AD-759 962

PREDICTION OF ENDURANCE TIME LIMIT FOR MUSCULAR WORK UNDER ALTERNATING WORK LOAD CONDITIONS

Texas Technical University

Prepared for:

Army Human Engineering Laboratories

May 1973

PREDICTION OF ENDURANCE TIME LIMIT FOR MUSCULAR WORK UNDER

ALTERNATING WORK LOAD CONDITIONS

by

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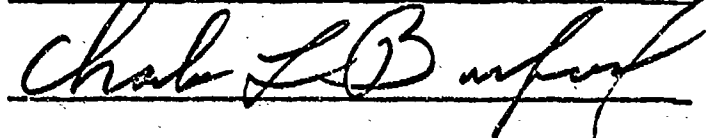
A DISSERTATION

IN

INDUSTRIAL ENGINEERING

Submitted to the Graduate Faculty
of Texas Tech University in
Partial Fulfillment of
the Requirements for
the Degree of

DOCTOR OF PHILOSOPHY

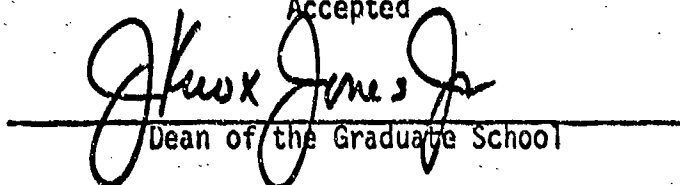Approved

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Chairman of the Committee

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Accepted

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Dean of the Graduate School

May, 1973

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DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)*	2a. REPORT SECURITY CLASSIFICATION
Center of Biotechnology and Human Performance Texas Tech University Lubbock, TX 79409	Unclassified
	2b. GROUP
	NA

3. REPORT TITLE

Prediction of Endurance Time Limit for Muscular Work Under Alternating Work Load Conditions

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

5. AUTHOR(S) *(First name, middle initial, last name)*

Subramaniam Deivanayagam

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
	142	56

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S)
DAAD05-69-C-0102	
b. PROJECT NO. 1T014501B81A	NA
c. Program Element 61102A	9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*
d. THEMIS Proposal No. 603	NA

10. DISTRIBUTION STATEMENT

Approved for public release; Distribution unlimited

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
None	U.S. Army Human Engineering Labs. Aberdeen Proving Ground, MD 21005

13. ABSTRACT

Endurance is defined as the ability to persist in an activity or task. The time duration one can persist or sustain on the task before fatigue makes him stop from continuing further is referred to as the endurance time limit. Fatigue and endurance are closely related terms. Low endurance shows up as early fatigue and longer endurance is obtained by reducing fatiguing conditions. Hence any attempt to study "endurance" should study "fatigue" as well.

DD FORM 1473 REPLACES DD FORM 1473, 1 JAN 64, WHICH IS OBSOLETE FOR ARMY USE.

Unclassified
Security Classification

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Endurance						
Fatigue						
Performance						
Capacity						
Work load						
Prolonge work						
Tasks						
Aerobic Capacity						
Oxygen uptake						
Heart rate						
Physiological						
Metabolism						
Monitor						

ACKNOWLEDGEMENTS

I would like to place on record my sincere gratitude to Dr.
M. M. Ayoub, the chairman of my advisory committee, for his direction
and encouragement throughout the entire study. I also wish to express
my indebtedness to Dr. R. A. Dudek, Dr. C. L. Burford, Dr. J. D.
Ramsey, Dr. A. E. Coleman, and Dr. C. Halcomb for their helpful advice
and constructive criticism. Thanks also goes to Messers C. D. Mittan,
J. L. Gibbs and C. E. Hipp for their technical assistance in construction
and maintenance of the equipment.

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INTRODUCTION

Endurance is defined as the ability to persist in an activity or task. The time duration one can persist or sustain on the task before fatigue makes him stop from continuing further is referred to as the endurance time limit. Fatigue and endurance are closely related terms. Low endurance shows up as early fatigue and longer endurance is obtained by reducing fatiquing conditions. Hence any attempt to study "endurance" should study "fatigue" as well.

