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CLASSIFICATION	SYSTEM NUMBER 150661
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TITLE

TOLERANCE TIMES FOR CONTINUOUS WORK TASKS WHILE WEARING NBC PROTECTIVE CLOTHING IN WARM AND HOT ENVIRONMENTS AND THE STRATEGY OF IMPLEMENTING REST SCHEDULES

System Number:

Patron Number:

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UNCLASSIFIED

December 1994

DCIEM No. 94-62.

DCIEM 94-62

TOLERANCE TIMES FOR CONTINUOUS WORK TASKS WHILE WEARING NBC PROTECTIVE CLOTHING IN WARM AND HOT ENVIRONMENTS AND THE STRATEGY OF IMPLEMENTING REST SCHEDULES

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EXECUTIVE SUMMARY

Canadian Forces personnel must be able to sustain operations in an environment contaminated with NBC agents. However, because of the thickness and low vapour permeability of the protective clothing ensemble, there is considerable heat strain associated with wearing full NBC protection in warm and hot environments. This report provides an updated analysis of the relationship between tolerance time while wearing the NBC clothing and the work intensity at ambient temperatures of 30°C and 40°C. The mathematical function which is used to describe this relationship defines an infinite tolerance time at a specific work intensity. If the oxygen consumption associated with this work intensity is above the oxygen consumption required for resting conditions, then implementing a specific work and rest schedule will increase the total tolerance time and the total work accomplished compared with a continuous work effort. Alternatively, if the oxygen consumption associated with an infinite tolerance time is below the value defined for a resting individual, then implementing work and rest schedules may not be the correct choice. Although tolerance time will be increased, the total amount of work that can be accomplished will decrease.

INTRODUCTION

During the past several years, the Environmental Physiology Section at the Defence and Civil Institute of Environmental Medicine has examined the heat strain associated with wearing nuclear, biological and chemical (NBC) protective clothing while performing exercise in warm and hot environments. This area of research was prompted by the former Directorate of NBC Coordination (DNBCC) which is now within the command of the Joint Staff, Training and NBC (J3 -TRG&NBC).

Canadian Forces personnel must be able to sustain operations in an environment contaminated with NBC agents. Clothing was designed, therefore, that effectively eliminated the interaction of the skin, eyes and respiratory tract with these toxic and potentially lethal agents. However, to acquire the desired level of protection, the clothing consisted of a thick, charcoal-impregnated semi-permeable overgarment together with impermeable rubber gloves, boots and respirator. As a consequence of the insulative qualities and low vapour permeability characteristics of the protective clothing, the effective control of body temperature is reduced. With normal operational or combat clothing, sweat production and evaporation increase in conjunction with the increase in heat production that occurs, for example, during physical work. Wearing the protective clothing, however, severly restricts heat loss through the evaporation of sweat. Therefore, core temperature increases more rapidly while performing continuous work and tolerance times are reduced compared with wearing combat clothing.

One possible solution to the problem of the heat strain associated with wearing the protective clothing is to reduce the amount of work performed, and therefore, the amount of heat produced, by personnel by resting at regular intervals. Indeed, the U.S. Army has specific work and rest guidelines for different ambient temperatures and work rates classified as light, moderate and heavy. Similar guidelines had not been established for the Canadian Forces NBC clothing. It was for this purpose that DCIEM was tasked originally by DNBCC. From our initial investigation at 30°C, it became apparent that tolerance time while wearing the NBC clothing could be predicted accurately from a knowledge of the average work intensity. This relationship between tolerance time and work intensity allowed work and rest guidelines to be developed for 30°C. As a result of the conflict in the Persian Gulf, guidelines were established also at 40°C. Since the original reports were completed, the relationship between tolerance time while wearing the protective clothing and the work intensity has been re-analyzed using a different mathematical function. Besides providing an equally good fit to the data, the new equations could be interpreted from a physiological and physical rather than just a mathematical perspective. The purpose of this report, therefore, is to provide an updated compilation of tolerance times for continuous work tasks while wearing the NBC clothing in warm and hot (i.e., 30°C and 40°C) environments and to suggest strategies for implementing work and rest schedules.

