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REPORT

FINAL REPORT

Respirator Performance Rating Tables for Mask Design

To

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Respirator Performance Rating Tables for Mask Design

Final Report

December 1990

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Respirator Performance Rating Tables for Mask Design

Abstract

The ultimate goal for respiratory protective mask designers is computer-aided design (CAD). CAD is usually used to assist with physical layout and fabrication, but physiological information can be incorporated into CAD processes as well. By this means, physiological effects of a candidate mask design can be evaluated before the mask is fabricated, thus leading to more effective and efficient mask development than has previous been possible.

The Performance Rating Table (PRT) is a beginning step to formulating physiological information in a way that can be useful for design. The PRT is an assessment of the task performance attributable to various mask factors. More than anything else, the PRT is a conceptual organization of information which has previously been too complicated to be of use in mask design.

A number of PRT's are presented in this report. The first four give performance ratings for generalized tasks at different rates of work for four different environmental conditions. The last PRT assigns performance rating values for specific representative military tasks for a temperate environment.

Best estimates of tabled values were obtained from the literature. It has become clear, however, that experimental designs of reported studies were rarely able to produce useful results. It cannot be overemphasized that PRT entries need much

more experimental confirmation before they can be considered to be completely valid.

The relationships of masks to their wearers are very complex: they affect sensory as well as physical interfaces. The PRTs reflect this complexity, and clearly indicate that while one or two mask factors are particularly critical for one set of work rates and environments, other factors may be more critical for other work rates or other environments. One mask may not be able to give satisfactory performance over all conditions of use.

Introduction

The ultimate goal of mask design engineers is to formulate contributing knowledge in such a way that various mask factors may be quantitatively determined. In this way, computer-aided design of masks could become a substantive reality, and design trade-offs would be better understood.

Mathematical modelling leads to this ultimate goal. Givoni and Goldman (1972) have constructed a workable model useful in determining trade-offs between work rates, environment, and protective clothing. However, mask design is not as simple as clothing design in that, in addition to the above factors, other factors associated with respiration, cardiovascular dynamics, and conscious awareness of irritants are present. With heat stress, the thermal mechanical problem is reasonably well worked out, and the main complicating factor is geometry of the body. The Givoni and Goldman model even circumvents geometrical complications. With masks, however, there are many complications: geometry, vision, communication, psychology, and respiration are among these. With thermal stress, body core temperature can be a simple indicator of the thermal state of the worker. With respiratory stress, no simple indicator has thus far been found.

Simple indicators have been postulated without much success. Johnson and Berlin (1974) advanced the notion that minimum exhalation time of people wearing masks could be this indicator. Other reports, such as by Harber et al. (1984), tended to confirm the exhalation time notion. A major difficulty with this indicator is that the minimum exhalation time can be sustained for long periods of time by exercising healthy individuals (Johnson and Curtis, 1978).

Another simple indicator which was advanced was that of pressure swing inside the mask. Love (1983) wrote that mask resistance was noticeable, but tolerable, if total pressure swing at the mouth did not exceed 17 cm H_2O. Such a criterion has a physiological basis in the limiting pressure which can be developed by the respiratory muscles, and the amount of reserve normally kept. O'Connell and Campbell (1976) related dyspnea to the ratio of developed mouth pressure to maximum possible mouth pressure, and this ratio, in turn, is related by experience and habit to length-tension inappropriateness. Mouth pressure swing, however, is only an indicator of mask acceptability and is not obviously related to limits of work while wearing a mask (Raven et al., 1982).

In trying to determine a reasonable screening test for respirator wear, Raven et al. (1982) found that subjects wearing masks were not able to cope with the additional respiratory stress if their dyspnea index, the ratio of minute volume to maximum voluntary ventilation in 15 seconds, exceeded 70%. The dyspnea index is related by mechanical factors to both minimum exhalation time and mouth pressure swing. However, its purpose is as a screening device and is not necessarily related to the limits of working while wearing a mask.

Thus, although a simple indicator of the limits of respiratory stress has been sought, a satisfactory indicator has not been found. We know that there are limits to pressure developed by the respiratory muscles, exhalation flow rate, and muscle fatigue. In addition, there are limits to oxygen debt, oxygen transport, deep body temperature, and tolerance of irritants. Mask tolerance can involve all of these to some extent, making a comprehensible mask model very difficult to ascertain.

Putting limits on acceptable breathing resistance is one way to define mask design criteria. However, this definition is subject to a sliding scale depending on what is acceptable and under what conditions acceptability was determined. We present in this report an alternative approach by defining the problem as fractional performance rating depending on resistance level, work conditions, environment, and other mask parameters. In this way, the effects of exceeding defined levels are made clear and design trade-offs may be made. While this approach does not give the mask designer the full model he requires, it nevertheless is a beginning toward that end. The Performance Rating Table (PRT) identifies components which should become part of the eventual model, gives magnitude estimates for specific sets of conditions, and gives a basis for further work in mask design.

The Performance Rating Table Concept

The Performance Rating Table (Table 3) quantifies effects of respiratory protective mask factors on the task performance of an individual wearing the mask. Individual cell entries estimate the percentage performance of a mask wearer compared to the no-mask condition. All entries are thus relative, and are scaled by assuming an entry value of 100.0 is equivalent to no performance degradation and an entry value of 0.0 is equivalent to complete performance degradation. The higher the entry value, the smaller is the relative degradation due to that factor.

Individual factors are grouped by categories. Deno et al. (1981) have shown that independent individual factors determining exercise performance are related by multiplication:

$$F_{TOT} = F_1 F_2 \cdot\cdot\cdot\cdot F_n \qquad (1)$$

where F_{TOT} = combined performance factor

$F_1, F_2, \cdots, F_n$ = individual performance factors

Thus, the product of the individual factor entries is the category entry. Likewise, total mask performance is given by the product of all factor entries or by the product of all category entries. Performance degradation is the inverse of mask performance rating.

If a mask is expected to have a 25% degradation in performance, then performance of the task by an individual is 75% of the performance expected without the mask. Translated into operational terms, a 75% performance rating value means that any normal individual is expected to require 4 hours with a mask to accomplish what he did during 3 hours without the mask. Or, to accomplish the complete task in the same amount of time requires 4 individuals where 3 were required before masks were worn.

be assumed, however, that an increase of 10 degrees of peripheral vision will totally remove performance decrement due to field of view.

Despite the above two assumptions, the PRT still can be very useful. First of all, mask technology is not presently subject to large changes, and so progress will most likely occur incrementally. Second, the table organizes information about a large number of mask parameters. While the numerical entries may change because of new mask technology, the organization of the table is not required to change. It will be much easier to construct new entry values given the old values for comparison.

3. All wearers are normal, healthy, young adults. Deaf individuals operate from a different communications base than those who can hear, and individuals suffering from chronic obstructive pulmonary disease may be unaffected by mask resistance. Likewise, there are particularly anxious individuals who are considered to react adversely to mask wear, but who represent no more than 10% of the population (Wilson, et al., 1986). Thus, numerical entries are given for average individuals.

4. Temperate environmental conditions are assumed. Thermal burdens associated with extreme temperatures and vision difficulties associated with cold, humid environments are not reflected in this table. Other tables will be constructed for other environments.

5. Work rates for the different categories are held constant for as long as they can be performed. As indicated in Table 1,

different work rates can be performed for different times, with the longest times corresponding to the lowest work rates (Johnson and Cummings, 1975). What this assumption means is that mask performance factors, which differ in their relative severities at different work rates, can be separated in an orderly fashion (Table 1).

Work categories in Table 1 were chosen to represent different stresses caused by masks on the wearers. This basic concept was originally proposed in Johnson and Cummings (1975). Under this concept, performance times of 5-15 minutes should result in maximum sensitivity to respiratory factors, 15-240 minutes should result in maximum sensitivity to thermal factors, and times greater than 2-4 hours should result in maximum sensitivity to psychological factors. Concomitant work rates are taken to be the maximums which can be performed for the requisite times. This concept is a reflection of the dominant time constants of response of about 30 sec, 45 sec, 50 sec, and 60 min for the heart, respiratory system, oxygen uptake, and thermal systems of the body (Johnson, 1991).

Since the Johnson and Cummings paper, other results have tended to confirm this model. Deno et al. (1981) showed that subjects could work on a treadmill for 33.2 min at work rates progressing to about 192 watts external work with no resistance, but that subjects could work for only 29.8 minutes at a final work rate of about 165 watts wearing a mask with resistance of 5.5 cm $H_2O \cdot L/sec$. There was only a 1% reduction in work rate due to the same resistances for subjects exercising for 1 hour. Wilson et al.

(1989A) and van Huss and Heusner (1965) obtained large decrements in performance, probably due to resistance, with subjects working in the respiratory range of about 240 W external work rate, whereas experiments by Dahlback and Balldin (1984), Harber et al. (1984), Zechman et al. (1957), and White and Hodous (1987) were not conducted in the work range most sensitive to respiratory stress. Contrarily, James et al. (1984) and Nielsen et al. (1987) designed their experiments to highlight thermal effects and so kept their work rates low enough to allow time for heat to build up in their subjects. When reading the literature, one way to reconcile conflicting results is to carefully note experimental designs.

Unfortunately, most published mask performance studies were not conducted at constant work rates. A graded exercise test, for instance, becomes an integrated test of many mask performance factors and the results cannot be attributable to any single set of factors. This has the disadvantage of confounding numerical results, desensitizing tests of differences between mask parameters, and limiting conclusions which can be drawn.

The assumption of constant work rate also means that performance data for dissimilar tasks can be given a common interpretation. For instance, vision tests involving reading could result in a 70% correct recognition of words, but a running tolerance time test could result in a 20% increase in time to run a certain distance. In the former case, a 70% performance rating is clear. In the latter case, performance rating might be considered to be 120% because time actually increases.

If the running tests were conducted at a constant rate of work for a variable amount of time (dependent on voluntary tolerance time) then the results could be easily interpreted as performance rating. What we have done here is to assume that a 20% increase in time while wearing masks can be interpreted as running 80% of the same distance in the same time that nonwearers ran the complete distance.

