBA was grossly limited by both the weight and the short wear duration (~15-30 min). Participants also complained that the SCBA reduced their field of vision and the

faceplates fogged up continuously. There were also problems with recharging the air cylinders and the lack of availability of filters for air-purifying respirators. Many complaints were aired about the discomfort of wearing PPE for long periods; respirators were so uncomfortable and restrictive that they were often discarded after a short period.

Lack of standardisation of equipment meant that teams from different organisations were unable to interchange equipment which made it difficult to match responders with appropriate supplies until an effective logistics and stores operation had been set up (days after the initial event). The conference recommended that guidelines should be developed for the appropriate PPE ensembles for long-duration disaster responses. If appropriate equipment is unavailable it should be developed quickly and it should be applicable to other major disasters (e.g. earthquakes, tornadoes) as well as terrorist attacks.

Despite the complex and varied nature of firefighting in the UK it may still be possible to distil the fundamental physical tasks required of the working firefighter into a few 'key elements'. A list and description of candidate 'key elements' will be presented at the end of this section and a review of the literature evidence relating to the metabolic load imposed by these elements is presented in Section 5.

3.2 FIREFIGHTING SCENARIOS

Worst Case Planning Scenarios – Response Options Planning Scenarios

A document from the Fire Cover Review of the Pathfinder Trial has been presented in draft form to the Central Fire Brigades Advisory Council (CFBAC, Thomas & Johnson, 2000). Fire Service flexible response is based on the concept of the worst case planning scenarios (WCPS). The WCPS are designed to assist Fire Services in determining the resources required for a limited range of incidents: 'the worst cases selected by a brigade for whom Fire Cover is to be planned for a particular risk area' (Thomas & Johnson, 2000, pg. 1). The document offers a list and some details of the refined CFBAC planning scenarios – the so-called Response Options Planning Scenarios (ROPS).

Some 330 scenarios were originally identified and defined in a Fire Research Division (FRD) Research Report 6/1997, and these became the subject of 'more extensive validation'. This validation resulted in the production of a total of 35 possible ROPS of varying intensity and severity. The ROPS identify the resources required to deal with generic situations. Three 'Incident Group' and 3 'Lesser Group' scenarios are described in detail in the ROPS document (Version 1.1). A top-level description of the Group, Type and Scenario is presented in Table 3.1.

Table 3.1. Response Options Planning Scenarios (ROPS), Thomas & Johnson (2000)

<i>Incident Group</i>	<i>Incident Type</i>	<i>Scenario (C1-C35)</i>
Fire: Buildings	Multiple Occupancy (MO): High-rise MO: Low-rise MO: Basements	Various specific scenarios are described and include the number of casualties rescued, the number of Fire Service personnel involved, some of the key equipment used for each scenario.
Special Services: Casualty retrieval	Hazardous materials incident Heigh Lifts Lock-in Water	Equipment includes: • 13.5m ladder, • aerial appliance • LX foam branch • etc.
Special Services: Casualty trapped	Extrication from machinery and structures Rail transport accident (above ground) Road traffic accidents Ship accidents Small aircraft accident Small boat accident	
Lesser scenarios	FDR1: Property other than buildings FDR3: Secondary fires FDR3: Chimney fires	These are generic fire incidents.

Each scenario is described from a Fire Service operational perspective. For example, Scenario C1 deals with rescuing 2 to 4 casualties from an internal staircase in a building. It describes the duties expected of Fire Service personnel at the scene and the approximate duration of each task. A Gantt chart (a graphical representation of the time-lines), showing the progression of tasks is shown, complete with task duration, the personnel involved in each task and the equipment used.

Although the scenario description may be sufficient for operational planning purposes, this document offers little in the way of detailed measurement to help the physiologist determine the metabolic demands of each task. While each ROPS may present enough detail to help with task and equipment allocation, no information regarding the methods used to design or quantify the tasks is presented in the document. If this document is approved by the CFBAC and they wish to model the metabolic demands of the scenarios, each will have to be reviewed, reassessed and validated from a physiological and ergonomic perspective. Only then can quantifiable data be generated about the metabolic load placed on the working UK firefighter.

A model produced by the Australian Fire Authorities, the Fire Brigade Intervention Model (FBIM)⁴ seems to have influenced the design and selection of the ROPS. Like the ROPS, the FBIM offers scenarios and operational details on a number of firefighting tasks. The WCPS tasks involve tasks performed in teams of the following tasks: casualty evacuation; search & rescue; operating heavy machinery; propping and shoring work; and carrying heavy equipment over rubble etc. As with ROPS document, the model is discursive and descriptive and not what could be described as a ‘mathematical’ predictive model. Although the FBIM may be relevant and appropriate

⁴ Anon (1997), Australian Fire Authorities, Fire Brigade Intervention Model, Version 2.1.

from an operational perspective (for Australian Fire Services), again it presents no physiological data or methodology that would enable the design of a true physiological model to assess the metabolic demands of the tasks. The FBIM presents flowcharts and algorithms that support operational decision making processes and in parts the document reads like an adjunct to Building Regulations. Taking all of this into consideration, it could not be used in its present state to inform the research question: how fit do firefighters have to be to perform their duties?

Tasks Performed in Chemical Biological Radiological Protective Clothing (CBRN)

This document refers to key tasks that firefighters might be expected to perform in CBRN protective clothing.⁵

Rescue Area/Hot Zone

1. Extrication of trapped casualties
2. First Aid treatment of trapped casualties
3. Confined space searching and rescue
4. Operating heavy rescue equipment
5. Propping and shoring
6. Surface search over rubble pile
7. Carrying heavy equipment over rubble pile
8. Gaining access to partially collapsed structure
9. Lifting and carrying casualties in suitable carrying devices, downstairs, upstairs, over rubble pile, in confined spaces over a range of distances - parameters yet to be determined
10. Detection and monitoring of the nature of the environment
11. Rescue of emergency service personnel.

Warm Zone/Treatment Area

1. Management of crowds requiring treatment/advice/reassurance and decontamination
2. First Aid treatment of casualties
3. Decontamination of public in the shower structures using warm water
4. Bagging and tagging of clothing
5. Lifting and carrying non-ambulant casualties
6. Decontamination of firefighters
7. Detection and monitoring of hazard
8. Decontamination of equipment.

⁵ Anon (2002), Mass Decontamination & Search and Rescue, Functional Mapping (Draft document), ODPM.

It is recognised by the UK Fire Services that CBRN clothing should not be worn in fire situations if avoidable, due to the increased metabolic load it presents to the working firefighter (see Sections 4 & 5). These tasks will therefore tend to be carried out in ambient temperatures and humidity with the exception of public showering structures.

Integral to the development of Point of Entry Selection (PES) Standards, which Optimal Performance Ltd. is currently undertaking, is the endorsement by the Project Steering Group chaired by the ODPM of a number of single-person simulations of key tasks which all UK firefighters must be able to perform. It was reasoned that without some 'gold standard' measures of job performance it would be impossible to validate any PES tests. So considerable effort was put in to design and get endorsed by the Steering Group what are referred to in the project, as 'Output Tests' required of trained firefighters. These Output Tests are to be used as the basis for designing appropriate input (selection) tests and standards and for validation purposes. The Output Tests have been refined via a reiterative process of discussions with subject matter experts and stakeholders to the project and a series of workshops and field studies, which culminated in the pilot study conducted at the FSC in September 2002. The study involved 23 male and female, whole-time and retained firefighters from 8 different brigades (Rayson & Wilkinson, 2002).

The scenarios, together with a brief description of the key tasks contained within them are provided in Table 3.2. In addition to these 3 scenarios, manual dexterity elements from a Road Traffic Accident, and the claustrophobia elements of a confined space search were identified as key tasks. Minimum acceptable standards of performance on these key tasks remain to be defined. If these key tasks are adopted by the Fire Service as the underpinning for the future national PES Tests, they may also serve a useful purpose for either assessing incumbent firefighter's operational capabilities, and / or be used as the basis for defining minimum aerobic and anaerobic requirements of the firefighter role.

Table 3.2. Three draft single-person simulations for trained firefighters for the PES project, Rayson & Wilkinson (2002)	
<i>Task name</i>	<i>Description</i>
Rural Simulation	Hose drag (50 m) from drum on appliance Walk/jog back to appliance (50 m) 70 mm Hose carry (200 m) Walk/jog back to appliance (200 m) 70 mm Hose run (2 x 25 m) Walk/jog back to appliance (150 m) Suction hose and basket carry (200 m) Walk/jog back to appliance (200 m) Light portable pump carry (200 m)
Domestic (S&R) Simulation	Hose drag (30 m) 30 kg Casualty carry (30 m) Walk (10 m) Crawl (20 m) 55 kg Casualty drag (30 m)
Domestic (Salvage) Simulation	135 ladder lift 135 ladder extension 135 Ladder climb

3.3 KEY FIREFIGHTING ELEMENTS

Although, as described above, the work of UK Fire Service is varied, it is possible to define a number of key elements that are repeated time and again during real, simulated and training exercises.

Firefighters perform a large number of discreet activities both singly and in teams. These include walking, running, crawling, climbing, lifting, lowering, carrying and hammering. Standard Operating Procedures (SOP) involve activities such as ladder lifting and raising, hose running and connection, connecting soft-suction hoses to water-supplies, manipulating and operating 'light' portable pumps, and rescue and evacuation procedures. The WCPS (see above) involve casualty evacuations, search and rescue, operating heavy rescue equipment, propping and shoring buildings, and carrying equipment over uneven surfaces (rubble, ploughed fields, etc.).

The physical demands of *some* of these operations are currently under investigation elsewhere (e.g. the Point of Entry Selection project, see Section 6), and some literature studies have been identified that have assessed the metabolic requirements of some task elements. The tasks investigated in these studies are largely variations of the following:

- Ladder manipulations; carrying, raising and lowering
- Stair climbing
- Hose running, dragging and operating
- Casualty Search & Rescue
- Victim/dummy carry
- Hot house operations in PPE including SCBA
- Overhaul (damping down after firefighting operations)
- Pike/Halligan tool operations
- Chopping operations.

Section 5.1 describes the literature that has attempted to quantify the metabolic load of these tasks.

CHAPTER 4

Modulating Influences on Firefighter Performance

4.1 FIREFIGHTER'S PERSONAL PROTECTIVE EQUIPMENT (PPE)

4.1.1 Introduction

Firefighters use a wide range of PPE. The standard 'fire kit' of tunic and leggings, together with boots, gloves, helmet, fire hood, with or without open-circuit breathing apparatus (SCBA) is probably the most commonly worn. Other items, such as gas-tight suits and other forms of chemical protective clothing; negative pressure respirators; eye protection and hearing defenders, are also worn when required.

Any form of PPE, virtually by definition, imposes some form of barrier between the wearer and the environment. In the case of the fire kit described above, this barrier results in total coverage of the body surface. As a consequence, in addition to their designed or intended effects, many forms of PPE have additional, often undesirable, impacts on the wearer. For example, full-face respirator masks can impair communication (unless fitted with a communication device) or restrict the wearer's field of view; thick protective gloves can reduce manual dexterity; etc. In addition to the direct effects of individual items of PPE particular problems can occur where a number of items are worn simultaneously. Two or more items of PPE may be mutually incompatible. As a result, wearer discomfort may be increased or, in more serious instances, the protection provided by one or more item might be degraded. In the present context, the 'side-effect' of particular relevance is that of the potential impact of items of PPE on thermoregulation and the risk of heat strain.

Hanson (1999) briefly described the main avenues through which PPE influences the level of heat stress and consequent risk of heat strain. Describing the development of a draft British Standard, specifically addressing this influence, the author listed three main factors that will be explored below:

- Effect of PPE on metabolic heat production rate
- Thermal insulation of PPE
- Effect of PPE on evaporation of sweat.

Over the last 10-15 years there have been marked changes in the PPE used by Fire Services in the UK. In particular, the design and fabrics used in firefighting ensembles have changed radically, replacing the traditional wool melton with modern synthetic fabrics. As a result, there is a long history of research into the demands and loads placed on firefighters by their clothing and other items of PPE. This examination of the

literature will focus on those more recent studies where PPE relevant to the modern service is used.

4.1.2 Effect of PPE on energy cost and consequent heat production

Wearing PPE can increase the energy cost of work, by adding weight to the body and/or by restricting movement. Given the inherent energy efficiency of the body (maximum 20-25%; Rodahl, 1989) much of this energy is 'wasted' as heat and requires to be dissipated.

A standard measure of the energy cost of work is oxygen consumption. In relation to the PPE worn by firefighters, Graveling *et al.* (1999) showed that, compared to shorts and T-shirt, wearing standard fire kit (excluding SCBA) increased oxygen consumption by approximately 15-20% at the workload used (treadmill walking at a gradient of 7.5% at a speed of 5 km.hr⁻¹). There was a further increase of a similar magnitude with the addition of SCBA. This essentially replicated the earlier findings of Love *et al.* (1996) using broadly similar test protocols. Collectively, these two studies, both involving the use of modern clothing compliant with current standards, showed that there were few systematic differences between different garment ensembles from different clothing manufacturers including, for example, a so-called lightweight fabric. However, the work of Love and co-workers (op cit), focussing primarily on SCBA, did show some differences between different standard SCBA and between these and a set fitted with a lightweight cylinder. These were in addition to the differences demonstrated between all SCBA and the closed circuit BA (SEFA) used at the time by Kent Fire Brigade in relation to the work on the Channel Tunnel.

More recently, Baker *et al.* (2000), again working with UK firefighters, recorded a significant increase in oxygen consumption of about 10%, attributable to fire kit (no SCBA). There are a number of possible explanations for this difference from the work of Love *et al.* (10% vs 15-20%). Firstly, while Love *et al.* utilised treadmill walking at 5 km.hr⁻¹ at a 7.5% gradient, Baker and colleagues used a faster speed (7 km.hr⁻¹) with a level treadmill. Although the impact of weight carrying uphill on a treadmill is not easily calculated it is likely that this itself will have accounted for a substantial portion of the higher energy cost. A further factor might be that the lower values documented by Baker *et al.* may be attributable to differences between the two studies in the general level of fitness of the subjects used. The 72 firefighters involved in the study by Love *et al.* had a similar average level of fitness to that recommended at the time by the Home Office (Home Office, 1988). The average fitness, measured as a predicted maximum oxygen uptake, was 46.4 ml.kg⁻¹min⁻¹, compared to the recommended level of 45 ml.kg⁻¹min⁻¹. In contrast, the 18 firefighters studied by Baker *et al.* were considerably fitter with a mean predicted maximum oxygen uptake of 61.6 ml.kg⁻¹min⁻¹.

Using various forms of US Fire Department fire kit Malley *et al.* (1999) recorded only slight differences in peak energy cost when wearing ensembles designated as 'traditional' 'modern' and 'modified modern' clothing although there were some differences in the rate of change of oxygen consumption over the exercise. From the written descriptions provided, all three forms of clothing were not markedly dissimilar to current UK Fire Service ensembles or to those tested by Graveling *et al.* (op cit). Modifying the uniform consisted of changes to the clothing worn underneath the fire kit, replacing the shirt and trousers normally worn, with a short-sleeved T-shirt and shorts.

In another UK-based study, Sykes (1993) referred to the combined effects of SCBA and full fire kit as increasing energy expenditure by approximately 33%, very close to the figures reported by Love *et al.* (op cit) and Graveling *et al.* (op cit). The author reported the results of a small-scale study in which seven firefighters were tested using cylinders of various weights. Compared to a then standard steel cylinder (12.5 kg charged), using a 6.5 kg composite cylinder resulted in a significant (19%) reduction in oxygen consumption. Curiously however, despite this large effect, cylinders of intermediate weights (9 kg and 11 kg) had no significant effect on oxygen consumption. The oxygen consumption when wearing the heavier of the two was actually marginally higher than that for the steel cylinder (although heart rates were slightly lower). The author offers no explanation for this curious result. One possible explanation lies in the biomechanical evaluations reported by Love *et al.* (op cit). It was noted that some SCBA sets were biomechanically preferable to others as they had a lower centre of gravity. It was also specifically noted that some composite cylinders had a longer neck than the steel cylinders they replaced. As a result, when fitted to SCBA, they sat higher on the back, increasing the second order (turning) moment of the set. Details of the cylinders used by Sykes (op cit) are not sufficient to allow this possible explanation to be explored further. However, as the differences were not statistically significant no great import should be attached to these differences.

At this stage it must be emphasised that this absence of any difference in energy cost between different forms of fire kit and SCBA does not necessarily reflect any differential impact on thermal load. This issue is examined in Sections 4.1.3 and 4.1.4.

The other PPE of any significant weight (and therefore an *a priori* assumption of an effect on energy cost) worn by firefighters is the totally enclosing gas-tight suit ensemble, again worn with SCBA. Comparatively few authors have reported measures of the influence of such clothing on work load/energy cost. Some have examined ensembles in which all joins between garments are taped (a common practice in some industries) creating a similar overall effect, although the garment itself is not necessarily of a heavy-duty construction. One paper in which this is the case is the comparatively old work of White and Hodous (1987). The authors compared four ensembles, including a lightweight air-permeable coverall, the same ensemble with SCBA instead of a filter respirator, the current US fire kit, and a heavy polyurethane and nylon chemical protective ensemble again with SCBA.

Unfortunately, although heart rates and ventilatory volumes were reported, the authors did not report oxygen consumption, making it difficult to obtain a reliable estimate of increased energy expenditure. The reported heart rates would not provide an accurate estimate of workload because of the high thermal load experienced, with significant increases in rectal temperature. Some indication can be obtained from the ventilatory volumes however (discounting the ensemble where SCBA was not worn). Depending on the external workload, wearing the heavy chemical suit resulted in a 5-15% increase in ventilatory volume, while the fire kit resulted in a 12-40% increase, again over the lightweight suit. Although great care should be exercised in interpreting the actual values indicated by this estimate it is clear that heavy clothing can result in a significant increase in the physiological cost of work.

Another relatively old paper to have examined 'gas protective clothing' (GPC) is that of Smolander *et al.* (1984). Oxygen consumption increased significantly in relation to the extra weight of the GPC with increases of about 25-30% depending on workload. These are very similar to the values reported above for fire kit and SCBA. As the weight of the ensemble resembled that of fire kit and SCBA (ensemble weight including SCBA

– 25 kg), this is not unexpected. Although a relatively old paper, the GPC worn is likely to have been a similar weight to the heavy duty suits worn in many brigades although heavier than the lighter disposable suits now available.

Williamson *et al.* (1999) reported on a comparison of the use of a HAZMAT protective ensemble with the addition of a cooling system. The clothing ensemble consisted of a gas-tight suit (Trelleborg) of unspecified fabric. It was used either with SCBA or with a cooled air supply (air-line) utilising liquid air. This latter system significantly reduced the level of thermal stress over the SCBA-based unit.

Cadarette *et al.* (2001) document the use of what they describe as the Self Contained Toxic Environment Protective Outfit (STEPO) available for use either with a self-contained 'backpack rebreather system' or in a tethered air configuration (air-line). Initial studies reportedly showed the STEPO system with air-line to allow greater evaporation of sweat and consequently longer tolerance time than the rebreather system. In a further development, a version with SCBA was developed. STEPO-R weighed 27 kg while STEPO-T weighed 22 kg, including an emergency breathing apparatus (as apparently envisaged in the UK). These weights also include a cooling undergarment, worn as part of the ensemble, but not that of the unit used to provide cooled water. Endurance times for work with intermittent treadmill walking/resting (20:10 minutes) at a temperature of 38 °C was significantly longer wearing STEPO-T (106 ± 39 min) compared to STEPO-R (83 ± 22 min).

This ensemble included the provision of cooled water. An alternative approach has been to cool the incoming air supply, connecting the air-line to the suit via a vortex cooler (Mihal, 1981). However, Affara *et al.* (op cit) caution that noise levels from the vortex device can be restrictive.

Payne *et al.* (1994) described the use of a gas-tight suit in which part of the air from the SCBA cylinder was used to provide cooling. The suit with cooling appeared to perform worse than that with cooling although, as they were different styles of suit, care should be taken in interpreting this finding.

Extrapolation of these findings to other applications is difficult because of the inclusion of a cooling system. In general, the costs are likely to be intermediate between those associated with using a similar garment with a negative pressure respirator and that where full SCBA is utilised. Some additional load will be created by the need to move a heavy compressed air-line acting as an umbilical to the air source.

These papers have all examined the metabolic cost of wearing heavy PPE in terms of oxygen consumption, with the indication that this will be reflected in greater energy production by the wearer. The paper of Hanson (op cit) provides an indication of this effect, tabulating estimates of metabolic rate increases for representative forms of PPE. Table 4.1 derived from this paper, presents the estimates for those forms of PPE most relevant to firefighters.

From this table, based on a review of the scientific literature available at the time, it can be seen that fire kit, with the addition of SCBA, adds an estimated 135 W.m⁻² to the energy cost of any work. To put this into perspective, BS EN 28996 provides guidance on the assessment of metabolic rate. It categorises work rate into five categories, ranging from 'resting' to 'very high'. An increase of 135 W.m⁻² would raise the category of the work being performed by two stages, so that 'low' work would become 'high' and 'moderate' would be reclassified as 'very high'. From this it can be seen that the impact on workload of wearing fire kit and SCBA is substantial.

Table 4.1. Estimates of additional metabolic rate attributable to PPE worn by firefighters (based on Hanson, 1999)

<i>PPE item</i>	<i>Resulting increase in metabolic rate (W.m⁻²), based on 1.8 m² body surface area.</i>
Negative pressure respirator (low moderate performance)	20
Self-contained (open circuit) breathing apparatus	60
Light chemical coverall (e.g. disposable)	20
Chemical protective ensemble (e.g. PVC) with hood, gloves and boots	50
Heavy insulative clothing ensemble (e.g. firefighters' gear of helmet, tunic, overtrousers, gloves and boots)	75

4.1.3 Thermal insulation of PPE

The next aspect of PPE to be examined is that of its insulative qualities. In referring to this issue, Hanson (op cit) indicates that the data most widely available is that of BS ISO 9920, although this mainly concerns everyday work-wear rather than specialised forms of work clothing (such as fire kit) or other items of PPE. The Standard produced as the result of the work described by Hanson (BS 7963) includes some data, for example for chemical protective coveralls and insulative clothing (although this appears to be cold weather insulation rather than fire protection). However, the detailed nature of these garments is not presented limiting the work's value in the present context.

Various parameters can be used to describe aspects of the insulative qualities of garments. For example, McLellan *et al.* (1996) describe a Nuclear, Biological and Chemical (NBC) suit in terms not only of the thermal insulation (in both 'clo' and also $\text{m}^2 \text{ }^\circ\text{C W}^{-1}$) but also vapour permeability, both parameters measured on manikins.

EN 469, the current standard for clothing for firefighting, defines clothing characteristics in terms of the physical insulative values for the component fabrics. However, as Holmér (1999) indicates, such standards are of little value in determining the overall insulative characteristics of a clothing ensemble and hence its likely impact on levels of heat stress.

To date, no papers have been found reporting appropriate clothing insulation parameters for either any form of fire kit, or of gas-tight suits (although the latter would be an unusual case and difficult to define). Most papers, such as that by Ftaiti *et al.* (2001) and Smolander *et al.* (1985) report solely the weight of test ensembles. Alternatively, authors such as Bernard (1999) report an overall correction factor for 'firefighter turn-out gear' for thermal stress as assessed using the WBGT thermal index without reporting the clothing parameters available for other ensembles. Although, as seen in the previous section, the weight of an ensemble has an indirect impact on heat stress by increasing the metabolic cost of work, it is a poor indicator of insulative ability. Documented values for some relevant ensembles such as flame retardant coveralls have been found (Barker *et al.*, 1999). However, these are only of peripheral importance due to the infrequency with which such garments are worn by firefighters.

A greater awareness and understanding of clothing parameters, including those items worn underneath the fire kit, is vital if any complex modelling of firefighter performance under thermal strain is to be undertaken. This is illustrated by the work of Bouskill *et al.* (2002). Although not involving the use of fire kit, the study showed how the effective insulation of clothing ensembles was affected by interactive effects between, for example, the number of clothing layers, movement of the wearer and external air flow.

No data have been found regarding the insulative characteristics of the form of gas-tight suits worn in UK Fire Brigades. However, their thick, rubberised construction is likely to result in a high level of insulation, albeit not providing the heat protection of standard fire kit. Some new designs of gas-tight suits currently available utilise lightweight, limited use fabrics. The garment element itself will have negligible thermal insulation irrespective of use with scuba or an air-line.

4.1.4 Effects of PPE on sweat evaporation

A further factor widely referred to in terms of static characteristics of fire kit is that of vapour permeability, specifically that of water vapour. Although the inclusion of a vapour permeable membrane is not currently a requirement under EN 469, manufacturers are expected to provide information about the vapour permeability of the clothing assembly. Many suppliers of fire kit into the UK do however include a vapour permeable membrane within the fabric layers of the tunic and overtrousers. In the case of relatively thin garments, such as disposable coveralls, an increasing degree of thermal stress can be related to decreases in vapour permeability. Thus, for a given level of thermal insulation, heat strain increases in going from relatively gas and vapour permeable fabrics, through liquid barrier/vapour permeable fabrics (the most well known of which is probably the proprietary brand 'Gore-Tex'), to water and vapour impermeable fabrics such as PVC or the proprietary fabric 'Tyvek F' (Hanson, *op cit*). However, studies on firefighting clothing from the US (White and Hodous, 1988), Canada (Frim and Romet, 1988) and the UK (Graveling *et al.*, 1999) have questioned the utility of this feature. Drawing on the results of experimental studies, supported by the published scientific literature and physical calculations, these various authors have suggested that such membranes had little real impact on the severe levels of thermal strain experienced by firefighters under simulated operational conditions.

EN 469 (Protective clothing for firefighters) establishes a static (fabric) test for vapour permeability rather than any test on a completed garment. To translate that to provide an understanding of the effect in an actual clothing ensemble it is necessary to know the 'clothing vapour resistance' (Havenith, 1999) of the particular ensemble. As an indication only of the likely impact of this Havenith and colleagues present 'estimated static clothing permeability' values for a selection of garments. Compared to a base 'index' of 0.38 for normal clothing, a one-piece semipermeable overgarment reduced the index to 0.15 while an impermeable overgarment resulted in a decrease to 0.06. Not surprisingly, a completely encapsulating suit (such as a gas-tight suit) is given an index value of 0.0. Interpretation of these 'index' values is difficult although the proportional changes do give some indication. What is apparent is the sizeable impact, even of the semi-permeable garment.

The effects of both insulation and vapour permeability of clothing on subsequent levels of heat stress are many and complex, as evidenced by papers such as Holmér (1999);

Havenith *et al.* (1999); and Parsons *et al.*, (1999). As these papers illustrate, knowledge and understanding of these factors is vital for successful modelling of thermal stress.

Together, the garment ensembles referred to above probably reflect the main categories of clothing that a firefighter may need to wear. Unless the nature of the chemical requires the high level of respiratory protection provided by a gas-tight suit, incidents such as chemical spillages would normally entail use of a chemical protective coverall, either of a neoprene or lightweight disposable construction. Such garments may also be used in other 'dirty' jobs where fire protection is not required. The nature of the garment required will be determined by the nature of the chemical spilt. Disposable coveralls are normally available in vapour permeable (normally used for inorganic chemicals) or impermeable forms (organic chemicals). In industry, a higher level of protection is often obtained by using an impermeable coverall with an integral hood, in combination with boots and gloves (taped at the joints) and some form of full-face respirator (e.g. air-fed positive pressure). In the Fire Service, the ready availability of SCBA and suitably trained personnel probably means that this option is rarely used, with gas-tight suits the ensemble of choice, providing the highest possible level of protection.