The word fatigue has more than one mearing, depending on the situation as well as the point of view and the background of the person concerned. The word does not have precise scientific meaning and it has been used in the scientific literature to denote a wide variety of conditions. Those who have studied fatigue find it hard to completely agree on a definition. But there are certain points concerning fatigue on which everyone concurs. As fatigue develops performance declines. Along with the decline of performance there is an increased effort on the part of the individual. Also, by reducing, if not completely e-liminating the conditions leading to fatigue, it is possible to post-pone the inevitable and thereby increase the endurance.

Sir Freaerick Bartlett (1952) proposed the following definition of fatigue:

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> "Fatigue is a term used to cover all those determinable changes in the expression of an activity which can be traced to the continuing exercise of that activity under its normal conditions, and which can be shown to lead, either immediately or after delay, to deterioration in the expression of that activity, or more simply, to results within the activity that are not wanted."

This definition of fatigue itself goes to show the complexity of the phenomenon involved.

The subjective feelings of undue fatigue are undesirable to the fatigued individual. The person feels hampered and his activities are reduced until he is forced to give up entirely. He may complain of pains and aches or more often of a general feeling of malaise and tiredness. He has no desire for any kind of work and is an immediate candidate for rest.

"We have learned through experience that the sensations of fatigue have a protective function similar to those of hunger and thirst. The sensations of fatigue force us to avoid further stress and allow recovery to take place." Grandjean (1969).

Forms of Fatigue

In general fatigue may either be localized in one or more muscles or may be general in nature characterized by a sensation of reduction in readiness to use energy. Grandjean (1969) suggested the following classifications of fatigue.

1. Muscular fatigue caused by overstressing the muscles.

2. Fatigue caused through stress on the visual apparatus.

3. Fatigue caused by physical stress on the whole organism.

4. Fatigue caused through mental work.

5. Fatigue due to stress on the psychomotor function.

6. Fatigue caused by monotonous or dull environment.

7. Chronic fatigue caused by a number of persistent fatiguing
    factors.

Fatigue in its many forms can result from a variety of causes
as mentioned above, either singly or in combination.   This fact makes
the study and control of fatigue all the more complex and difficult

Objective of the Present Research

The objective of this research is to develop a satisfactory
means of predicting the endurance time limit for alternating work load
situations. It is possible to develop a mathematical model relating
the energy requirements of the task to the endurance time limit, if
the individual's capacity limitations are known. This would be similar
to those developed by Bink (1962) and Chaffin (1966) - for constant
work load situations. However, the task energy requirements are not
so easily computed, especially for the alternating work load situations.
Hence a procedure for computing the equivalent energy expenditure rate
becomes necessary. Another model can be developed to compute this,
taking into consideration the build up or gradual increase in energy
output rate. Such models could be applied in a number of different
fields, such as industry, sports, recreation, military and even in
domestic activities to predict endurance time limit.

It would be highly desirable if it is possible to predict the
endurance time limit with reasonable accuracy and reliability, given
the condition of the individual such as aerobic capacity, age, weight,

etc. and the profile of the alternating work such as the intensity
and duration at each level.

Review of Previous Research

A vast amount of scientific literature has been generated in the
field of fatigue in general during the past few decades alone. Inter-
est in this area was shown first probably during the turn of the cen-
tury. F. W. Taylor and F. B. Gilbreth are noteworthy pioneers in
this respect. Since their days, the problem has been studied by re-
searchers from different disciplines and a number of theories have been
put forth. It will be an almost impossible task to survey the entire
literature presently available, considering the quantity involved.
Hence only material directly relevant to this research are mentioned
in the following pages.

In summarizing the various theories put forward by researchers
to date, Simonson (1971) suggests the following as the five fundamental
processes involved in fatigue due to physical work.

1. Accumulation of fatigue producing substances mostly as waste
   products of metabolism such as lactic acid, carbon dioxide,
   etc.

2. Depletion of energy yielding resources necessary for work.

3. Changes in the physiochemical states of muscle fibers and
   substrate.

4. Disturbance of regulation and coordination.

5. Transmission fatigue involving impulse transmission from
   nerve to muscle.

The involvement of any one of these fundamental processes depends on the type of work and fatigue. There can also be interaction among these processes in any given case, making it difficult to pinpoint any one of the processes as the primary cause.