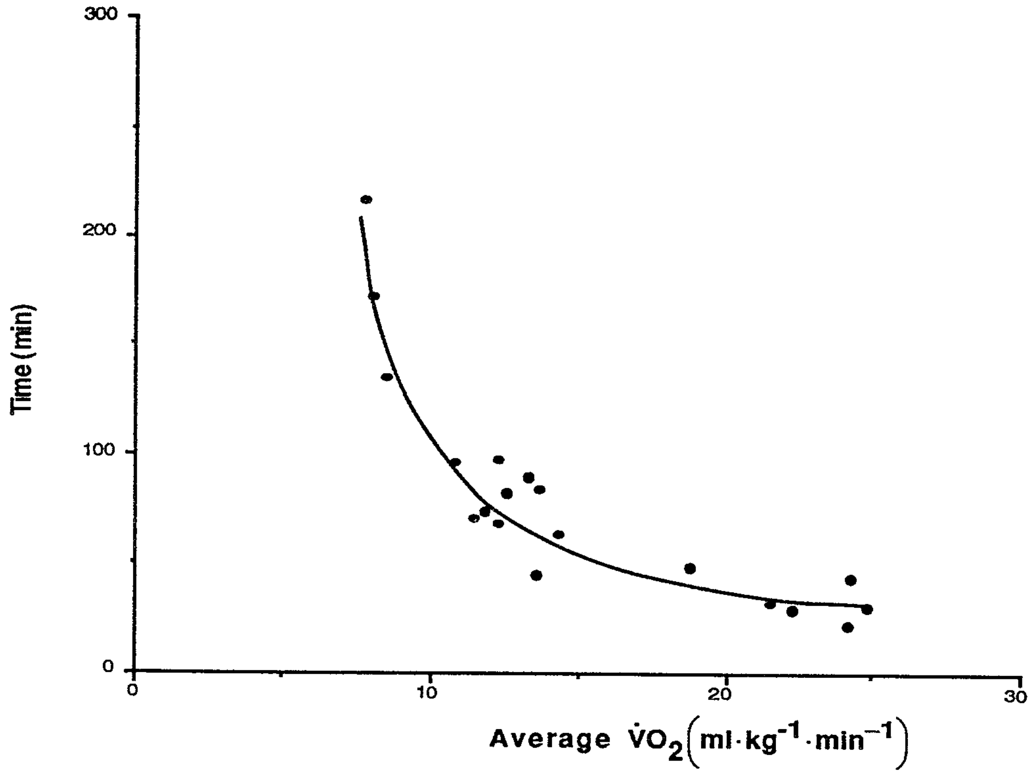
Part 1: Tolerance Times for Continuous Work Wearing Full NBC Protective Clothing (TOPP High)

The decreasing curvilinear relationship between tolerance time and the average metabolic rate is shown in Figure 1 for 30°C and 50% relative humidity. Although the data represent conservative end-points defined by ethical constraints, Commanding Officers should expect moderate heat illness and physical exhaustion casualties associated with these values. Personnel will not be able to continue operations unless the protective clothing is removed. For example, Figure 1 shows that there will be significant heat stress casualties after about 50 min if the troops are working continuously at a work intensity, or oxygen consumption ($\dot{V}O_2$), of about 15 $ml \cdot kg^{-1} \cdot min^{-1}$. This level of $\dot{V}O_2$ is required for an activity like trench digging. The relationship shown in Figure 1 can be defined by the following equation;

$$\text{Time (min)} = \frac{593.1}{\text{Avg. } \dot{V}O_2 - 4.7} \qquad (1).$$

In this equation, the numerator represents heat storage, $\dot{V}O_2$ is the metabolic rate or rate of heat production and 4.7 is the average rate of heat loss in this environment. The most important application of this equation is the fact that infinite tolerance time is defined by division by zero, i.e., when the average $\dot{V}O_2$ equals 4.7 $ml \cdot kg^{-1} \cdot min^{-1}$ for equation (1) above. Whether this value is greater than or less than the $\dot{V}O_2$ equivalent of 4 $ml \cdot kg^{-1} \cdot min^{-1}$ for a resting individual has very important implications when work and rest schedules are considered for a particular military task or operation (see Part 2 below).