Newer forms of gas-tight suits, normally designated as being 'limited use' utilise similar materials to the vapour-impermeable disposable coveralls. They therefore have similarly high resistance to sweat evaporation. However, usage with an air-line would provide a degree of dry air flow through the garment that would alleviate this to some extent and would therefore be preferable to usage with SCBA.

For thermal protection, coveralls are available in a wide variety of heat-resistant or flameproof fabrics. However, these appear to be rarely used in the Fire Service although they would result in a marked reduction in thermal strain.

4.2 THERMAL ENVIRONMENTS EXPERIENCED BY FIREFIGHTERS

4.2.1 Introduction

Firefighters can be exposed to very hot working environments. Such a statement is virtually tautologous as the title 'firefighter' implies. However, although such exposures are indeed an intrinsic part of the work of the firefighter the environments to which they are exposed would appear to be far more variable. In Finland, according to Smolander *et al.* (1985), the yearly mean regional temperatures range from -1°C to +6°C. The authors conducted a study of the physiological strain associated with wearing a gas-tight suit (Drager) in such conditions. Despite an ambient temperature of +2°C and snow throughout the test an average of 37 minutes work resulted in an increase in body (rectal) temperature of 0.8°C. Although only a small study, this field study illustrates that the potential exists for significant increases in body temperature in relatively cool ambient conditions and that it is therefore not sufficient to focus solely on the elevated temperatures encountered during live firefighting.

Data for the UK (www.metoffice.gov.uk) indicates average minima ranging from -0.2 °C for Inverness to 3.1 °C for Cornwall. Average maxima range from 18.1 °C, again for Inverness, to 22.2 °C for London (Greenwich). However, extremes ranging from as low as -27.2 °C in Braemar to 37.1 °C in Cheltenham have been recorded within the last 10 years.

In addition to naturally occurring ambient conditions, firefighters can be required to work in artificially created (non-fire) environments covering temperatures both above and below normal ambient. In preparing BS 7915, relating to cold indoor environments it was found that the vast majority of below ambient temperatures were encountered in the food industry (Graveling *et al.*, unpublished report to BSI). Cold store temperatures were generally around $-24\text{ }^{\circ}\text{C}$, although isolated instances of temperatures down to $-40\text{ }^{\circ}\text{C}$ were identified and, in one instance a temperature of $-50\text{ }^{\circ}\text{C}$ was reported. In this context it should be noted that SCBA is 'conditioned' at $-30\text{ }^{\circ}\text{C} \pm 3\text{ }^{\circ}\text{C}$ prior to testing, although only wearer tested at $-15\text{ }^{\circ}\text{C} \pm 3\text{ }^{\circ}\text{C}$.

4.2.2 Heat Exposure

No published data have been found regarding the elevated temperatures that firefighters are exposed to during actual operational conditions. Consequently, it is necessary to rely on those measured during training, or other simulations, to provide some measure of exposure. Clearly, the value of this will depend heavily on the extent to which the simulated conditions in training truly represent operational environments.

The question of heat exposure during training was examined by Graveling *et al.* (in press) on behalf of the Fire Service. The authors carried out a survey of all training establishments in the UK. While temperatures are routinely documented during firehouse exercises, this survey revealed that little of this information was of value. It transpired that, in many establishments, firehouse temperature was recorded primarily to protect the fabric of the building, normally with sensors located at, or close to, ceiling height. As a result, the data obtained were of no utility in establishing the temperatures to which the firefighters undergoing training routines were exposed.

Some environmental data relating to firehouse temperatures have been published in studies carried out in other countries. A series of studies by Smith and co-workers (Smith *et al.*, 1997; Smith and Petruzzello, 1998; Smith *et al.*, 2001) involved the use of live fires in a training establishment in the USA. Smith *et al.*, 1997 reported an average room temperature at chest height of $89.6\text{ }^{\circ}\text{C}$ obtained through the use of two pallet fires in the same room. The authors report a standard deviation about this mean of $16.6\text{ }^{\circ}\text{C}$ indicating the variability of temperatures achieved from 'controlled' fires. In a further study, the same research group (Smith and Petruzzello, 1998) reported temperatures in two training rooms with live fires as varying between 53.6 and $78.7\text{ }^{\circ}\text{C}$.

These studies illustrate a further problem in relation to heat exposure - it is not possible to determine the actual levels of heat to which firefighters were exposed from the details provided. The test routine entailed a 'dummy drag' in one environment with a live fire; bucket carrying between two levels (no temperature indicated); hand pumping in a second live fire environment; hose hauling on an outside balcony (no temperature indicated); and wood chopping at an intermediate level with no live fire. In a later paper, involving the same routine (Smith *et al.*, 2001a) the authors do report separate average temperatures for the three indoor work zones of $46.6\text{ }^{\circ}\text{C}$, $60.5\text{ }^{\circ}\text{C}$ and $49.3\text{ }^{\circ}\text{C}$. However, although the total duration of the exercise is reported, the time spent in each environment is not. Consequently it is not possible to determine the actual temperature 'dose' experienced. In a further publication, apparently of the same study, the authors (Smith *et al.*, 2001b) report the test area temperatures as averaging $46.67\text{ }^{\circ}\text{C}$, $60.57\text{ }^{\circ}\text{C}$ and $49.37\text{ }^{\circ}\text{C}$ respectively. Given the fluctuations in temperature obtained in a short space of time with live fires, citing temperatures to the nearest $0.01\text{ }^{\circ}\text{C}$ implies a totally spurious accuracy.

Williams *et al.* (1996) reported the findings of a small-scale study in Canada with what appears from the description to be a very similar training routine to those conducted in many UK fire-training establishments. Temperatures in the ‘smokehouse’ were estimated to be in the range of 260 °C to 430 °C. No indication is given as to the source of that estimate which, from experience in UK firehouses, is highly unlikely to be an accurate indication of temperatures at working levels.

Clark *et al.* (1998) reported the results of a study in a ‘concrete burn building’. Temperatures on the second floor of the building, where three controlled fires were located and where the exercises were conducted ranged from 76.7 °C to 93.37 °C. According to the report, subjects manoeuvred a hose ‘from room to room’ and yet separate temperatures are not reported from these different rooms, again making it impossible to establish actual heat ‘dose’.

House (1996) reported the results of studies on military firefighters carrying out exercises in environments heated by what were described as ‘Class A’ fires (wood and paper). The reported temperatures illustrate the sometimes-marked differences between what can be measured within the firehouse and the actual exposure temperatures. On entry, ‘overhead’ temperatures were described as being between 400 °C and 800 °C while temperatures recorded by heat sensitive patches on helmets and BA sets were stated to be within the ranges 42 °C to 56 °C (helmet) and 42 °C and 48 °C (BA). These data should however be interpreted with caution as it appears that the firefighters routinely worked behind the shelter of a ‘waterwall’ shielding them from much of the heat.

Some of the most extensive information available about temperature exposures in training environments comes from UK-based studies, conducted by or on behalf of the Fire Service (Home Office Fire Research and Development Group). Foster and Roberts (1993 and 1994) report the development and use of a BA harness instrument with various environmental measuring sensors including air temperature, radiative load and humidity. In the more detailed 1993 text, data are presented in relation to an instrumented firefighter following the route used during training exercises and in relation to deliberate attempts to achieve extreme exposures. Tabulated data, together with annotated graphical presentations, are included for 11 exercises at Moreton-in-Marsh. Sensors on the firefighter recorded temperatures at waist, chest and shoulder height throughout. Temperatures above 120 °C were not experienced for more than two minutes at any one time and, on only two occasions did temperatures briefly exceed 180 °C. For each of the exercises, times exposed to different temperatures were tabulated in 20 °C stages. An abstraction of these data is presented in Table 4.2.

Table 4.2. Environmental (temperature) data from 12 fire training exercises

Exercise Number	Temperature exceeded for more than 2 minutes (°C)
1	160-180
2	120-140
3	80-100
4	40-60
5	100-120
6	80-100
7	80-100
8	100-120
9	80-100
10	100-120
11	120-140

As well as air temperatures, the authors documented radiant heat loads, a parameter not frequently recorded. The highest thermal radiation recorded was $4.5 \text{ kW}\cdot\text{m}^{-2}$ at an air temperature of $120 \text{ }^\circ\text{C}$. In 'exploring' the limits of exposure, the authors reported that a recorded radiative exposure of $10 \text{ kW}\cdot\text{m}^{-2}$ resulted in damage to equipment.

Graveling *et al.* (1999) utilised a radiant heating panel to provide a heat source for simulating grass-fire beating. The panel had a radiative surface of 0.75 m^2 and the rated heat output was 7.5 kW , yielding an effective heat source of $10 \text{ kW}\cdot\text{m}^{-2}$. Firefighters were able to work in front of this without adverse effects although some bleaching of clothing was observed. However, with radiative heat reducing logarithmically with distance, working at a distance from the panel of $1.2 - 1.5 \text{ m}$ would mean that the impinging load was considerably lower.

Love *et al.* (op cit) reported environmental temperatures recorded during live fire exercises in the M.V. Sir Henry at the Fire Service College. Sensors were located at intervals around the route planned for the exercise participants, all at around shoulder height (1.5 m). In a 'short duration' exercise, one crib fire was lit in the lower forward hold at the lowest level. A graphical illustration of one set of data shows the importance, not only of measuring at different points within a training facility but also of relating these measurements to the location of the firefighters and to the time spent in any particular location within the facility. Thus measurements at two locations (unspecified) remained at or below $50 \text{ }^\circ\text{C}$ for the entire duration of the exercise while those at a third started at around $100 \text{ }^\circ\text{C}$, rose to almost $350 \text{ }^\circ\text{C}$ and then fell back to around $100 \text{ }^\circ\text{C}$ by the end of the exercise. Across 18 repeats of the same exercise, the average mean upper hold temperature was $48 \text{ }^\circ\text{C}$ (range $40\text{-}60 \text{ }^\circ\text{C}$); that in the between levels shaft was $100 \text{ }^\circ\text{C}$ (range $60\text{-}130 \text{ }^\circ\text{C}$); and that in the lower hold was $116 \text{ }^\circ\text{C}$ (range $75\text{-}175 \text{ }^\circ\text{C}$). The authors draw attention to the fact that the same size and type of fire was used on each occasion, testimony to the unpredictable nature of fire!

In a second 'long duration' exercise, temperature exposures during the exercise were more varied as a larger area of the vessel was used with only one fire (in the engine house). Again, illustrative graphs of temperatures against time show the extent of this variation with sensors more remote from the location of the fire recording temperatures starting from ambient ($15\text{-}20 \text{ }^\circ\text{C}$) and rising to around $70 \text{ }^\circ\text{C}$ (with one location reaching about $90 \text{ }^\circ\text{C}$). In contrast, sensors closer to the seat of the fire approached $300 \text{ }^\circ\text{C}$ within 10 minutes of the exercise starting although they fell rapidly within the next 10 minutes. Given the documented duration of this extended exercise (with a cylinder change mid-way) the team would not have reached the seat of the fire before the temperatures had fallen significantly. Love and co-workers only report indicative temperatures for this exercise, ranging from typical peaks of around $260 \text{ }^\circ\text{C}$ near the fire, falling to around $60 \text{ }^\circ\text{C}$ during the later stages of the exercise. With times recorded for each stage, the research team were able to calculate an approximate 'time-weighted average' temperature exposure for each team of firefighters and use these values in subsequent statistical comparisons.

Elgin and Tipton (2000) reported air temperatures close to and on instructors during training exercises at the Fire Service College. Temperatures were recorded using freestanding thermocouples at heights ranging from 0.3 m to 1.8 m in 0.3 m intervals. In addition, instructors were fitted with sensors at the shoulder, waist and hip. Mean static temperatures from 'sheltered positions' varied with height. As an indication, average temperatures from the fixed sensors at approximately waist height (1.2 m) ranged from $65 \pm 0 \text{ }^\circ\text{C}$ in the ship (M.V Sir Henry) to $414 \pm 40 \text{ }^\circ\text{C}$ in a container (Fire Attack exercise). No ranges of temperatures are given. The authors stated that no

correlation was obtained between the static measures and the temperatures measured on the instructor's tunics despite placing the sensors where the instructors would spend most of their time during the exercise. For comparison purposes, readings on the firefighters at waist height averaged 48 °C with a reported range of 30-146 °C.

In a follow-up to this study (Eglin and Tipton, 2002) temperatures were again recorded during exercises at the Fire Service College using both static and mobile (body-borne) measurement sensors. From the static sensors, average mean temperatures varied from 22 °C (0.3 m) to 112 °C (1.8 m) with average maximum temperatures ranging from 36 °C to 233 °C over the same height range. However, not all instructors worked on the same floor as the static sensors and were clearly not in the same thermal environment. The mean temperature measured on the outside of their tunics was 48.4 ± 11.2 °C during one exercise and 39.2 ± 15.6 °C during the second. The maximum temperatures measured during these exercises were 95.6 ± 49.2 °C and 79.2 ± 31.9 °C.

Graveling *et al.* (in press) reported the results of a study of acceptable temperature exposures for firefighter training. Data collected were used to generate draft guidelines for the management of heat stress during training. A total of fifty records were obtained from three training establishments relating to fire behaviour (flashover) training. Exposure times ranged from 6 minutes to 40 minutes, with maximum exposure temperatures ranging from 118 °C to 250 °C, yielding an average of 173 °C.

For exposures during search and rescue activities maximum exposures were considered misleading as the firefighters often spent little time in the fire compartment but longer searching areas heated by the fire. Consequently, this study introduced the idea of 'time-weighted averages' in determining heat exposure. The concept of the time-weighted average is well established in occupational hygiene in providing an accurate estimate of exposure to an environmental hazard. In essence, where exposure to a particular hazard varies over time and place, the effective load on an individual or group of individuals must reflect that variation. A justification for the use of this approach in occupational hygiene exposures is provided by Atherley *et al.* (1985).

Applying this to thermal exposures, if a firefighter spent ten minutes at a temperature of 40 °C and one minute in a different room where the temperature was 140 °C then a straight arithmetical average of the two values (90 °C) would give a misleading picture. With a time-weighted average (TWA), the value of 40 °C is multiplied by the duration (10 min) to give a value of 400. Adding the one minute at 140 °C gives a total of 540 which, when divided by the total duration of 11 minutes, gives a TWA of 49 °C.

Thus, in the work of Graveling *et al.* (in press), although short-term exposures as high as 240 °C were recorded from participating UK training centres, calculated time-weighted average temperatures ranged from 30 °C to 153 °C with an average of 79 °C.

The use of the TWA is subject to some limitations. Firstly, averaging the 'peaks and troughs' of exposure should not mask any directly harmful effects of the peaks. For example, in noise exposure, acute hearing damage can occur at noise levels above 120 dB(A). Averaging exposures across time might result in a level below this. Noise exposure also illustrates a further limitation of the approach in that it assumes that the effects of the environmental hazard are linearly related to level. In the case of noise this is incorrect as noise damage risk varies logarithmically with exposure level. Even here however, the established procedure for determining overall noise exposure in fluctuating conditions is to take a TWA based on logarithmic averaging.

The use of TWA in relation to estimating the risk of thermal strain is addressed by Morris and Graveling (1986). The authors presented the question as to whether averaging exposures introduced any physiological bias into heat strain estimates. They describe their own studies where it was shown that arithmetically averaging the workload element of heat strain was a valid procedure and refer to the work of Mairiaux *et al.* (1986), where a similar approach to heat exposures was shown to be acceptable. As with noise exposures however, the authors do caution that the averaging procedure should not be allowed to mask potentially damaging short-term exposures. In the firefighting context, exposure to very high heat levels, probably due to radiant heating from direct exposure to a live fire may overcome the insulative characteristics of the fire kit resulting in a burn injury although, if an average heat exposure was calculated, including a search period away from the seat of the fire, this might be regarded as physiologically acceptable in terms of heat strain for the duration of exposure.

4.3 THE THERMAL DEMANDS

4.3.1 Recorded body temperatures

Measurement location

There are many different approaches to the measurement of body temperature. EN ISO 9886 lists measurements at six different sites, together with urine temperature as possible measures of body core temperature. To these can be added the use of temperature sensitive pills (e.g. Eglin and Tipton, 2000) and infra-red measurement of tympanic temperature (e.g. Graveling *et al.*, in press). Edwards (1978) illustrated the variations in level and time course of temperature measurements obtained from locations including rectal, oesophageal, and ear canal (aural). Since the work of Edwards, a number of authors have published comparisons of different measurement sites. For example, Newsham *et al.* (2002) echo the work of Edwards in reporting differences in the time history of temperatures from different sites.

Graveling *et al.* (1999) reported on a brief comparison of rectal and aural temperatures carried out during their work on firefighters' clothing. The authors cite early work by Lind (1957) that demonstrated that rectal temperature, historically the first choice measurement site, could lag behind measurements from other sites, particularly when body temperature was rising rapidly. Graveling and co-workers reported a significant correlation between simultaneous measurements from the two sites but with a slight (0.1 °C) offset from a 1:1 relationship. The slightly higher aural temperatures were seen as consistent with the higher thermal mass of the abdominal contents leading to a lag in response of rectal temperature to any change.

Although no formal statistical comparisons were reported, Eglin and Tipton (2000) compared the use of rectal, aural and radio-pill measurements. Graphical presentations of rectal vs. pill data would suggest an offset towards rectal although the text indicates a higher average pill temperature. The authors attribute most of the variability to measurements obtained using the pill. In their discussion, the authors cite other work implying that the infra-red measurement of tympanic temperature was unreliable although what little data they report using this device do not appear to support this, given the previously stated variability in pill readings.

Graveling *et al.* (in press) reported a formal comparison of tympanic (infra-red) and aural temperatures. They reported a highly significant linear correlation between the

two, with slightly (0.2 °C) higher tympanic than aural temperatures, again in line with physiological expectations. However, the authors do report that the IR temperature-measuring unit was thermally unstable and would yield misleading readings if the temperature of the unit were altered. Subject to keeping the unit at the same temperature as the room where readings were to be obtained the authors concluded it could be used to give reliable readings.

4.3.2 Evaluative criteria

In interpreting the significance of measurements of body temperature, however measured, it is necessary to establish what constitutes a 'safe' upper limit. Hanson *et al.* (2000) cite a World Health Organisation limit for 'heavy work' of 38°C although the authors then suggest, on the basis of other reported studies, that this is unnecessarily conservative. This view is echoed by Muir *et al.* (2001) in commenting on the US ACGIH guidelines based on the same (38 °C) limit. Graveling *et al.* (in press) suggest using a limit of 39 °C for firefighter training, arguing that there was no evidence from their extensive studies of firefighters training in elevated temperatures that such levels presented a risk of injury.

In compiling this review, many papers have been identified involving exposure to elevated temperatures in which body temperature limits have been utilised. None of these has been as low as 38 °C. For example, working with Finnish firefighters, Smolander *et al.* (1984) used a limit of 38.8 °C (rectal); while, in a series of studies utilising military personnel, Gonzalez *et al.* (1997) used either 38.8 °C (UK) or 39.3 °C (Canada) rectal temperature. Cadarette *et al.* (1999) used a higher limit of 40 °C again measured rectally, this time with US military subjects. In the UK, Baker *et al.*, working with firefighters, did not report a formal limit although, from the text, it would appear that a temperature of 40 °C (rectal) was regarded as a *de facto* safe limit.

These suggested safe limits for body temperature should be borne in mind in assessing the significance of the levels reported for firefighters during training exercises. These limits are based on the risk of acute injury: heat syncope (fainting) or, in more serious cases, heat stroke. There is no evidence of any chronic effect of repeated heat exposure.

4.3.3 Body temperatures achieved by firefighters

An extensive body of literature exists relating to the physiological responses to work in the heat. However, much of this is derived from climate chamber based studies with subjects frequently wearing only limited clothing. Graveling *et al.* (in press) reported that the most extensive data set of physiological responses to firefighter training, identified during the preparation of guidance on firefighter training, was that reported by Love *et al.* (1996) in their report on the physiological effects of wearing BA. Seventy two firefighters participated in a series of exercises based on standard training regimes (see Table 5.14). So, although the data were not derived from actual training sessions the results obtained should be reasonably representative. Three different training scenarios were examined, all in elevated temperatures: a short duration fire/rescue exercise (average 29 minutes); a long duration fire/rescue exercise involving a cylinder change (average 65 minutes); and a gastight suit/chemical spillage exercise (20 minutes). Aural (ear canal) temperatures were recorded for all participants. In the hottest conditions, during the short duration exercise, average aural temperatures exceeded 39 °C. Much lower aural temperatures were recorded during the cooler, long

duration exercise (when the overall average temperature was 38.2 °C) and in the gastight suit exercise (cooler temperatures but with the additional insulation and vapour impermeability of the enclosing suit) when still more modest increases were recorded.

Working with firefighter instructors, Eglin and Tipton (2000) reported that the highest rectal temperature recorded in their studies was 39.4 °C with two other instructors having rectal temperatures exceeding 39 °C. Maximum pill and aural temperatures were 40.6 °C and 39.0 °C respectively. Pill temperatures in excess of 39.0 °C were recorded in eight instructors.

In a later study (Eglin and Tipton, 2002) the authors reported further rectal temperatures of instructors following hot fire exercises. The highest rectal temperature recorded in one exercise was 38.8 °C in 2 instructors and during another was 39.0 °C in one instructor. However, the authors comment that, although the instructors were in the Fire House for some considerable time (more than 40 minutes) they were only carrying out safety observations and so their workload (and consequent metabolic heat load) was relatively low. It is interesting to note that, after the exercise, the rectal temperature apparently continued to rise, illustrating the thermal lag with measurements from this body site.

Ilmarinen and Makinen (1992) presented brief details of heat strain in training exercises performed by Finnish firefighters. They reported final rectal temperatures among a group of male firefighting students ranging from 38.5-41.4 °C at the end of an extended training period (1.5 hr) including 'typical firefighting tasks'; 38.1 to 39.3 °C at the end of a 25-30 minutes period in a flashover facility; and a temperature of 40.0 °C recorded on one student at the end of 20 minutes spent in a 'burning house'.

Foster and Roberts (1994) recorded aural temperature in one subject during extensive studies of environmental temperatures. The temperature record shows a temperature already apparently elevated at the start of recording (38 °C) rising to over 40 °C. Care should naturally be exercised in interpreting data from a single session on a single subject.

In the USA, Smith *et al.* (1997) reported the results of physiological measurements obtained on firefighters performing a training drill described as a simulated ceiling overhaul task. Interestingly, the task was performed in both cool (13.7 °C) and hot (89.6 °C) environments to allow the impact of the heat to be assessed separately from the workload. Tympanic temperature (infrared) was little changed at the end of the work period in the cool (+0.3 °C). However, in the hot conditions, the mean tympanic temperature was 39.8 °C (an average increase of approximately 3 °C). The authors do however cast some doubt over the tympanic temperature readings indicating that they would have expected a greater increase in the cool conditions and a smaller increase in the hot conditions (given the relatively short duration). They cite studies that apparently present conflicting opinions as to the accuracy of this form of measurement.

Smith and Petruzzello (1998) reported a further series of studies, this time utilising a firehouse exercise (dragging a hose dummy; carrying a 5-gallon pump up stairs; hoisting a hose; and chopping wood. The value of the study for this report is limited as the entire exercise lasted only 5-6 minutes. Despite this, mean increases in tympanic (infrared) temperature in excess of 1 °C were reported.

Finally, Graveling *et al.* (in press) documented further instances of elevated body temperatures. Firstly, the authors visited a number of UK training establishments to

identify temperatures routinely collected during fire training. At a number of centres, temperatures in excess of 39 °C were often obtained and were regarded as typical by training centre staff. At one such centre, the training session lasted approximately thirty minutes and the highest reading post exercise was 40.4 °C (an increase of 3.3 °C). In another instance, the highest temperature recorded was 39.6 °C. Following this, data collection systems were established at a number of establishments throughout the UK. For search and rescue training (probably the closest to operational firefighting) a total of 124 usable sets of data were obtained from participating firefighters. Of these, 22 had body temperatures (tympanic) of 39 °C or more, with a maximum documented of 40.5 °C. The authors drafted guidelines for hot fire training intended to limit the body temperature to below 39 °C.

4.4 RESPIRATORY DEMANDS

As firefighters occasionally operate in extremely hazardous conditions, respiratory protection is often essential and no review of the work of firefighters would be complete without discussing this topic. There are many types of Respiratory Protective Equipment (RPE)⁶. Each has its own recommended operating environment and offers varying degrees of protection against environmental hazards. The three prime types are:

- *Filtering devices*: half facemasks with air filtering fixed or removable mesh screens and canisters
- *Attached air-line apparatus*: full face masks with an integral demand valve attached by a pressure hose, to an immovable high-pressure air supply
- *Self-contained breathing apparatus (SCBA)*: these can be either open circuit (OCBA), which vent expired air directly to the atmosphere, or closed circuit (oxygen re-breathing systems which include filters to neutralize CO₂ accumulation – CCBA).⁷

SCBA uses discrete bottled pressurised supplies of either air, oxygen (O₂) enriched air, or pure O₂. They may also incorporate positive pressure inside the facemask to protect against inspiratory atmospheric air in the event of a facemask leak. The majority of UK Fire Services currently utilise open circuit devices with continuous positive airways pressure (CPAP) within the facemask. The cylinders are usually charged with filtered air.

Firefighters' SCBA consists of a metal back-plate which is attached to the wearer by heat resistant adjustable composite straps. The webbing straps include an adjustable chest strap and waistband. The back-plate has attachments to support a high-pressure cylinder, the dimensions and capacity of which vary with the make and model of SCBA. The cylinder attaches to a first stage pressure reducer that is attached to a low-pressure demand valve via a high-pressure hose coupling assembly. The demand valve operates to provide a constant positive airways pressure within the facemask of ~6 cm H₂O up to airflow rates of 300 l·min⁻¹ (Dräger Ltd, Technical Spec. 048B, 1996). Positive pressure is present in the facemask as a safety feature to prevent inspiration of noxious

⁶ Respiratory Protective Equipment (RPE) should not be confused with subjective assessment questionnaires, Ratings of perceived Exertion (also RPE). To avoid confusion in the present document exertional scales will be described as (RPE_x).

⁷ By convention UK Firefighters refer to their breathing apparatus as 'SCBA'. This convention has been used throughout the review. When Closed-circuit Breathing Apparatus is discussed it will be described as CCBA.

gases in the event of a facemask leak. Operational SCBA in Europe are required to conform to quality standards - BS EN ISO 9001, approvals EN136/137.

A Finnish survey recently concluded that firefighters performed maximal rescue tasks demanding SCBA wear only about four times per year (Lusa *et al.*, 1994), which is insufficient to generate a training adaptation. Further, firefighters will not generate training adaptations to SCBA wear during training drills, unless the training is of sufficient intensity, duration and frequency. Given the terms and conditions of whole-time and retained firefighters (shift rotations, part-time working), high levels of firefighter tolerance to SCBA may not be easy to ensure.

Some published research has indicated that UK firefighters wear SCBA less than once per week (Scott 1988; Love *et al.*, 1994), suggesting that firefighters probably do not develop or maintain any specific physiological tolerance to SCBA wear. It seems that general in-service physical training was “insufficiently intense” to maintain the physical fitness levels obtained following a 13-week recruit training course among UK firefighters (Ellam *et al.*, 1994), and this may hold true for SCBA adaptations also.