What makes this procedure somewhat incorrect is that rates of work under masked and unmasked conditions are not the same. Running 80% of the distance in the same time means that work rate is less while wearing a mask. Even this could be corrected if work rate were proportional to speed of running, but such is not the case. A definition of performance rating of:

$$\text{Performance rating} = 1 - \left[\frac{\text{rate of work with mask}}{\text{rate of work without mask}}\right] \qquad (2)$$

is reasonable, but violates the necessary table condition of constant work rate.

Nevertheless, experimental results are subject to much variability and totally comparable entries for the Performance Rating Table are not presently available. Thus, within the uncertainties of tabled values, we have considered a 20% increase in running time to be an 80% performance rating. All performance ratings were calculated from:

$$\text{Performance rating} = \frac{\text{mask results}}{\text{control results}} \qquad (3)$$

6. <u>Masks and hoods are assumed to be worn for an extended period of time which doesn't depend on the work rate.</u> Thus, very heavy work rates that normally cannot be performed for more than 2 minutes will still be subject to degradation from mask harness pressure, which takes many hours to have an effect. Masks will be considered to have been worn for an indefinitely long period before the work and for an indefinitely long period after.

7. <u>Task variety increases as performance time increases.</u> The types of tasks expected to be performed at very light rates of work are much more varied than those at very heavy rates of work. The reason for this assumption is natural: very light work rates can be performed for many hours, and the opportunity to change elemental tasks in that time is large. Contrarily, a work rate which can be performed for no more than 2 minutes does not offer much time to change jobs. Occupationally speaking, a clerk-typist is expected to be much more wide-ranging in the types of elemental tasks performed than is a firefighter inside a burning building.

<u>Definition of Work Rates</u>

Tasks are given in the general terms of very light work, light work, moderate work, heavy work, and very heavy work. These categories are to be construed to consist of occupational duties and not leisure activities. Thus, light work for a clerk could consist of typing, filing, answering the phone or recognizing and greeting people. There is a communications and attention demand in occupational duties not required of many light leisure time activities such as light reading, writing letters, or watching TV. Occupational duties will thus require different numerical entries than would leisure activities.

The normal physiological definition of these work categories is not used here. Instead, the work category classification is given in Table 1. The range of efforts given with the work categories used here is much wider than allowed by the normal classifications, and is expected to result in a wider range of mask effects. Performing heavy work, for instance, will likely result in mask interference with respiration, whereas performance time for the other work categories is not expected to be greatly influenced by respiratory burden.

In completing Table 1, performance times were used to obtain oxygen uptakes after the method in Kamon (1981), aerobic fractions were obtained from Astrand and Rodahl (1970), metabolic rates were determined considering the caloric equivalent of oxygen to be 20.18 W·sec/L (4.82 kcal/L from Johnson, 1991), and various muscular efficiencies were assumed based on the types of tasks represented by each work classification. Physical work rates were calculated from metabolic rate and muscular efficiency.

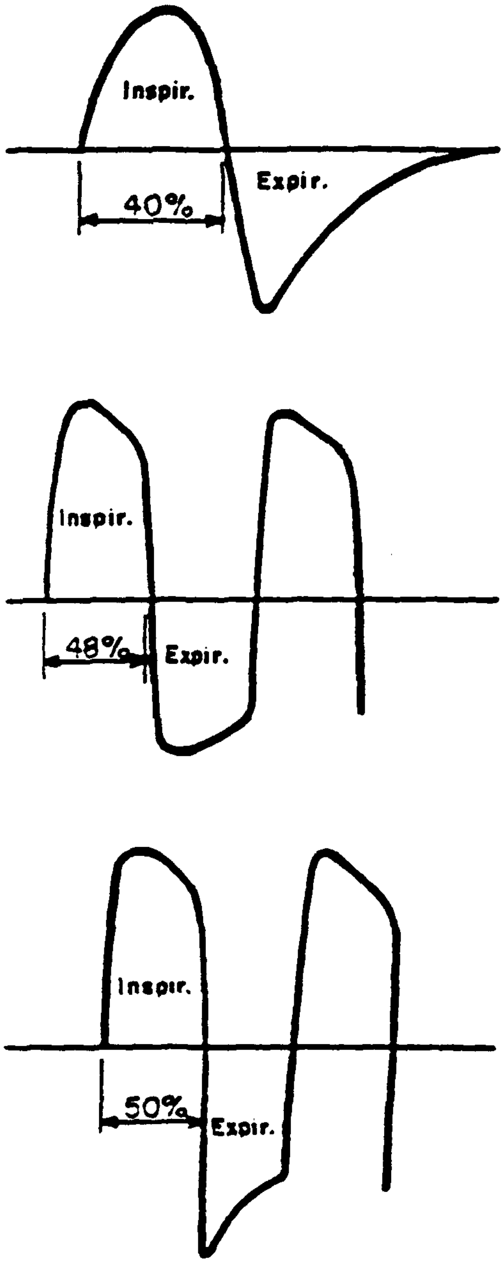
In calculating peak flow, minute ventilation was first obtained from oxygen consumption using Astrand and Rodahl(1970). Account was taken of the different respiratory waveforms expected for each work category (Figure 1). Inhalation waveshapes were assumed to be sinusoidal for very light and light work, and trapezoidal for moderate, heavy, and very heavy work (Johnson,

Table 1. Work Categories Used in the Performance Rating Table.

Work Classification	$\dot{V}_{O_2}/\dot{V}_{O_2\,max}$ Percent	Oxygen Consumption L/min	Respiratory Ventilation L/min	Peak Flow L/min	Aerobic Fraction Percent	Metabolic Rate watts	Metabolic Rate (kcal/min)	Metabolic Rate mets	Muscular Efficiency Percent	Physical Work Rate watts	Physical Work Rate (kcal/min)	Performance Time
Very Heavy	100	3.2	220	528	50	2150	(30.9)	20	20	430	(6.2)	2 min
Heavy	95	3.0	94	226	85	1190	(17.0)	11	20	240	(3.4)	10 min
Moderate	70	2.2	51	128	98	755	(10.8)	7	18	140	(1.4)	50 min
Light	20	0.6	15	59	100	202	(2.90)	2	5	10	(0.15)	8 hr
Very Light	8-10	0.3	8	31	100	105	(1.51)	1	0	0	(0.00)	Indefinitely

	Representative Activities	Principal Stress
Very Heavy	Sprinting	Energy and oxygen storage
Heavy	Running at 9-10 mph unencumbered, skiing, playing squash	Respiration
Moderate	Climbing hills, shoveling fast	Heat
Light	Washing clothes, polishing. light gymnastics, walking at 2 mph	Long term stress
Very Light	Lying, sitting, reading, answering phone, intermittent typing	Long term stress

Caloric equivalent of oxygen = 20.18 W.sec/mL = 4.82 kcal/L
1 met = 105 W



Very Light
Light

$$\text{max flow} = \left(\frac{\text{avg flow}}{0.4}\right)\left(\frac{\pi}{2}\right) = 3.927 \text{ avg flow}$$

Moderate

$$\text{max flow} = \left(\frac{\text{avg flow}}{0.48}\right)\left(\frac{6}{5}\right) = 2.500 \text{ avg flow}$$

Heavy
Very Heavy

$$\text{max flow} = \left(\frac{\text{avg flow}}{0.5}\right)\left(\frac{6}{5}\right) = 2.400 \text{ avg flow}$$

Figure 1. Assumed respiratory airflow waveforms for different work rates. From these come the relationships between maximum and average flow rates.

1984). Inspiration was assumed to account for 40% of the breathing period for very light and light work, 48% for moderate work, and 50% for heavy and very heavy work (Johnson, 1984). These resulted in peak flow being 3.927 times average inspiratory flow (minute ventilation) for very light and light work, 2.500 times average flow for moderate work, and 2.400 times average flow for heavy and very heavy work. Note that transient inspiratory flows can achieve much higher values.

Mask Factors

Mask factors have been generalized and collected to give a relatively small number. In Table 2 are listed many mask elements considered and the factors in which they have been placed. Thus the mask factor called vision field size actually consists of many elements dealing with side-to-side, up and down, straight ahead, and relational fields of gaze.

Some of the elements appearing in Table 2 would be expected to change if the type of mask changed. Notably, a self-contained air supplied mask would require the addition of flow capacity, with elements of maximum flow rates and storage tank volume, to the respiratory factor. Also, greater mask protection factors usually require greater filter element bulk and weight. Thus, mask protection factor is a strong contributor to the mask physical structure element.

Table 2. Mask Factor Elements Considered in the Performance Rating Table.

Vision

- Field Size
  - Peripheral Vision
  - Binocular Vision
  - Depth Perception
  - Field of Gaze
  - Below Horizontal Field
  - Interpupillary Distance
  - Eye Relief
- Acuity
  - Resolution
  - Color
  - Light Transmission
  - Eye Correction
  - Glare/Haze

Communications

- Intelligibility
  - Rasti Test
  - Signal-to-Noise Ratio
  - Reverberation Time
  - Frequency Content
  - Amplification
  - Speech and Hearing
- Distance
  - 50% Attenuation
  - Amplification
  - Dead Space Size
  - Nose Cup Shape
  - Mounting
- Direction
  - Intelligibility Contour Plot
  - Location of Voicemitter

Respiratory

- Resistance
  - Inhalation/Exhalation Resistances

Table 2. Continued.

Resistance Cont'd

Valve Location
Airflow Path
Resistance Inconstancy
Elastic Load

Dead Space

Valve Location
Airflow Path
Exhaled Carbon Dioxide

Thermal

Moisture Removal

Thermal Balance

Moisture Accumulation
Convection
Radiation
Inlet Temperature

Personal Support

Drinking/Eating

Medical Procedures

Valsalva Maneuvers
Drug Administration
Cardiopulmonary Resuscitation
Nasal/Visual Lacrimation
Skin Trauma

Physical

Compatibility

Corrective Vision
Connections
Helmet
Entry/Exit
Sighting
Clothing
Air Source
Communications
Canisters

Table 2. Continued.