Figure1 *The relationship between time and the average oxygen consumption ($\dot{V}O_2$ $\dot{V}O_2$) while wearing full NBC protective clothing (TOPP High) at 30°C and 50% relative humidity.*



For 40°C and 50% relative humidity, the relationship between time and work intensity was described as follows;

$$\text{Time (min)} = \frac{842.4}{\text{Avg. } \dot{V}O_2 + 1.94} \qquad (2) .$$

Infinite tolerance time could not be achieved in this environment since division by zero is defined at a negative $\dot{V}O_2$ (i.e., -1.94 ml·kg^{-1}·min^{-1}). Obviously, oxygen will always be consumed and thus, must always be greater than zero. Finally, with less humid conditions (i.e., 40°C and 30% relative humidity), the following equation defined the relationship between time and metabolic rate;

$$\text{Time (min)} = \frac{763.3}{\text{Avg. } \dot{V}O_2 - 2.16} \qquad (3) .$$

Infinite tolerance time also could not be attained in this environment since the average $\dot{V}O_2$ of 2.16 ml·kg^{-1}·min^{-1} is below the $\dot{V}O_2$ equivalent of most resting soldiers (i.e., 4 ml·kg^{-1}·min^{-1}).

From the three equations presented above, tolerance times can be estimated for various military tasks if the approximate work intensity required to perform these tasks is known. These values are outlined below in Table 1.

Table 1: *Tolerance times (minutes) for continuous light, moderate and heavy work tasks in full NBC protective clothing (TOPP High) at ambient temperatures of 30° and 40°C with different levels of relative humidity.*

Work Task and Classification	Work Intensity (ml kg^{-1} min^{-1})	30°C, 50% RH	40°C 30% RH	40°C 50% RH
Guard Duty, Labour Detail, Light	5 - 6	455	200	105
Marching 3.7 km/h (2.3 mph), Moderate	10	115	100	70
Marching 5.4 km/h (3.4 mph), Moderate	13	70	70	55
Trench Digging, Scouting Patrol, Heavy	15	60	60	50
Forced March, Tank Crew Firing Drill, Very Heavy	20	40	40	40

It should be noted that at the work intensities classified as heavy or very heavy, tolerance times are seemingly unaffected by a change in environmental conditions, whereas the reverse is true at metabolic rates classified as light. The thickness of the NBC overgarment together with the low vapour permeability of the protective ensemble not only creates a barrier that restricts the movement of NBC agents from the environment to the body but also, this barrier restricts the movement and subsequent evaporation of water vapour from the skin surface to the environment. Heavy work intensities are synonymous with high levels of heat production. If the evaporation of sweat is restricted then the rate of heat production, i.e., the intensity of work, will be the dominant factor in determining the rate of increase in body temperature and tolerance time. At lighter work intensities, there is sufficient time for some water vapour to move through the NBC overgarment and be evaporated to the environment. The amount of sweat evaporated from the protective clothing will then become a function of the vapour pressure of the environment. Lower ambient temperatures and/or levels of humidity will enhance the evaporation of sweat. As the evaporation of sweat from the clothing and skin surface is increased, the rate of increase in body temperature is slowed and tolerance time is enhanced.

Commanding Officers must not expect their personnel to be able to continue beyond the tolerance times shown in Table 1 without allowing individuals to remove the NBC protective clothing. If this is not possible, significant heat stress casualties should be anticipated.

Part 2: The Strategy of Implementing Work and Rest Schedules

From the three equations presented in Part 1, the average intensity of effort (i.e., $\dot{V}O_2$) that could be continuously exerted for a given duration could be calculated. Work and rest schedules could then be developed for a given work task that would allow this duration or tolerance time to be achieved.