Research also suggests that the intensity, type, and duration of in-service fitness training may need to be modified to ensure that active firefighters are best able to provide optimal performance at times of greatest need. This has implications for the effects of RPE on the respiratory system and may add to the detrimental effect of SCBA wear under extreme working conditions.

4.5 SCBA ENTRY TABLES

The physiological data of work rates used to certify respirators were derived from formative studies conducted by Silverman *et al.* in the 1950s. The bench testing machines against which respirators are measured work at varying rates, but generally, firefighters' SCBA entry control tables are calculated on the following breathing pattern:

Breathing frequency = 24 b.min⁻¹

Minute ventilation = 40 l.min⁻¹

Peak Inspiratory Flow Rate = 120 l.min⁻¹.

The duration of individual sets are calculated according to their air capacity. The above breathing pattern is still in operation in the UK Fire Service (Home Office Technical Bulletin 1/97), and represents a ventilatory requirement for exercise that is little more than unencumbered jogging in PE kit! It would be expected that firefighters exposed to high exercise demand, and high levels of thermal and emotional stress, would breathe at significantly higher rates than those used to calculate the SCBA entry tables. This claim is supported by laboratory evidence. One extreme study, for example, reported minute ventilation >100 l.min⁻¹ for firefighters wearing fire-kit and SCBA during a particularly intensive exercise on a treadmill in the laboratory (Louhevaara *et al.*, 1995). Other studies have reported minute ventilation >95 l.min⁻¹ (Donovan, 2000), >67 l.min⁻¹ (Donovan, 1999) and >63 l.min⁻¹ (Louhevaara *et al.*, 1985, 1995; Lusa *et al.*, 1994). All of these results were elicited during steady state or maximal exercises in the laboratory under controlled conditions and in cool environmental temperatures. Others have reported values below 50 l.min⁻¹ in simulated tasks, although these measures were indirectly assessed (e.g. pressure drops) (Love *et al.*, 1994). The SCBA Entry Tables would appear to be out-of-date and inadequate and in need of review.

4.6 THE RESPIRATORY EFFECTS OF SCBA MASS

Borghols and co-workers (1978) examined the costs on cardio-respiratory function of wearing heavy weights on the back during exercise. This study monitored O_2 , F_C , and \dot{V}_E , during treadmill walks at $5\text{ km}\cdot\text{hr}^{-1}$ while carrying loads of varying weight in 9 moderately fit, healthy male volunteers. The authors reported that at rest and when standing still, carrying the extra mass made little difference to the variables monitored. However, during walking or climbing exercise, each kg of extra mass carried resulted in increase in O_2 , F_C , and \dot{V}_E , of $0.03\text{ l}\cdot\text{min}^{-1}$, $1.1\text{ b}\cdot\text{min}^{-1}$, and $0.6\text{ l}\cdot\text{min}^{-1}$, respectively. These results have serious implications for firefighting performance in full turn-out PPE and SCBA which can weigh as much as 25 kg, and suggest that it is imperative for the mass of safety equipment to be minimised wherever possible.

In 1983, Gordon *et al.* investigated the effect of load carriage during treadmill walks at varying speeds and grades. Results indicated that an added load worn on the back (up to 50% of volunteers' body mass) resulted in "substantially larger increases in F_C and RPE_x than did unloaded walking for equivalent increases in power" (pg. 289). Biomechanical analysis of the walking gait especially at the higher gradients showed that the added load forced the volunteers to "lean forward in order to bring the centre of gravity back over the base of support" (Gordon *et al.*, 1983, pg. 296).

Such alterations to normal gait are counteracted by eccentric and isometric contraction of various muscle groups that include the hamstrings, the muscles of the lower back and the abdominal wall, and various muscles in the shoulders and neck. Many of these same muscle groups also act as accessory muscles of respiration during times of high ventilatory demand. Additionally, isometric contraction of the shoulders, upper chest and upper-limbs, which has been shown to restrict blood flow (Faulkener, 1968) may impact negatively on respiratory muscle function. Finally, all of these factors may be exacerbated by thermal stress, and may result in sub-optimal firefighting performance.

Manning and Griggs (1983) investigated the metabolic costs of working in SCBA and attempted to determine whether reducing the mass of the SCBA would reduce significantly the F_C demands of firefighting. They monitored the F_C of five professional firefighters during routine firefighting drills under three conditions (no SCBA, light SCBA (7 kg) and heavy SCBA (15 kg)). Results showed that standard firefighting activities were often performed at very high intensities, and that the volunteers exercised almost exclusively above their individual 'anaerobic thresholds'. This led the authors to conclude that "even a routine firefighting activity can be considered to be a major exertional undertaking" when SCBA is worn (pg. 217). The report also showed that firefighters adjusted their performance levels in line with the physiological stresses involved in the specific task. The authors also suggested that in future, the metabolic costs of wearing different SCBA are determined while exercises are performed "under anaerobic conditions" (Manning & Griggs, 1983, pg. 217). There are certain problems with this recommendation however as firefighters wear SCBA at workloads of varying intensities (Duncan *et al.*, 1979). It seems reasonable to suggest that the best indications of the cost of SCBA wear will be determined utilising test protocols that closely match actual firefighting duties (see Section 5).

In 1984, Louhevaara and colleagues began a series of investigations into the cardio-respiratory effects of wearing RPE during exercise. Initially a group of 12 highly trained retained firefighters ($VO_{2\text{max}}$ of $\sim 4.5\text{ l}\cdot\text{min}^{-1}$; or $64.9\text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) were monitored during a series of visits. The authors reported that SCBA "hampered respiration, which led to hypoventilation" (Louhevaara *et al.*, 1984b, pg. 244). At the highest work rate,

SCBA wear elicited very high levels of exertion (97 % F_{Cmax} , 78 % VO_{2max} , and 58 % V_{Emax}). Minute ventilation during exercise was $>63 \text{ l}\cdot\text{min}^{-1}$ during steady-state exercises in the laboratory with cool ambient temperatures.

In 1985, Louhevaara and colleagues again investigated the effects of SCBA on breathing pattern, gas exchange and heart rate during exercise in 13 retained firefighters. Each volunteer performed two treadmill walks, once in sports kit and once in fire-kit and SCBA. As in the previous study, volunteers' minute ventilation exceeded $63 \text{ l}\cdot\text{min}^{-1}$ in cool conditions. Wearing the SCBA during exercise hampered gas exchange, and increased heart rate and breathing frequency compared with control levels. The changes in gas exchange were interpreted by the authors to indicate that alveolar hypoventilation had developed during the low intensity exercise levels, and that the concentration of CO_2 in the blood had "probably increased to an intolerably high level, which ultimately resulted in a strong increase in breathing frequency and effort" during the later stages of the exercise (Louhevaara *et al.*, 1985, p 215).

Sports research indicates that the maximal work time is related the % VO_{2max} at which the exercise is performed (Ahlborg *et al.*, 1967; Saha *et al.*, 1979). It is widely accepted that wearing SCBA reduces maximal work duration to exhaustion by as much as 20%, and decreases maximal working to a similar degree (Raven *et al.*, 1977, 1981, 1982; Manning and Griggs 1983). Louhevaara *et al.* (1986b) attempted to determine the maximal exercise duration when SCBA was worn in 13 fit whole-time firefighters. The volunteers performed two treadmill walks during a single visit, at three intensities, once in sports kit and once in SCBA in demand mode but without fire-kit.

As expected, results from the two tests showed that wearing SCBA increased significantly the metabolic costs of exercise compared with control scores in sports kit only. The increase in VO_2 was greater during the moderate and heavy stages, and F_c increased more in SCBA at all exercise intensities. The results showed that for individuals with VO_{2max} of $3.5 \text{ l}\cdot\text{min}^{-1}$ working at $\sim 70\%$ VO_{2max} , the estimated exercise duration would be ~ 18 minutes. In the light of their results, the authors recommended that firefighters require a VO_{2max} greater than $>3.5 \text{ l}\cdot\text{min}^{-1}$ (or $43.8 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ for a firefighter weighing 80 kg) in order to be able to perform their duties adequately.

Another study, which utilised a tethered air-line respirator, concluded that respirator wear leads to significantly more oxygen uptake than without (Wilson *et al.*, 1989). These researchers suggested that individuals with VO_{2max} greater than $50 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ have the greatest chance to "override the effect of respirator work on performance" (pg. 92). However, the majority of UK firefighters are probably less aerobically fit than this (see Section 6).

Louhevaara and co-workers (1995) investigated the effects of a fire-protective clothing system and SCBA on the maximal physical work performance of 12 professional firefighters (VO_{2max} $4.02 \text{ l}\cdot\text{min}^{-1}$ and $46.9 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$). Volunteers completed two incremental treadmill walks to volitional fatigue once in sports kit and once in full firefighting ensemble (including SCBA, mass $\sim 25.9 \text{ kg}$). At exercise intensities below maximal, the firefighting ensemble increased significantly the physiological and perceptual responses compared with control in sports kit. Additionally, the ensemble reduced the exercise duration and the maximal walking speed at termination of exercise by $\sim 25\%$, which was a more marked effect than that reported by Raven *et al.* in 1977.

Louhevaara *et al.* (1995) also suggested that the most powerful individual predictors of tolerance to SCBA wear were %body fat, height, and the maximum rating of perceived exertion (RPE_x) obtained during baseline control tests.

4.7 RESPIRATORY FACTORS AND FIREFIGHTING ENSEMBLE

4.7.1 General Physiological Effect

Firefighting in SCBA and fire-kit may have a number of other important physiological effects on the efficient operation of the human respiratory system. Sothmann *et al.* (1992a) referred to the physiological demand that arduous firefighting tasks placed on the pulmonary system. These authors noted that the added load on the respiratory system caused by wearing SCBA “increases the work of breathing and may result in workers with marginal pulmonary function being unable to ventilate adequately” (pg. 28). This is possibly the first reference that alludes to a potential for firefighters’ otherwise healthy respiratory system and respiratory muscles to be a “weak link” in the chain of physical performance. The suggestion was that firefighters’ respiratory musculature may play an important, and as yet poorly understood, role in firefighters’ work performance.

Donovan and McConnell (1998) compared the physiological variables of 8 whole-time UK firefighters with those of 10 matched UK civilians. Maximum Inspiratory and Expiratory Pressures (measures that assess the strength of the respiratory muscles) were significantly higher in the firefighter group although in all other aspects the groups were virtually identical (two group mean $\text{VO}_{2\text{max}}$ was $54.7 \text{ ml}\cdot\text{kg}\cdot\text{min}^{-1}$). These data strongly imply that firefighters demonstrated significantly stronger respiratory musculature than a matched group of civilians.

The relationship between respiratory muscle strength and exercise performance remains open to debate, but recent research suggests that strong respiratory muscles may offer protection against respiratory muscle fatigue (McConnell *et al.*, 1996). The precise functional significance of this is unclear, but respiratory muscle fatigue may exacerbate the sensation of breathlessness and impair performance during firefighting tasks. It is not clear whether strong respiratory muscles are a self-selective prerequisite for firefighting, or the result of in-service training developments. If firefighting improves respiratory muscle function, then it might be useful to include respiratory muscle testing and training for recruit firefighters. Further research investigating this question might prove valuable.

4.7.2 Lung Compliance

The restrictive effects of the SCBA may force firefighters to breathe on a lower part of the pressure/volume curve of the lung, to avoid reductions in lung compliance (Hlastala and Berger, 1996). This in turn may add to the overall work of the respiratory muscles and reduce the efficiency of gas exchange, especially during intensive exercise in the heat.

4.7.3 O₂ Requirements of the Respiratory Muscles

Recent research has shown that the oxygen cost of the ventilation achieved during heavy exercise may approach 15% of the total oxygen uptake, and that blood flow to

the respiratory muscles during hyperventilation may equal or exceed blood flow to the exercising locomotor muscles (Dempsey *et al.*, 1996, Harms *et al.*, 1997, 1998). The same researchers have also suggested that excessive requirements of ventilatory work during heavy exercise may cause reflex vasoconstriction in locomotor muscles resulting in impaired endurance performance. In firefighters, the respiratory muscle competition for blood flow may be increased by the reflex vasodilatation of superficial capillaries of the skin; the normal response to working in the heat. Each of these factors may add to the work of breathing in firefighters and may compromise firefighting performance especially during intensive work in extreme heat.

Given that firefighting activities can elicit very high levels of VO_2 and that SCBA presents a significant resistance to thoracic excursions, it is entirely possible that firefighters respiratory muscles may become fatigued during work bouts in SCBA. Additionally, firefighting encompasses whole- and upper-body exercise, and there is ample evidence to show that this increases VO_2 demands of exercise compared with walking alone (Åstrand and Rodahl, 1986, pg. 360). Firefighting activities may thus impact on the energy cost of respiration to a greater extent than walking or stepping exercise alone. Blood flow restrictions that compromise the efficiency of working skeletal and respiratory muscles may thus be exaggerated during firefighting operations, and this may add to the relative intensity of the exercise. In this instance, respiratory muscle blood flow compromise may become evident at relatively lower exercise intensities. If this is the case, then the Harms *et al.*, (1997, 1998) findings may well underestimate the effect of firefighting exercise and SCBA wear on the energy costs of ventilation in working firefighters.

If firefighting activities are capable of inducing respiratory muscle fatigue, then it is possible that respiratory muscle training may retard its development and thus improve exercise performance. The work of Dempsey, Harms and others suggests a mechanism whereby respiratory muscle training may operate to improve ventilatory performance that in turn may impact positively on overall performance.

4.7.4 Constant Positive Airways Pressure (CPAP)

As noted above SCBA operates with a constant positive airways pressure (CPAP, range 3.3 to 6.0 cm H_2O) within the facemask. Medical research has indicated that CPAP may hinder the performance of the inspiratory muscles. It is hypothesised that CPAP may impact negatively on the inspiratory muscles by altering the resting length of the muscle fibres placing them at a mechanical disadvantage (Daubenspek, 1995). On the other hand research by Arborelius *et al.* (1983) suggested that CPAP at the level present in SCBA facemasks had little impact on the ventilatory responses of firefighters during cycle ergometry in the laboratory. Conversely, the perception of many firefighters is that CPAP assists air into the lung and thus acts to make breathing easier (West Midlands Fire Service, personal communications). Two studies were undertaken to investigate this issue during a PhD project (Donovan, 2000). The results showed that CPAP at the level produced by firefighters SCBA probably makes no measurable difference to the exercise performance of firefighters.

4.7.5 Dead Space

As a result of the physical composition of the human respiratory system, a portion of inspired air does not reach the alveoli and thus does not take part in gas exchange. When firefighters breathe through SCBA facemasks the external dead space is added to

the alveoli dead space and is thus cumulative. The resultant increased dead space increases the proportion of ventilation that does not take part in gas exchange (wasted ventilation). This in turn requires the individual to increase ventilation by either increasing tidal volume, breathing frequency or both. Research suggests that breathing with added external dead space hampers ventilation and results in increased minute ventilation, breathing frequency and reduced tidal volume (Kelman and Watson, 1972). The added external dead space may lead to increased retention of CO₂ at lower exercise intensities that may result in increased breathing efforts later in the exercise (e.g. Dressendorfer, 1977; Louvevaara *et al.*, 1985). Conversely, it has been argued that a large dead space will increase the build-up of CO₂ in the inspired air and result in hyperventilation. In response to this possibility, SCBA manufacturers have reduced the DS volume within their masks by incorporating small, internal ori-nasal masks (dead space ~90ml). This allows expired air to exhaust directly to the atmosphere with minimum CO₂ recirculation inside the mask. A dead space of 90 ml is unlikely to affect significantly, firefighters' respiratory system dynamics.

During a study by Shimozaki *et al.* (1988), volunteers' subjective responses to respirator wear were assessed. Results showed a linear relationship between inspiratory resistance and subjective response, and that expiratory and inspiratory loading produced similar subjective effects. Dead space loading produced very little subjective effect either in discomfort or exertion (Shimozaki *et al.*, 1988, pg. 108). Other researchers have noted that respirator wear can result in the sensation of breathlessness, which has been shown to be a limiting factor in exercise and can reduce the tolerance to inspiratory resistance (Fishman and Ledlie 1979; Burdon *et al.*, 1982).

4.7.6 Breathlessness (Dyspnoea) and SCBA wear.

Studies have suggested that tolerance to respiratory loads may be affected by respiratory timing (breathing depth and frequency) and the individuals' load sensitivity (Harber *et al.*, 1988, 1990). Research has also indicated that irrespective of the respiratory loading, "breathlessness scores increase progressively with continued exercise" (Lane *et al.*, 1987, pg.63), and subjective load sensitivity increases at higher exercise intensities (Lane *et al.*, 1987).

In general terms, tests that utilise RPE_x show large standard deviations, indicating wide inter-individual variability in response to respirator loads. Shimozaki *et al.* (1988) suggested that although inspiratory loads may have greater *physiological* effects than either expiratory loads or dead space, there was little difference in the *perceptual* responses to any of these loads. On the other hand, Fishman and Ledlie (1979) and Burdon *et al.* (1982) reported that inspiratory resistance can lead to the perception of dyspnoea. Although the results are ambivalent, if there is a perceptual response to added respiratory loads, it is possible that *inspiratory* loading (caused by SCBA wear) will have a greater perceptual effect on breathing than either DS or expiratory loading.

An added complication to this discussion is that there is little inspiratory or expiratory resistance to airflow within the facemask of firefighters' SCBA. There is however a considerable restriction to thoracic excursions caused by the restrictive mass and strapping of SCBA. The effect of the restriction to thoracic excursions on respiratory muscle function is yet to be fully understood.

The challenge of assessing firefighters' breathlessness during laboratory tests relates to researchers' inability to present adequate work-related tasks. Given the psychological

stresses involved in firefighting (fear, shock, adrenaline-led fight and flight responses), neither laboratory-based tests nor field-based simulations can be expected to elicit the same psychological responses that are elicited by real-life firefighting scenarios. Ethics approval would normally preclude the inclusion of dangerous practices and the resultant 'sanitised' laboratory tests will thus probably appear safe, secure and somewhat tame to experienced firefighters. In the past, firefighter volunteers have been asked to report subjective responses retrospectively by recalling perceptions during emergency operations (e.g. Faff and Tutak, 1989). Such subjective responses measured during laboratory tests are always likely to underestimate those elicited by the real-life scenarios and care must be taken when interpreting such data. As a result, firefighters' ratings of perceived exertion and breathlessness would probably always be lower than would be seen in a civilian population who undertake the same task.

4.8 OTHER FACTORS

While there are many anecdotal reports of the influence of other factors on the strain associated with firefighting tasks no formal studies of these have been identified. For example, entry into a smoke-logged environment with little or no visibility is widely regarded as adding to the physical strain of any work in such environments. Papers such as Lusa *et al.* (1993) have reported studies of 'smoke-diving' but such studies do not exclude the influence of elevated temperatures. During data collection at the Fire Service College, Love and co-workers observed higher physiological responses among those designated as team leaders (Graveling, personal communication) but did not formally examine this phenomenon. Mental factors such as uncertainty and apprehension will undoubtedly influence physiological parameters such as heart rate. What is not clear is whether this, in turn, will adversely affect task physical performance.

These influences should not be confused with the influence of heat on psychological task performance. A review of (psychological) task performance in the heat was published by Ramsey (1995). The author presented the collated results from numerous studies, grouped into 'mental or simple' tasks (reaction time, time estimation, simple cognitive function) and 'other perceptual motor' tasks (e.g. tracking, vigilance, vehicle or machine operation). These results show little or no effect of heat exposure on simple task performance while the performance of more complex tasks was affected at temperatures generally in excess of 30 °C WBGT. Such decrements could be observed with durations of exposure of less than 10 minutes although most studies employed longer exposures. The author drew parallels between the exposure limits proposed by NIOSH (National Institute for Occupational Safety and Health, 1986), based on physiological strain, and the perceptual motor effects, suggesting that they were broadly similar. However, a distinction was also made between statistical significance and practical significance, sounding a note of caution in attempting to apply the collated findings to practical situations.

Hancock and Vasmatazidis (1998) went a stage further. They argued that because of the importance of psychomotor or mental performance in many industrial tasks, exposure criteria should be set on the basis of *unimpaired* performance. This would result in lower exposure limits than those based on physiological risk.

The authors of both papers drew attention to the considerable variability in the relationship between mental/psychological performance and heat exposure. Effects appear to be highly task dependent (in some cases, heat exposure may improve

performance) as well as being influenced by factors such as additional 'stresses' (e.g. noise) and skill level. This makes it difficult to transfer findings from one study or occupational group to another or between different measures of performance.

Smith and Petruzzello (1998) reported the results of a study specifically on firefighters in which both physiological and psychological factors were studied. The purpose of the study was to examine the effects of different configurations of firefighting gear, notably NFPA 1500 standard gear and a pre-NFPA standard configuration. Building temperature for the two configurations was virtually identical (66.9 ± 2.1 °C and 67.5 ± 3.5 °C respectively). The firefighters performed a series of training activities: dragging a hose dummy; carrying a 5-gallon pump can up two flights of stairs and discharging it; hoisting a hose; and chopping on a block of wood. Psychological performance, measured as either the speed or the accuracy of reaction to a numerical display, was not significantly affected, in comparisons either with the pre-exposure test (unheated) or with either clothing ensemble. However, variability in response time did significantly increase in the NFPA-1500 clothing trials. It should also be noted that the thermal exposure levels were not high with a highest mean body temperature of 37.3 °C.

To summarise, psychological factors such as uncertainty, anxiety etc. will influence psychological parameters. In addition, exposure to elevated temperatures will have an adverse affect on psychological task performance issues such as cognition and decision-making. A further broad area, beyond the remit of this review, is that of more acute (traumatic) effects. Exposure to extreme temperatures or other harrowing circumstances such as may be associated with explosions etc. may have a traumatising effect. The potential aftermath of this in the form of 'post traumatic stress disorder' is increasingly recognised. However one area possibly warranting further evaluation is the possible immediate effect of such circumstances on task performance.

CHAPTER 5

The Demands of Firefighting

5.1 KEY TASK ELEMENTS OF FIREFIGHTING

5.1.1 Introduction

This section describes some of the key task elements that firefighters are required to perform together with the metabolic demands of the tasks as reported in the literature. Any paper that offers a quantification of the (physiological) demands of firefighting task elements are identified and reviewed below in chronological order. A final subsection will focus more closely on those studies and reports that are most directly relevant to UK firefighters.

A number of researchers have substantiated the importance of representing the aerobic demands of a task in terms of its absolute oxygen demand (VO_2) as well as its mass corrected value, i.e. in terms of $\text{l}\cdot\text{min}^{-1}$, as well as $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ (Rayson *et al.*, 2000; Bilzon *et al.*, 2001). Where both values are reported in the literature they are represented here.

5.1.2 1970s

Lemon and Hermiston (1977b) attempted to quantify the energy cost of firefighting and monitored the work involved in performing 4 “routine work tasks”; a ladder climb, a victim-carry, a ladder erection, and a hose drag. The heart rate (F_c) and VO_2 of 20 firefighters were monitored while working in fire-kit but without SCBA. Volunteers’ performance during the tasks were monitored closely by supervising officers but no attempt was made to control the speed or intensity of their activity other than to issue the instruction to work at “firefighting speed” (pg. 559). Results indicated that the tasks elicited ~70% of the volunteers’ $\text{VO}_{2\text{max}}$ (mean duration of tasks was 43 s), and that firefighters with $\text{VO}_{2\text{max}}$ in excess of $40\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ would be better able to cope with the work demands (Lemon and Hermiston 1977b).

The Lemon and Hermiston study (1977b) may have underestimated the demands of firefighting. The 4 tasks they monitored were performed singly, thus reducing the cumulative effects of continuous firefighting. Furthermore, there were no environmental hazards - the tasks were performed in daylight, under ambient outdoor temperatures, nor were there any of the psychological stresses that would normally be associated with actual firefighting. The authors themselves highlighted the difficulty in conducting assessment on non steady-state tasks as the tasks were “subject to larger error variance” (pg. 560).

5.1.3 1980s

In 1982 Davis and co-workers examined the relationship between simulated firefighting tasks and physical performance variables in 100 professional firefighters. The volunteers performed a 5-stage fire drill in cool ambient conditions (see Table 5.1). Volunteers' performance was timed and their F_C was monitored throughout the test.

The primary measure of task performance was exercise duration (mean task duration 7 min). The group mean F_C for the drill was $169 \text{ b}\cdot\text{min}^{-1}$ (91% $F_{C\text{max}}$), although many of the volunteers reached 97 % $F_{C\text{max}}$ during the most strenuous part of the exercise (simulated rescue). The authors point out that in the absence of both heat and the added mass of SCBA, "it may be inferred that the aerobic capacity of the firefighter is not, on the average adequate to complete typical firefighting tasks at the pace observed in this study" (Davis *et al.*, 1982, pg. 66).

Table 5.1. Five sequential firefighting tasks, Davis et al. (1982)

No.	Task name	Description	% duration (7 min)
1	Ladder drill	Extend and retract a 35 ft ladder under control	7.8%
2	Standpipe carry	Carry a 45.7 m single jacket standpipe hose (33.1 kg) to the top of a drill tower (total vertical height 28.5 m)	22.6%
3	Hose pull	Pull a 6.35cm diameter hose (23.5 kg) up to the 5th floor window of the drill tower (28.5 m) with the aid of a utility line and hose roller	13.7%
4	Simulated rescue	Carry/drag a 53 kg dummy from the 5th floor of the drill tower to the ground (28.5 m)	34.1%
5	Forcible entry	Using a 3.6 kg hammer, strike a rail sleeper 30 times "as forcibly as possible"	21.8%

The results showed that muscular strength, aerobic endurance, body mass, and body fat are all good indicators of firefighting performance. Firefighters with 'optimal' scores in each of these parameters appeared to have the ability to "complete all tasks quickly by exhibiting a resistance to fatigue brought on by the demands of the earlier tasks" (Davis *et al.*, 1982, pg. 65). These authors also noted that firefighter performance tends to decline with advancing age.

Although the Davis *et al.* (1982) paper is rather old and the PPE worn is now out-of-date, the test drill appears to have criterion validity and the results are relevant as they demonstrate the high intensity nature of firefighting task elements. The results also show that even when self-paced, firefighters perform their duties at maximal or near-maximal intensities (at least when they are being monitored by researchers). It is likely that if this drill were to be carried out in hot conditions and SCBA worn, the volunteers would have still exercised at the same relative intensity, but would have taken longer to complete the task (self-pacing). Whether the extended times would have been acceptable from an operational perspective is a different matter and can only be answered by Fire Service personnel.

During a study by Manning and Griggs (1983), 5 male firefighters (aged 21-31yrs) performed a standardised firefighting exercise (see Table 5.2). The volunteers were divided into teams of 2 (a 'nozzle man' and a 'backup man'). Volunteers' heart rate was

monitored throughout the test, which was performed outside in a moderate ambient temp (36 °C, relative humidity 54%). Each volunteer completed a total of three drills, 1 without SCBA, 1 with light-weight SCBA (7 kg), and 1 with heavy SCBA (15 kg). Heart rate data at each checkpoint are presented in the paper and show that the volunteers' heart rates increased throughout the drill and were higher (almost maximal) when heavier SCBA was worn.