Whatever might be the fundamental process involved in fatigue, it is reasonable to expect a relationship between the rate of energy expenditure in physical work and the endurance. Muller (1953) made an attempt to predict the endurance time limit for any kind of physical task based on the energy requirements of the task. He believed that the energy for muscular work comes from either the stored reserve source or by direct oxidation in the tissues. The latter is limited by the capacity of lungs, heart and blood vessels to deliver oxygen to the working muscles. According to him, a normal adult can expend an energy rate of 4 kcal/min without going in for the reserve energy. The reserve for such a person would be a total of 24 kcal, which he could draw at any rate as required. In effect Muller calls the 4 kcal/min as the endurance limit and states that any work demanding more than this rate would draw upon the reserve. Once the reserve of 24 kcal is exhausted, the person has to stop working so that recovery may take place and the reserve energy may build up again.

On the basis of his experience of over forty years, both in industry and in research, Lehmann (1962) proposed maximum limits for performance from one minute to one year. These limits are presented in Table 1. The values are given in terms of work calories, i.e., over and above the resting values, based on 280 work days per year, 26 work days per month, and 8 hours per day. The underlined values

TABLE 1

MAXIMUM PERFORMANCE LIMITS IN TERMS OF EXCESS
CALORIES (OVER RESTING RATE)

Year	Month	Week	Day	Hour	10 Min	1 Min
61600	57200	13200	2200	275	46	4.6
	62920	14500	2420	305	51	5.1
		15480	2640	330	55	5.5
			3080	385	64	6.4
				523	87	8.7
					129	12.9
						25.0

Note: (i) Adopted from E. Simonson (1971)
(ii) 1 Calorie = 1000 calories = 1 Kilocalorie

represent the limits for the various time periods. The values along
the rows show the equivalent values for the shorter work periods; for
instance, 616.000 kcal/year corresponds to 2,200 kcal/day or 275 kcal/
hours. The values refer to an average worker thirty to forty years of
age and of medium body build.

Felder (1959) proposed certain estimates for the age corrected
maximum allowable loads for prolonged work with the arm ergometer and
bicycle ergometer. Table 2 shows his values of maximum allowable loads.
He assumed a mechanical efficiency of 18 per cent for the arm ergometer
and 24 per cent for bicycle ergometer.

In order to estimate the allowable energy expenditure for
prolonged work up to 1800 minutes, Bink (1962) proposed the equation,

TABLE 2

MAXIMUM ALLOWABLE LOAD (40 PER CENT OF MAXIMUM VO_2) FOR PROLONGED
WORK WITH ARM AND BICYCLE ERGOMETER FROM AGE 20-70

Age	Relative Maximum VO_2	Allowable kcal/min	Ergometer Load mkg/sec	
			Arm	Bicycle
20	100	4.06	13.00	17.34
30	87	3.53	11.31	15.08
40	77	3.13	10.03	13.37
50	72	2.92	9.35	12.47
60	66	2.68	8.58	11.44
70	57	2.31	7.40	9.87

Note: Adopted from E. Simonson (1971)

$$A_t = \frac{\log 5700 - \log t}{3.1} \quad X \quad A.$$

where A_t gives the energy expenditure in kcal/min for t minutes and
A represents the maximum aerobic capacity of the individual expressed
as kcal/minute.

Based on the above work by Bink, Chaffin (1966) later constructed
a mathematical model to predict the working time, given the energy re-
quirements of the task. According to him, the average physical
working capacity.

$$APWC = \frac{\log 4400 - \log t}{0.187}$$

where t is the working time. By equating the APWC to the energy requirements of the task, it is possible to predict the allowable time on the task. This model is based on a normal subject of 35 years of age with a maximum working capacity of at least 16 kcal/minute.

The models of Bink and Chaffin provided for corrections for differences in age and physical working capacity in terms of maximum aerobic capacity. However, they failed to take into consideration the weight differences of the individuals.

Christensen (1962) believes that in order that a task may be maintained throughout the 8 hour work day by an average worker, the average energy requirements of the task should be within 250 kcal/hours above the resting values.