For example, to achieve a tolerance time of 3 hours under environmental conditions represented by equation (1) (i.e., 30°C and 50% relative humidity), the average work intensity or $\dot{V}O_2$ should approximate 8 $ml \cdot kg^{-1} \cdot min^{-1}$. This intensity of effort exceeds the value defined for light exercise (shown in Table 1), thus a work and rest schedule would not be required to achieve a tolerance time of 3 hours for light exercise (see Table 2). However, marching at 3.7 $km \cdot h^{-1}$ demands an average $\dot{V}O_2$ of 10 $ml \cdot kg^{-1} \cdot min^{-1}$; this value exceeds the average $\dot{V}O_2$ required to continue for 3 hours in these environmental conditions dressed in NBC clothing. Therefore, a work and rest schedule must be implemented to achieve this goal. Using the $\dot{V}O_2$ equivalent of 4 $ml \cdot kg^{-1} \cdot min^{-1}$ for a resting individual, the duration of the work and rest phases could be calculated to achieve the desired tolerance time of 3 hours. In Table 2, 20 minutes of marching at 3.7 $km \cdot h^{-1}$ followed by 10 minutes of rest would produce a weighted average of 8 $ml \cdot kg^{-1} \cdot min^{-1}$ and the desired tolerance time of 3 hours, i.e,

$$\frac{(20\,min \times 10\,ml \cdot kg^{-1} \cdot min^{-1}) + (10\,min \times 4\,ml \cdot kg^{-1} \cdot min^{-1})}{30\,min}$$

$$= \frac{240\,ml \cdot kg^{-1}}{30\,min} \quad \text{or} \quad = 8\,ml \cdot kg^{-1} \cdot min^{-1}.$$

In this previous example, the time spent marching (20 min) and resting (10 min) was selected arbitrarily but the proportion of work time to rest time, i.e., 2 to 1, was necessary to produce the desired average $\dot{V}O_2$ of 8 $ml \cdot kg^{-1} \cdot min^{-1}$. The same average $\dot{V}O_2$ would result from a 40 min walking phase and a 20 min rest period.

Table 2: *Suggested work and rest schedules for achieving tolerance times from 1.0 to 5.0 hours in full NBC protective clothing (TOPP High) at 30°C with 50% relative humidity.*

30°C, 50% RH	Tolerance Time (hours)				
	1.0	2.0	3.0	4.0	5.0
Labour Detail, Light	NR	NR	NR	NR	NR
Marching 3.7 km/h (2.3 mph), Moderate	NR	25/5	20/10	15/15	10/20
Marching 5.4 km/h (3.4 mph), Moderate	NR	20/10	15/15	10/20	10/25
Trench Digging, Heavy	25/5	15/15	10/20	10/25	10/30
Forced March, Very Heavy	25/5	15/20	10/20	10/30	10/40

NR = not required. The tolerance time can be achieved with ***continuous*** *work for the described task.*
25/5 = 25 minutes of work followed by 5 minutes of rest. This pattern of work and rest is continued until the required tolerance time is achieved.

Using similar procedures, work and rest schedules were calculated to achieve the desired tolerance times outlined in Tables 3 and 4 for 40°C and 30% or 50% relative humidity, respectively.

Table 3: *Suggested work and rest schedules for achieving tolerance times from 1.0 to 5.0 hours in full NBC protective clothing (TOPP High) at 40°C with 30% relative humidity. Abbreviations are as described for Table 2.*

40°C, 30% RH	Tolerance Time (hours)				
	1.0	2.0	3.0	4.0	5.0
Labour Detail, Light	NR	NR	NR	20/10	10/20
Marching 3.7 km/h (2.3 mph), Moderate	NR	20/10	10/20	10/30	5/55
Marching 5.4 km/h (3.4 mph), Moderate	NR	15/15	10/30	10/50	5/55
Trench Digging, Heavy	25/5	10/15	10/40	10/70	5/55
Forced March, Very Heavy	25/5	10/20	10/50	5/55	5/85