Table 5.2. A 5-minute exercise drill, from Manning and Griggs (1983)

Task name	Description
Hose extension (1)	Two firefighters donned turn-out gear and SCBA and walked or ran 30m to a fire engine (Checkpoint 1)
Hose extension (2)	They extended a 3.3 cm hose 30 ft (to Checkpoint 1) then pulled the uncharged hose 150ft (checkpoint 2), then charged the hose
Hose extension (3)	The 'nozzle man' pulled the hose up a flight of stairs (Checkpoint 3), while the backup man assisted by pulling the hose from the base of the stairs
Firefighting	The second man joined the 'nozzle man' at the top of the stairs. They extinguished a crib fire with short bursts of water (Checkpoint 4)
Hose drag	The volunteers then dragged the hose back to Checkpoint 1 and finished (Checkpoint 5)

In their conclusions Manning and Griggs (1983) confirmed that firefighters tended to work at very high levels and that “regardless of the weight of the SCBA... firefighters exert themselves from 85% to 100% of their maximum and adjust their work output to maintain near-maximal levels” (pg. 215).

Romet and Frim (1987) investigated the energy demands of firefighting tasks in a field-based trial. They monitored heart rate and rectal and skin temperatures during the tasks. Volunteers wore full PPE including SCBA. Ambient temperature during the trials was 16 °C, although live fires were fought in some of the 6 scenarios that lasted from 20 to 48 minutes. A total of 8 firefighters volunteered for the study. Each activity was timed and the tasks were broken down into roles - 1 Crew Captain, 1 Lead Hand, 1 Secondary Helper and 2 External Firefighters. Unfortunately, the actual scenarios were not described in detail but involved responding to an alarm, approaching some buildings, evaluating the situation, searching for and evacuating victims and extinguishing fires. In total, data were collected on 23 man-runs.

The results showed that the metabolic demands of firefighters varied according to the role they undertook. The lowest physiological demand was always placed on the Crew Captain while the greatest demand was faced by the Lead Hand (as demonstrated by F_C and temperature data). This study demonstrates the need for task rotation during extended firefighting activities and also confirms the need for firefighters to have good physical fitness.

The same year (1987) Misner and co-workers investigated gender difference in US firefighters (37 males and 25 females) during simulated firefighting tasks. The findings are summarised in Table 5.3, where means (sd) are given. On every aspect of measurement, men's performance was superior to women's. The British Government's current strategy of wishing to increase the number of women firefighters poses a

dilemma for the Fire Services, as very few women can match the operational performance of their male counterparts.

Table 5.3. The 9 tasks monitored in the Misner et al. study (1987)

Task No.	Name	Description	Male score (s)	Female score (s)
1	Hose couple	3 hoses were coupled as rapidly as possible	13 (2)	17 (3)
2	Flexed arm hang	Volunteers hung from a horizontal bar with chins at the level of the bar for as long as possible	65 (17)	47 (21)
3	Body lift and carry	Picking up and carrying a 34kg dummy for a total of 100 ft	17 (1)	21 (3)
4	Obstacle run (in a contained area of 1,110 ft ²)	Consisting of a 'dodge' run, a window crawl through, a sandbag lift and carry, a tube carry, a tube crawl through and a horizontal ladder crawl	84 (9)	103 (16)
5	Modified stair climb	Subjects wore SCBA (13 kg) and carried a hand pump (22.7 kg) up 3 flights of stairs (total of 42 steps) as quickly as possible	14 (2)	24 (7)
6	Ladder lift	Lift a 15 ft ladder (22 kg) from a truck place it on the ground clap hands and return it to its place	8 (3)	12 (5)
7	Forcible entry	Use a 4 kg hammer to hit a 36.8 kg tyre along a waist-high metal table a distance of 12 ft.	9 (4)	21 (14)
8	Dummy drag	A 64.5kg articulating dummy was dragged a total of 80 ft.	9 (2)	11 (2)
9	Stair climb	Carrying a rolled hose (29 kg) on back up 3 flights of stair as quickly as possible	13 (2)	18 (3)

The authors analysed the relationship between the volunteers' physical characteristics and the results generally match what would be expected. Results indicated that volunteers' body composition had a moderate association with performance. In particular, high body fat was seen to have a negative effect on performance while high fat free mass was associated with good performance (particularly those tasks that involved force production). In general the results confirmed that the leaner the firefighter the better they perform at these types of activities.

5.1.4 1990s

Sothmann *et al.* (1990) investigated age as a limiting factor in firefighter performance and attempted to determine a minimum standard of aerobic fitness in firefighters. They monitored the performance of 150 male firefighters (not enough female firefighters were available to form a controlled group) of varying ages and grouped them according to $\text{VO}_{2\text{max}}$, rather than age during simulated firefighting tasks. The authors

argued that $\text{VO}_{2\text{max}}$ is a sensitive indicator of cardio-vascular status and exercise performance and that it has “important implications for sustaining dynamic physical work” especially in hot environments (Sothmann *et al.* 1990, pg. 218).

The authors suggested that $33.5 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ was the *minimum* aerobic power level for completion of their test drill although this allowed little emergency reserve. They also stated that those volunteers with aerobic power more than $33.5 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ had a significantly higher probability of completing the task (described in Table 5.4).

Table 5.4. A 7-stage firefighting drill, from Sothmann et al. (1990)	
Task No.	Description
1	Climb 4 flights of stairs (84 steps) while carrying an axe
2	Enter 54 °C room filled with non toxic smoke and search for a dummy
3	Remove 68 kg dummy and drag it down a 50 ft hallway
4	Re-enter the warm room and perform 20 pulls of a simulated pike-pole (overhaul)
5	Walk down 3 flights of stairs, pick up a 25 kg hand pump and carry it back to the room
6	Re-enter the smoke filled room and chop through a block of treated pine positioned horizontally 1m above floor
7	Perform 20 more pulls on the pike pole simulator

To assess the metabolic demand of the drill Sothmann *et al.* (1990) equipped a smaller ‘Norm’ group (n=20) with a gas analysis system to measure VO_2 . Volunteers were instructed to perform the drill at ‘normal firefighting pace’; the total duration of the task was timed and formed the raw score for the task. The aerobic fitness of the Norm group was $39.9 (\pm 5) \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ and $3.3 (\pm 0.4) \text{ l}\cdot\text{min}^{-1}$.

The mean VO_2 for the Norm group during the drill was $2.5 \text{ l}\cdot\text{min}^{-1}$, which represented 76% of the group’s $\text{VO}_{2\text{max}}$. Mean (SD) heart rate during the drill was $173 (9) \text{ b}\cdot\text{min}^{-1}$ (over 90% of their age predicted maximum), and the mean task duration was ~9 min (range 5.5 to 14 min). The minute ventilation for the drill was $46.7 (3.4) \text{ l}\cdot\text{min}^{-1}$ (range 39.9 to $51.8 \text{ l}\cdot\text{min}^{-1}$) - significantly higher than that used by UK SCBA entry tables ($40 \text{ l}\cdot\text{min}^{-1}$, see comments under Respiratory Factors and SCBA). Considering the relatively low temperatures encountered (54 °C), these values might be considered to be modest although the volunteers are likely to have reduced their exercise intensity if the drills had been performed in hotter temperatures.

In 1991 and 1992 Sothmann and colleagues investigated firefighters’ F_C responses to exercise in SCBA. During the initial study (1991), the F_C and VO_2 of 10 professional firefighters ($\text{VO}_{2\text{max}} \sim 40 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) were monitored during treadmill tests in the laboratory, and during hot fire-simulations in a drill-house. The treadmill assessment produced an $F_C:\text{VO}_2$ relationship for each volunteer, which was then compared with the VO_2 measured during firefighting simulations (Sothmann *et al.*, 1991). The simulations involved 10 firefighters completing the same drill as described Table 5.4.

Group mean (\pm sd) heart rate during the drill was $176 (\pm 10) \text{ b}\cdot\text{min}^{-1}$ and the mean VO_2 was $31.0 (\pm 7.0) \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$. These results showed that the treadmill derived $F_C:\text{VO}_2$

relationship significantly *overestimated* the actual VO_2 during the simulated tasks by ~20%. This suggested that firefighting activities performed in modest heat (54°C) elevated exercise F_C to a greater extent than it elevated O_2 . Using multiple regression analysis the authors produced a correction factor⁸ that accounted for 59% of the variance associated with the prediction of VO_2 during firefighting tasks.

The authors attributed the anomalous results to the type of exercise performed by firefighters. There is abundant evidence to support the hypothesis that F_C levels tend to increase when exercise is performed in the heat (Åstrand and Rodahl, 1986; Duncan *et al.*, 1979), and during isometric (as opposed to isotonic) muscle contraction. Heart rate can also become elevated during times of high psychological stress (Cox, 1985). All of these factors are present during firefighting emergencies.

In addition to the F_C results, the report also showed that during the simulated firefighting tasks, there was a significant inverse relationship between the performance time and the relative $\text{VO}_{2\text{max}}$ at which the volunteers worked. These results confirm not only that firefighters are able to self-select their work intensity but also that the mean intensity selected was 73 % $\text{VO}_{2\text{max}}$ for a 9 min scenario. The fitter the firefighters were, the faster they performed.

In a follow-up study, Sothmann *et al.*, (1992), monitored the same volunteer group during real emergencies. Volunteers' F_C was recorded while fighting structural fires and a single mean individual F_C was derived for each emergency monitored. The firefighters worked in SCBA for ~15 min (range 8-28 min), and exercised at a mean F_C of 157 (± 8) $\text{b}\cdot\text{min}^{-1}$ (~88% $F_{C\text{max}}$). Using the corrective formula derived during the earlier study (Sothmann *et al.*, 1991), the VO_2 during the emergencies was estimated to be 2.05 $\text{l}\cdot\text{min}^{-1}$ and 25.6 $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ (a mean of 63 % $\text{VO}_{2\text{max}}$, range 44 - 86%). These corrected results are lower than those measured during other simulated firefighting activities (Davis *et al.*, 1982; Louhevaara *et al.*, 1985; Romet and Frim, 1987), though the duration was longer.

Another important conclusion of the Sothmann *et al.* review (1992a) was that existing firefighter simulations failed to replicate adequately the actual environmental and work demands that “stress the circulatory and pulmonary systems” of firefighters (pg. 29). This highlights the need for adequate, task-specific, controlled and standardised firefighting assessment protocols.

A problem with the Sothmann *et al.* studies is that work rate of the volunteers during the simulated and actual firefighting tasks could not be described in detail nor was the time spent performing each individual task recorded. For example, in the first study it is not known how long each firefighter spent in the 54 °C room, and in the second study, safety considerations meant that the firefighters could not be monitored inside the domestic buildings during the actual emergency calls. The researchers had to rely on post-activity interviews to determine the physical tasks performed. The authors used their error estimation to predict the aerobic demands of the tasks using only a single mean heart rate for the whole task (~15 min duration). The authors then go on to advocate a minimum aerobic standard for working firefighters from these assumptions.

As a prelude to developing a standardised fitness screening protocol for firefighter applicants, Canadian researchers attempted to characterise the physical demands of firefighting (Gledhill and Jamnik, 1992). For their study, an initial task analysis of all firefighting duties was followed by a physiological characterisation of those tasks

⁸ Fire suppression $\text{VO}_2 = 1.09$ (treadmill VO_2) -11.37, $r^2 = 0.59$ (SEE not reported), Sothmann *et al.* (1991).

deemed by firefighters to be the most physically demanding. The following tasks, ranked in order of difficulty, were considered to be the most physically demanding by Canadian firefighters who responded to a survey (pg. 209):

- Carrying equipment up stairs in a high-rise building
- Advancing a charged hose
- Breaking down doors, walls, ceilings, and roofs
- Raising ladders
- Working overhead with a pike pole or other equipment
- Rescuing victims
- Raising or lowering equipment from high-rise windows via ropes
- Vehicle extrications
- Carrying equipment long distances from a truck to a fire site.

Gledhill and Jamnik (1992) weighed all of the equipment carried by firefighters and used a cable tensiometer to determine the forces involved in hoisting, dragging and pushing items during normal firefighting training operations. Data on the F_C , O_2 , and blood lactate⁹ of 60 firefighters were collected during a total of 27 individual task elements.

It is not possible to describe all of the so-called “Representative Sample of Physically Demanding Firefighting Operations” but those tasks that are similar to ones already described are presented in Table 5.5. Volunteers were asked to perform the tasks in ‘a normal firefighting manner’.

<i>Description</i>	<i>Duration s</i>	<i>F_C b min⁻¹</i>	<i>VO₂ ml kg⁻¹ min⁻¹</i>
Climbing up high-rise stairs carrying a Halligan tool	128	163 (2)	44.0 (1.5)
Advancing 2.5inch charged hose	39	166 (7)	30.9 (3.0)
Remove 90kg dummy and drag it along a hallway	25	148 (14)	20.0 (1.3)
Hoisting equipment (wet hose to dry – under running)	188	135 (8)	26.3 (1.7)
Perform 20 pulls on a pike pole simulator	39	161 (6)	23.6 (1.3)

Mean F_C and VO_2 during the most intense activity (carrying equipment up stairs) were $163 \text{ b} \cdot \text{min}^{-1}$ and $44.0 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$, respectively. Strength applications included lifting and carrying weights (up to 36.3 kg), pulling objects (up to 61.4 kg), and working with objects in front of the body (up to 56.8 kg). The most demanding activities elicited peak

⁹ Lactate (lactic acid) is a bi-product of anaerobic muscle contraction and can be used to assess the aerobic/anaerobic, or intensity of physical work.

lactate concentrations of between 6 and 13.2 mM, indicating that firefighting operations utilised a “substantial involvement of the anaerobic energy system” (Gledhill and Jamnik, 1992, pg. 212). These results match those of confirming earlier research (e.g. Manning and Griggs 1983). Furthermore, ~90% of the activities monitored demanded a mean VO_2 of $23 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$. Both maximum and mean VO_2 values represented 85% and 50% of $\text{VO}_{2\text{max}}$, respectively. These researchers recommended that a minimum $\text{VO}_{2\text{max}}$ standard of $45 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ be maintained by all active firefighters (Gledhill and Jamnik 1992, pg. 212), and this is the standard currently required of UK recruit firefighters (Home Office 1984-1985).

Although the work of Canadian, US and UK firefighters is ostensibly the same, there are one or two strategic differences that may need to be considered when reviewing this research. For example, low-level domestic buildings in the US and Canada tend to be wooden framed and ‘dry-walled’ which enables firefighters to break through walls and ceilings to gain entry to the fire site much more easily than is possible in the UK. Furthermore, US and Canadian firefighting tends to have specific roles (e.g. SCBA wearers, axe men etc.). This suggests that any aerobic fitness standards set for these firefighters may not necessarily be apposite for firefighters in the UK who tend to have a more generic and inclusive role.

Lusa and co-workers (1993) investigated the physiological effects of “smoke diving” tasks on Finnish recruit firefighters. While wearing SCBA and full fire-protective clothing, 35 healthy firefighting students (19-27 yrs) performed a standardised smoke-diving drill (entry into a hot smoke-filled room); simulating a shipboard fire. The task took place in a solid metal building (15 x 15 x 10 m) with a mean room temperature of 110 °C. The volunteers were required to search for and rescue a 70 kg dummy and were asked to complete the drill carefully without competition (task duration ~17 min).

During the exercise the volunteers’ mean heart rate was $150\text{b}\cdot\text{min}^{-1}$ (79 % $F_{C\text{max}}$ as attained in a laboratory cycle-ergometer test). Volunteers’ peak F_C reached 95% of max at the height of the exercise and the estimated VO_2 was $2.4 \text{ l}\cdot\text{min}^{-1}$, which represented 60% of the volunteers’ $\text{VO}_{2\text{max}}$. This smoke-diving exercise was seen as physically very demanding even for the young and fit subjects.

Lusa *et al.*’s (1993) study is a good example of a strenuous simulated firefighting task, but the high temperatures inside the room precluded the use of gas analysers. VO_2 data were estimated from the drop in pressure of the SCBA cylinders and utilising a non-validated conversion factor to estimate oxygen consumption.¹⁰ Once again this report demonstrates the difficulties involved in assessing the metabolic demands of actual firefighting simulations and highlights the dangers of predicting metabolic loads from laboratory-based relationships (see Sothmann *et al.*, 1992).

A similar piece of research was conducted in Sweden by Lindvik *et al.* (1995) who monitored the metabolic demands of shipboard firefighting in a small group of whole-time firefighters. They documented the physical stress on firefighters wearing SCBA in order to establish concrete requirements/guidelines of their general fitness. Although medical tests were conducted on the firefighters and some anthropometric data were presented in the report, the baseline treadmill test was sub-maximal and lasted only 8 minutes (7° incline and $5.6 \text{ km}\cdot\text{hr}^{-1}$). Group characteristics were $n = 12$, age 36.5 (range 28-46) yrs, mass 78.17 (63-89) kg.

¹⁰ Lusa *et al.* (1993) assumed that $22.5 \text{ l}\cdot\text{min}^{-1}$, equated to $1 \text{ l}\cdot\text{min}^{-1} \text{VO}_2$. This correction factor was taken from the work of Louhevaara *et al.* (1984).

Field tests were performed in simulated shipboard conditions. Variables measured during the tests included blood pressure, body mass, RPE data, lactate (assayed from capillary blood taken from the finger), heart rate, air use (from pressure drops in SCBA cylinders from start to end of the test). Volunteers fought pallet fires in a three room mock-up of a ship. There were 4 scenarios and the volunteers wore full turn-out gear including SCBA (see Table 5.6).

Name	Description	Time (sec)	F_c range b min⁻¹	Rise in core temp	Air use l' min⁻¹
Search and Rescue in a cold environment	Carry a 38 mm hose and nozzle under 8 Bar pressure. Cut a log using a chainsaw, search for and rescue a dummy (52 kg)	34	140-160	1.2°C	39.3
Search and Rescue in a hot environment	Carry a 38 mm hose and nozzle under 8 Bar pressure. Cut a log using a chainsaw, search for and rescue a dummy (52 kg)	31	170-190	2.4°C	44.5
Cold and warm missions using two charged cylinders	1 - Walk 900 m, enter a building and climb 45 m vertical height	59	>200	3.2°C	68.6
	2 – Carry hose up and down ladders, walk 150 m and change air cylinders				
	3- Hot search fire suppression (see above)				
	4 – Remove SCBA helmet and gloves and complete a puzzle				
Penetrating hot environments	1 – Hot search/fire suppression Carry a 38 mm hose and nozzle under 8 Bar pressure, follow designated route	37		2°C	64.5
	2 – Repeat activity after a short break				

Under the hot conditions the temperatures were 800 °C at ceiling level and 5-600 °C at 2 m above the floor. The results showed that firefighters using SCBA are “subjected to extremely demanding physical and psychological stresses that are so extreme, that they border the capacity of what a human body can withstand...” (pg. 2). The results also show that “physiological strength as well as experience is of major importance for safe and efficient performance” (pg. 29).

The Lindvik *et al.* (1995) study is interesting because the exercise drills were realistic and complex. However the measurement methodology was weak - estimating air use from pre- to post-exercise drops in cylinder pressure is crude and subject to wide error variance. Modern systems are available that can measure and store minute-by minute drops in cylinder air pressure. Other weaknesses include the lack of an aerobic/anaerobic fitness profile of the volunteers – without this information it is not possible to ascertain how hard they were working relative to their individual exercise maxima. The thermocouples in buildings were not positioned at the same level as subjects who would have stayed low to the ground during the tests (note the 25-30% drop in temperature in the two measures noted).

Smith and co-workers in 1996 assessed the physiological and psychological responses of 15 US firefighters to firefighting training drills. Subjects performed two simulated firefighting tasks: advancing a fire hose (unspecified type), and chopping on a wood block set 1.2 m above the ground. The tasks were performed for 8 minutes each and were set inside a structure that contained controlled fires (ambient temperature 77-93°C). Unfortunately, as in the Lindvik *et al.* (1995) study, they did not report the baseline fitness profile of their volunteers.

The firefighters wore full PPE including SCBA (mean total mass 23.2 kg). The tasks were designed with input from BA training instructors who also monitored volunteer performance. In general the results showed that 16 minutes work in warm ambient temperatures was sufficient to produce significant increases in heart rate, core temperature, and perceptions of exertion and thermal load. In fact the results suggested that the physiological load was “substantial” (pg. 1067).

Smith *et al.* followed up this study the following year and reported the effects on the physiological and psychological responses of 16 male firefighters to a different training drill. The drill consisted of a simulated ceiling ‘overhaul’ (using a tethered bucket weighing 10 kg that was suspended by a cable from a ceiling). Volunteers were required to raise the bucket 68.6 cm, by pulling down on the cable with a Pike pole (1.3 kg). Volunteers performed the task at a rate of 12 pulls·min⁻¹ (entrained by a verbal count). The task lasted for 16min and was performed in two temperature conditions, cool (13.7 °C) and hot (89.6 °C). Although the above task is not necessarily relevant to the work of UK firefighters it does show that researchers had begun to control the timing and work rate of volunteers performing simulated firefighting tasks.

Williford *et al.* (1999) examined the relationship between physical fitness and performance of firefighting tasks and described the metabolic demands of the tasks on 91 US firefighters, of ~32 years of age (see Table 5.7). The drill was performed at a ‘steady but rapid pace’ (pg. 1181) and the volunteers had 6-weeks to practice the test before the test-day. The test was performed in full firefighter turnout gear and SCBA. Output measures were the start, finish and intermediate times. The total mean task duration was 304 (±138) seconds.

Results showed that the volunteers exercised at a mean of 92 %F_Cmax (similar to the results of Sothmann *et al.*, 1990) and demonstrated that they were working at near maximal levels. Results also showed a strong association between performance times and volunteers’ % body fat, aerobic fitness (measured via a 1.5 mile run), grip strength, sit-up and pull-up scores, and their height and weight.

The authors developed two linear regression models from the baseline physiological data and the total task duration for the whole group. The second model predicted firefighters’ test performance using their fat free weight, time to complete a 1.5 mile

run, and the number of pull-ups (chin raises) performed. The formula is reported to have a reliability coefficient (r^2) of 0.53 and a standard error of estimate (SEE) of 96 s. In other words their predictive formula could account for only about half of the variance associated with the prediction, and the SEE is only accurate to ~32% of the reported total mean duration. It is doubtful, therefore, that this formula is reliable enough to be used to predict firefighter performance from the three physiological measures and therefore could not be used as either an entry qualification or as an indicator of incumbent firefighter performance.

Table 5.7. A 5-stage firefighting simulation, Williford *et al.* (1999)

Task	Description	Duration Mean (SD) s
Stair Climb	Volunteers climbed to the top of a drill tower carrying 30.3 m hose (22 kg)	54 (14)
Hoisting	Volunteers hoisted a section of hose (16.36 kg) to the top 5th floor of the tower	32 (22)
Forcible Entry	Use a sledge hammer (4.1kg), to drive a metal beam (75 kg) over 1.52 m	30 ~(19)
Hose advance	Advance a charged hose (3.8 cm) at rapid pace a distance of 30.5 m	19 (19)
Victim rescue	Drag a 79.5 kg mannequin backwards for 30.5 m	48 (29)

A major weakness of the Williford *et al.* (1999) study was the baseline physiological data collected on their volunteers. Full laboratory-based assessment of volunteers' aerobic status might have strengthened their data and may have improved the accuracy of their predictive models, although these data would not be available to recruitment panels (a reason for using the 1.5 mile run time in the first place). In general though, this study confirmed what was already assumed to be the case, i.e. firefighters need to be lean, aerobically fit and reasonably strong in order to complete their work efficiently and safely.

5.1.5 2000 and Onwards

Smith *et al.* (2001) reported on the effect of strenuous live-fire drills on cardio-vascular (c-v) and psychological responses of firefighter recruits. The study monitored the c-v (heart rate, stroke volume, and aortic blood flow) in 7 healthy male firefighter recruits. During the drills the recruits wore full turn-out gear plus SCBA (total mass 26.2 kg). The test drills are similar to those described throughout this section (see Table 5.8).

Table 5.8. Simulated firefighting tasks, from Smith *et al.* (2001)

Name of Task	Description
Dummy drag	Volunteers descended 15 steps and dragged a 'hose dummy' (24.1 kg), on hands and knees around the perimeter of a room (4.3 by 5.5 m)
Extinguisher carry	Involved carrying a 5-gallon bucket (23.6 kg) up 2 flights of stairs (30 steps). They then discharged a 2.5 gal hand pump
Hose hoist	Involved hoisting a hose (19.5 kg) up and down a drill tower (total of 16.8 m), in a controlled manner
Wood chopping	Volunteers finally descended 15 steps and performed a chopping task. This involved moving a log of wood (109 kg), along a bench a total of 152.4 cm, using a horizontal chopping action with a sledge hammer (7.3 kg)

Heart rate results showed that the volunteers worked at or near their F_{Cmax} (as predicted by the 220-age formula, Astrand and Rodahl 1986), and that by 16 minutes after test termination they had recovered to pre-test values. Volunteers' ratings of perceived exertion (RPE_x) also indicated that they had worked near their limits of their tolerance.

It is interesting to note that in the 3 papers from Smith *et al.* reviewed in this section, 3 different simulated drills were used in their investigations. It seems that no standard drill has been accepted by the US Fire Services (at the time of their publications Smith *et al.* were located in the University of Illinois), even though many investigators from the US have expended a great deal of time and effort assessing firefighters during simulated tasks.

The penultimate published paper to be reviewed in this section (Bilzon *et al.*, 2001) is perhaps the most interesting in that volunteers' work-rates while performing the simulated firefighting activities were closely controlled. The researchers attempted to quantify the metabolic demand of simulated shipboard firefighting procedures currently practised by Royal Navy (RN) part-time firefighters, and to identify a minimum level of cardiovascular fitness commensurate with satisfactory performance. 49 volunteers (34 males and 15 females) were monitored during the study. Volunteers' baseline VO_{2max} was assessed using a standardized treadmill test, (mean scores males $52.6 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$, females $43.0 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$), and F_{Cmax} . During the main trials, volunteers were randomly assigned to complete several 4-min simulated shipboard firefighting tasks. The tasks are described in Table 5.9.

The tasks were performed at a work rate that was endorsed as a minimum acceptable standard by Training Officers. The volunteers wore two different styles of dress, the RN firefighting ensemble and the Action Working Dress (neither style is used by UK civilian firefighters). Volunteers' F_C and VO_2 were recorded at 10-s intervals during rest, exercise and recovery. Participants completed all tasks within an allocated time with the exception of the DC task, where 11 subjects (all females) failed to maintain the endorsed work rate. The drills were designed to last 4 min so that an almost *steady-state* metabolic demand could be assessed during the final minute of the exercise.