The various studies mentioned above concern working at a constant rate of energy output. It is rare that a man works at any constant rate. Most often it is found that the intensity of the work fluctuates if the worker is allowed a free hand. During the less intense period the worker enjoys a relative rest which enables him to persist longer in the activity than if he were to continue at a constant rate. Astrand and Rodhal (1970) suggested that the accumulation of excessive metabolites is less in intermittent exercise compared to work at a constant rate. This could again be beneficial in increasing the endurance time.

Muller and Karasch (1955) used three different combinations of work - rest intervals to study their effect on endurance time. With 5 minutes work and 7.5 minutes rest, there was rapid onset of fatigue in less than 20 minutes. With 2 minutes work and 3 minutes rest the

same work rate could be maintained for nearly an hour before the onset of fatigue. With 0.5 minutes work and 0.75 minutes rest, the subjects did not feel any hardship at all even after an hour.

Similar findings are also reported by I. Astrand, et. al. (1960), Christensen, Hedman, and Saltin (1960) and Simonson and Enzer (1941).

Another fact that has not been accounted for in the available models is the gradual increase in energy expenditure for prolonged work even though the external work output is the same. This is usually observable as an increase in the oxygen uptake over time by an individual engaged in physical work while accomplishing the same work output.

I. Astrand (1960) observed a gradual increase in oxygen uptake in an experiment that lasted for 3 hours. The subjects were performing continuously for 50 minutes followed by a 10 minute rest period. There was also a lunce break of one hour in between the seven 50 minute runs. During each succeeding run the oxygen uptake increased even though the work rate was constant.

Ekelund and Holmgren (1964) report that the oxygen uptake at the 50th minute of the work was about 8 per cent higher than at the 10th minute. The experiment involved six subjects on non steady state exercise.

Saltin and Stenberg (1964) studied four young men working at 70 per cent of their maximum aerobic capacity for a total of 180 minutes out of 195 minutes of elapsed time. They observed that the oxygen uptake rose by about 5 per cent on the average.

Ayoub, Burkhardt, Coleman and Bethea (1972) conducted a series of experiments involving a number of subjects walking on a treadmill

according to two different alternating work profile conditions. They
reported a build up in oxygen uptake and heart rate in all their
experiments.

Such increases in oxygen uptake were also reported by Dill
et. al. (1931), Cobb and Johnson (1963), Rowell, et. al. (1969),
Hartley, et. al. (1970), Christensen, Hedman and Saltin (1960), and
Gleser and Vogel (1971).

The cause for this rise in oxygen uptake as reported by various
authors is not determined yet. There are two possibilities, namely,

      i) a gradual decrease in the mechanical efficiency and

     ii) a slow change over from primarily glycogen substrate to

          fatty acids for fuel for muscular contraction.

A decrease in mechanical efficiency requires additional oxygen
uptake to keep up the work output. The decrease in efficiency is
brought about by the recruitment of additional muscles to relieve the
tired primary muscles. These additional muscles so recruited are not
primarily best suited for the function and hence are less efficient in
accomplishing the task. Further a deterioration in motor coordination
may also partly account for the decrease in mechanical efficiency.

In cases of prolonged work the muscle glycogen is gradually
exhausted and more and more of free fatty acid is used as fuel in the
process of muscular contraction. For the same energy output, fat re-
quires more oxygen than glycogen. Krogh and Lindhard (1920) were the
first to observe this phenomenon. They reported that oxygen uptake
increases as high as 5 to 10 per cent when fat becomes the primary

source of energy. This phenomenon is associated with a simultaneous decrease in the respiratory quotient.

The graduate increase in oxyg a uptake means that the energy expenditure rate is not constant even in cases of seemingly constant rate of work output. Hence it is unreasonable to use a simple average energy output rate in cases of alternating or intermittent work load conditions. The models presently available to predict endurance are found deficient in this respect.