Compatibility Cont'd
Rifles
Night Vision Goggles
Helmet Mounted Displays
Anthropometry
Size/Fit
Component Location
Facial Fit
Pressure Points
Physical Structure
Weight
Bulk
Center of Gravity
Flexibility
Material
Psychological
Identification
Skin Irritation/Itching
Local Awareness
Claustrophobia

While these elements may not be exhaustive, they do indicate that some functional grouping is necessary in order to deal with the many influences on mask performance. Numerical values in Table 3 are meant to reflect overall effects of many elements.

Performance Rating Values

Comparison between studies for the Performance Rating Table requires estimates of work rates. These are not often given in published reports. In cases where sufficient information was given in methods sections, metabolic work rates were calculated from (Givoni and Goldman, 1971):

$$W = M\zeta\ [(2.7 + 3.2\ (S-0.7)^{1.65} + 100G\ (0.23 + 0.29\ (S - 0.7))] \quad (4)$$

$$S > 0.7 \text{ m/sec}$$

where W = metabolic rate, W
M = subject mass, kg
ζ = terrain coefficient, usually assumed to be 1.0 for treadmill running, dimensionless
S = treadmill speed, m/sec
G = treadmill grade, fractional

and external work rates were assumed to be 20% of the above calculated value (20% muscular efficiency).

a. Vision

Reports of effects of mask vision on exercise performance have not been found. Beginning with the highest levels of exercise, as long as some minimal vision is present, vision factors should have little relative effect. Difficult tasks, such as running as fast as possible, or carrying very heavy loads do not usually require much visual ability. Indeed,

Table 3. Performance Rating Table for Temperate Environments ($20^{\circ}C$). Values indicate percent performance of an M-17 mask wearer compared to no-mask performance.

	Work Rate				
	Very Light	Light	Medium	Heavy	Very Heavy
Vision	93	95	97	99	99
Field Size	96	97	98	100	100
Acuity	97	98	99	99	99
Communications	94	95	98	99	100
Attenuation Dist.	99	99	99	99	100
Intelligibility	95	97	99	100	100
Direction	100	99	100	100	100
Respiration	100	98	94	80	81
Resistance	100	99	99	84	84
Dead Space	100	99	95	95	96
Thermal Factors	100	95	95	100	100
Moisture Removal	100	100	100	100	100
Thermal Balance	100	95	95	100	100
Personal Support	93	94	95	95	95
Drinking/Eating	93	94	95	95	95
Medical Procedures	100	100	100	100	100
Physical Factors	64	69	87	92	97
Physical Structure	76	90	98	98	98
Compatibility	85	78	90	95	100
Anthropometry	99	99	99	99	99
Psychological Factors	95	95	98	100	100
Total Performance Rating	49	52	69	69	74
(Total Performance Degradation)	(51)	(48)	(31)	(31)	(26)

attention during heavy and maximal exercise is directed mostly inward, and effective field size narrows. It is possible, however, that running over rough terrain could be handicapped by imperfect vision. For this reason a small percentage performance decrement is attributed to vision at high work rates.

Tasks performed at moderate work rates, on the other hand, are more exacting, and require better vision. Percentage performance decrement has thus been assigned a higher value for moderate work rates.

A large amount of literature exists concerning visually impaired people. Kastenbaum (1981) simulated 20/200 vision on normal people by means of filters in their line of sight. Visual acuity scores suffered a 23-35% performance decrement. However, spatial arrangement scores suffered by only 1-4%. Legge et al. (1981) compared character size and contrast polarity effects on reading rates between normal individuals and sighted, but visually impaired, subjects with different pathologies. Reading rates varied with character size, but were 64-80% slower in the visually impaired. Various levels of contrast between characters and background gave about a 23% reading performance decrement. Fridal et al. (1981) have shown that practice can increase reading speed of the visually impaired (training effect) and Fletcher (1981) has shown that spatial orientation remains despite loss of sight.

Since the tasks we envision for the resting condition involve a great deal of reading and other sight-intensive tasks these results are pertinent. Blind people develop strong listening skills which help them cope with visual impairment (Wood, 1981). Presumably this would also occur with mask wearers over time. Mask and hood interference with listening may cause additional interactive effects by interfering with compensatory mechanisms.

Loss of vision can have severe psychosocial effects, leading to depression (Emerson, 1981). Movement in unfamiliar spaces with visual impairment can also lead to psychological stress and increased heart rates (Tamaka et al., 1981).

It is not expected that any specific task will monopolize the complete performance time at the lower rates of work. In this case, vision effects will be much less over the entire time than for acute incidents within that time span. Thus, performance decrement figures given above have been reduced accordingly.

More active tasks which involve movement can be performed by blind people, but proprioceptive clues must be learned. Blind subjects demonstrated better balance than sighted, but blindfolded, subjects (Gipsman, 1981). Since we have already discussed how spatial sense is retained with visual impairment, proprioceptive information would presumably not be required to perform well as long as some measure of sight remained.

A comparison of girls' and boys' high school track and field records (Howard, 1989) with visually-impaired girls and boys track and field records (Buell, 1983) shows about a 25% performance decrement for running events (100 yard dash, 400 meter dash, and 800 meter run), and 30%-60% performance decrement for field events (long jump, triple jump, discus, shot put, and javelin).

Of the two subcategories, field size and acuity, field size is presumed to be slightly more important at low work rates, where environmental awareness is greatest. At very heavy work rates, some visual acuity decrement is presumed to linger because higher minute volumes sometimes lead to lens fogging.

b. Communications

We have found relatively little information regarding performance decrement due to communications impediments. Masks degrade speech and hoods degrade hearing. Both of these are likely to be much more important for the types of tasks envisioned for low work rates than for high work rates. Results from military trials have shown performance decrements of 50-60% in selected communications measures. In the case where tasks are varied and some compensation is possible, overall performance decrement for the full time period represented by the workload is expected to be much less due to the integrative nature of our approach. In cases where communications are of paramount importance, obstacles represented by the mask and hood are likely to lead to secondary effects of psychological frustration, cardiac stress, and increased physical work rate. Coordination of interpersonal movements is made much more difficult to achieve with communications impediments, but those tasks which can be carried out largely independently can still be accomplished with little penalty.

In the communications subcategories, direction is presumed to be the least important for any general task. Of course, there are certain tasks where directionality could become most important. Intelligibility is presumably especially important when the messages conveyed are most complex. Such situations arise most often at the lowest work rates. Attenuation of sound with distance is most important when the work rates (and presumed running speeds) are high enough to cause relatively large distances between speaker and listener.

c. Respiration

The most valuable reference for effects of respiratory aspects of masks is the report written by vanHuss and Heusner (1965) summarizing results from a series of tests using different work and mask conditions. Comparisons between their regular mask with hood and bareheaded conditions indicated M17 performance degradation. Comparisons between their modified mask and bareheaded gave indications of non-resistance effects.

Physical work rates for their half-mile runs were calculated to be from 500 to 560 W, which classifies the work rate as "very heavy." Under this work rate the regular M17 mask caused a 50% degradation in performance time, but some account must be taken for the work rate dependent on mask condition and the fact that subjects did not work to exhaustion.

Performance times for subjects running on a treadmill at 10 mph, 0% grade until exhaustion were about 6-7 1/2 minutes. Calculated physical work rate was 440W, indicating that the subjects were in particularly superb condition. Performance degradation was 22% for the regular mask and 11% for the modified mask.

Their interval runs of treadmill running at 10 mi/hr, 10% grade for 30 seconds and standing at rest for 30 seconds repeated until exhaustion showed 25% degradation of performance time with regular mask and 16% for modified mask. Since time constants for ventilation and oxygen uptake are about 45 seconds (Johnson, 1991), physiological responses were more likely to act as if this were a constant work rate rather than off-on work. Oxygen uptake rates of 3.5 L/min and performance times of 5-6 1/2 min both indicate a very heavy work classification.

Deno et al. (1981) tested work performance of individuals wearing masks with various resistance levels. Their short term test protocols kept neither work rate nor total time constant. A 14% reduction in work rate was attributed to their resistance R_1 (=5.5 cm $H_2O\cdot$sec/L) at calculated physical work rates of 160-190W.

They tested prolonged exercise of 1 hour duration with only a 1% reduction in work rate due to the same mask resistance. Calculated work rates were about 135W. The dead space contribution to each of the above performance degradations must be added.

Johnson and Berlin (1973) modified M17 masks with three resistance levels and required subjects to run on flat terrain at a constant rate until exhaustion. Calculated physical work rates were about 300 W. Extrapolation of their data back to zero resistance gives a 5% reduction in the number of laps run due to M17 mask resistance. Dead volume effects are not included. Since extrapolation to zero requires an assumption of linearity which may not be true over that large a range, the mask resistance effect at that work rate could very well be higher.

Babb et al. (1989) tested subjects running for two miles at their maximum rates up a 5% grade. Calculated work rates were about 90 W. Despite the low work rate, resistance accounted for a 9% increase in performance time, hypercapnic air for a 1% increase, and hot inhaled air for a 4% increase. Performance degradations with combinations of resistance, hypercapnia, and hot air could not be predicted by considering the factors independently. Their work rates were very light for such large performance degradations. Their results may be suspect because their subjects needed to anticipate maximum rates at which they could run under each condition. Neither work rate nor performance time was held constant.

A great number of other reports concerning physiological effects of respirator wear have appeared. Some (Wilson et al., 1986; Raven et al., 1981A; A. Hodous et al., 1986; Raven et al., 1981B; Wilson and Raven, 1989) have been performed in an attempt to provide guidance for medical surveillance of mask wearers and have not provided information useful here. Others have included the proper type of performance degradation data, but on the wrong kinds of masks (Dahlback and Balldin, 1984; Raven, 1983; Verstappen et al., 1986; White and Hodous, 1987; Wilson et al., 1989A; Wilson et al., 1989B). Some did not make comparisons useful for our purposes (Harber et al., 1984; Love, 1983; Shimozaki et al., 1988; Hodous, et al., 1989; Johnson and Cummings, 1975).