Table 5.9. Simulated shipboard firefighting tasks (data are means (SD)), from Bilzon *et al.* (2001)

<i>Task</i>	<i>Time (min)</i>	<i>Description</i>	<i>Peak VO₂ ml kg⁻¹ min⁻¹</i>
Boundary cooling (BC)	4	Hose was supported in right hand (10 kg), and then operated in a figure of 8 patterns across a bulkhead for 20 s before shutting off for 10 s. The cycle is repeated 8 times in 4 min	23 (6)
Drum carry (DC)	4	Foam drums (30 kg) were carried down 2 flights (4 m) and walked down a 25 m hallway. The route was performed 4 times each circuit taking 1min	43 (6)
Extinguisher carry (EC)	4	A foam extinguisher (11.2 kg) was carried along a route to include stairs (vertical height 4 m) and a simulated ship's deck (total distance 32 m). The route was performed 4 times each circuit taking 1min	39 (4)
Hose run (HR)	4	16 x 12.3 hose-reels (7.1 kg) were unreeled during a 4 min period.	38 (5)
Ladder climb (LC)	4	Subjects carrying a charged hose under one arm, descended a ladder (2.8 m), released hose, walked 14m and climbed back to the start. The route was performed 6 times in 4 min	38 (5)

Performing the tasks required a group mean metabolic demand of 32.8 ml·min⁻¹·kg⁻¹. The tasks also elicited heart rates between 89 and 92% of maximum in the females and only slightly less in the male volunteers. The report estimated that healthy subjects can sustain such firefighting tasks at ~80% VO_{2max} when wearing SCBA for this duration (16 min), and recommended that RN personnel achieve a VO_{2max} of 41.0 ml·min⁻¹·kg⁻¹ as an *absolute minimum* standard. Subjects with a higher VO_{2max} would be able to complete the combination of tasks listed with greater metabolic efficiency and less fatigue, and therefore be more effective.

The methodology used in this study represents a breakthrough - using steady-state measures may be the only way to ensure that the metabolic data collected are accurate and realistic (see comments ref. Lemon and Hermiston, 1977b). The Bilzon *et al.* (2001) study is the only one found that has taken steady-state measures during complicated and realistic tests. Unfortunately, the cool ambient conditions, the RN personnel monitored (not firefighters), the shipboard firefighting drills and the PPE worn mean that the results cannot be transferred directly across to Local Authority firefighting tasks. The methodology used and the design criteria for the task simulations may however, be worthy of duplication in a civilian Fire Service setting.

5.2 WILDLAND FIREFIGHTING

Although wildland firefighting is currently a major issue for the international firefighting community, very little on the subject has been published in the peer-reviewed scientific literature. A number of conference abstracts and presentations have been given to various scientific gatherings, but little of substance can be gathered from short articles of this sort as the data presented and methodologies cannot be scrutinised. Literature evidence is scarce and it is suspected that much of the difficulty lies in collecting data on geographically dispersed firefighters performing extended,

difficult and uncontrolled tasks in wild and undulating terrain. In a review article for Fire International, Budd and Brotherhood (1998) précised the findings of a research project that studied the physiological effects of wildland firefighting on Australian firefighters.

In this article the authors correctly point out that although firefighting simulations had provided useful information, their relevance to actual wildland firefighting was unclear because such simulations could not reproduce “the complexity of the wildfire environment, nor the firefighters behavioural responses to it” (pg. 25). The authors proceed to discuss the results of Project Aquarius, “the first comprehensive investigation to have been made of firefighters in action against real forest fires” (pg. 25).

During the project four 7-man crews (sic) were studied while they fought well-developed experimental fires. Their firefighting method was to build a 1 m wide gap in vegetation (a ‘fire line’) around the whole perimeter of the fire. Scientists monitored various physiological variables and used themselves as controls; they were in the same warm environment but performed far less physical work. The results obtained were reported as consistent between the 4 crews, three summers and two states (Western Australia and Victoria) and are presented in an official Australian Government publication (Budd *et al.*, 1996). Unfortunately at the time of preparing the present review, a copy of this document was not available. A summary of its major findings as reported by Budd & Brotherhood (1998) are presented below:

Work load: *Firefighters paced themselves at their preferred work rates (as has been noted in many other studies), but their energy expenditure during firefighting had a mean of 488 watts (estimated as a VO_2 1.45 l.min⁻¹)¹¹. This demonstrates the moderate-intensity nature of the extended activity.*

Heat Exposure: *Fire increased the ambient temperature by only 3°C and had a negligible effect on wind speed and humidity (Australian conditions). The radiant heat exposure was ‘little more than sunlight’ (again Australian norms!). It is interesting to note that the firefighters worked with bare face, hands and forearms (demonstrating pragmatic choice of clothing when performing extended tasks in the heat!). Fortunately, under these conditions using this clothing ensemble the firefighters were able to keep a safe distance between themselves and the fire.*

Heat Balance: *The main challenge of wildland firefighters’ PPE was to let (metabolic) heat out rather than to keep the (fire generated) heat out. The combined heat load faced was 688W (488W from metabolic work and 200W from fire and weather). Volunteers’ core temperature was maintained by normal metabolic means (i.e. sweating).*

Clothing: *Clothing for wildland firefighting needs to have high vapour permeability, low weight and low insulative properties. It must also expose some bare skin to allow firefighters to sense and thus control their exposure to the radiant heat. The lightweight clothing worn in the Aquarius Project maintained volunteers’ thermal equilibrium (as measured by rectal thermometry).*

Physiological and subjective responses: *Volunteers’ mean F_C and core temperatures rose by 70 b.min⁻¹ and 0.8 °C, respectively, during firefighting tasks due to effective work rest schedules. Firefighters felt the work to be ‘somewhat hard’, that they were just ‘too warm’ and ‘wet’ with sweat (mean responses to RPE_x scales). Temperature*

¹¹ 488 W = 488 J.sec⁻¹ = 7 kcal.min⁻¹ = 1.45 l.min⁻¹.

data showed that the existing heat stress guidelines were not relevant to this activity as the volunteers physiological variables failed to reach those predicted by the tables for the conditions faced.

Water use: *Firefighters sweated at the rate of 1-2 l.h⁻¹, but only replaced 45% of the fluid loss by drinking, leading to dehydration. One of the strongest recommendations of this report was to monitor more closely the hydration levels of wildland firefighters.*

Fitness requirements: *Although the fitness requirements of wildland firefighting are high, self-pacing of effort meant that the firefighters were able to cope with the demands of the work. However, the fitter firefighters were more productive (as would be expected) and equipped with sufficient 'emergency reserve' to cope with most emergency situations as they arose. The same was not true of the less-fit volunteers.*

Perhaps the most interesting findings of the Aquarius project are that the volunteers were not exposed to a serious thermal load and were able to move away from the direct radiant heat when they felt the fire was getting too close. This was a simulated Wildland study and the fires were initiated under controlled conditions. Whether firefighters during actual wildfires can exert the same amount of control over their exposure is open to debate, but it is expected that under certain circumstances the thermal load would be quite severe. Another point raised in this study is the need for task specific clothing, a point that has been raised by serving firefighters in discursive essays printed in Fire International Magazine (e.g. Scott, 2001, not reviewed in this document). Finally, as is often the case with exercising individuals, it was evident that the volunteers' sweat rates were high but that they were not drinking enough fluid to maintain a state of normal hydration. This point was also noted in a US study on the total energy expenditure of Wildland firefighters (Ruby *et al.*, 2002, see below).

It might be argued that the test conditions in the Aquarius Project bear little relationship to the work of UK firefighters; ambient temperatures in the Australian 'bush' are not the same as those seen in heathland fires in the UK. However, in an unpublished research project Davies (2001, see below) suggests that dehydration is an issue for firefighters operating in cooler climates.

Davies (2001) monitored the weight loss of 15 trainee firefighters (13 male and 2 female) to assess their hydration status during simulated RTA drills (see Table 5.10). Three simulated RTA procedures were completed over a 3-day period, one per day. Nude body weights were recorded pre and post exercise. The RTA simulations were completed in full turnout gear and safety goggles but no SCBA. The tasks varied from (1) casualty carer; (2) cutting equipment operator; (3) supply and carry of all operational equipment required; (4) observer of operations. The weather conditions for each test day were overcast, with a moderate wind, ambient temperature ~13°C.

Table 5.10. Fitness characteristics of volunteers, Davies (2001)

Characteristics	Male (n=13)	Female (n=2)
Age yrs)	27.4 yr ± 3.9	26 ± 4.2
Height (cm)	179.4 ± 4.8	158.8 ± 8.8
Weight (kg)	82.0 ± 11.9	59.5 ± 6.4
Body fat (%)	15.4 % ± 2.3	21.9 % ± 3.4
VO _{2max} (ml.kg ⁻¹ .min ⁻¹)	53.9 ± 3.19	52.1 ± 0.2

Results showed significant differences ($p < 0.01$) in pre-post body weight during the simulated RTA procedures, which is indicative of the onset of dehydration. These results seem to confirm that UK firefighters are as prone to water loss through sweating as the Australian firefighters during wildland firefighting (see below), noted above even though very different ambient conditions applied.

The final study reviewed here is a US report on the total energy expenditure of wildland firefighters (Ruby *et al.*, 2002), which showed that a ‘doubly labelled water methodology’¹² could be used to assess the total energy expenditure of wildland firefighters even if they are geographically dispersed, providing the sample is taken at a consistent time. Unsurprisingly, the results showed that the firefighters demonstrated consistently high total energy expenditure (averaging ~ 17.5 mJ·day⁻¹, of which ~ 8.9 mJ·day⁻¹ was categorised as being derived from physical activity) and a tendency to dehydrate.

5.3 KEY TASKS OF UK FIREFIGHTERS

There follows a brief review of some published papers and technical reports produced for the Office of the Deputy Prime Minister and its predecessors relevant to the tasks of UK Fire Services, but some of these have not been published in peer-assessed journals.

Oldham *et al.* (2000) investigated the validity of simulated work tasks in relation to real life firefighting. They assessed 4 drills that had been used regularly as part of recruit training courses run by the Manchester Fire Service and compared them with simulations performed on a test rig. The results of this study will not be discussed at length here as they concentrate on issues of muscle fatigue (EMGs were used in the assessment) and exercise duration. However, it is of general interest to note the tasks considered by a UK Fire Service to be ‘key’; see Table 5.11).

Results of EMG data suggest that two of the simulated tasks (9 m ladder and hauling an extended line) were not significantly different than the real firefighting tasks and are therefore suitable for training and assessment purposes. The other two tasks (13.5 m ladder and dead lift) were significantly different in terms of their muscle demands. The single operator extending the 13.5 m ladder elicited significantly more muscular demand than the real task and necessitated a reduction in test rig weight. The dead lift was significantly different in the simulation as moving a barbell proved to be significantly easier than moving a quarter share of an LPP.

¹² Doubly labelled water is $2\text{H}_2\text{O}$ and H_2^{18}O , an orally taken marker to assess whole-body hydration status from urine samples.

Table 5.11. Key tasks as designed by the Manchester Fire Service, from Oldham *et al.* (2000)

Name of Task	Drill Description	Simulation
9m ladder	Under-running a 9 m ladder to the vertical position. The base is maintained in position by 2 colleagues	Under running a 9 m ladder on a simulation rig.
Dead lift	Dead lift of a 'light-weight' portable pump (normally a 2-4 person task)	Dead lift of a barbell with a 50 kg weight (single person simulation)
13.5 m ladder	Placing a 13.5 m ladder on a fire engine, (normally a 2 person task)	Placing a 'stripped down' 13.5 m ladder on a fire engine (single person task)
Hauling an extended line	Hauling an extended line on a 13.5 m ladder	Hauling an extended line on a simulated rig containing a 50 kg weight.

5.3.1 Practical Aptitude Tests for Fire Service recruits (David *et al.*, 1995)

In Part I of the study David *et al.* (1995) monitored training tasks, the physiological capacities required of firefighter recruits, and conducted a review of the tasks identified as 'key' to firefighting. They monitored training drills and took measures of volunteers' physiological responses. The tasks monitored are presented in Tables 5.12 and 5.13.

Table 5.12. Drills performed on a UK Fire Service training course, David *et al.* (1995)

Drill	Duration min	Mean (SD)	HR b.min⁻¹	Mean (SD)
Hose	14 (11.6)		149 (15)	
Pump	10 (4.8)		146 (14)	
Ladder	6 (5.3)		136 (19)	
Casualty	2 (1)		149 (21)	
Composite	41 (20)		133 (14)	
BA wear	23 (11)		146 (22)	
RTA	31 (0)		140 (13)	
Water relay	19 (11)		151 (12)	
Fire Extinguishing	4 (4)		129 (9)	

Table 5.13. Metabolic demands (mean (SD)) of selected firefighting drills, David et al. (1995)

Task	Mean VO₂ ml kg⁻¹ min⁻¹	HR (SD) b min⁻¹
Run out and make up a length of hose x 5	38.2 (7.4)	159 (7)
Slip, pitch and stow - 13.5 m ladder	28.5 (8.6)	151 (20)
Slip, pitch and stow – 9 or 10.5 m ladder	27.7 (10.3)	137 (16)
Pump Drill (soft suction)		
- crew number 3	28.4 (4.8)	144 (13)
- crew number 4	33.4 (7.3)	158 (11)
Locate and rescue casualty in firehouse in BA	26.1 (3.9)	149 (17)
Walk carrying a stretcher in SCBA (200 m)	18.6 (2.4)	110 (12)
Walk with stretcher + casualty wearing SCBA (200 m)	26.7 (2.9)	128 (6)

The tasks requiring greatest strength were the carry down, and the light-portable pump carry. The tasks requiring greatest aerobic conditioning were the SCBA wear, the hose running and the water relay. As with all similar studies on the metabolic demands of firefighting drills, the results suggest that firefighters require high levels of strength, aerobic and anaerobic power; and good functional reach, manual dexterity, flexibility, co-ordination, and balance.

The strengths and weaknesses of this report are discussed in Section 6, but in general one strength is that the report presents actual VO₂ and F_C data on training drills on UK trainee firefighters. However, it gives no explanation of the validity of the scoring system used that appears to be based on subjective assessment (of Training Officers) and scored on physical performance, skill and behavioural responses. Further, the validation is based on training drills, not actual firefighting performance, and the results of this study may be 'out-of-date' due to the removal of height and age restrictions on firefighter trainees.

5.3.2 The Physiological effects of wearing SCBA (Love et al., 1996)

This report is also discussed in Section 6 and is referenced elsewhere as Love et al. (1996). It is fundamentally an assessment of firefighters' SCBA, but physiological data are presented. Part of the study investigated the effects of SCBA wear during simulated shipboard firefighting tasks at the Fire Service College in Moreton-in-Marsh. Volunteers' body and skin temperatures were measured pre- and post-exercise, heart rates were monitored continuously and air use was calculated from the pre- to post-test drop in cylinder pressures. The results will not be reviewed extensively here but generally match what would be expected from a series of exercises of this type. Table 5.14 describes the tasks developed specifically for this study and the group mean results.

Table 5.14. Simulated shipboard firefighting (means (range)), Love *et al.* (1996)

Task	Time (mins)	TFC b min⁻¹	Total Air use (l)	Minute volume l min⁻¹ (BTPS)¹³
Short fire exercise	>25	145	1250	47.4
Temp ~100-150°C Wooden pallet fire - firefighter team entered building & descended vertical ladder to 1st floor level ('tween deck). Team conducted a right hand search using a guideline to locate 2 casualties. Casualties were recovered by reversing the entrance route.		(102-198)		
Gastight suit exercise	20	134	1345	74.0
Volunteers wore PPE including SCBA plus gas-tight suits & operated in teams of 4. They lifted and carried containers (25-30 kg) in ambient temperatures of 28-30 °C. Body temps were monitored at 5, 10, 15 and 20 min.		(86-173)		
Long duration exercise	~58	141	2360	44.8
Volunteers followed a guideline down an extended route into the 'engine room' and back. They repeated the circuit and picked up a 50l container and continued to the end of the route.		(93-187)		

The minute ventilation data reported here supports the suggestion that the estimate used to calculate the SCBA entry tables ($40 \text{ l} \cdot \text{min}^{-1}$) under-represents the actual demands of strenuous firefighting (see Section 4.5).

Strengths and weaknesses of this particular study are similar to those of other papers; field information is generated but much of the data is weakened by a lack of control over volunteers' workload, indirect assessment of air use, lack of gas analysis and no RPE data.

5.3.3 Lilleshall Report: A Fitness Standard for LFEPA (Brewer *et al.*, 1999).

This two-phase report was prepared for the London Fire and Emergency Planning Authority (LFEPA). Phase I involved the physiological assessment of 220 personnel (206 males and 14 females) from LFEPA. Phase II was an assessment of the physical demands encountered by firefighters when at work.

Phase II assessed the demands of London firefighting. The researchers monitored firefighter heart rate (F_C) data at 3 Fire Stations for consecutive day-night-day shift over a 1-year period. They also measured F_C and lactate production in 69 firefighters during 8 simulated incidents at the Fire Service College (FSC). The authors predicted the aerobic demands of firefighting simulations (VO_2) using the $F_C:\text{VO}_2$ relationship that was generated in the laboratory (volunteers' $\text{VO}_{2\text{max}}$ was generated using the MSFT).

¹³ Data were converted into Body Temperature and Pressure Saturated (BTPS) - the standard conditions of gas in the lung.

Unfortunately the tasks simulations used are not described in detail in the report, making a detailed review of the results impossible (see Table 5.15).

No.	Task	Duration	F_C (b min⁻¹)	VO₂¹⁴ (ml kg⁻¹ min⁻¹)
1	Ship	45	161	40.0
2	High-rise fire	30	153	32.8
3	Garage	69	122	30.5
4	Guidelines	20	145	36.5
5	Car fire	18	136	35.1
6	Rubbish	15	125	32.0
7	Domestic	60	133	34.1
8	Support action	25	98	25.1

The accuracy of the field-based data presented in the Brewer *et al.* (1999) report is questionable as the assumptions made regarding the relationship between F_C and VO₂ during firefighter simulations are erroneous. Heat and psychological stressors are likely to increase volunteers' heart rate to a greater extent than steady-state exercise alone, and this will tend to render the F_C:VO₂ relationship an *overestimation* of the actual aerobic demands of a task (see review of Sothmann *et al.* 1991). That psychological stress is present in firefighting is confirmed in the report itself, which stated that:

“The single most demanding strain experienced by a firefighter is at the initiation of a call-out, when the station alarm sounds. On a number of occasions, heart rate levels were found to increase to values in excess of 170 b.min-1 (approximately 85% of maximum). This is likely to be a combination of psychological and physiological strain...” Brewer et al. (1999, pg. 30).

Using the authors' methodology, the volunteers' would be estimated as exercising at ~85 % VO_{2max} while they were simply donning their PPE and moving towards the fire engines! Although there is an apparent linear relationship between heart rate and oxygen uptake, this relationship breaks down when work rate exceeds 80% of maximum (Graveling *et al.*, 1999, pg. 59). The relationship also breaks down when other stressors are present that cause heart rates to increase (e.g. psychological stress, thermal stress, dehydration, illness etc.).

5.3.4 The degree of Protection Afforded by Firefighters' Protective Clothing (Graveling *et al.*, 1999)

Graveling *et al.* (1999) assessed the operational effectiveness of fire-kit. Firefighter volunteers wore standard fire-kit during simulated exercises both with and without SCBA. During the tests the volunteers were fitted with heart rate monitors and

¹⁴ Estimated from the VO₂: F_C relationship.;

temperature sensors, pre- and post- exercise weighing was completed to assess total water loss through sweating. The three exercises are described and the results are presented in Table 5.16.

Heat and Humidity Exercise. Volunteers walked a circular route (weaving in and out of obstacles) carrying chemical canisters containing sand and gravel. Obstacles included a small staircase (two steps up and two down), and a horizontal bar at waist height for the volunteers to stoop under. The pattern was repeated for 5 minutes at a steady pace as dictated by the observers. The teams of 4 stopped for temperature data to be recorded.

Radiant Heat Exercise. This exercise simulated wildland firefighting (beating out a grass fire) and was conducted in an enclosed area. Two volunteers at a time beat the floor at a rate of 30 b.min⁻¹ using short handled beaters. The exercises lasted for 2 minutes and were followed by 1 minute of stepping (15 cycles per minute) then a return to the beating exercise for a further 2 minutes. Temperature data were logged away from the radiant heat source (output 7.5 Kw, effective heat source of 10 kW.m²). The test cycle was repeated for a maximum of 6 cycles.

Simulated Real Fire Exercise. A team of 4 entered a building at a high level and passed through a heat barrier created by live pallet fires. They moved down to a lower level and located a charged hose. One pair of firefighters extinguished a fire, the other pair waited nearby. Once the fire was extinguished, the team continued in a searching pattern and the tasking was reversed when a second fire was extinguished. The team retraced its journey to the start point and the exercise was terminated.

Table 5.16. Fire test results (temperatures are °C), Graveling *et al.* (1999)

<i>Exercises</i>	<i>Temperature</i>	<i>Mean Aural Temperatures</i>		<i>Heart rate (b min⁻¹)</i>	
		<i>Without SCBA</i>	<i>With SCBA</i>	<i>Without SCBA</i>	<i>With SCBA</i>
Heat and Humidity	WBGT Temp 33.8 (±3.0)	Range 38.0-38.6	Range 38.3 -38.6	Range 178 - 192	Range 185 – 190
Radiant Heat	30.0 heat source 10k Wm ²	Range 37.5 -37.9	No data presented	Range 176 - 188	Range 181 - 191
Real fire	Not given	No non- SCBA condition	Range 37.9 -38.2	No non- SCBA condition	Range 162 - 190

The study showed that simulated firefighting activities can elicit significant thermal loads and can force firefighters to work at high heat rates for extended periods of time; for some of the volunteers heart rates approached their individually predicted maximum. The results also showed that SCBA increases the metabolic demands of a task, even though the volunteers tended to modify their work rate to compensate for the added load imposed by the SCBA.

The simulated firefighting tasks monitored in this study are interesting but, unfortunately, no air use or gas exchange data are presented, presumably because it

was not a primary requirement of the study. The object of the study was to assess the protection given to firefighters by their fire clothing, not to assess the demands of key firefighting tasks. Prediction of oxygen uptake, calculated from the drop in cylinder mass pre- to post-treadmill exercise are reported and show that SCBA wear generally increases the aerobic demand of a task by ~78%, results similar to those presented in other trials (e.g. Louhevaara *et al.*, 1995). Unfortunately predicted oxygen uptake data are not presented for the firefighting simulations in the Graveling *et al.* (1999) report. It would be interesting to reproduce this trial but from the perspective of quantifying the physiological demands of the task simulations. The thermal effects of firefighting tasks and firefighting PPE are discussed elsewhere in this section.

5.3.5 Physiological Monitoring of Firefighter Instructors (Eglin & Tipton, 2000)

The physiological responses of 13 FSC training instructors were monitored during some 44 firefighting drills (Eglin & Tipton, 2000). The authors monitored volunteers' temperatures at a number of sites and also took heart rate and sweat loss readings. The results of the main part of this study are presented in Section 4.3 but the results from a pilot study are presented here.

Eglin & Tipton (2000) monitored the VO_2 and F_C of 4 instructors during 3 simulated rescues of a 50.7 kg mannequin wearing a SCBA (total mass 66.6 kg). The volunteers wore PPE but no SCBA as the drills were performed in cool temperatures to allow the gas exchange measures to be recorded. The exercises and some major results are presented in Table 5.16. The aerobic power of the volunteers was assessed using a sub-maximal stepping protocol and used F_C at the end of the test to predict volunteers' $\text{VO}_{2\text{max}}$ (after Astrand and Rhyning, 1954).

The exercises took place in the FSC mock-up of a ship and the volunteers wore fire-kit and a respiration and gas analysis system (Metamax, Cortex Biophysik) in place of a SCBA. The exercises lasted between 20 and 100 min and the duration of heat exposure ranged from 4 to 90 min. Pre-test data were taken and gas exchange data recorded every 20 s during rest periods. Heart rate was recorded using a telemetric chest strap monitor (Polar Electro Oy, Finland). No VO_2 data for these tasks are recorded in the report; instead the authors used the VO_2 data to predict the rise in body temperature and to estimate the total energy expenditure in kcal for each drill.

Table 5.17. Metabolic costs of simulated victim rescue (means (SD)), Eglin & Tipton (2000)

<i>Exercise</i>	<i>Duration (s)</i>	<i>Energy expenditure (kcal)</i>	<i>Heart rate b min⁻¹</i>	<i>Predicted Rise in body temp (°C)</i>
Flat drag Mannequin on level concrete surface (30 m)	30 (5)	28.6 (9.9)	155 (7)	0.4 (01)
Low Gantry assisted rescue of mannequin from lower gantry down two sets of ladders/stairs – 3 m descent with 11 steps and 1 m descent with 6 steps).	133 (28)	46.6 (5.4)	160 (5)	0.6 (0.1)
High gantry assisted rescue of mannequin from the upper gantry via a lower accommodation and 'tween decks.	44 (29)	147.6 (15.8)	158 (8)	0.6 (0.1)

5.3.6 The Physical Capabilities of Firefighter Instructors (Elgin and Tipton, 2002)

Elgin and Tipton (2002) followed up their earlier research and investigated whether FSC SCBA instructors would be capable of performing an emergency rescue task after monitoring hot exercise drills. Throughout the hot fire exercises and rescue tasks the instructors wore full fire-kit and either SCBA or a data logger to monitor ventilation and gas exchange. There were two main parts to the study.

In the first part of the study, 10 firefighter instructors undertook 2 simulated rescues that involved dragging a dummy (80.6 kg) along a flat (23 m) and down 2 flights of stairs (see Table 5.17). This rescue task was developed with help of a survey document completed by some 48 Fire Services and took place in the ship simulator at FSC. Volunteers' group mean aerobic power was $43.7 (\pm 9.4) \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ (predicted from either sub-maximal stepping or cycle ergometry). Before this experiment the instructors had not been exposed to heat within the previous 12 hr. The rescue was undertaken approximately 10 min after they had acted as safety officers during hot fire training exercises (hot exercise duration ~ 40 min). In this part of the study all of the instructors completed the task successfully.

In the second part of the study, 7 firefighter instructors undertook a similar rescue drill but this time only ~ 79 sec after being in a hot fire exercise (hot exercise duration ~ 41 min). One of the instructors was unable to complete the task successfully and managed to drag the dummy only 20 m. The tasks took place in a cool part of the simulator.

Table 5.18. Simulated victim rescue (mean (SD)), Elgin and Tipton (2002)

<i>Exercise</i>	<i>Duration (s)</i>	<i>Max Heart rate (b min⁻¹)</i>	<i>Rectal temp (°C)</i>
Instructors dragged a dummy (~85 kg) along a corridor (0.95 m wide and 15 m long) and down 2 flights of stairs (total vertical height 5.8 m).	41.7 (7)	182 (20)	38.29 (0.7)

Although the BA instructors were capable of performing the rescue 10 min after monitoring an exercise in the heat, the rescue tasks resulted in near maximal heart rates suggesting that the instructors had little spare physical capacity. If the rest between simulations in the heat and casualty rescue was reduced to less than 90 seconds, the likelihood of being unable to complete the task was significantly increased. Similarly, if a trainee had required rescuing towards the end of an extended drill in the heat, the instructors may not have been capable of performing a rescue without help from another instructor.

The authors suggested that in “less favourable situations (higher deep body temperatures, greater levels of dehydration, less fit or experienced instructors, or a casualty heavier than 85 kg) a rescue may not be possible” Elgin and Tipton (2002, pg. 3).

Both of the Elgin and Tipton reports have demonstrated the extreme nature of monitoring firefighting drill in hot conditions. The important thing to notice here is that FSC instructors do not actually conduct firefighting activities themselves; they are simply acting as instructors and assessors of trainee performance. It has been noted in a number of studies that BA instructors are adept at using their experience to find optimal (cool) places from which to monitor ‘hot-house’ drills. Despite this the heat

alone was enough of a stressor to hamper their ability to perform an arduous but short duration task. Logically this suggests that actually performing firefighting tasks in hot conditions presents a serious load to working firefighters.