Table 4: *Suggested work and rest schedules for achieving tolerance times from 1.0 to 5.0 hours in full NBC protective clothing (TOPP High) at 40°C with 50% relative humidity. Abbreviations are similar to Tables 2 and 3.*

40°C, 50% RH	Tolerance Time (hours)				
	1.0	2.0	3.0	4.0	5.0
Labour Detail, Light	NR	15/15	NP	NP	NP
Marching 3.7 km/h (2.3 mph), Moderate	NR	5/25	NP	NP	NP
Marching 5.4 km/h (3.4 mph), Moderate	NR	10/70	NP	NP	NP
Trench Digging, Heavy	45/15	10/80	NP	NP	NP
Forced March, Very Heavy	18/12	5/55	NP	NP	NP

NP = not possible to implement a work/rest schedule. Even with complete rest these tolerance times could not be achieved without significant heat stress casualties.

Whether or not the environmental conditions cause an increase in core temperature at rest while wearing the protective clothing has important implications concerning the total work accomplished and the decision to implement work and rest schedules. First, there is no question that implementing work and rest schedules will increase tolerance time compared with performing the work task continuously. The use of a work and rest schedule simply decreases the average work intensity and, thus, prolongs tolerance time according to the relationships described by equations (1), (2) and (3). If the main objective is to prolong tolerance time, then the lowest possible average work intensity should be selected. In some environments, however, tolerance time may not exceed 3 or 4 hours even under resting conditions. If this time is not sufficient for the dissipation of the "agent " in the area, then a decision must be made of whether to implement work and rest schedules during the move to a "clean" area. According to Table 4 at 40°C and 50% relative humidity, for example, personnel could march at 3.7 $km \cdot h^{-1}$ for 1 hour while wearing the protective clothing. Obviously, after 1 hour a distance of 3.7 kilometres would have been covered. Implementing the work and rest schedule suggested in Table 4 would increase tolerance time to 2 hours but only 20 minutes of this total time would consist of actual marching. Thus, after 2 hours, a distance of only 1.2 kilometres (i.e., 1/3 of 3.7 kilometres) would have been completed. Therefore, the decision to implement a work and rest schedule may not be the most prudent decision for these environmental conditions. In contrast, at 30°C and 50% relative humidity, implementing work and rest schedules not only increases tolerance time but also this strategy increases the total work accomplished compared with a continuous work schedule. For example, marching at 5.4 $km \cdot h^{-1}$ could be continued for 70 minutes under these environmental conditions according to Table 1. However, implementing a 20 min exercise and 10 minute rest strategy not only increases tolerance time to 120 minutes but also increases the total work time to 80 minutes. Similarly, selecting a 15 minute work and 15 minute rest schedule increases total tolerance time to 180 minutes of which 90 minutes would be performed marching at 5.4 $km \cdot h^{-1}$. When body heat can be lost to the environment at rest, then implementing a work and rest schedule would be advised. Therefore, it would be wise to implement work and rest schedules with environmental temperatures below 35°C. A more difficult decision, as outlined above, must be made at temperatures above 35°C.

There is one other important factor that must be remembered if the guidelines outlined within this report are followed. It was emphasized in Part 1 that Commanding Officers should not expect their personnel to continue beyond the tolerance times shown in Table 1 for continuous work tasks unless the protective clothing can be removed which promotes a more effective heat loss to the environment. A similar reminder is associated with the work and rest schedules shown in Tables 2, 3 and 4. Soldiers should be able to continue for 4 hours if 15 minutes of marching at 2.3 mph is alternated with 15 minutes of rest at 30°C (see Table 2). However, personnel will be close to exhaustion at this time. Therefore, if the clothing cannot be removed after 4 hours, alternative strategies must be selected. Obviously, increasing the duration of the rest periods will extend tolerance time. In fact, because infinite tolerance time was associated with a metabolic rate that exceeded a resting condition, the decision to implement complete rest while wearing the protective clothing at 30°C may be the wisest decision. However, operational requirements may not allow this choice to be a viable option.