Unless experimental comparisons were made between masked and unmasked conditions, dead space and elastic load effects must be added to performance decrements caused by resistance alone. Zechman et al. (1957) report that CO_2 buildup has little effect at rest, but a large effect on performance during moderate (their description) exercise.

Concerning the effect of dead volume on performance decrement, the M17 mask possesses a measured dead volume of about 300 mL (Cummings et al., 1960). Added to an internal dead volume of about 200 mL, total respiratory dead volume of despite the increased narcotic effect of CO_2 with time (Billings, 1973) and the increase in the proportion of tidal volume represented by dead volume.

d. Thermal Effects

James et al. (1984) published results of thermal studies for five subjects walking on a treadmill at work rates of 58 and 116 W for 1 hour in 85°F environment. Differences they found could be due to three factors: additional weight of the mask (supported by observed increases in metabolic rates and heart rates), increased respiratory work (supported by increased observed minute volumes), and decreased heat loss (supported by increased oral temperatures). Thus, masks appear to have significant thermal effects as long as the work is maintained for long enough time to overcome thermoregulatory adjustments and thermal inertia.

Snook and Ciriello (1974) found that manual handling tasks were effected greatly by heat stress. Their subjects working in 71°F, 45% RH and 87°F, 65% RH showed a 20% reduction in lifting work load, 16% reduction in pushing work load, and 11% reduction in carrying work load at the hotter condition.

This difference due to time/intensity of work was noted by Gwosdow et al. (1989) who said ". . . firemen, miners, and rescue workers tolerate hot, humid air inside respirators or facepieces for the time required to complete their jobs . . .", yet " . . . surgeons wearing surgical masks for 15 minutes in air-conditioned operating rooms experience a 5°C rise in respirator air temperature and a 16% increase in respirator air humidity. Such thermal conditions have been related to subjective fatigue and increase in the number of mental errors."

Thermal effects are thus likely to be little to none for heavy and very heavy work, but significantly high for moderate and light work rates. Heat stress resulted in an 11% performance decrement for mental tasks from Mortagy and Ramsey (1973) and a 5% degradation from Hancock and Pierce (1985). The latter authors also found no significant interaction between heat stress and background noise on mental performance.

For more physically active tasks, such as running, Babb et al. (1989) found that breathing hot air (45°C, 95% Rh) increased the time to run 2 miles by 4.2%. Data from a report by Johnson and Berlin (1973) concerning subjects running until their voluntary endpoints showed a 7% reduction in distance run due to clothing worn. A paper by White and Hodous (1987) would have also been valuable here, but they did not use a maskless control.

As long as temperate environmental conditions are maintained, thermal effects due solely to the mask are rather limited. It is only when the environment becomes more adverse that mask thermal effects are expected to become very large.

e. <u>Personal Support</u>

Personal support becomes a mask problem only at the longest performance times (lowest work rates), as long as the wearers do not begin in malnourished, dehydrated, or medically ill conditions. The M17A1 mask is equipped with drinking devices which allow the passage of 0.1 L/min liquid. Maximum sweat rates are about 1.6 kg/hr, meaning that replenishment of water at maximal sweat rates requires about 16 minutes out of each hour. Assuming that drinking without a mask takes negligible time, and neglecting attachment time of the drinking device to the liquid source, this is a performance decrement of about 25%.

Unstressed skin sweats at a rate of 6% of maximal (Johnson, 1990), which makes the water burden of sweating very small in a temperate climate. Urine excretion is about 1 L/day (Ganong, 1963), an amount which requires only 10 minutes to resupply the body. Together, these two demands require 4% of the time in an 8 hour day.

Starvation for a little over a day has been found to cause about a 32% decrease in the endurance of men performing high intensity work (Henschel et al., 1954). Since the only means to nourish wearers is through their drinking devices, very little nourishment can be supplied during the longest wear times.

Some compensation is present at the longest wear times, since work rates are so low that extraordinary muscular efforts and maximum sweat rates would not be required. Effects of lack of food intake and limited liquid intake are not quite as large as they otherwise might be. However, deprivation, especially at the lightest work rates, may add considerably to the psychological burden of the mask. This is especially true if sleep deprivation is added to those for food and water.

The effect of the difficulty of medical procedures involving the face are somewhat more difficult to assess. If the wearer is not medically ill at the time the mask is donned, and if he does not develop illness while wearing the mask, then medical procedures will not be required and there is no effect of the mask. However, a simple medical condition such as a cold is very difficult to bear inside a mask, and the requirement of mouth-to-mouth resuscitation can involve performance decrements from not just one, but at least two, individuals.

f. Physical Characteristics

The M17A1 mask weighs slightly less than 9.8 N (1 kg mass). This represents about 1.4% of the normal body weight of a man and should therefore increase physical work rate by 1.4%. The off-center placement of the mask, however, causes an additional metabolic burden to be endured by the body. Givoni and Goldman (1971) use a term proportional to the square of the product of the carried load and the walking speed to account for eccentric loading. This additional physiological load will itself add to the respiratory and cardiovascular burdens of the mask. James et al. (1984) measured, on 5 subjects walking on a treadmill for 1 hour, an average increase of 11 kcal/hr (2.7 W external work) while wearing a full facepiece mask compared to no mask. This represents about a 2% increase in metabolic rate, and is due, not only to the mask weight, but also to the added respiratory and cardiovascular burden of the mask resistance, dead space, and weight. Raven (1983) reported a 20% reduction in maximal work capacity when wearing a SCBA, likely 16 kg in mass (Wilson et al., 1986). An increase of 2.7 W external work should add about 26% to performance time for light work, 6% for moderate work, 4% for heavy work, and 2% for maximal work (Johnson and Cummings, 1975; Kamon, 1981). Performance decrements over a wide variety of work rates, however, were shown to become 5% with no resistance (Johnson and Cummings, 1975).

Allowing a variety of tasks at the light work rate would presumably allow the wearer to assume different postures and somewhat relax the neck muscles that support the head and mask. It is expected, therefore, that the high performance degradation expected at the low work rates would be attenuated somewhat over the course of the work period. For the resting condition, resting the head would be permitted at certain times, but the mask bulk may not permit complete postural relaxation. For very intense work, performance times are so short that task variety is not too likely and performance degradation attenuations are not expected.

The difficulty in assigning values for physical structure/respirator weight is that the primary effect of the weight is to add to the cardiovascular, respiratory, and thermal burdens of the wearer. We have chosen to reduce values of degradation due to weight burden to avoid accounting for the same effect twice.

Mask compatibility with other equipment items can be the most serious contributor to task performance degradation. If the task involves brushing the teeth, then performance degradation reaches 100%. If the task involves sighting through binoculars, then performance degradation can easily reach 50% or more. On the other hand, touch typing will be largely unaffected by mask wear. Again assuming that task variety increases as performance time increases, average assumed performance degradations due to physical incompatibility of masks with other necessary equipment are given in the Table 3.

Anthropometrical considerations include fitting and pressure generated on certain facial locations. Facial configuration has been reported to significantly change apparent mask resistance (Johnson and Berlin, 1973), but this effect has already been included as a respiratory value. Irritation and skin abrasion have been noted (Johnson and Cummings, 1975). These take several hours to days to develop, and so are not likely to be encountered at the high work rates. In addition, the presence of these types of irritations are most likely to be noticed at the low work rates and not at the high work rates. Indeed, these irritations can lead to psychological intolerance to the mask.

Facial hair growth can affect the mask seal (Hyatt et al., 1973). Increasing seal pressure to overcome beard growth can exacerbate the irritation problem. Ingrown hairs and skin disruptions can lead to long term wear problems.

Work performance degradation is not likely to be due directly to the discomfort associated with anthropometric factors. Rather, discomfort and irritation are more likely to cause attention to be turned from the task to be performed to the state of the wearer. These effects will be included under psychological factors. The only direct consideration included in the Performance Rating Table under anthropometric factors is the case where medical conditions associated with edema or skin irritation removes the wearers from the task. Under the assumptions made about mask wear, anthropometric factors are time, not task, dependent.

g. Psychological Factors

Morgan (1983A & 1983B) has reviewed psychological considerations of mask wear. He states that about 10% of the population manifest severe psychological responses to stress. Morgan and Raven (1985) were able to predict individuals with respiratory distress while wearing masks on the basis of anxiety trait tests given prior to testing. There were no efforts in these papers to produce quantitative predictions.

Much has been written linking anxiety to respiration (Shershow et al., 1973; Morgan and Raven, 1985; Wilson et al., 1984; Wilson et al., 1989). Briefly, as response to inhaled

CO_2 decreases, depression and introversion increase, anxiety decreases, and mask breathing difficulty decreases. The link between mask breathing difficulty and CO_2 responsiveness is largely physiological because mask dead space will tend to cause hyperventilation. A conflict arises because mask resistance tends to cause hypoventilation and increased respiratory work.

Long term wear of a mask can interfere with rest and sleep, leading to feelings of fatigue and lethargy (Colligan and Tepas, 1986). Such feelings are more likely to be felt for tasks which demand a long time to perform as compared to tasks which are intense enough to be completed in a short time. The quote previously given from Gwosdow et al. (1989) concerning thermal perceptions also lead to the conclusion that psychological awareness depends on the level of physical effort produced: low physical efforts allow time to become aware of feelings.

What are psychological problems, and how can they be distinguished from the other mask factors previously considered? For purposes of this effort, psychological effects are those which involve perception, and especially, emotion. They are usually directed toward individual aspects of respirator wear such as facial pressure, breathing resistance, vision, sweating, or facial isolation. Psychological awareness is probably physiologically derived, but augmented by emotion. Psychological reactions require the ability to pay them some attention before they become important. Emotional responses lead to hyperventilation, tachycardia, and acute increases in circulatory levels of epinephrine. Such responses augment the burden of the respirator.

Parenthetically, some individuals are more prone to be sensitive to discomfort, and some are more emotional. Such individual differences alone could cause tremendous differences in work tolerance times while wearing respirators. Morgan and Raven (1985) demonstrated this with their subjects, but large intersubject variability in all other reported tests could probably be caused by differences in anxiety levels. Because the Performance Rating Table indicates average responses, there may be a large deviation in psychological factor values for some individual wearers.