CHAPTER 6

The Fitness and Physiological Requirements of Firefighters

6.1 INTRODUCTION

Given the methodological difficulties in assessing accurately the physiological demands of firefighting, it has proven extremely difficult to determine accurately the best physiological indicators of firefighter performance (see Section 3). This may in part explain the relatively small volume of publicly available research papers that report the physiological demands of UK firefighting, despite the high profile and the at times, high intensity nature of the job.

The Review Team has evaluated the literature presenting the fitness profile of international firefighters, but consider that in general, this information is not directly relevant to the present review, as no direct association can be made between firefighting populations from different countries. However, it may be illuminating to identify those fitness characteristics that other countries have identified as being good indicators of an ability to complete firefighting tasks effectively and safely, and to review these in this section. Additional international fitness data that relate to answering the objectives of this review, but less directly are reported in Table C.1 in Annex C. A small body of evidence exists that identifies the fitness profile of the UK firefighting population, and this section will focus primarily on these reports.

6.2 BACKGROUND: GENERAL HEALTH OF FIREFIGHTERS

It was only when epidemiological studies and medical tests indicated that firefighters seemed prone to ischaemic heart disease (Gardner *et al.*, 1974) and the incidence of coronary heart disease (CHD) in firefighters began to increase (Peabody, 1974; Ralph, 1974) that serious attention was turned to the physical conditioning of firefighters in the US (see Annex C).

Other epidemiological studies have looked at the effects of chronic changes in body composition (e.g. Gerace and George, 1996; Loke *et al.*, 1980) and the pulmonary function of firefighters as it relates to occupational exposure to smoke and inhaled particulates (Bermon *et al.*, 1994; Giudotti, 1995; Large *et al.*, 1990). As expected, the respiratory research largely confirms perceived wisdom, namely, that inhalation of the irritants and particulates prevalent in smoke can damage lung function in firefighters. Furthermore copious studies have shown that firefighters who smoke cigarettes tend to exhibit greater respiratory deficit, greater small-airways obstruction, and perform less well in firefighting tasks than their non-smoking peers (e.g. Loke *et al.*, 1980; Sparrow *et al.*, 1982; Horsfield *et al.*, 1988).

6.3 FIREFIGHTER FITNESS (INTERNATIONAL)

Barnard & Duncan (1975) monitored the F_C responses of 35 male firefighters (aged 23 to 42 yrs) before, during and after emergency call outs. Although no fitness data are presented in the report the volunteers were described as 'being in good health without any overt symptoms of heart disease' (pg 247). Barnard & Duncan observed extremely high F_C responses in all of the volunteers both immediately after the alarm was raised, *en route* to the emergency, and during the firefighting tasks. As expected, short bouts of high intensity firefighting activity elicited high F_C , but the increased F_C monitored while the firefighters were approaching the fire are suggestive of high levels of psychological as well as physiological stress.

Lemon & Hermiston (1977a) reported age-related decrements in all of the variables measured in their study of 45 US firefighters (grip strength, upper body and leg strength, and VO_{2max}). The mean (1SD) aerobic power of the group was 40.6 (5.28) $ml \cdot kg^{-1} \cdot min^{-1}$, and they carried 20.4 (5.0)% body fat. The authors concluded that the US firefighting population were no fitter than their sedentary US peers. Given the physical demands of firefighting, Lemon & Hermiston (1977a) considered that firefighters should be expected to possess a better fitness profile than their sedentary counterparts. The authors also suggested that US firefighters would probably benefit from a structured fitness training programme.

In a follow-up study, Lemon & Hermiston (1977b) quantified the energy cost of some simulated firefighting tasks. The F_C and VO_2 of 20 firefighters were monitored during simulated firefighting tasks, which were performed in fire-kit but without SCBA. The tasks elicited $\sim 70\% VO_{2max}$, and firefighters with VO_{2max} in excess of 40 $ml \cdot kg^{-1} \cdot min^{-1}$ were better able to cope with the demands of the work. This was one of the first papers to recommend a minimum aerobic standard for professional firefighters. These data are reported here as a comparison to the current UK Fire Service entry standards for recruit aerobic fitness (45 $ml \cdot kg^{-1} \cdot min^{-1}$, which is set at that level for recruits in part to allow for expected age-related declines in aerobic fitness).

A number of papers have shown that on-the-job fitness training improves firefighters' aerobic power (by as much as 20%), their general fitness profile and firefighters' work performance (e.g. Puterbaugh & Lawyer, 1983; O'Connell *et al.*, 1986; Smolander *et al.*, 1984). However, if a 12-week exercise training programme elicited a 20% improvement in VO_{2max} (as reported by Puterbaugh & Lawyer), the baseline fitness levels must have been fairly low. This supports many researchers' contention that firefighters are not as fit as they could or probably should be (Kilbom, 1980; Lemon & Hermiston 1977a and 1977b etc.).

O'Connell and others (1986) assessed the energy costs of simulated stair climbing which they considered to be a job-related task for firefighters. They asked firefighters wearing turnout gear and SCBA to climb on a stair-treadmill ergometer (laddermill) for 5 minutes at 60 steps per minute. The 17 volunteer firefighters' aerobic power was ~ 48 (8.6) $ml \cdot kg^{-1} \cdot min^{-1}$ - slightly higher than the mean reported for UK firefighters (see below). These data suggest that firefighters should maintain an aerobic fitness level of at least 39 $ml \cdot kg^{-1} \cdot min^{-1}$ to perform the exercise task comfortably. O'Connell *et al.* admitted that this minimum fitness level did *not* allow for a 'safety margin' for firefighters during extreme emergencies. Further, the authors did not confirm that the firefighters would be fit to perform any firefighting duties at the end of their stair climb exercise modality!

Ben-Ezra & Verstraete (1988) also investigated firefighter responses to laddermill exercise. They recommended, “task-specific modes of training and testing such as stair-climbing be employed for firefighters” (Ben-Ezra & Verstraete 1988, pg. 105). The authors reported that laddermill exercises produced lower VO_{2max} and F_{Cmax} results than treadmill exercises. They monitored the results of 38 firefighters (mean age 35 yrs), with a treadmill VO_{2max} of 43.1 (1.4) and a laddermill VO_{2max} of 40.1 (1.4) $ml \cdot kg^{-1} \cdot min^{-1}$, respectively. It has been understood for years that fitness is mode-specific with different exercise modalities eliciting different metabolic demands (Åstrand and Rodahl, 1986). This is an important factor to consider when relating fitness scores to actual work tasks.

Faff and Tutak (1989) reported that Polish firefighters with a VO_{2max} greater than 39.0 $ml \cdot kg^{-1} \cdot min^{-1}$ were significantly better able to cope with exercise in hot conditions than their less aerobically fit colleagues. These results are similar to the recommendations of O’Connell *et al.* (1986) noted above.

Sothmann *et al.* conducted a series of studies in the early 1990s to determine (among other things) fitness of firefighters and the metabolic demand of firefighting in the US. In 1990 they presented evidence to suggest that firefighters, irrespective of their age, required a VO_{2max} of 33.5 $ml \cdot kg^{-1} \cdot min^{-1}$ to complete a moderately intensive simulated firefighting task of relatively short duration ~13 min (see Section 3). However, the authors confirmed that their minimum standard might not have allowed sufficient emergency reserve to enable firefighters to cope with more demanding emergency tasks. They therefore suggested that “given such contingencies... a more desirable VO_{2max} standard might be 41 $ml \cdot kg^{-1} \cdot min^{-1}$, the minimum standard at which all individuals successfully performed the (exercise) protocol” (Sothmann *et al.*, 1990, pg. 233).

Sothmann *et al.* (1992a) also acknowledged that speed of action in the early stages of a fire is a vital factor in controlling its spread. Therefore, firefighters needed to work quickly and efficiently, especially early in the emergency. Research has shown that individuals with higher aerobic power are able to work harder and for longer than individuals with a lower aerobic power (Åstrand and Rodahl 1986; Davis *et al.*, 1982; Sothmann *et al.*, 1990). The same is true of firefighters - supporting the need for firefighters to exhibit high levels of aerobic power. Furthermore, evidence shows a strong association between increasing age and declining VO_{2max} (Åstrand and Rodahl, 1986; Buskirk and Hodgson, 1987). This argument has been used by some to justify the need for a maximum retirement age for firefighters. This Review Team suggests that the age of a firefighter is irrelevant if it can be demonstrated that they are capable of performing the role with ‘reasonable’ safety. What is needed is a valid and defensible test of firefighting performance. The age argument is moot if a firefighter is demonstrably capable of performing the role. Longitudinal studies have shown that chronic exercise activity can retard age-related declines in VO_{2max} (Åstrand and Rodahl, 1986), further underlining the need for firefighters to incorporate regular fitness training into their work schedules.

Myhre (1997) assessed the relationship between certain physiological variables and performance on simulated firefighting tasks. Myhre monitored 279 US firefighters (272 males and 7 females) during a ‘standardised strenuous task’. The mean aerobic power of the volunteers was ~39.4 $ml \cdot kg^{-1} \cdot min^{-1}$. Myhre noted, unsurprisingly, that performance on the task was significantly associated with volunteers’ VO_{2max} , % body fat and strength. This is one of very many studies demonstrating a relationship between various aspects of fitness and firefighting performance. In general, these reports

confirm that the fitter the firefighter, the better they are able to perform strenuous tasks (e.g. Cheung & McLellan, 1999; Donovan & McConnell, 1999b).

6.4 THE FITNESS OF UK FIREFIGHTERS

Very few large-scale studies have reported the fitness profile of UK firefighters. The reason for this is unclear but may relate in part to the cost of human factors research and the fragmented nature of the UK Fire Service. It is recognised that some Fire Services independently assess the physical fitness of their firefighters, however these data have not been reported here for two important reasons. Firstly, there has been no consistency of data collection either in terms of exercise methodology or of data acquisition methodology among the Fire Services, and secondly, as far as the Review Team is aware, the data have not been collated and no cohesive report is available for review. A summary of fitness data is provided in Table 6.2 at the end of this section, while the key papers are reviewed below.

6.4.1 The Chelsea College Report: Scott *et al.* (1988)

The first and most prominent study of UK firefighter fitness is the Chelsea College Report (Scott *et al.*, 1988). This was the first national project since the addition of an extra fire-watch in the late 1970s to investigate the health and fitness status of UK firefighters. It was a 3-year medical and physiological assessment of firefighters from 6 Fire Services. The aims were to determine how firefighters acquired and maintained their fitness; to identify the level of fitness they maintained; and to develop a greater understanding of what the general fitness requirements of firefighters were.

The project utilised data from questionnaires, fitness tests on firefighters, workload evaluation and a longitudinal study of recruits from the London Fire Brigade. Results showed that most firefighters considered themselves to be above average in muscular strength, stamina and general fitness. The majority stated that firefighters participated in some form of energetic recreational activity in their leisure time but were dissatisfied with the level of physical fitness training they received at work. The aerobic fitness of 40 London Fire Service recruits was reported to be $46.3 \text{ ml}\cdot\text{kg}\cdot\text{min}^{-1}$ (measured via maximal cycle ergometry). For the 300 or so incumbent firefighters tested during the field-based tests (Phase III), their aerobic power was only $43.7 \text{ ml}\cdot\text{kg}\cdot\text{min}^{-1}$ (estimated via sub-maximal cycle ergometry). This aerobic fitness level was considered to be average for the UK male population. The group's respiratory function was reported as above average although this is unsurprising considering that respiratory fitness is an entry requirement for firefighting. Worryingly though, approximately 60% of the sample were considered to be obese or excessively obese, as indicated by the assessment of their body fat.

In their summary the authors stated that the *“daily energy expenditure of firefighters was equivalent to moderate industrial work it was found that most firemen (sic) were physically fit enough to carry out their daily work routine without suffering undue fatigue. However 5 per cent were working at one quarter of their maximum aerobic capacity during a typical work day. When undertaking some drills and fire calls, 25 per cent were working at one half of their maximum aerobic capacity. These would endure undue physical stress at major fire incidents and during some drills”* (pg. 1–Summary).

The authors concluded by recommending that a concerted effort to encourage on-the-job fitness training needed to take place as a matter of urgency and stated that “the undertaking of such fitness training and the maintenance of body weight within the recommended range for height/build will not only help in producing a more efficient workforce but will in addition be beneficial to all personnel when off duty” (pg 30).

Ellam *et al.* (1994) reported that the aerobic fitness and general strength of a group of 40 UK firefighter recruits actually fell following 18-months of firefighting service compared with their fitness levels immediately after completing the recruit training course. These authors reported the results gathered during the Chelsea College Report (1984), which is reviewed below. The Ellam *et al.* cohort had a mean age of 23 yrs, (range 18-30 yrs) and a mean height of 1.77 (0.05) metres. Their mean VO_{2max} after 18 months on station fell from 50.0 (7.3) to 46.3 (7.0) $ml \cdot kg^{-1} \cdot min^{-1}$. Their group mean anaerobic power changed from 628 (168) Watts to 754 (161) Watts, as measured using a standardised cycle ergometer protocol (the Wingate Test, Dotan & Bar-Or, 1983). By the end of the monitoring period the volunteers' body fat had increased from baseline from 16.3 (4.9) % to 19.2 (4.1) % although their lean body mass was unchanged at 62.7 (4.3) kg.

These results throw up an interesting conundrum. According to Ellam *et al.* (1994) the chronic physical work of firefighting was insufficient to maintain the aerobic fitness levels demanded by Fire Service Training Establishments. This could mean that the training demands are unrealistically high and unrepresentative of actual firefighting requirements, or that a large proportion of incumbent firefighters may be unfit to perform the task required of them. Given the current absence of adequate quantification of the fitness profile of current UK firefighters and the poor understanding of the physical cost of firefighting, these questions cannot currently be answered with any degree of confidence.

6.4.2 The Institute of Occupational Medicine: Love *et al.* (1996)

This report investigated the physiological effects of wearing SCBA at work, the main thrust being to examine the efficiency of SCBA. Fitness data are presented on 72 incumbent firefighters (4 of whom were female) with a mean age of 31 years. Their mean height and weight were 1.79 m and 80 kg respectively, and the group mean body fat was 17% (range 10-27%). The results estimated volunteers' aerobic power to be 46.4 $ml \cdot kg^{-1} \cdot min^{-1}$, estimated from sub-maximal treadmill tests using gas exchange data. The aerobic power of these volunteers was slightly greater than that found in the Chelsea College study (Scott *et al.* 1988).

6.4.3 The Robens Institute Report: David *et al.* (1997)

This study investigated practical aptitude tests for recruit firefighters and formed a cornerstone of the recommendations for practical fitness tests for candidates that were promulgated by the Implementation Working Group (IWG) on Point of Entry Selection Tests (PES, Fire Service Circular 11/2000). This report presents baseline data for their recruit volunteers (n = 30, mean (SD)) as: age 25 (3) yrs, height 176 (7.6) cm, weight 70.2 (6.6) kg, and VO_{2max} 55 (5.7) $ml \cdot kg^{-1} \cdot min^{-1}$. VO_{2max} was predicted either from the MultiStage Fitness (bleep) Test or from a cycle ergometer test. However, the low subject numbers, the prediction of fitness rather than direct measurement from ventilation and gas exchange, and the changes in recruitment regulations since the

completion of this study (e.g. removal of age and height limits) weaken the results, conclusions and recommendations of this study.

6.4.4 Lilleshall Report: A fitness Standard for London Firefighters: Brewer *et al.* (1999)

This report was prepared for the London Fire and Emergency Planning Authority (LFEPA) and was conducted in two phases. Phase I involved the physiological assessment of 220 personnel (206 males and 14 females) from LFEPA. Phase II was an assessment of the physical demands encountered by firefighters when at work.

In Phase I the basic anthropometric and fitness data were collected on 46 recruits, 138 whole-time firefighters and 22 non-firefighters (NDF). These data are presented in Table 6.1.

Age (yrs)	No	Gender/ Type	Height (cm)	Mass (kg)	Body fat %	VO _{2max} (ml min ⁻¹ min ⁻¹)
26	46	Male recruits	180	77.4	15.2	52.2
35	138	Male firefighters	177	85.3	17.9	48.1
31	10	Female firefighters	172	67.3	23.5	43.7

Aerobic fitness was assessed using the MSFT. It is interesting to note that ~10% of the male firefighters and all of the female firefighters had aerobic fitness levels below that required for entry to the UK Fire Service (45 ml.kg⁻¹.min⁻¹). Although this entry level was originally set to allow for age-related declines, it has so far not been reassessed to reflect the removal of an upper age limit for recruits.

6.4.5 Assessment methods for predicting Maximal Oxygen Uptake for LFEPA: Evetts *et al.* (2000)

A number of exercise protocols have been used by UK Fire Services to predict the aerobic fitness of UK firefighters. These range from static cycle ergometry, shuttle running to stepping exercises. Two of the most popular methods were assessed for LFEPA - the sub-maximal Chester Step Test (CST) (Sykes, 1995) and the maximal MSFT (Leger and Lambert, 1982), the results compared with those measured directly using ventilation and gas exchange during a treadmill run to volitional fatigue. Both of the predictive tests were shown to *underestimate* the actual VO_{2max} of the subjects. They also showed that the results from CST were significantly more variable than those of the MSFT. In fact, the designer of the CST states that the predictive score produced by the CST is only precise to within 12-15%. It is understood that LFEPA have used the Evetts *et al.* (2000) results to reduce the entry qualification for their candidates (the MSFT pass level at the time was Level 9, Shuttle 4, equivalent to a VO_{2max} of 45 ml.kg⁻¹.min⁻¹).

Shortcomings of using tests like the CST and the MSFT to estimate the aerobic power of individual candidates are that they are not directly task-relevant, they bear little relation to the actual work of UK firefighters and they are predictive tests. The MSFT, while fine for assessing athletes in games like hockey and football (for which the test was designed), is not directly relevant for assessing the aerobic fitness of either candidate or incumbent firefighters. Furthermore it is clear that when using a test with the degree of built-in error such as the CST ($\pm 12-15\%$) as an entry test for individuals, its validity depends largely on where the pass/fail point is set. Passing tests such as these may not necessarily demonstrate an individual's ability to complete standardised firefighting tasks.

6.4.6 Fit for Duty? Seeking a healthier Fire Service: HMFSI (2000)

This Home Office review considered that the advice to fire brigades to provide regular 6-monthly fitness checks (few Fire Services do in fact conduct regular fitness assessments of any kind) for all whole-time operational personnel¹⁵ was insufficient and should be extended to cover retained personnel. The report's authors saw "compelling reasons for ensuring that all operational personnel are fit to undertake the duties required of them" (pg. 76), and recommended compulsory testing for operational personnel and optional testing for non-uniformed and fire control staff. The authors saw three potential benefits of regular fitness testing: assurance that staff were fit to undertake their role, improved health of the work force, and improved attendance at work. In addition to these recommendations the report was generally critical of both the high incidence of sickness absence and ill-health retirement in many brigades and the lack of standardised controlled procedures to document and deal with both sick absence and ill-health retirements.

6.4.7 Point of Entry Selection Tests: Rayson & Wilkinson, for ODPM (2002)

As part of the development work on the Point of Entry Selection (PES) Project being performed by Optimal Performance Ltd. for the Office of the Deputy Prime Minister, a pilot study was conducted at the Fire Service College. In September 2002, field measures of fitness were made on 23 firefighters (Rayson & Wilkinson, 2002). The 23 volunteers from eight different brigades around the country comprised 17 men and 6 women. Of the 23 firefighters, 7 were retained. Mean height and weight were 1.75 m and 82 kg. Body fat averaged 22.3% and fat free mass 63.7 kg. Mean VO_{2max} as estimated from the MSFT were $46.9 \text{ ml.kg}^{-1}\text{min}^{-1}$ and 3.82 l.min^{-1} . Eight of the group had scores below $45 \text{ ml.kg}^{-1}\text{min}^{-1}$, significantly below the minimum standard required for Fire Service recruits. Three of these were below $40 \text{ ml.kg}^{-1}\text{min}^{-1}$ and 1 was below $30 \text{ ml.kg}^{-1}\text{min}^{-1}$.

¹⁵ Promulgated under a Dear Chief Officers Letter (DCOL 2/1996).

Table 6.2. A review of the fitness of UK firefighters

Reference	Description/ Methology	Variable Measured	Results mean ml kg min⁻¹ (1SD)	n	Comments
Bilzon <i>et al.</i> (2001)	Metabolic demands of simulated shipboard firefighting.	VO _{2max} – treadmill and gas exchange.	52.6 (5.2)	34	Royal Navy male firefighters sample data (age ~ 26yrs).
Bilzon <i>et al.</i> (2001)	Metabolic demands of simulated shipboard firefighting.	VO _{2max} – treadmill and gas exchange.	43.0 (8.1)	15	Royal Navy female firefighters aerobic power (age ~26yrs).
Brewer <i>et al.</i> (1999)	Fitness standard for the London Fire Service	VO _{2max} – MSFT.	~52.2 - recruits ~48.1 – firefighters	206	This 'Internal Report' is reviewed extensively in Sections 5 & 6.
David <i>et al.</i> (1997)	From the Robens Institute study in Practical Aptitude tests for recruit firefighters.	VO _{2max} Predicted either from MSFT or cycle ergometry	55 (5.7)	~90	
Donovan (2000) Unpublished thesis	Treadmill tests to determine the respiratory effects of SCBA.	VO _{2max} – treadmill and gas exchange.	52.0 (5.7)	26	Volunteers used were taken from a cohort of experience firefighters, but they tended to be from a sporting background.
Donovan & McConnell (1998b)	Assessing the respiratory muscle strength of firefighters.	VO _{2max} – treadmill and gas exchange.	54.7 (4.8)	8	Small group of firefighter sportsmen.
Donovan & McConnell (1999a)	Effects of SCBA in ventilatory performance	VO _{2max} – treadmill and gas exchange.	56.5 (6.2)	8	Wide age and fitness range of volunteers intentional for study, but may skew data.
Elgin & Lipton (2000)	The effects of monitoring hot drill on BA Instructors	Sub-maximally (stepping and cycle ergometry)	43.1 (7.7)	13	Volunteers were BA instructors.
Elgin & Lipton (2001)	The effects of monitoring hot drill on BA Instructors	Sub-maximally (stepping and cycle ergometry)	43.7 (9.4)	13	After monitoring a hot drill, 1 out of 7 was unable to complete a simulated victim rescue. This demonstrated the effects of heat exposure.

continued

Table 6.2. A review of the fitness of UK firefighters (continued)

Reference	Description/ Methology	Variable Measured	Results mean mi kg min⁻¹ (1SD)	n	Comments
Ellam <i>et al.</i> (1994)	Wingate test on cycle ergometer	Max anaerobic power	754 (W)	40	See above
Love <i>et al.</i> (1996)	Assessment of the physiological effects of wearing SCBA	VO _{2max} , treadmill tests (sub-maximal)	~46.4 ~3.7 l.min ⁻¹	72	Sub-maximal estimation of aerobic power.
Scott <i>et al.</i> (1988)	The Chelsea College Report into firefighters fitness.	VO _{2max} , cycle ergometry sub-maximal)	~46.3	40	This was the fitness status of London Fire Service recruits after 18 months on Station, (see Ellam <i>et al.</i> (1994)
Scott <i>et al.</i> (1988)	The Chelsea College Report into firefighters fitness.	VO _{2max} , cycle ergometry sib-maximal)	~43.7	300	This was the fitness status of volunteers for 6 Fire Services throughout the UK during the Phase III field trial.

6.5 THERMAL TOLERANCE

6.5.1 Introduction

In occupational health and safety, exposure limits to environmental hazards such as noise and vibration are normally based on the susceptibilities of the working population to injury from the agent in question. Commonly, an exposure limit is established based on the exposure level at which the most susceptible 5% of the population would be at risk. By definition, therefore, 95% of the working population could safely be exposed to greater levels. In developing permissible duration for work in elevated temperatures by Mines Rescue men using the SEFA CCBA, Graveling and Miller (1989) indicated that this could be seen as unnecessarily restricting the work of the majority of Rescue men. The authors suggested that operational effectiveness could be improved if those most susceptible to the effects of heat exposure could be identified and excluded from the Service.

Firefighters do require a degree of thermal tolerance to perform safely and effectively in operational conditions involving elevated temperatures or, as is apparent from earlier sections, where clothing and workload factors may themselves create adverse thermal conditions. At present, this would seem largely to be left to self-selection by recruits, coupled with some exclusion during training. However, this situation is not entirely satisfactory and at least one occasion is known of where a trainee firefighter was unnecessarily rejected (Graveling, personal communication).

Graveling *et al.* (in press) briefly touch on this issue in reporting the development of guidelines for firefighter training. They draw attention to the existence of 'heat tolerance' tests in the scientific literature (e.g. Kenney *et al.*, 1986), pointing out that Ilmarinen and Makinen (1992) had recommended the inclusion of heat tolerance testing in the selection procedures for Finnish firefighters.

6.5.2 Heat acclimatisation

In addition to any innate 'tolerance' of the heat there is considerable interest in the extent to which those exposed to the heat can develop further tolerance. The concept of 'heat acclimatisation' is well established in the physiological literature. The process of acclimatisation is widely considered to include both psychological and physiological processes. Psychological acclimatisation can be regarded as 'becoming accustomed to' or 'getting used to' the heat; consciously or subconsciously modifying behaviour to reduce the adverse affect of heat exposure. Mairiaux and Malchaire (1985) describe this process as one of 'self-pacing' where workers in hot conditions will modify their rate of work (if possible) to cope with elevated environmental temperatures.

Physiological acclimatisation is a more complex process involving progressive changes to physiological systems including increased sweat production, earlier onset of sweating, and the production of more dilute sweat (Hanson and Graveling, 1997). Such acclimatisation occurs to a level proportional to the acclimatising environment and requires daily (but not necessarily continuous) exposure. Lind and Bass demonstrated some acclimatisation effects after 100 minutes of daily exposure. Leithead and Lind (1964) state that a degree of acclimatisation is retained for up to one month although they cite work suggesting that much of the benefit can be lost over a weekend of non-exposure. While there is little doubt that whole-time firefighters serving at a busy station will become accustomed to the effects of the heat there must

therefore be some question as to whether genuine physiological acclimatisation occurs to any significant extent among serving firefighters.

Some other physical or physiological factors have been shown to influence heat tolerance. There are clear differences between races and it is probable that genetic factors have some effect on variations in sweat rate (Edholm and Weiner, 1981; Weiner, 1976). Parsons (1993) reports that fit people acclimatise to the heat more rapidly although others (e.g. McLellan and Frim, 1994; Aoyagi *et al.*, 1994) have suggested that improved fitness does not enhance heat tolerance when wearing impermeable (NBC) clothing. Cheung *et al.* (2000) state that individuals with higher proportions of body fat have a lower heat tolerance and McLellan (1998) suggests that women can also be at a thermoregulatory disadvantage when working in the heat while wearing extensive protective clothing. On a daily basis, Parsons (1993) reports that abstaining from alcohol consumption and the use of supplementary vitamin C can also be beneficial.

The interrelationships between these different factors, and the magnitude (if any) of any effect within the firefighter population are not known. Nevertheless, it is important to recognise that there are many factors potentially influencing thermal tolerance and therefore operational effectiveness.