Finally, the tolerance times and work and rest schedules presented in this document were derived from mean data generated from experimental trials conducted in an environmental chamber. Approximately 10-15% variation should be expected for the continuous tolerance times presented in Table 1. Also, the data have not considered the influences of solar radiation and wind. Tolerance times will be reduced and rest periods should be increased if solar radiation is high. Conversely, since the wind will increase evaporative cooling from the NBC clothing, tolerance times should increase at a given metabolic rate as wind speed increases.

SUMMARY

A decreasing curvilinear relationship exists between tolerance time while wearing NBC protective clothing and the average work intensity. The mathematical function used to describe this relationship allows an infinite tolerance time to be defined at a specific work intensity or $\dot{V}O_2$. If this oxygen consumption is above the value associated with resting conditions, then implementing a specific work and rest schedule will increase the total tolerance time and the total work accomplished compared with a continuous work effort. Alternatively, if the $\dot{V}O_2$ associated with an infinite tolerance time is below the value defined for a resting individual, then implementing work and rest schedules may not be the correct choice. Although tolerance time will be increased the total amount of work that can be accomplished will decrease.

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1. ORIGINATOR (the name and address of the organization preparing the document. Organizations for whom the document was prepared, e.g. Establishment sponsoring a contractor's report, or tasking agency, are entered in section 12.) D.C.I.E.M. P.O. Box 2000 North York, Ont. M3M 3B9	2. DOCUMENT SECURITY CLASSIFICATION (overall security classification of the document including special warning terms if applicable) Unclassified

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Tolerance times for continuous work tasks while wearing NBC protective clothing in warm and hot environments and the strategy of implementing rest schedules.

4. DESCRIPTIVE NOTES (the category of the document, e.g. technical report, technical note or memorandum. If appropriate, enter the type of report, e.g. interim, progress, summary, annual or final. Give the inclusive dates when a specific reporting period is covered.)

Technical Report

5. AUTHOR(S) (Last name, first name, middle initial. If military, show rank, e.g. Doe, Maj. John E.)

T.M. McLellan

6. DOCUMENT DATE (month and year of publication of document) October, 1994	7a. NO. OF PAGES (total containing information. Include Annexes, Appendices, etc.) 14	7b. NO. OF REFS (total cited in document) 0

8a. PROJECT OR GRANT NO. (if appropriate, the applicable research and development project or grant number under which the document was written. Please specify whether project or grant) 51CA12A (Project No.)	8b. CONTRACT NO. (if appropriate, the applicable number under which the document was written)
9a. ORIGINATOR'S DOCUMENT NUMBER (the official document number by which the document is identified by the originating activity. This number must be unique to this document.)	9b. OTHER DOCUMENT NO.(S) (Any other numbers which may be assigned this document either by the originator or by the sponsor)

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Canadian Forces personnel must be able to sustain operations in an environment contaminated with NBC agents. However, because of the thickness and low vapour permeability of the protective clothing ensemble, there is considerable heat strain associated with wearing full NBC protection in warm and hot environments. This report provides and updated analysis of the relationship between tolerance time while wearing the NBC clothing and the work intensity at ambient temperatures of 30°C and 40°C. The mathematical function which is used to describe this relationship defines an infinite tolerance time at a specific work intensity. If this intensity is above the oxygen consumption associated with resting conditions, then implementing a specific work and rest schedule will increase the total tolerance time and the total work accomplished compared with a continuous work effort. Alternatively, if the work intensity associated with an inifinite tolerance time is below the value defined for a resting individual, then implementing work and rest schedules may not be the correct choice. Although tolerance time will be increased, the total amount of work that can be accomplished will decrease.

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work intensity, work and rest schedules, warm and hot environments, NBC protective clothing

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