We will assign table values for psychological factors based on two premises: first, psychological factors are considered more important as work rates decrease, because of the attention factor discussed above; second, performance degradation values attributable to psychological factors will be those above and beyond values already attributed to primary causes of degradation. Thus, vision handicap alone will cause degradation; the emotional response to vision handicap can cause additional degradation. There are no studies, to our knowledge, that have experimentally made this distinction.

Other Environmental Conditions

In addition to the temperate environment Performance Rating Table, other tables can be constructed for hot, humid (85°F DBT, 95% RH), hot, dry (120°F DBT), and cold, dry (-25°F) conditions. All use departures from temperate conditions as the basis for table entries.

a. Hot, Humid Conditions

Under hot, humid conditions thermal factors are an obvious performance degradation factor. James et al. (1984) showed that subjects working in the heat (85°F WBGT) wearing full facepiece masks averaged 7-8 beats/min higher heartrate and 0.4° to 2.3°F higher oral temperature (depending on work rate) than subjects without masks.

Mortgagy and Ramsey (1973) showed that thermal stress gave a 6% performance decrement (in correct detections) when initially placed in at 90°F Effective Temperature (ET) environment. After one hour, performance decrement was 15%. This would be expected, since in one hour enough time would have passed for the thermal environment to influence body temperature. It is likely that steady-state should have been reached in this time.

The NIOSH criterion for sedentary workers (Ramsey et al., 1975) indicates a hyperbolic relationship between WBGT and performance time in the heat. Up to 240 min may be spent in a 32°C WBGT environment, but only 15 min should be spent at 43°C WBGT.

When determining performance rating for mask thermal factors, under hot, humid conditions, total thermal environment for the wearer must be considered. Unlike temperate conditions, where body temperature does not depend strongly on the clothing worn, hot and humid environmental effects can be severe, even at rest, if clothing does not permit sufficient loss of heat.

Thermal performance decrement was determined using the Givoni and Goldman model (Givoni and Goldman, 1972; Johnson, 1991) for all work rates despite the more extreme work load range than the model was developed for. It was assumed that wearers had equilibrated to the environmental conditions before beginning to work at the specified rate. Work rates, performance times, and assumed running speeds are given in Table 4.

Two clothing ensembles were assumed to be worn: the standard fatigue uniform (clo = 1.4; im = 0.48) and the CB overgarment over the utility ensemble (clo = 2.11, im = 0.48). The mask and hood (clo = +0.17, im = -0.09) were added as well.

Because the model is largely empirical and all relevant details have not been published, a short explanation of the present model usage will be given. Givoni and Goldman (1972) gave values for clo and im including a pumping coefficient based upon an effective wind velocity composed of actual wind speed and limb movements during exercise. There values for the standard fatigue uniform were clo = $0.99V_{eff}^{-0.25}$ and im = 0.75

Table 4. Work Rates, Performance Times, and Assumed Running Speeds for the Givoni and Goldman Model.

External Work Rate (W)	Physiological Work Rate (W)	Performance Time (sec)	Assumed Speed (m/sec)
430	2150	120	6.7
240	1190	600	4.5
140	755	3,000	2
10	202	28,000	0
0	105	280,000	0

$V_{eff}^{0.25}$ (a typographical error in the published paper listed the latter as im/clo), where the clo and im coefficients (0.99 and 0.75) differ from the tabled values (1.4 and 0.48) because of a windspeed different from 1 m/sec when the clo and im values were measured. Similar values for the standard fatigue plus overgarment are clo = 1.50 $V_{eff}^{-0.2}$ and im = 0.51 $V_{eff}^{0.2}$. It is difficult to tell from these what the measurement windspeed actually was. Goldman (1990) stated that it was usually 50 or 75 feet/min, but backward calculations indicate that it should be closer to 5 m/sec.

When the hood and mask values were added to the model, corrections were made to the overall clo and im values based upon a measurement air velocity of 5 m/sec and using an effective windspeed exponent of either 0.20 or 0.25, depending on whether the mask and hood were added to the fatigue uniform or the overgarment uniform. In addition, since the mask and hood completely cover the head with an impermeable layer, body surface area available for sweat removal was reduced by 11%. It can be argued that removal of that much area for moisture transfer should require that an im correction not be applied to the overall ensemble im value, but the im correction was applied anyway to account for interference with moisture removal through the neck of the garment. These corrections have no significant effect on the general conclusions which can be drawn from the model results.

The model was first used to determine the final equilibrium temperature if the work rate, clothing, and environmental conditions were to last indefinitely. Then the model was used to calculate the final body temperature at the end of the presumed performance time for each work rate. Results appear in Table 5.

For comfort, rectal temperature must be less than 38.2°C. There is a 25% risk of heat casualties for unacclimatized men at a rectal temperature of 39.2°C, a 50% risk at 39.5°C, and nearly 100% risk at 40°C (Johnson, 1991). As seen from Table 5, if equilibrium temperatures were reached at the highest rates of work, all wearers would become heat casualties. Fortunately, the highest work rates have the shortest performance times, and some final temperatures remain in the comfortable range. There is not a lot of difference between final temperatures for standard fatigues and fatigues with CB overgarment.

The mask and hood have their greatest effects, as expected, in the light and moderate work ranges. It is in these ranges that performance times are long enough and heat generation high enough that body temperature shows the greatest response.

In Table 6 are performance degradation rates related to deep body temperature for three different performance criteria: cognition, motor skills, and dexterity (Goldman, 1989). Based on Table 6 and Figure 2, approximate performance decrements

Table 5. Results of Givoni and Goldman Model for Hot, Humid Environment (29.44°C, 85% RH).

Work Rate	Std Fatigue Uniform Equil Temp	Std Fatigue Uniform Final Temp	Fatigue Uniform with Mask and Hood Equil Temp	Fatigue Uniform with Mask and Hood Final Temp
430 W	45.53°C	37.17°C	62.56°	37.29°C
240	40.49	37.56	41.70	37.76
140	39.16	38.47	39.76	38.84
10	37.49	37.49	37.68	37.68
0	37.14	37.14	37.29	37.29
	Fatigues plus CB Overgarment		CB Overgarment with Mask and Hood	
430	196.56	37.47	409.67	37.63
240	47.00	37.90	53.91	37.87
140	41.26	39.55	42.93	40.06
10	37.95	37.95	38.20	38.20
0	37.47	37.47	37.63	37.63

Table 6. Performance Decrement Related to Body Temperature.

Category	Core Temperature	Degradation
Cognition	39.6°C	80-100%
	38.5	60- 80
	38.3	40- 60
	37.7	20- 40
	37.2	0- 20
Motor Skill	40.2	80-100
	38.9	60- 80
	38.5	40- 60
	38.1	20- 40
	37.2	0- 20
Dexterity	39.0	80-100
	38.8	60- 80
	38.0	40- 60
	37.7	20- 40
	37.2	0- 20

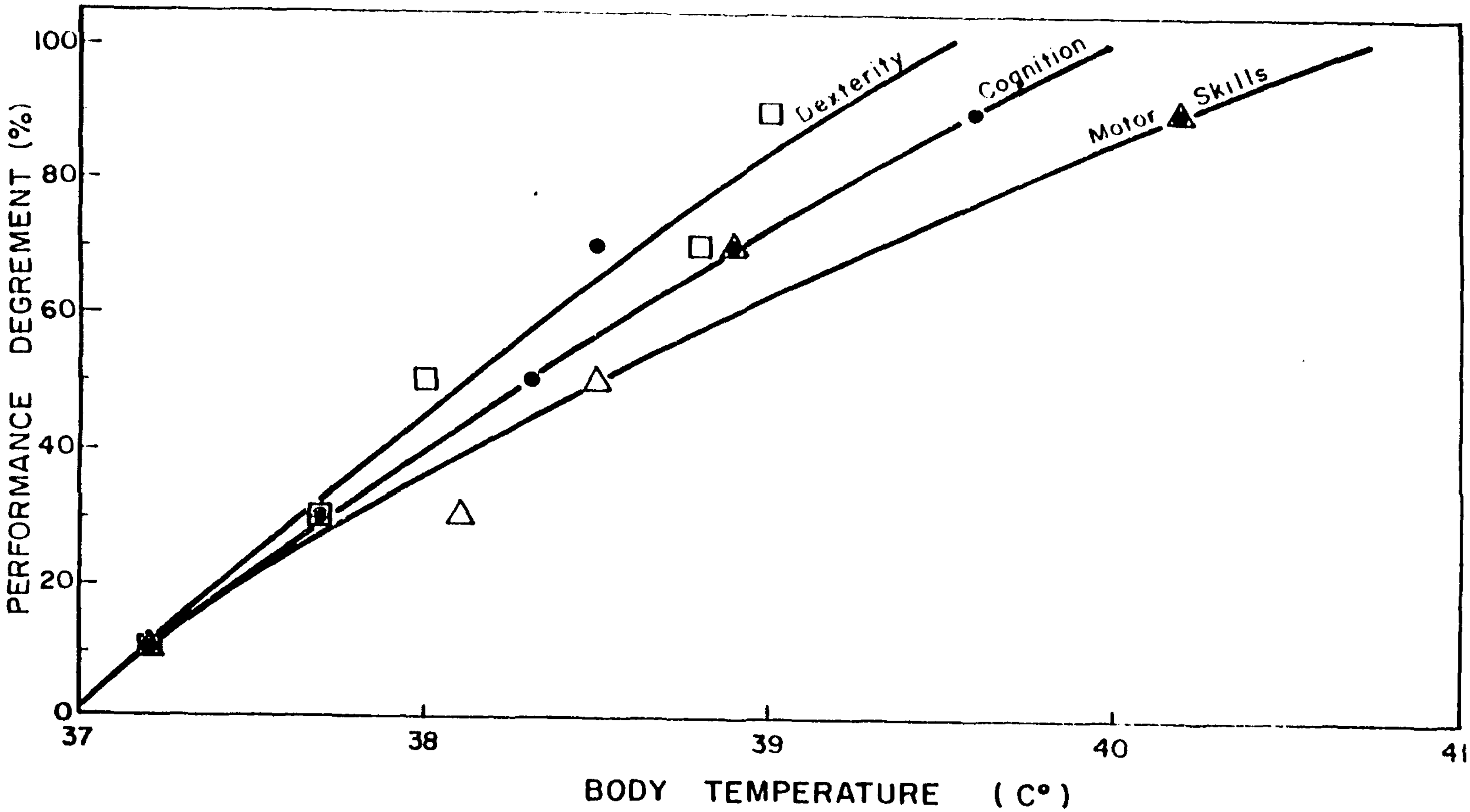


Figure 2. Approximate performance decrements for dexterity, cognition, and motor skills as body temperature rises.

were obtained for the various final temperatures listed in Table 5. Differences (Table 7) were then used as the basis for the entries for the Performance Rating Table for Hot, Humid Environments (Table 8).