6.5.3 Aids to tolerating the heat

Finally, a number of studies have examined approaches to increasing operational effectiveness by seeking to reduce the impact of heat exposure. Many of these relate to enhancing recovery and are therefore of more relevance to long-duration incidents where re-commitment of firefighting teams might be required. Among these are the studies reported by House *et al.* (1997) advocating the immersion of the hands and forearms in water to accelerate heat loss, or the use of a fan, also to accelerate cooling (Carter *et al.*, 1999). Love *et al.* (1996) recommended consideration of these approaches within the UK Fire Service. Because of the highly insulative nature of firefighters clothing, there is also believed to be some evidence that such techniques can also be beneficial in 'pre-cooling' firefighters prior to committal. In addition, recognition of the role of dehydration in reducing heat tolerance (McLellan *et al.*, 1999a) means that more consideration should be given to ensuring adequate fluid intake before, during and after operations (Stirling, 2000; Williams *et al.*, 1996; Davies, 2000; Budd & Brotherhood, 1996).

Others studies have examined the creation of a cooler microclimate inside clothing through the use of cooling devices such as ice jackets. There is evidence that such devices can be effective in reducing the effects of heat stress (e.g. Affara *et al.*, 1994; McLellan *et al.*, 1999b) although some practical operational difficulties would need to be overcome.

CHAPTER 7

Summary Findings

7.1 PREAMBLE

Modern firefighters constitute a highly skilled and professional service, with a wealth of experience and expertise in dealing with a wide range of incidents and hazardous situations. The UK Fire Services are widely regarded as among the safest and most efficient in the world and the working practices and decision making processes that have evolved and developed since the last war are the main reasons why the service has been so effective. Firefighters and their Fire Officers have an understanding of what is feasible and safe, largely based on their experience. However, with the introduction of new equipment or some new task there is an inevitable delay as experience is acquired before safe and efficient working practices are established. There is also a need to codify safe working practice for operational guidance and training and as the basis for specifications for equipment and building regulations.

It is incumbent, therefore, on planning authorities to see whether the natural process of trial and error in adapting to new circumstances can be circumvented to anticipate and prepare for change. There are a number of ways in which the role and function of the Fire Service may change in coming years:

Changing role: The threat of major disasters as a consequence of terrorist activity has been heightened by recent events in America and Africa. Similar incidents involving tall buildings, nuclear installations, underground systems and chemical and biological contamination have to be considered.

Changing buildings and materials: New materials and construction techniques are making larger and taller buildings more common and changing the nature of the risks such as that of burning plastic releasing toxic fumes.

Changing clothing and equipment: New equipment and clothing generally improves performance but in the process can change factors that limit working time. For instance, lighter BA may change the major physiological challenge from load carriage to thermal exposure.

Changing personnel: The physical and physiological characteristics of personnel are changing with shifting patterns of recruitment. There is a general deterioration in the fitness of the UK population, which is unlikely to improve significantly in the near future, and increasing recruitment of women might also have a bearing on the physical capabilities that can be expected of firefighters.

The intended outcomes for this review and any subsequent research are to:

- Reduce risk from work activity of firefighters
- Improve guidance for firefighter operational practices and training

- Improve planned and dynamic risk assessment
- Modify procedures for building design, approval and use
- Elicit improvements to the Building Regulations.

Central to all these objectives is the need to know how long various levels of work can be sustained under a variety of operational conditions before performance deteriorates significantly. 'Performance' encompasses physical performance such as loss of strength, slowing of movement, loss of manual dexterity but also impaired decision-making and risk assessment. In addition, consideration must be given to the possibility that the physical and environmental demands may present a risk to the health or safety of operational staff.

To the best of our knowledge there are no regulations or guidelines as to how much or how long a firefighter can work, as there are for, for instance, lorry drivers or soldiers on a route march. In practice much of the work is self-paced so questions such as "how far can a firefighter carry a hose" begs the question of how quickly the task has to be completed. The obvious answer is "at a reasonable speed" but there is no definition of what is meant by "reasonable" speed. It is very likely that firefighters do naturally fall into a work pattern where they are working at a reasonable speed but there is no documentation of the actual work patterns when attending a fire or other incident. It is because such basic information is absent that the present review does not attempt to draw even preliminary conclusions about safe working procedures or dimensions of buildings.

The Review Team set out to conduct an international review of literature and report on the extent of knowledge concerning the operational physiological capability of firefighters and to identify the knowledge gaps. This section summarises the main findings about what is and what is not known. Possible avenues for future research are provided at Section 8.

7.2 FIRE SAFETY LEGISLATION

The two major documents that provide the legislative framework for the fire safety of buildings, their occupants and to the Fire Service are the DoE's Design Principles of Fire Safety (1996) and the DETR's Building Regulations (1991). While these documents cover most aspects of new buildings design and materials structure from the point of view of fire safety, commenting on safety egress and Fire Service access in case of emergency, the level of detail from a Human Factors perspective is severely wanting. Where details are specified, such as the provision of firefighting shafts for buildings with floors above 18 metres and below 10 metres for example, lifts are not an absolute requirement, so stair climbing must be assumed to be a possible physiological demand. The specification of a maximum distance of 60 metres from a mains outlet to the limit of the building may provide a limit for hose running, but takes no account of the physiological capabilities.

That no empirical Human Factors evidence is presented or referenced to support the regulations that concern firefighter access is surprising and raises questions as to their appropriateness and relevance. The legislation needs to be revisited in light of more knowledge about reasonable Worst Case Planning Scenarios and ROPS that are expected of firefighters bearing in mind their fitness, the PPE they are required to wear and the environment in which they are expected to operate.

7.3 FIREFIGHTER KEY TASKS

The roles and responsibilities of firefighters in the UK are broad and ill defined from a Human Factors perspective. Key firefighting ‘elements’ that have been widely reported include ladder handling, stair climbing, hose work, search and rescue, and tool operations. However, there is no consensus on duration, intensity, frequency, rest periods – details that are crucial to determining workloads and their acceptability. The draft Worst Case Planning Scenarios (Thomas & Johnson, 2000) that await CFBAC endorsement, provide a start in the identification of a range of scenarios that encapsulate the requirements of firefighters. However, although time lines are provided for sub-tasks with personnel and equipment specified providing an operational framework, the level of detail required from a Human Factors perspective is lacking. Indeed, there is no empirical evidence provided in the document to demonstrate that the scenarios depicted in the Gantt charts are achievable by firefighters. Current project work to develop new Point of Entry Selection Tests attempts to overcome some of these shortcomings via single-person simulations of: a rural fire with water relay; a domestic search and rescue of two casualties; and ladder lifting and extension. However these two initiatives (WCPS and PES) are not currently aligned.

Numerous attempts have been made to define firefighting scenarios (e.g. Thomas and Johnson, 2001), firefighting tasks (e.g. David *et al.*, 1995) and what we have called ‘key task elements’ (e.g. Oldham *et al.*, 2000). About 30 studies have been reviewed in this document from the UK and overseas that report the energy expenditure, heart rate and core temperature responses to firefighting key task elements. However, a real difficulty exists in the quantification and measurement of individual and concurrent tasks when they are carried out in the field. A lack of consensus over operational requirements, both internationally and nationally, poor standardisation of task performance, and the lack of control over work rate, hamper the area and defy the formation of an adequate definition of the physical requirements of firefighting from a Human Factors perspective. Genuine methodological difficulties in assessing accurately the actual physiological and biomechanical demands of firefighting have further hampered attempts at quantifying these requirements, although robust modern equipment is becoming available that may be able to answer some of these questions.

- That said, the following points seem to hold true for most of the reports reviewed:
- Firefighters perform a huge number and range of tasks. Frequent activities include climbing (stairs or ladders); pushing, pulling, lifting and carrying (heavy equipment or casualties); and chopping (to gain entry)
- Firefighting tasks range in duration from a few seconds to several days. The duration of many set tasks and drills are largely ill-defined – within safety constraints, tasks are often completed as quickly as possible to lessen the impact of fire-related damage to people and property
- Most firefighting operational tasks are performed self-paced, usually at the highest sustainable pace tolerable by the firefighters; this is largely dependant on the individual fitness of firefighters
- Many firefighting tasks are team-based; the work rate will be determined and limited largely by the least fit member of the team

- Where the metabolic costs of firefighting tasks are reported, they are mostly poorly controlled and quantified, usually assessed from indirect evidence (e.g. pressure drop in SCBA cylinder contents)
- Aerobic fitness, muscle strength and endurance, and body composition are major determinants of firefighter performance.

7.4 THE FITNESS AND PHYSIOLOGICAL REQUIREMENTS OF FIREFIGHTERS

A number of studies from around the world, including some from the UK, have reported various parameters of firefighter fitness. These reports indicate that various cohorts of firefighters have mean aerobic powers in the range of 32 – 57 ml.kg⁻¹.min⁻¹. The UK studies tentatively indicate that UK firefighters have a mean VO_{2max} of ~ 43 ml.kg⁻¹.min⁻¹. Additionally, these studies suggest that an increasingly large proportion of the UK firefighting population carry more body fat than is optimal for performance and than is recommended for good health. Some are reportedly morbidly obese.

Most of the reports suggest that basic physical strength is not a problem as far as male firefighters are concerned, but some have suggested that female firefighters need to pay special attention to maintaining and improving muscular strength. Many studies indicate that greater strength is associated with enhanced operational performance.

Smoking hampers firefighters' performance and is a major risk factor in a number of fatal medical conditions. This suggests that anti-smoking initiatives should be maintained and extended.

Limitations of all the studies reviewed in this document make extrapolation and interpolation of the data precarious for the current tasking. These limitations include:

- non-UK nationalities studied (making direct comparison with the UK population unreliable)
- non-representative volunteer groups (potentially fitter than the firefighting norm)
- small test numbers (as low as 7) reduce the reliability of the statistical analyses reported
- different and inappropriate exercise testing modalities (e.g. cycle ergometry), which are not representative of firefighting
- sub-maximal exercise testing (reduces the accuracy of individual results)
- older studies, especially those from the UK, do not reflect the recent changes in firefighter demographics (increased drive to employ female and ethnic minority firefighters)
- some studies predate changes in UK entry standards (e.g. removal of height and age restrictions).

Consistent findings conclude that firefighters seem to be no fitter than their sedentary non-service peers and are fatter than is recommended, and that the physical demands of the job are insufficient to enhance or maintain role-specific fitness levels. Some reports have shown that physical training programmes engender large (>20%) improvements in fitness, suggesting a low start point of fitness among firefighters; a significant potential for improvement; and that physical training offers a cost-effective method of enhancing performance and improving health.

In general terms, it is clear that for operational firefighting 'more fitness is better', i.e. the fitter and healthier the workforce, the harder and quicker they will be able to work, the more efficient they will be, and the quicker they will recover. This is particularly true when working in demanding thermal environments, especially when wearing PPE and SCBA. To date national fitness training and assessment of the UK firefighting population as a whole is not being undertaken and the national fitness profile of the current UK firefighting population is currently unknown.

From the literature evidence reviewed here, it is impossible to describe accurately the fitness profile of UK firefighters, or to confirm that the UK firefighter health and fitness profile meets the requirements of the normal or occasionally more extreme demands of firefighting. The physiological and biomechanical demands of operational firefighting remain largely unknown, although the most demanding of firefighting tasks require near-maximal effort, sometimes sustained for long periods.

7.5 THERMAL ENVIRONMENTS, DEMANDS AND TOLERANCE

Although exposures to normal climatic factors are well known, the temperatures to which firefighters are exposed during actual firefighting and related activities such as search and rescue are unknown. Some guide can be provided from studies of training environments although there is strong anecdotal evidence that firefighters will behave differently in an actual incident and may therefore be subject to higher temperatures than those documented during training. Determination of temperature exposures is complicated by the fact that the temperature can change considerably between different compartments in a fire. As a result 'fire temperatures' or other single measures are unlikely to provide an accurate estimate of actual exposures. Increased use of body-borne monitoring would allow the creation of a database of temperatures. However, these are only of value if collected in conjunction with a record of workload and, ideally, the physiological responses (particularly body temperature) of the firefighters involved. Current data of this type are neither collated nor interpreted in a cohesive manner.

Different sites in the body can be used to record 'body' or 'core' temperature. Rectal temperature has often been used in the past but other, more socially acceptable approaches are now available and, with suitable precautions, can give reliable data. There is clear evidence that, at least during firefighter training, some firefighters attain body temperatures in excess of what would be considered a safe level (38 °C by the WHO) and may therefore be at risk of heat-induced illness. Frequent reports of 39 °C and occasional reports of 40 °C are apparent, though views differ as to what an appropriate upper limit should be, as individual tolerance to elevated temperature varies considerably. Recently Graveling *et al.* (in press) proposed that 39 °C as an upper limit during firefighter training at elevated temperatures. What is not known, because few if any data are available, is how comparable the conditions in training are to those likely to be experienced in operational situations. If the consensus is that operational conditions are less severe then dangerously high body temperatures are less likely to occur. If however the view is that operational activities can take place at similar or higher temperatures, then this has considerable implications for the safety and operational effectiveness of firefighters.

There are many factors potentially influencing thermal tolerance and therefore operational effectiveness of firefighters. Firefighters require a degree of thermal tolerance to perform safely and effectively in operational conditions involving elevated

temperatures or where clothing and workload factors may themselves create adverse thermal conditions. At present, thermal tolerance would seem largely to be left to self-selection by recruits, coupled with some exclusion during training and on-the-job. This situation is unsatisfactory and there is a case for considering 'heat tolerance' tests for firefighters. Heat acclimatisation occurs with regular exposure, but it is doubtful if firefighters ever become heat acclimatised, which requires exposure on most days for at least an hour a day. Race, gender and genetic make-up advantage some firefighters and disadvantage others. Adequate hydration before, during and after operations is essential and needs to be monitored on the ground. Abstaining from alcohol consumption and the use of supplementary vitamin C can also be beneficial, as can pre-cooling. The interrelationships between these different factors, and the magnitude (if any) of any effect within the firefighter population are not known.

7.6 PERSONAL PROTECTIVE EQUIPMENT

Wearing modern firefighters' protective clothing results in an increase in energy cost of approximately 10-15%. Adding SCBA can increase this load by a further 10-15%. There is some evidence that lighter composite cylinders do provide some benefit, but there is no evidence to favour any one style or make of clothing or SCBA. This increased energy cost of physical activity while wearing PPE, estimated at adding 135 W.m⁻² to the energy cost of any work, will be reflected in an increase in metabolic heat production. This would, for example, raise the category of the work performed from 'low' to 'high' and from 'moderate' to 'very high', by BS EN 28996's assessment of metabolic rate.

While the ways in which PPE can influence heat stress and consequent strain are well established in general terms the level of knowledge concerning that worn by firefighters is best described as 'patchy'. The effective insulative qualities are not well understood in terms relevant to evaluating potential thermal strain. This has considerable implications for any attempts to predict or model heat stress/strain under operational conditions. Despite advances in fabric technology, standard firefighter clothing is heavy, deliberately highly insulative, and of limited vapour permeability, three factors known to significantly influence the level of thermal strain.

The thick, rubberised gas-tight suit worn by firefighters in many brigades is equally heavy and of zero vapour permeability. Any impact on sweat evaporation is exacerbated by the release of exhaled air inside the suit, rapidly creating a saturated atmosphere. The insulative characteristics of such garments are not known but, on the basis of the fabric used, are expected to be high.

Lightweight disposable coveralls and similar chemical suits are of negligible weight and thermal insulation. Nevertheless, even vapour-permeable forms have a high level of resistance to water vapour and consequently create a potentially high level of thermal stress on the wearer. Newer forms of gas-tight suits, normally designated as being 'limited use' utilise similar materials to the vapour-impermeable disposable coveralls. They therefore have similarly high resistance to sweat evaporation. However, usage with an air-line would provide a degree of dry air flow through the garment that would alleviate this to some extent and would therefore be preferable to usage with SCBA. The addition of a cooling system to the PPE, via for example, cooled water or an air-line can significantly reduce the level of thermal stress over the SCBA-based unit and prolong performance.

While these factors are known and recognised in general terms their effects are less well quantified or documented. A greater awareness and understanding of clothing parameters, including those items worn underneath the fire kit, is vital if any complex modelling of firefighter performance under thermal strain is to be undertaken.

7.7 RESPIRATORY DEMANDS AND EFFECTS

Respiratory protection is essential to firefighters operating in hazardous environments. There are many types of RPE each with its own recommended operating environment and offering varying degrees of protection against environmental hazards. The three prime types are: filtering devices, attached air-line apparatus, and self-contained breathing apparatus (SCBA). The latter can be either open circuit or closed circuit. Evidence from the UK indicates that firefighters wear SCBA less than once per week. With this exposure rate, firefighters may not develop or maintain any specific physiological tolerance to SCBA wear.

The SCBA entry control tables are derived from work conducted in the 1940's and 1950's. They are based on an assumed breathing rate and volume equivalent to unencumbered jogging in sports clothing. Evidence of significantly greater breathing demands among firefighters exists in a number of studies. Indeed, most of the metabolic studies indicate that firefighters operate at or near their maximum capacity, especially in the early stages of an incident. The SCBA entry tables would therefore appear to be inadequate and in need of review.

Full turnout gear of PPE including SCBA weighs between about 15 and 25 kg. For every kilogram of extra mass carried oxygen uptake, heart rate, breathing frequency and ventilation increase, as does the sensation of breathlessness. External loads have the greatest proportional impact at the highest workloads - the zone that firefighters perform in during operational emergencies. In addition to the effects of the load, the wearing of SCBA may impact on respiratory function, in effect by compressing the thoracic cavity and increasing the load placed on the respiratory muscles. Maximal work capacity is reduced by about 20-25% under PPE and SCBA.

The greater the level of aerobic fitness, the greater is the chance of the firefighter overriding the effect of wearing PPE, especially respirator work. However, aerobic fitness and respiratory muscle strength are independent factors. The lighter the PPE, the less impact it will have on operational performance. Training the respiratory muscles may offset the decrement in performance associated with SCBA wear. Allowing more exposure to working in SCBA may encourage training adaptations to SCBA wear.

7.8 OTHER FACTORS

While there are many anecdotal reports of the influence of other factors (e.g. smoke) on the strain associated with firefighting tasks no formal studies investigating these other factors have been identified. Psychological factors such as uncertainty, anxiety and apprehension will undoubtedly influence physiological parameters such as heart rate. What is not clear is whether this, in turn, will adversely affect physical task performance.

In addition, exposure to elevated temperatures will have an adverse affect on psychological task performance issues such as cognition and decision-making, although the effects on any particular task are difficult to predict. Any effect is more likely with complex tasks involving a series of cognitive processes and actions rather than simple reactions. This is consistent with anecdotal reports of mistakes in command and control functions in hot climates.

CHAPTER 8

Research Priorities

The research priorities identified in this section have been prioritised into three subsections entitled Primary, Secondary and Tertiary Research Priorities. Each potential Research Project has been given a unique number for ease of future reference. Within a subsection, the order of presentation does not necessarily imply precedence. A greater level of detail has been provided for the primary research priorities, as presumably these will be pursued with most urgency.

8.1 PRIMARY RESEARCH PRIORITIES

Research Project 1: Quantify the Physiological Requirements of Firefighter Key Tasks and Identify the Limiting Factors to Performance

Safety and efficiency are the two major operational concerns of the Fire Service and both require judgements to be made about the workload that firefighters can undertake in different circumstances. The variables that have to be taken into consideration are:

- tasks (carrying, dragging, lifting, on the level or up or down stairs)
- ambient conditions (primarily heat)
- physical load (equipment, including BA and PPE)
- type of PPE and RPE worn
- stature, body composition, strength and aerobic fitness of firefighters
- gender and age of firefighters

The Incident Commander has to decide how many personnel are required to carry out the necessary tasks and how long they can continue to work safely and efficiently. Currently these judgements are largely based on experience and on the capacity of the BA used and it is to the credit of all of those in positions of responsibility that the UK Fire Service is among the safest and most efficient in the world. There is, however, a need to quantify the impact of the factors listed above on work capacity, partly to support and assist those in command, partly to anticipate how new equipment, responsibilities and techniques will impact on work capacity, and partly to assist in revising building regulations so they are consistent with modern working practices.

Currently, both 'normal' and 'extreme' scenarios which firefighters in the UK Fire Service are likely to face are poorly defined. It is not surprising therefore that the workloads firefighters are likely to endure during these scenarios remain to be fully quantified. Of greater concern is the lack of knowledge as to whether firefighters can even perform tasks that might be expected of them, or for how long the tasks can be sustained. Lack of information about the specifications of the scenarios/tasks is compounded by the lack of accurate and detailed knowledge about the fitness and work capacity of firefighters, and also by the gaps in knowledge relating to the thermal

and metabolic strain associated with the various configurations of PPE and RPE likely to be employed.

An urgent need exists for the Fire Service to define in detailed operational terms, reasonable Worst Case Planning Scenarios, that firefighters are expected to perform under operational conditions. Once these scenarios are defined, Human Factors specialists should determine the workload associated with these tasks, to establish both whether firefighters are likely to be able to carry out their duties in an effective and safe manner, and to identify what the limits to performance are, so that the potential to extend the performance envelope can be explored.

- This project is likely to involve the following phases:
- Devise simulations of the scenarios
- Measure performance and monitor firefighters on the scenarios
- Manipulate limiting factors to define and extend the performance envelope
- Analyse and report the findings.

Outcome measures may include for example: success or failure on the task, time to completion, heart rate, core body temperature, skin temperature, energy cost, air usage, perceptions of fatigue and thermal comfort, and other or alternative measures of cardiovascular and thermal stress and strain.

This work will be challenging as there are real difficulties faced when attempting to quantify individual and concurrent tasks when they are carried out under operational conditions. Consideration should be given to standardisation of task performance, control over work rate, and individual performance within a team task. Careful selection of methodology is essential given the environmental conditions and physical challenges encountered.

Research Project 2: Determine Appropriateness of Fire Safety Legislation

The appropriateness and relevance of the criteria within the DoE's Design Principles of Fire Safety (1996) and the DETR's Building Regulations (1991) that pertain to the expectations on and operational requirements of firefighters should be reviewed. The basis, for example, for the provision of firefighting shafts and firefighting lifts for buildings, and the specification of a maximum distance from a mains outlet to the limit of the building have no empirical foundation. The legislation needs to be revisited in light of more knowledge about 'normal' scenarios and reasonable Worst Case Planning Scenarios that are expected of firefighters bearing in mind their fitness, the PPE and RPE they are required to wear, the environment in which they are expected to operate, and the speed at which they are required to work. The review of the legislation would logically be conducted following completion of the Research Project 1.

8.2 SECONDARY RESEARCH PRIORITIES

Research Project 3: Establish Fitness of Firefighters

The fitness profile of UK firefighters remains largely unknown. Fitness norms for UK firefighters need to be established by role, age, gender and possibly race. The current lack of knowledge prevents the ability to comment on the likely operational effectiveness of UK firefighters to perform any given task. This dearth of knowledge exists despite the number of studies that have reported the fitness of firefighters in countries around the world, including some in the UK.

Research Project 4: Review SCBA Tables & Optimise SCBA Cylinders

The SCBA entry tables are in need of review. They were derived from work conducted in the 1950's by Silverman *et al.* and are based on an assumed breathing pattern of 24 breaths.min⁻¹, and a minute ventilation of 40 l.min⁻¹. There are several sources of evidence for significantly greater breathing demands (e.g. Louhevaara *et al.*, 1985 & 1995; Donovan, 1999 & 2000; Lusa *et al.*, 1994). Others have reported values between 39 and 70 l.min⁻¹ in simulated firefighting tasks, although these measures were indirectly assessed (e.g. Love *et al.*, 1994). Indeed, most of the metabolic studies indicate that firefighters operate at or near their maximum capacity, especially in the early stages of an incident.

Inevitably there is a trade-off between the size, capacity and weight of SCBA cylinders. Often the capacity of the cylinder is the limiting factor prompting the team to withdraw from the incident. The physical size of the cylinders may limit a firefighter's access to enclosed spaces. The weight of SCBA increases the energy cost by around 10-15% and reduces maximal work capacity by a similar magnitude. Ultra light-weight cylinders have been shown to alleviate some of the decrement in work performance. Smaller individuals tend to use less air but their performance is impaired to a greater extent than larger individuals using standard size cylinders. There is scope for investigating the size, capacity and weight of SCBA cylinders to optimise operational performance in firefighters.

Research Project 5: Quantify the Extent to which PPE and RPE Compromises Performance

Thermal, metabolic and respiratory strain in firefighters associated with PPE and RPE, including SCBA, should be explored further to identify the trade-off between protection from environmental hazards and the compromise in operational performance wearing PPE and RPE brings. It is known that wearing protective clothing and SCBA each result in an increase in energy cost of approximately 10-15%, increasing metabolic heat production by an estimated 135 W.m⁻². While the ways in which PPE can influence heat stress and consequent strain are well established in general terms the level of knowledge concerning that worn by firefighters is best described as 'patchy'. Whereas the thermal effects of the clothing material is fairly well understood, less is known about the physiological effects of the completed garment, and the effects of the interactions of various materials and clothing configurations.

The effective insulative qualities of firefighters' PPE are not well understood in terms relevant to evaluating potential thermal strain. In particular the benefits of light-weight PPE and RPE, especially the ultra light-weight cylinders should be explored. Building on the output from Research Project 1 would seem logical. Decrements in performance on the simulations can be quantified with each level of additional stress (e.g. under the various configurations of protective clothing, including the standard fire kit, the gas-tight suit, and the lightweight disposable coverall, with and without SCBA). Serious consideration should be given to the idea of a layered approach to protective clothing (as partly examined by Graveling *et al.*, 1999) for example with standard undress uniform replaced by a fireproof stage 1 one or two piece coverall which could be worn for appropriate operations as a lighter garment.

Research Project 6: Quantify Thermal Environments

The temperatures to which firefighters are exposed during actual firefighting and related activities such as search and rescue should be investigated, if possible during operations, rather than, or in addition to, training exercises. This will inform the specification of the scenarios firefighters are likely to encounter, and will feedback into

the design of PPE and the manner in which training in hot environments is conducted. Use of body-borne monitoring should be considered to populate a database of temperatures. Peak values and Time Weighted Averages should be recorded. Ideally, workload and the physiological responses (particularly body temperature) of the firefighters involved should also be made.

Research Project 7: Quantify Impact of Other Factors on Firefighting Performance

The effect of factors such as different operational environments, uncertainty and apprehension on the strain associated with firefighting tasks, and the affect these factors have on task performance itself, should be explored. In particular, little is known of the effect on performance of firefighters being confronted by incidents of the scale being considered within the context of the 'new dimension' of terrorism following September 11th. Moreover, there is scant knowledge on how best to manage the longer-term psychological health of firefighters responding to incidents of this scale. The effects of exposure to different operational environments on psychological (mental) performance during complex tasks involving a series of cognitive processes and actions should be investigated. The extent to which physiological strain is associated with these psychological factors should also be included and how best to manage the immediate and longer-term psychological health of firefighters.

8.3 TERTIARY RESEARCH PRIORITIES

Research Project 8: Determine the Effectiveness of Physical Training Programmes to Enhance Operational Effectiveness of Firefighters

Research evidence has demonstrated that the physical demands of a firefighter's job are insufficient to enhance or maintain role-specific fitness levels (Ellam *et al.*, 1987). The fitness of UK firefighters is thought to be little different from that of the general population (Rayson *et al.*, 2003) and yet the physical demands of firefighting can be very high. Indeed effective and safe performance of operational tasks is dependent on high fitness levels. Several reports have shown that physical training programmes engender large (~20%) improvements in fitness, suggesting not only that the baseline fitness levels are low but also that physical training offers a cost-effective method of enhancing operational performance and improving health.