Values for thermal performance ratings for the mask and hood appear to be rather high. This is because the majority of thermal performance decrement is the result of the clothing and environment, with little contribution by the mask and hood. For the case of the CB overgarment, added values of mask and hood contributions to performance decrement are artificially low because even without mask and hood the total performance decrement approaches and cannot exceed 100%.

Mask acceptance, a psychological factor, was shown by Nielsen et al. (1987) to be largely determined by environmental factors, but mask temperature and humidity influenced it. Warm, humid breathing air decreased mask acceptance. Their results were obtained with about 80W external work and quarter-facepiece masks.

More time would be required to replenish liquids in the hot, humid environment. It can be anticipated that maximum sweating rates would be incurred, and that drinking liquid through drinking devices would result in the maximum performance decrement of 25%, especially for the light and medium rates of work.

Sweat from facial skin will not be readily evaporated and will accumulate inside the mask. It is possible that

Table 7. Performance Decrements for Different Clothing and Work Rates for Hot, Humid Conditions (29.44°C, 85% RH).

Work Rate	Std Fatigue Uniform Dexterity	Std Fatigue Uniform Cognition	Std Fatigue Uniform Motor	Fatigues with Mask and Hood Dexterity	Fatigues with Mask and Hood Cognition	Fatigues with Mask and Hood Motor	Difference Dexterity	Difference Cognition	Difference Motor
430 W	5.7	8.0	6.7	10.5	14.1	13.1	+ 4.8	+ 6.1	+ 6.4
240	20.2	26.4	25.8	27.1	35.1	34.5	+ 6.9	+ 8.7	+ 8.7
140	50.0	64.9	61.9	60.6	79.0	73.4	+10.6	+14.1	+11.5
10	17.6	23.1	22.4	24.6	32.0	31.4	+ 7.0	+ 8.9	+ 9.0
0	4.7	6.8	5.4	10.3	13.9	12.9	+ 5.6	+ 7.1	+ 7.5
	CB Overgarment			CB Overgarment with Mask and Hood			Difference		
430	16.9	22.2	21.5	22.8	29.7	29.0	+ 5.9	+ 7.5	+ 7.5
240	32.0	41.5	40.7	31.0	40.2	39.4	- 1.0*	- 1.3	- 1.3
140	78.1	100.0	89.7	89.0	100.0	97.3	+10.9	0.0	+ 7.6
10	33.5	43.5	42.5	41.6	53.9	52.2	+ 8.1	+10.4	+ 9.7
0	16.9	22.2	21.5	22.8	29.7	29.0	+ 5.9	+ 7.5	+ 7.5

*These small negative values are anomalous results of the regression equations used for calculation, and are within the error bands for the equations.

Table 8. Performance Rating Table for Hot, Humid Conditions (29°C, 85% RH). Values indicate percent perfomance of an M-17 mask wearer compared to no-mask performance.

	Work Rate				
	Very Light	Light	Medium	Heavy	Very Heavy
Vision	75	75	70	70	75
Field Size					
Acuity					
Communications	94	95	98	99	100
Attenuation Dist.	99	99	99	99	100
Intelligibility	95	97	99	100	100
Direction	100	99	100	100	100
Respiration	100	98	94	80	81
Resistance	100	99	99	84	84
Dead Space	100	99	95	95	96
Thermal Factors	93	91	89	92	94
Moisture Removal	98	98	98	98	98
Thermal Balance	95	93	91	94	96
Personal Support	75	75	75	90	95
Drinking/Eating	75	75	75	90	95
Medical Procedures	100	100	100	100	100
Physical Factors	64	69	87	92	97
Physical Structure	76	90	98	98	98
Compatibility	85	78	90	95	100
Anthropometry	99	99	99	99	99
Psychological Factors	75	75	75	85	90
Total Performance Rating	24	25	28	36	47
(Total Performance Degradation)	(76)	(75)	(72)	(64)	(53)

breathing resistance (including exhalation valve popping) will increase because of this, but any increase will not likely be significant. More importantly, lens fogging may become a very real problem, and significant lens fogging can lead to performance decrements of 25-60%. Although this performance decrement could arguably be indicated as a thermal factor value, it was decided to put the entry into vision to clearly separate vision from heat accumulation effects.

No significant additional performance decrement is anticipated for communications, respiratory, and physical factors.

b. Hot, Dry Conditions

Dry heat exposure is worse, but evaporative heat loss is much greater in hot dry compared to the hot humid condition. Because of the low relative humidity which is likely to prevail at such a high temperature, mask fogging will be assumed to be nil despite facial sweating. This will have a major impact on both vision and psychological factors. Vision may suffer somewhat from glare or strong sunlight, but since it is possible that work would be performed out of direct sunlight, no account was taken of this possibility. There is a somewhat stronger possibility of the wearer requiring medical assistance in these severe conditions, but it is hard to include a figure which reflects this higher probability. Also, anthropometric mismatches may be more likely to occur in this environment compared to the temperate environment, but

Table 9. Results of Givoni and Goldman Model for Hot, Dry Environment (49°C, 30% RH).

Work Rate	Std Fatigue Uniform Equil Temp	Std Fatigue Uniform Final Temp	Fatigue Uniform with Mask and Hood Equil Temp	Fatigue Uniform with Mask and Hood Final Temp
430 W	52.98°C	38.04°C	131.13°C	38.33°C
240	42.25	38.48	47.15	38.78
140	40.62	39.64	42.66	40.56
10	38.47	38.47	38.93	38.93
0	38.02	38.02	38.33	38.33
	Fatigues plus CB Overgarment		CB Overgarment with Mask and Hood	
430	520.09	38.41	1268.81	39.73
240	60.27	38.53	82.27	38.74
140	45.54	40.99	50.19	40.95
10	39.13	39.13	39.67	39.67
0	38.41	38.41	38.73	38.73

Table 10. Performance Decrements for Different Clothing and Work Rates for Hot, Dry Conditions (49°C, 30% RH).

Work	Std Fatigue Uniform			Fatigues with Mask and Hood			Difference		
Rate	Dexterity	Cognition	Motor	Dexterity	Cognition	Motor	Dexterity	Cognition	Motor
430 W	47.2	46.1	36.5	59.4	57.1	45.8	12.2	11.0	9.3
240	65.3	62.2	50.3	76.7	71.6	59.0	11.4	9.4	8.7
140	100.0	91.3	80.1	100.0	100.0	97.7	0.0	8.7	17.6
10	64.9	61.9	50.0	82.2	75.9	63.1	17.3	14.0	13.1
0	46.6	45.5	36.0	59.4	57.1	45.8	12.8	11.6	9.8
	CB Overgarment			CB Overgarment with Mask and Hood			Difference		
430	62.4	59.7	48.1	74.8	70.1	57.5	12.4	10.4	9.4
240	67.2	63.9	51.8	75.0	70.3	57.7	7.8	6.4	5.9
140	100.0	100.0	100.0	100.0	100.0	10.0	0.0	0.0	0.0
10	89.2	80.9	68.2	100.0	91.8	80.8	10.8	10.9	12.6
0	62.4	59.7	48.1	74.8	70.1	57.5	12.4	10.4	9.4

Table 11. Performance Rating Table for Hot, Dry Conditions (49°C, 30% RH). Values indicate percent performance of an M-17 mask wearer compared to no-mask performance.

	Work Rate				
	Very Light	Light	Medium	Heavy	Very Heavy
Vision	93	95	97	99	99
Field Size	96	97	98	100	100
Acuity	97	98	99	99	99
Communications	94	95	98	99	100
Attenuation Dist.	99	99	99	99	100
Intelligibility	95	97	99	99	100
Direction	100	99	100	100	100
Respiration	100	98	94	80	81
Resistance	100	99	99	84	84
Dead Space	100	99	95	95	96
Thermal Factors	90	85	85	87	90
Moisture Removal	98	98	98	98	98
Thermal Balance	92	87	87	89	92
Personal Support	75	75	75	90	95
Drinking/Eating	75	75	75	90	95
Medical Procedures	100	100	100	100	100
Physical Fctors	64	69	87	92	97
Physical Structure	76	90	98	98	98
Compatibility	85	78	90	95	100
Anthropometry	99	99	99	99	99
Phychological Factors	75	75	75	80	85
Total Performance Rating	28	29	37	45	57
(Total Performance Degradation)	(72)	(71)	(63)	(55)	(43)

the lack of hard data makes it difficult to quantify.

c. Cold, Dry Conditions

A properly-fitted M17 mask will not experience significant fogging in cold, dry conditions. Thus, vision should not degrade performance above that expected for temperate climes. Communications performance rating was similarly determined, although denser cold air should couple to the voicemitter and stiffer mask material to improve sound transmission. Wearing the mask should somewhat attenuate effects of breathing cold air, but whatever small advantage this effect gives will be placed under thermal factors. While the mask loses heat to the air both inspired and surrounding, this heat comes from the face. Close contact between the cold mask and the face could tend to be much more uncomfortable than the face without the mask in still air. In a strong wind, however, the small insulation value of the mask is probably helpful. Conscious awareness of these conditions leads to entry of their values under psychological factors rather than thermal factors. This is especially true since adversity tends to heighten awareness of discomfort.

The mask should have very little thermal effect on the wearer no matter what the work rate, since significant amounts of body heat are difficult to accumulate in this climate. Small adjustments in posture or other clothing can easily offset any thermal burden of the mask.

Stiffening of the mask material in cold conditions can exacerbate compatibility and anthropometric elements. If the mask facepiece does not bend as well, it will be more difficult to fit to nonnormal facial contours or to conform to mating equipment. Drinking could be much more difficult in the cold if the liquid is not cleared completely from the drinking tube and forms ice.

Specific Tasks

Performance ratings have been estimated for specific tasks more or less of interest only to the military. Unlike previous performance rating tables, which were purposely constructed with a general definition of work in mind, tables for specific tasks apply to defined work where work rates may sometimes vary in task accomplishment.

Temperate environmental conditions have been chosen for this table. Extension of the table to other environmental conditions can be accomplished along lines already presented for previous tables.

Information sources for table entries are largely military field trials. Very few, if any, of these trials were conducted using standard fatigue uniforms with and without masks and hoods. Most were conducted with full protective clothing ensembles. Entries were estimated from these data, allowing for effects that different pieces of protective clothing should have on specific chores and particular items of equipment.

Table 12. Performance Rating Table for Cold, Dry Environment (-32°C, 70% RH). Values indicate percent performance of an M-17 mask wearer compared to no-mask performance.

	Work Rate				
	Very Light	Light	Medium	Heavy	Very Heavy
Vision	93	95	97	99	99
Field Size	96	97	98	100	100
Acuity	97	98	99	99	99
Communications	94	95	98	99	100
Attenuation Dist.	99	99	99	99	100
Intelligibility	95	97	99	100	100
Direction	100	99	100	100	100
Respiration	100	98	94	80	81
Resistance	100	99	99	84	84
Dead Space	100	99	95	95	96
Thermal Factors	100	100	100	100	100
Moisture Removal	100	100	100	100	100
Thermal Balance	100	100	100	100	100
Personal Support	93	94	95	95	95
Drinking/Eating	93	94	95	95	95
Medical Procedures	100	100	100	100	100
Physcial Factors	57	61	78	82	86
Physical Structure	76	90	98	98	98
Compatibility	83	75	88	93	98
Anthropometry	90	90	90	90	90
Psychological Factors	80	80	85	90	100
Total Performance Rating	37	41	56	55	66
(Total Performance Degradation)	(63)	(59)	(44)	(45)	(34)

a. Rifle Firing/Sighting

Studies have shown that much field rifle firing is performed with much less careful aiming than generally presupposed. Nonetheless, vision is an important factor in rifle firing and physical compatibility of the mask with rifle sights is also important. When sighting, the mask facepiece is contorted to produce a visual line along the rifle. This contortion may cause leakage of air from the mask periphery and visual distortion.

Rifle firing is characterized by at least a momentary low rate of work and breath holding. Total degradation with the entire CB ensemble is approximately 40%, with most of that estimated to come from the mask, with some contribution of the gloves.

b. Artillery Firing/Sighting

Artillery sighting is similar to rifle sighting, but target identification is somewhat less important depending on the particular piece of artillery being fired. The amount of noise produced by the guns or mortars is considerable, and hand signals are the major means of communication. There is some interference between the mask and equipment. Ammunition is heavy, and the rate of work is high enough to cause body temperature to rise. The entire CB ensemble can cause a nearly 50% performance degradation, but the mask and hood contribute a minor amount to heat degradation.

c. <u>Small Weapons Maintenance</u>

Important in small weapons maintenance is vision, some personal support, and physical factors. Total degradation wearing the full CB protective ensemble is estimated to be about 28%, but much of this is likely due to gloves and not the mask and hood.

d. <u>Heavy Equipment Repair</u>

In heavy equipment repair there is a large dependence on positioning oneself as well as heavy assemblies and light parts. Repair of mobile vehicles often involves small clearances between parts and underneath; a sense of feel is definitely required. For moving into position, the mask and hood probably interfere with this task. Once into position underneath the vehicle, the mask and hood may even be of assistance in keeping fluids, dirt, and foreign objects from the eyes and face. An estimated 55-70% degradation occurs while wearing full CB protective gear. Much of this is probably due to the loss of a sense of feel while wearing gloves.

e. <u>Driving</u>

Driving vehicles depends most on vision. Field of view does not influence driving too much if the head is free to move from side to side or hazards are not expected to appear from the side. Experienced drivers tend to sight far down the road, thus decreasing required field of view.

Thermal effects can be important inside a warm vehicle, but it is doubtful whether heat would be accumulated faster while wearing a mask and hood. Responding to thermal stress requires liquid replacement, and drinking could be very awkward while driving wearing a mask. Degradation due to the entire CB protective ensemble is estimated to be about 41%. Not over half of this would be due to mask and hood.

f. Loading Ammunition

Loading ammunition can involve a combination of light and heavy work rates. Drinking while wearing the mask can occur during resting periods when no ammunition is to be loaded. Because of this, the most important mask factors are vision, respiration, thermal factors, and some psychological factors. Total degradation while wearing full CB protective gear is estimated to be 47%, with 17% due to the mask.

g. Night Reconnaissance

Using night vision equipment requires good mask visual properties. Mask and vision equipment designers have been aware of potential incompatibilities for many years and have attempted to minimize interferences. Communications abilities are relied upon to inform others of reconnaissance results. Total degradation is estimated at 50%, with most of this due to masks and hoods.

h. Radio/Teletype Operation

This task really becomes mainly radio operation, which requires vision for reading, communications abilities, and equipment compatibility between the ratio mask. Since this task is classified as very light work, personal support and psychological factors can be important. Degradation of this task is estimated to be about 50%, with most degradation due to the mask and hood.

i. Console Monitoring

Console monitoring personnel must visually recognize information (often in subtle shades of color) on their screens and manually or verbally act on what they see. Most important to their task is vision. Personal support (drinking) can interfere with console monitoring. Degradation with the total CB protective ensemble is estimated to be about 23%, with a good part of that due to the gloves.

Discussion of the Tables

It was our intention, with this approach, to build a framework for further work leading to better mask design information. The Performance Rating Table adds some structure to a very confusing set of information concerning mask effects and design trade-offs available.

There perhaps is no other technical field where so much has been written about so little basic information. To the mass of these reports has now been added this one. These results are as dependent as others on the basic studies cited in this report: we depend strongly on careful methods, scrupulous interpretation of results, and conscientious reporting. What we have attempted that

Table 13. Performance Rating Table for Specific Tasks Performed in a Temperate Environment. Values indicate percent performance of an M-17 mask wearer compared to no-mask performance.

	Rifle Firing/ Sighting	Artillery Firing/Sighting	Small Weapons Maintenance	Heavy Equipment Repair	Driving	Loading Ammo	Night Recon	Radio Operation	Console Monitoring
Vision	87	97	93	95	98	95	95	95	98
Field Size	100	99	97	99	99	97	100	100	100
Acuity	87	98	98	96	99	98	95	95	98
Communications	100	100	100	100	100	100	85	89	98
Attenuation Dist.	100	100	100	100	100	100	94	100	100
Intelligibility	100	100	100	100	100	100	95	89	98
Direction	100	100	100	100	100	100	95	100	100
Respiration	100	96	100	98	100	95	100	100	100
Resistance	100	99	100	99	100	98	100	100	100
Dead Space	100	97	100	99	100	97	100	100	100
Thermal Factors	100	97	100	98	99	95	100	100	100
Moisture Removal	100	100	100	100	100	100	100	100	100
Thermal Balance	100	97	100	98	99	95	100	100	100
Peraonal Support	100	95	98	94	90	100	93	93	93
Drinking/Eating	100	95	98	94	90	100	93	93	93
Medical Procedures	100	100	100	100	100	100	100	100	100
Physical Factors	79	87	96	85	100	98	64	64	96
Physical Structure	100	98	98	85	100	98	76	76	98
Compatibility	79	89	98	100	100	100	85	85	99
Anthropometry	100	100	100	100	100	100	99	99	99
Psychological Factors	95	95	95	95	98	98	95	95	95
Total Performance Rating	65	71	83	69	86	82	46	48	81
(Total Performance Decrement)	(35)	(29)	(17)	(31)	(14)	(18)	(54)	(52)	(19)

is different is to amalgamate those basic studies in a way that assists mask designers. It seems that research physiologists and design engineers have been separated for a great many years. Through this mechanism we hope to bring them together in a mutually understandable endeavor. Thus, while design engineers could not hope to generate the basic physiological results they need to satisfy their mask design requirements, research physiologists have not been given a clear set of hypotheses against which to test. What resulted has been confusion for mask design.

Individual entry values for the Performance Rating Tables are certainly subject to argument. There may be considerable error in individual entries. There may also be factors and components missed, and assumptions unstated. However, it is our hope that instead of generating arguments, we generate test results; instead of producing words, we produce facts. Thus, we offer the entries in the Performance Rating Tables as interim values until either or both better data or a better data organization comes alone.

Given that, it is interesting to note that we found mask performance ratings to be lower at the lower rates of work. We certainly had opposite impressions before filling out the tables. But physical and psychological categories can be so important at the low work rates that they overwhelm all others. Much of mask lore is anecdotal, and the results of this study show that the anecdotes must be carefully scrutinized to determine the conditions under which they occurred before any conclusions can be drawn.

In a study to determine military user reactions to masks while they performed work, it was found that tasks at higher work rates, such as loading ammunition, were interfered with less by mask wear than were tasks at lower work rates, such as rifle sighting and maneuvering (Crue, 1990). Results such as these tend to confirm the general trends in the Performance Rating Tables. Therefore, it is likely that our Performance Rating Tables and their entries have some degree of validity.

The Performance Rating Table for temperate environments shows how important are mask factors generally considered to be peripheral. True, vision, communications, and breathing resistance are important, but for masks to be worn for long period of time, mask weight, fatigue effects, sensory presence, and personal support (such as drinking) need more design attention.