Research Project 9: Establish Thermal Tolerance Limits

Graveling *et al.*'s (in press) proposal that a core temperature of 39 °C be used as an upper limit during training should be investigated further to ascertain whether this is the most appropriate limit to use. Consideration should be given to the variability of individual tolerance to elevated temperatures, the interaction between core and skin temperatures, and the consequences of operating up to the suggested limit on health and operational performance (both physical and psychological).

Research Project 10: Develop a Thermal Intolerance Test

Firefighters require a degree of thermal tolerance to perform safely and effectively in operational conditions involving elevated temperatures, or where clothing and workload factors may themselves create adverse thermal conditions. At present, thermal tolerance of firefighters is not assessed and therefore not known, unless an incident during training or operations has exposed a firefighter's lack of tolerance. This somewhat random approach is unsatisfactory given the serious and potentially fatal consequences of heat illness and heat injury.

A 'heat intolerance' test for applicant firefighters and incumbent firefighters should be developed, potentially for both mass screening of firefighters and for assessing firefighters who have experienced thermal intolerance in training or on-the-job. Consideration would need to be given to the practicalities of any proposed procedures. Minimal use of technology and invasive techniques should be involved, while maximising safety precautions.

Research Project 11: Establish Dose-Response and Benefits of Heat Acclimatisation

Heat acclimatisation occurs with regular exposure, but it is doubtful if firefighters ever become heat acclimatised, which requires exposure on most days for at least an hour a day. A series of studies should be conducted to establish:

- whether firefighters are acclimatised, partially or fully
- the minimum dose-response required to develop acclimatisation
- the minimum dose-response required to maintain acclimatisation
- the likely benefit on operational effectiveness and safety.

Research Project 12: Conduct Heat Tolerance Interventions

A number of intervention methods are available to enhance heat tolerance. These range from ensuring adequate hydration and rehydration, to the use of supplements (e.g. vitamin C, amphetamines), and physical cooling of the body or parts of the body via pre-cooling or via cooling vests or headgear for example. A review of literature should be conducted to consider which interventions might best serve firefighters engaged in operational procedures. One or more of these interventions should then be investigated via a controlled intervention study ideally using standardised firefighter tasks.

Research Project 13: Establish Dose-Response to SCBA Tolerance

Evidence from the UK indicates that firefighters wear SCBA less than once per week and that this exposure rate probably does not develop or maintain any specific physiological tolerance to SCBA wear. An investigation should be conducted to establish if firefighters undergoing their regular training and operations have developed any physiological tolerance, the dose-response to identify both what minimum stimulus is required and what is optimal.

Research Project 14: Determine the extent to which Respiratory Muscle Training Enhances Firefighter Performance

Maximal work capacity is reduced by about 20-25% under PPE and SCBA. Part of this reduction is due to the additional weight carried and part is thought to be due to compression of the thoracic cavity and the increasing load placed on the respiratory muscles. Training the respiratory muscles may modulate inefficient breathing patterns and offset the decrement in performance associated with SCBA wear and may enhance maximal performance without SCBA wear. Inspiratory Muscle Training has been shown to improve athletic performance among civilians. The potential for improvement in firefighter performance while using SCBA is considerable and should be investigated via a controlled intervention study.

CHAPTER 9

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ANNEX A

MOD Standards 1997 – Human Factors for Designers of Equipment

This Defence Standard (Def Stan) is a 13-part document covering all aspects of equipment design from a human factors perspective. The parts include sections for maintainability, anthropometrics, voice communication, auditory information, vision and lighting. The most relevant section to the present review is the 47-page Part 3, described briefly below.

Part 3: Body Strength and Stamina

Body strength is described as the measure of the force that the body can apply to external objects, and stamina is the capacity of the individual to perform continuous physical work. Given that performing work that requires maximum strength is highly fatiguing and potentially damaging to the body, knowledge of the maximum strength of a workforce is of limited use to equipment designers. Therefore, force limits referenced within this document relate to those forces accepted as being within the capacity of young, fit, military personnel. The forces indicated within this document are therefore consistent with long-term safety or, those that can be used in emergency situations. Data are also presented for gender differences in strength and stamina of military personnel.

Stamina is a function of an individual's physical fitness, and depends on the status of their health, their heart and lungs, and on their general body strength. An individual's physical fitness will determine the rate at which a task can be performed continuously. Exceeding this rate will result in physical and mental fatigue. Work/rest schedules are therefore essential for the efficient operation of physical tasks.

External physical work is related to the ability of the muscles to generate force by converting fuel into contraction without and with the use of oxygen. There is a close association between “physical work performance, oxygen uptake and body heat production/energy consumption” (Def Stan Part 3, pg 7). Human work rate is usually measured in terms of heat production and expressed as kilocalories (kcal) per unit of time. 1 kcal is the equivalent of 4186.8 joules. The SI metric used throughout the document is the joule.

Measurement of human energy expenditure is complex and difficult to obtain outside of the laboratory. Given that oxygen is carried to the working muscles via the blood circulatory system, pulse-rate has often been used as an indicator of work-rate (e.g. Brewer 1999). However, heart-rate and pulse-rate can be affected by many factors including emotional stress, thermal load and medical conditions, using it as a measure of work-rate may lead to errors in estimation (Sothmann *et al.*, 1992).

This Def Stan offers tables to indicate the work-rate for a given work intensity ($\text{kJ}\cdot\text{h}^{-1}$), including the rest time required per 8 hour shift at the relevant work rate. These data are reproduced in Table A1.

Table A1. Additional heat production due to occupational activity: whole body activity and rest times for a given work rate				
Work Rate	Rest required per 8 hour shift (hr)	Additional Heat Production (kJ hr^{-1})		Equivalent Pulse rate (b min^{-1})
		Male	Female	
Resting	1.5	0	0	60 - 70
Light work	2	2930	2093	75 - 100
Moderate	2.75	5440	3770	100 - 125
Heavy	3.75	11300	5020	125 - 175

It is not possible to compare directly the heat production figures presented in Table A1 with the estimates of metabolic rate class presented in BS EN 7963:2000 (Table 4.1) as the units of measure used in that standard are $\text{W}\cdot\text{m}^2$.

This Def Stan also defines age-related declines in strength and stamina of incumbent military personnel and presents gender differences (Figure 3, pg 13). Other factors given in the document are the effects of posture, hand grip, the range of movement (ROM) of joints. Section 7 details the strength of whole-body activities, and the forces (in kg) that can be exerted in different directions within the reach of the individual.

Lifting, pulling and pushing

Lifting guidelines are comprehensive and suggest that for a 95th percentile male the maximum force exerted in a close lift to the waist (either from standing or squatting position) is 46 kg, while for a 30th percentile male the force is reduced to 12 kg. The figures for females are given as 20 kg and 10 kg respectively (see Figure 10, pg. 29). These values are for lifting and lowering a mass on no more than two occasions per hour. Lifting and pulling tasks are appraised using a NIOSH equation (see Def Stan pg. 33) and take into account the mass lifted, the number of repetitions, the angle of lift and any shoulder rotation involved in the movement. Tables are provided for ease of reference (Def Stan pg. 36-38).

Using these tables (if ratified for use within the UK Fire Service), it would be possible to calculate the lifting or pulling limits of any relevant firefighting task if they could be identified. In pulling, for example, the tables calculate that for a male, with height of hands at 64 cm and a pull distance of 15 metres, an initial force of 38 kg can only be moved once every 8 hours. For a female the same activity can be performed on a mass of 22 kg. For pushing, using the same criteria, the mass limits are 31 kg and 18 kg for males and females respectively. It is important to note, however, that in emergency situations these recommendations can be over-ruled, but the physical consequences for the worker may be serious and chronic.

Maximum load carriage

The Def Stan refers to a review by Haisman (1988) that stated that there was no obvious definition of a maximum weight of a backpack because of the widely varying conditions that might apply. However, he recommends, “one third of the lean body weight of a healthy young male soldier is a sensible recommended maximum load that can be carried” (pg. 40). Using this formula the mass limit for carrying over distance for an average male soldier is 20 kg, and for a female it is 13 kg. This assumes the load distribution on the back is even. The standard also recommends 4 essential elements for safe load carriage over distance:

- Elimination of local strain
- Maintenance of ‘normal’ posture
- Maintenance of normal and free gait, and
- Chest freedom

The above recommendations may be useful when designing and purchasing Self-contained Breathing Apparatus (SCBA) and other RPE and PPE for the Fire Service.

Summary

Given that some of the work of firefighters and military personnel is considered to be roughly analogous, it might be reasonable to assume that the strength, stamina and workload guidelines for designers offered in this Def Stan could be used to inform the design of firefighting equipment and workloads. However, if these standards were to form legally defensible guidelines for strength, stamina, pushing and pulling workloads for the UK Fire Services, then the data on which these standards are based would need to be validated specifically for the firefighting population.

ANNEX B

Manual Handling Regulations

Musculoskeletal disorders are the biggest single cause of work-related sickness absence in the UK (Jones *et al.*, 1998). Of these, back injuries due to manual handling are a major component. Incapacity of a team member due to a traumatic back injury would clearly severely compromise the operational effectiveness of a firefighting team.

The Manual Handling Operations Regulations, 1992 place a series of requirements on employers in the UK with a view to preventing the risk of handling-related injury. Briefly these require employers to avoid the need for hazardous manual handling if at all possible, to make a suitable and sufficient assessment of any hazardous manual handling operation that cannot be avoided, and to take reasonably practicable steps to reduce any such risks identified. Although it is understood that at least some police activities are exempted from this and other health and safety legislation, no such blanket exemption is believed to apply to the Fire Service. Indeed, Guidance Note 24 specifically refers to the emergency services, indicating an expectation of compliance but acknowledging that the application of the concept of reasonable practicability extends to not requiring actions that would result in an inability to provide the public with an adequate rescue service.

As part of the guidance to the application of the Regulations, a series of numerical guidelines are provided. Applying particularly to lifting and lowering activities, these relate the position of the load to what might be considered to be an acceptable weight to be lifted. The values presented are considered to 'provide a reasonable level of protection' to around 95% of men and women. Weights indicated range from 25 kg close to the body at about waist height to 5 kg at arms length above shoulder height or at floor level. While specifically stated not to be statutory limits to lifting the accompanying text does state that loads exceeding the guideline figures by a factor of more than about two should come under particularly 'close scrutiny'. Reduction factors apply for a predominantly female workforce (67%) and for other factors such as frequency of handling.

Although the application of these Regulations and guidelines to emergency situations can be questioned, it should be recognised that these do represent possible risks to health. Apart from the legal position, adherence as far as possible to this guidance will help to reduce the risk of injury and therefore reduce the risk of compromising operational effectiveness.

ANNEX C

The Physical Fitness of International Firefighters

Introduction

Considering the high profile and high intensity nature of the job, the volume of publicly available research into the physiological demands of firefighting is not as extensive as might be expected (see Section 5). However, there are a number of studies that report the fitness profile of groups of the international firefighting community. A brief review of the literature that has not already been provided in Section 6 is presented in this Annex in chronological order. Table C1 at the end of this Annex lists the aerobic fitness data from these international papers.

There is one point of caution to be mentioned here. A paper by Roberts *et al.* (2002) reported that US Federal Law currently “prohibits pre-employment physical examinations of firefighter recruits” (pg. 271). It is understood, however, that US Fire Services get around this law by making an offer of employment provisional, subject to the recruits’ fitness level which is assessed during training. Despite increasing their expenditure in terms of recruit wastage, this is extremely interesting as it suggests that some of the more recent studies in the US are potentially starting from a much lower baseline than those from other countries. It also has implications for interpreting the results of any recent US-based study that reports on the metabolic demands of firefighting tasks as a proportion of volunteer fitness.

The 1970s

Lemon & Hermiston (1977b) quantified the energy cost of a group of firefighting tasks. Their results indicated that the firefighting simulations elicited ~70% of the volunteers’ VO_{2max} , and that firefighters with VO_{2max} in excess of $40 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ would be better able to cope with the demands of the work. This was one of the first papers to recommend a minimum aerobic standard for professional firefighters.

The Lemon & Hermiston study (1977b) probably underestimated the most intensive demands of the firefighting, because the 4 tasks they monitored were performed singly, reducing the cumulative effects of continuous firefighting, SCBA was not worn during the exercise, and there were no environmental hazards, i.e. the tasks were performed in daylight, under ambient outdoor temperatures on the drill yard. Sections 4 and 5 discuss the evidence that wearing SCBA and other PPE during physical activities increases significantly the physiological demands of the task.

Duncan *et al.*, (1979) measured the physiological costs of wearing firefighter clothing on 11 professional firefighters and stated that the clothing ‘imposes significant stress on firefighters, especially when working in the heat’ (pg. 521). Even though this paper is rather old and the clothing tested now out-of-date the paper does present fitness data on serving US firefighters in 1979 (see Table C1).

The 1980s

Kilbom (1980) conducted an influential review of the firefighter fitness literature up to that point and reported that despite the sometimes severe demands of the job and their need to possess higher than normal levels of aerobic fitness, firefighters worldwide tended to be no fitter than the general sedentary male population. Kilbom recommended a minimum entry standard for recruit firefighters (i.e. they should be able to cycle on an ergometer at a work rate of 200 W for at least 6 minutes). Furthermore, to allow for the expected age-related decline in physical work capacity, Kilbom also suggested that recruit firefighters (irrespective of their age), should be able to cycle at a work rate of 250 W for the same duration. The relevance of these recommendations for today's UK firefighters is doubtful, as the physical profile of the international firefighting population at the time is likely to be significantly different to that of today's UK firefighting population. Some fitness data from the Kilbom review are presented in Table C1.

Many international papers have shown that on-the-job, task-specific fitness training can improve firefighters' aerobic power (by as much as 20%), their general fitness profile and their work performance (Puterbaugh & Lawyer 1983; O'Connell *et al.* 1986; Smolander *et al.*, 1984; and others). However, if a 12-week exercise training programme can elicit a 20% improvement in VO_{2max} (as reported by Puterbaugh & Lawyer), the baseline fitness levels must have been fairly low, which supports many researchers' contention that firefighters are not as fit as they could or probably should be (Kilbom, 1980; Lemon & Hermiston, 1977a and 1977b; Louhevaara *et al.*, 1985 etc.).

A formative series of studies conducted in Finland throughout the 1980s and 1990s by Louhevaara, Lusa, Smolander and others presented fitness data on a number of Finnish firefighters groups both in stand-alone and comparative studies. Much of this work concentrated on the metabolic costs and respiratory demands of working in PPE including SCBA. Some of these studies have been reviewed in Section 5 and the fitness data are presented in Table C1.

The 1990s

The passing of age discrimination legislation in the US in 1978 made it necessary to justify a mandatory retirement age for firefighters (55 yrs at that time). If age was to be confirmed as a reasonable basis for termination of an individuals' firefighting contract, it had to be shown that the majority of the population above the retirement age would either be unable to perform firefighting tasks adequately, or that it would be unreasonable to perform individual testing (Sothmann *et al.*, 1992a). The onus was placed on US Fire Services to defend the extant mandatory retirement age. As result of this debate an assessment of firefighting was required and funding for such research became available (in the US at least).

Sothmann (1992a), referred to the physiological demand that arduous firefighting tasks placed on the pulmonary system and noted that the added load on the respiratory system caused by wearing SCBA "increases the work of breathing and may result in workers with marginal pulmonary function being unable to ventilate adequately" (pg. 28). This is possibly the first reference that alludes to a potential for firefighters' respiratory system (even if clinically healthy) to be a "weak link" in the chain of physical performance. The suggestion was that firefighters' respiratory musculature may play an important and as yet poorly understood, role in firefighters' work performance.

Lindvik *et al.* (1995) monitored the physiological responses of 12 whole-time Swedish firefighters during simulated shipboard tasks. It is unfortunate that no fitness data were presented in this report making its findings hard to interpret. However, the test developed for this study is recommended as a good test drill for assessing Swedish firefighters. It also states that the “ultimate threshold value for passing the test is at least 40 ml·kg·min⁻¹” (pg. 29). Although this aerobic power level may seem reasonable, it may not allow enough spare capacity for an emergency reserve.

2000 and Onwards

Clark *et al.* (2002) described a study of the body composition of 218 whole-time US firefighters with a mean VO_{2max} of 44.6 (5.0) ml·kg⁻¹·min⁻¹. Results showed that 60% of the cohort was overweight and 32% could be classed as ‘morbidly obese’. Body composition is an important indicator of general health and it is an important indicator of a firefighter’s fitness for duty; body fat is an excellent insulator and high levels of body fat (body fat %) will inevitably increase workload and increase the effects of thermal stress during exercise. These effects will be exacerbated when work is performed in hot conditions and when PPE is worn.

The anaerobic power of incumbent female firefighters was recently investigated by Findley *et al.* (2002). The anaerobic profile of 10 female firefighters (using a Wingate cycle ergometry protocol) was compared with a matched group of civilians. Volunteers’ peak and mean power was 451.6 (69.6) and 314.1 (32.7) W respectively. Again, these results showed that the firefighters did not score significantly better than their civilian peers. What is particularly interesting about the Findlay *et al.* study (2002) is the comment that the level of anaerobic power needed to perform firefighting tasks is “unknown at this time” (pg. 474), a point that confirms this Review Team’s understanding.

Peate *et al.* (2002) investigated the relationship between the perception of fitness and estimated VO_{2max} in 101 US firefighters (96 male and 5 female) with a mean age of approximately 32 years and a mean VO_{2max} of 41.8 (7.7) ml·kg·min⁻¹. The volunteers rated their own fitness profile by responding to a questionnaire and then performed either a treadmill or step test (both tests were sub-maximal). No association was found between the firefighters’ self-perception of fitness and their estimated aerobic power. It seems that an individual’s assessment of their own fitness profile is not a reliable indicator of their actual physical capabilities. Furthermore, the low aerobic power exhibited by these volunteers suggests that there is a real need for on-the-job fitness programmes in US firefighters. The UK situation may well be the same.

Roberts *et al.* (2002) monitored the fitness levels of firefighter recruits before and after a supervised training programme in the US. The results show significant improvements in volunteers’ aerobic power (from 35.0 to 45.0 ml·kg·min⁻¹) following 16 weeks of fitness training. The aerobic power was estimated from sub-maximal cycle ergometry. This report demonstrates the value of fitness training in all groups but especially in groups with low baseline fitness levels.

Dawson *et al.* (2000) produced a report that recommended minimum fitness standards for Australian firefighters. The authors used survey data from 112 respondents to identify the most physically demanding firefighter tasks. They included video recordings of actual tasks and also monitored the performance on these tasks of 8 firefighters (7 male and 1 female). Results of the test validation are presented in Section 5. The volunteers’ mean VO_{2max} (estimated from the MSFT) was ~ 48 ml·kg⁻¹·min⁻¹,

which demonstrates the relatively high aerobic fitness level of this group when compared with the purported fitness of the general UK firefighting population.

Summary

A number of studies from around the world report various measures of firefighter fitness. These reports indicate that firefighters have a mean aerobic power in the range of 32 – 57 ml.kg⁻¹.min⁻¹. The UK studies reported in Section 6 tentatively indicate that UK firefighters have a mean of ~43 ml.kg⁻¹.min⁻¹. It is not possible to be sure that these fitness levels are adequate for efficient firefighting performance.

Table C1. A Review of the Fitness of International Firefighters

Reference	Description/ Methodology	Variable Measured	Aerobic Power ml kg min⁻¹ (1SD)	n	Comments
Clark <i>et al.</i> (2002)	Body mass index and health status in firefighters	VO _{2max} – treadmill and gas exchange.	44.6 (5.0)	168	The cohort included 5 female and 4 ethnic minority firefighters. This US study suggested that the Body Mass Index (BMI) might be a useful health screening index for US firefighters.
Davis <i>et al.</i> , (1982)	Although the fitness data are presented, the method used to measure them is not presented.	VO _{2max} unknown methodology	39.6 (6.4)	100	Male firefighters. Given the size of the cohort the data should be powerful but the paper does not report how it was gathered.
Faff and Tutak (1989)	Cycle ergometry, oxycon-4	VO _{2max}	41.4 (8.8)	18	
Gavhed and Holmer (1989)	Thermoregulatory responses of firefighters to exercise in the heat.	VO _{2max} maximal cycle ergometry using ventilation and gas exchange	49.9 (5.0)	24	Suggested that whole-time firefighters were only slightly better adapted to working in the heat than their retained peers. This evidence is supported by many thermal factors research (see Section 4 of the present review).
Gledhill and Jamnik (1992)	Field tests	VO _{2max}	48.7 (7.0)	53	Determined the mean aerobic demand of a maximal task. The volunteers were ~30 yrs old, 179 cm tall and weighed 81.6 (±12.3) kg.
Horovitz & Montgomery (1993)	Physiological profile of Canadian firefighters compared with norms for the Canadian population.	VO _{2max} – assessed from sub-maximal F _C data at end of step test.	~31.5 (50-59yrs) ~33.5 (40-49 yrs) ~37.5 (30-39 yrs) ~45.0 (19-29 yrs)	1,303	The data and showed that Canadian firefighters were less aerobically fit than their civilian peers. It also showed that they were generally stronger and more flexible.

continued

Table C1. A Review of the Fitness of International Firefighters (continued)

Reference	Description/ Methodology	Variable Measured	Aerobic Power ml kg⁻¹ min⁻¹ (1SD)	n	Comments
Kilbom (1980)	Review of laboratory fitness tests	Aerobic power mean of reports reviewed	~40.1	672	This is a very rough estimate of the mean aerobic power of firefighter fitness calculated from Table 4 of the Kilbom (1980) review. The reports referenced cannot be validated and the methodology cannot be assessed. Age related declines in performance seem to be "deeper in firemen than in other groups" (pg 56).
Lemon & Hermiston (1977a)	Max test for <40yrs	VO _{2max} measured (treadmill)	41.5 (5.3)	30	Poor aerobic power displayed by these firefighters.
Louhevaara <i>et al</i> , (1995)	Testing the maximal work performance in fire-protective clothing.	VO _{2max} – treadmill and gas exchange.	46.9 (range 33.4-73.3)	12	Wide range of fitness. Data therefore probably not taken from a representative sample of the firefighting population.
Louhevaara <i>et al</i> , (1994)	Development of a fitness test battery, described in detail in the paper	VO _{2max} (probably treadmill and gas analysis)	46.8 (range 29.7-67.0)	59	Results skewed by some very fit firefighters (max aerobic power was 67.7 ml.kg.min ⁻¹). The VO _{2max} assessment protocol was not described, but was probably a treadmill test, given methodologies described in earlier papers.
Louhevaara <i>et al</i> , (1986)	Breathing pattern and SCBA	VO _{2max} – treadmill and gas exchange.	4.7 (range 29.4-82.3)	9	Compared effects of SCBA on breathing pattern in firefighters vs. construction workers. Groups very different – construction workers VO _{2max} was 2.89 ml.kg.min ⁻¹ .
Louhevaara <i>et al</i> , (1985)	Max working duration in SCBA.	VO _{2max} , treadmill trial.	57.0 (range	13	The cohort were very fit firefighters, one had a VO _{2max} of 82.3 ml.kg.min ⁻¹ (he was an international cross-country skier).

continued

Table C1. A Review of the Fitness of International Firefighters (continued)

Reference	Description/ Methodology	Variable Measured	Aerobic Power ml kg⁻¹ min⁻¹ (1SD)	n	Comments
Louhevaara <i>et al.</i> , (1985)	Effect of SCBA on gas exchange etc.	VO _{2max} (treadmill test, gas exchange)	4.2 l.min ⁻¹ (range 2.9-5.3)	13	Influential papers, especially as an indication of the respiratory demands of SCBA wear.
Louhevaara <i>et al.</i> , (1984)	Cardio-respiratory effects of SCBA	VO _{2max} (treadmill test, gas exchange)	64.9 (9.3)	12	Well trained firefighters skew the data. The report is valid from a respiratory perspective.
Lusa <i>et al.</i> (1993)	Field-based trial. Thermal effects of PPE.	VO _{2max} (treadmill test, gas exchange)	51.0 (6.0)	12	Well trained group. Other methods questionable (i.e. using Ventilation to estimate VO ₂ during field-based tests).
Lusa <i>et al.</i> (1993)	Responses of firefighting to smoke-diving in the heat.	VO _{2max} (cycle-ergometry, gas exchange)	52.4 (5.2) 4.1 (0.5) l.min ⁻¹	35	Volunteers were trainees, therefore a biased population.
Myhre (1997)	Assessed the relationship between physical measures and job performance	VO _{2max} Unknown assessment	~39.4	279	Showed a significant but weak relationship between VO _{2max} , strength and % body fat and performance during exercise (simulated emergency drills).
Montoliu <i>et al.</i> , (1997)	Comparison between laddermill and treadmill VO _{2max}	VO _{2max} (treadmill test, gas exchange)	34.7 (range 25.7-48.5)	44	Interesting study comparing two exercise modalities. Shows that the treadmill may overestimate the demands of firefighting work!
O'Connell <i>et al.</i> (1986)	Energy costs of simulated stair climbing	VO _{2max} (treadmill test, gas exchange)	3.97 (0.6) l.min ⁻¹	17	Interesting study comparing different exercise modalities. Also used the METS method of estimating workload. (1 MET – 3.5 ml.kg.min ⁻¹).
Peate <i>et al.</i> (2002)	Fitness self-perception and aerobic fitness in firefighters.	VO _{2max} two tests, (step and treadmill) both were sub-maximal	41.8 (8.6)	101	In terms of the present review this is a large cohort.

continued

Table C1. A Review of the Fitness of International Firefighters (continued)

Reference	Description/ Methodology	Variable Measured	Aerobic Power ml kg min⁻¹ (1SD)	n	Comments
Petersen <i>et al.</i> , (2000)	Hyperoxia and simulated firefighting.	VO _{2max} , cycle ergometry.	51.8 (6.1)	17	Results showed that enriching the O ₂ content of SCBA air can produce a small improvement in performance. However, the technical difficulties involved, combined with the increased risk of fire in an O ₂ enriched environment, probably renders this technology largely redundant.
Puterbaugh and Lawyer (1983)	Cardiovascular effects of an exercise programme	VO _{2max} , test modality was not described	3.67 (0.7) l.min ⁻¹	27	This paper showed that a 12-week fitness training programme could elicit a 20% improvement in VO _{2max} in a small group of incumbent firefighters. 45.6ml.kg.min ⁻¹ is the cohort's baseline level.
Smolander <i>et al.</i> (1984)	Muscle endurance after wearing gas-impermeable clothing	VO _{2max} , treadmill test (ventilation and gas exchange)	~53.9	6	Small numbers of well-trained firefighters probably do not represent the population norm.
Sothmann <i>et al.</i> , (1991)	VO ₂ , error of heart rate estimation.	VO _{2max} (treadmill test, gas exchange)	40.6 (6.2)	10	Excellent study - shows that you cannot use heart-rate to estimate oxygen consumption during field tests.
Sothmann <i>et al.</i> , (1992)	Heart rate responses to actual emergencies	VO _{2max} (treadmill test, gas exchange)	40.0 (6.4)	10	Interesting collection of heart rate data during real fires. Self-reporting of firefighting activities inevitably weakens the report.

This project was carried out for the Building Disaster Assessment Group in the Office of the Deputy Prime Minister. This group was established to consider the issues, for fire authorities and their fire and rescue services in the UK, that have been highlighted by the World Trade Centre incident of 11th September 2001. This report focuses on a review of the published literature on the physiological capability of firefighters to perform their wide-ranging operational duties, and to provide recommendations for further research to fill the knowledge gaps.

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