For the most part, anthropometry has not been considered to cause much performance degradation. This is so because much design effort has been spent producing a series of mask sizes which can fit a large range of face sizes. Without this effort, anthropometrical factors would be much more important and design attention would have to be directed toward amelioration. Thus, just because anthropometry does not appear in the tables as causing much performance degradation does not mean that it should be forgotten.

Turning to the Performance Rating Tables for Hot Conditions, it should be clear that the masks and hoods are not as bad as often perceived. Much of the performance degradation that occurs in the heat is due to the remainder of the CB protective ensemble. The mask and hood cover the head, the center of sensory attention, and are thus blamed for extreme discomfort.

Performance ratings in the heat for mask and hood effects must be interpreted carefully. What Table 8 shows is that performance ratings are degraded to a low of 16% if the individual is able to perform in the first place. Table 7 shows that there are cases where the clothing ensemble totally degrades performance, and, in this case, masks and hoods cannot cause any additional degradation. If thermal degradation due to clothing could somehow be solved, then masks and hoods would themselves degrade performance to the extent shown in Table 8.

Thermal performance decrements for the hot, dry environment while wearing CB ensembles are more severe than for the hot, humid conditions. Just working for an hour in a CB ensemble is enough to totally degrade performance, and cause nearly 100% heat casualties. Little of this can be attributed to the mask and hood. Even while wearing fatigues the same is true. This environment would be even more severe if strong solar radiation were considered.

If, somehow, the overwhelming thermal effects of the clothing ensemble could be made negligible, the mask and hood would have performance ratings as given in Table 11.

This demonstrates a strength and a weakness of the Performance Rating Table concept. The strength is that the ratings provide clear indication of those factors which are most in need of attention. The weakness is that performance ratings lower than zero are not possible. Thus, performance can be degraded no more than 100%, although several factors may tend to cause this much degradation. This limit of performance degradation violates the linearity assumption, explained earlier, that the tables are based upon.

The Performance Rating Table for cold, dry environmental conditions contains values which demonstrate higher performance ratings than in hot conditions. Mask and hood thermal factors are of little to no consequence in the cold.

The table for specific tasks was filled out using the general table for temperate environments as a guide. Performance degradations are reasonable in light of measured or estimated values obtained from other sources. Several of these tasks involve an integration of various rates of work as given in the general table. Specific task entries were obtained using an informal weighting of entries in the general table.

To be noted in each of these tables is how close most performance ratings are to 100. While total performance ratings may be significantly low, individual mask factor ratings are often in the range of 90-100. This means that performance due to these particular factors is close to the unencumbered performance. The law of diminishing returns indicates that much more design effort will be needed to remove the last few percent performance degradation than was necessary to remove the first many percent. Thus, while the mask gives an overall low performance rating, most of its individual elements are in the area of diminishing returns.

For that reason, the mask and hood must be considered from a total systems viewpoint and more total effort should be expected to be expended to make marginal gains.

It is clear that to use the table in mask design, more input information is necessary than ever before. Designers must now begin to know something about the types of work that mask wearers are trying to accomplish. They must also know how the various mask factors interrelate: will an increase in vision field size, for instance, affect mask dead space? They must also know about characteristics of the population which will wear their masks: are they generally more anxious, or more elderly than has been assumed in this table? Mask designers must know more information, but the Performance Rating Table at least gives them a way of identifying the kinds of information to be sought.

Discussion on the Use of the Tables

These tables can be useful for a number of purposes:

1. They can highlight areas needing work.
2. They can be used to separate sometimes conflicting mask evaluation results by time, task, and environmental criteria.
3. They can be used to compare present mask performance with anticipated evaluation results of new mask designs.
4. They can be used to provide a framework for understanding of complex mask and hood effects.

As with any engineering design tool, there is a certain amount of variability which has not appeared in the table. Thus, some nonagreement can be expected between individual entries and some test results. Just because each batch of steel produced for bridge trusses is not as uniformly strong as other batches does not mean that the design formulas for bridge design are invalid. Similarly, some nonagreement between Performance Rating Table values and some individual test results does not invalidate the table. Nonagreement could be caused by human subject variability, uncontrolled conditions, poor experimental design, or a host of other factors.

a. <u>For the Manager</u>

The use of the Performance Rating Table can lead to more effective and efficient mask development. It is very inefficient to have to produce a mask before it can be evaluated; it is much better to attempt to evaluate mask designs before they leave the drawing board. A Performance Rating Table can be constructed for new mask designs while they are still in early developmental stages. Managers must then be watchful that final mask evaluations do not differ significantly from the proposed tables.

The other implication of the Performance Rating Table is that it can show that one mask for a wide range of tasks and environments, while feasible, does not optimally satisfy any requirement. The result is that all users are unsatisfied to some extent. There is no way around this problem except to produce masks which are designed for specific uses. Modular mask elements can reduce the logistical burden of this approach, but to expect mask designers to produce masks that perform optimally for all uses in all environments is unrealistic.

b. For the Engineer/Designer

Engineers are taught in school to conceptualize and calculate. Mask design problems, especially those involving performance ratings, have been able to be conceptualized, but not calculated. The result of this is that anyone who could conceive of a new mask concept could become a mask designer and there was little distinction between an engineering approach and a trial-and-error approach.

The Performance Rating Table is a first attempt at quantification of mask physiological effects. There are still other steps required before a full calculation procedure is possible. However, it is important for engineers to become knowledgeable in the concepts behind the Performance Rating Table so that other tables can be constructed during new mask development. The ability to quantify mask effects will make you more valuable to your organization.

c. For the Physiologist

Until now, the physiologist was interested in learning how masks affected a host of physiological variables. Physiologists performed the service of mask evaluation and had little input into mask design. That must change if better masks are to be produced.

The Performance Rating Table gives a framework for new physiological information that must be generated and classified in ways useful for designers. There should be sufficient justification in the table to keep physiology laboratories busy for many years. The results of these tests should not only be table entries, but whole mathematical models. The table can provide the basis for your contribution to mask design.

Mask design requires not just goals, but also information about design trade-offs. If all goals cannot be met, then the engineer must be given enough information to make informed choices. Since many mask elements are in the area where the amounts of improvement are gotten with ever-increasing input efforts, physiologists are required to lend their expertise to the design task. Providing the engineer with that information will make the physiologist's contribution invaluable.

Future Work

The Performance Rating Table is meant to be a beginning - a way to unravel the complexities of mask physiological effects. There are limitations to this approach, but at least a first attempt has been made. Additional effort should be expended to:

1. provide better table entry values. As previously stated, most experimental results reported in the literature were not obtained under proper experimental conditions.

2. provide individual models to replace table entry values. This should be an eventual goal, where providing complete models could enable extension of the table to new mask technologies and to conditions not now possible.
3. provide a translation between mask physical/geometrical layout and entry values. This would allow, for example, a mask visual factor entry to be determined once lens layout was completed.
4. provide a matrix of mask element interrelationships. Such a matrix would show the effects of one mask element on another and give an indication whether all mask elements can assume their design values at the same time.
5. provide a computer-aided design (CAD) program to include physiological evaluation of masks at the design stage. Such a CAD program could begin in a rudimentary fashion and be made more elaborate as information described above becomes available for inclusion.

The ultimate goal of this effort should be to make all aspects of mask design able to be assisted by computer. If this goal could be met, the mask design process could be streamlined, and mask development would become one of developing the design process itself: providing better input information to the CAD program and extending the program to include new technological approaches.

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SUPPLEMENTARY

INFORMATION

Assumptions

Several assumptions have been made in developing this table.

1. The basis for the table is the air-purifying military mask technology represented by the M-17. That is, masks are assumed to consist more or less of standard facepieces, held on the head with standard harnesses, sealed to the face with a passive peripheral seal, using charcoal filters without auxiliary power, and not including communications-assist devices except for voicemitters. Hoods have also been assumed to be worn. Large changes in mask technology will render numerical entries invalid and perhaps even require changing mask factors considered.

The M-17 was chosen as the standard because there is a great deal of historical data available for that mask, and M-17 masks are available to generate comparison experimental data with other masks. The M-17 represents a large proportion of modern mask technology without classification difficulties associated with current masks. There are no modern civilian masks with comparable attributes.

2. A linearity assumption has been made. This means that changes in mask design parameters cause proportional changes in performance of wearers. This cannot be completely true for large changes in masks, but linearity can be considered correct for small perturbations of mask parameter values. For example, if field of view is indicated to account for 5% of performance decrement (95% performance rating), then an increase of 2 degrees in peripheral vision may reduce the performance decrement to 4%. It should not

a mask wearer is about 500 mL. End-tidal CO_2 is about 5% until the hyperventilation past the anaerobic threshold (at 1.5 L/min oxygen uptake) depresses it to about 3% during maximal exercise. Below the anaerobic threshold, inhaled alveolar carbon dioxide percentage is:

$$\left(\frac{V_D}{V_T - V_D}\right)\left(F_{ET\,CO_2}\right) = F_{A\,CO_2} \tag{5}$$

where V_D = dead volume, mL
V_T = tidal volume, mL
$F_{ET\,CO_2}$ = fraction of CO_2 in end-tidal air
$F_{A\,CO_2}$ = fraction of CO_2 in inspired alveolar air.

Above an oxygen uptake of about 2.2 L/min, Martin and Weil (1979) measured a nearly constant tidal volume of 2.5L. Thus, for moderate work, inhaled CO_2 is about 1%.

Craig et al. (1970) reported on the results from one subject exercising on a treadmill at about 215 W external work while inhaling 1.1% CO_2. The subject had a 4% lower time to exhaustion compared to room air. The same subject breathing 2.4% CO_2 also had a 4% lower performance time. Other subjects breathing other percentages of CO_2 had 5-9% performance decrements. We conclude from this that dead volume has minimal effect, perhaps 5% at high moderate to high work rates. At very high work rates, dead volume by itself would be expected to have smaller effect due to lower end-tidal CO_2 percentages, but dead space-mask resistance interactions at very high work rates may cause severe degradation. At light work rates, performance decrement would be expected to tend toward zero