A model that would take into consideration the gradual increase in energy output rate and also the fact that a man rarely works at a constant work level will have a considerable practical significance. Most industrial tasks require sustained performance for a number of hours. A worker in the actual situation usually alternates between more active and less active periods in performing any task. These are pertinent facts and a model including these would be useful in predicting the endurance time limit. Further it could also be of use in work design. For example, introducing a light task between difficult tasks might eliminate certain fatiguing conditions. Moreover a scientific method of computing the traditional "fatigue allowance" rather than by rule of thumb is possible by using such a model.

CHAPTER II

DEVELOPMENT OF THE MODELS

For the purpose of developing the models in this investigation, it will be assumed that the normal worker is a young adult of about 25 years of age, 70 kilograms in weight, and having an aerobic capacity of 45 milliliters/kg body weight/minute. Any deviations from these norms can be easily accounted for and such procedures are mentioned elsewhere in this chapter.

Endurance Time Limit Model

A model to predict the endurance time limit should be developed based on constraints similar to those suggested by Bink (1961) and Chaffin (1966).

1. Short term energy expenditure limitation:

According to Astrand (1960), the maximum oxygen uptake of an individual of 25 years age and in good health would be on the average 45 ml/kg/min. Such an individual can, for at least 4 minutes, easily sustain an activity requiring his maximum oxygen uptake without any serious physiological consequences. Assuming that one liter of oxygen consumed would equal on the average 4.85 k calories of metabolic energy released, it can be said that over any four minute period, the worker should not exceed an energy expenditure rate of

$$\frac{45}{1000} \times 4.85 = 0.21825 \text{ kcal/kg/min.}$$

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2. Eight hour energy expenditure limitation:

If an individual is to maintain a constant rate of work through 8 hours of a work day he could not exceed a rate of more than 50 per cent of his maximum, according to Astrand (1960). However, most other researchers tend to believe that only a much lower figure is possible. Michael, Howarth and Hutton (1961) found that 35 per cent of maximum aerobic capacity is the limit for continuous work on a bicycle for 8 hours. Passmore, Passmore and Durnin (1955) proposed a limit of 30 per cent of maximum. Such lower limiting figures are supported by Christensen (1962), Bink (1962), Lehman (1962), Muller (1953) and a number of others based on their own findings. The discrepancy between Astrand and others is due to the facts that Astrand used athletic type subjects and also introduced 10 minutes rest after each 50 minutes of work.

Hence it is very reasonable to consider that 33 per cent of maximum aerobic capacity is the limit for 8 hours of sustained performance. Under such a condition during any 8 hour period, the worker should not exceed an energy expenditure rate of,

$$0.33 \ x \ \frac{45}{1000} \ x \ 4.85 \ = \ 0.0728 \ kcal/kg/min.$$

3. Long term energy expenditure limitation:

The total energy expended during a day should preferably be matched by food intake in terms of calories. Of course, exceeding the limit a little on any particular day or two will not seriously affect the physiological system. However, from the viewpoint of long term effects, it is advisable that on the average the daily energy expenditure

is compensated by food intake. For the normal subject being considered the average daily calorie intake is about 3500 kcal/day (Chaffin, 1966).

Based on the above during any 24 hour period, the worker should limit his energy expenditure rate to within,

$$\frac{3500 \ (kcal)}{70 \ (kg)} \times \frac{1}{24 \times 60} = 0.0347 \ kcal/kg/min.$$

The above three limitations are specifically expressed in terms of energy expenditure per unit body weight. This is done in order to account for the weight differences among the individuals. Presently available models by Bink (1962) and Chaffin (1966) lack in this respect.

The three constraints mentioned above cover a time period of 4 minutes to 24 hours. It is reasonable to expect that any task violating any one of the constraints would be difficult for the normal worker to accomplish. Also the allowable time on any task could be determined by the limitations imposed by the constraints mentioned above. In order to obtain the allowable time the three constraints were related in a single expression. Such an expression is useful in estimating the allowable time for any energy expenditure rate other than those representing the constraints. Further the expression is also useful in estimating the maximum permissible rate of energy expenditure for any given period of time from 4 minutes to 24 hours.

The constraints suggest a logarithmic relationship between the energy expenditure rate and allowable time. Hence the logarithm of the allowable time is used along with the corresponding energy expenditure rate to be fitted to a straight line. The equation of the resulting straight line is,

$$E = 0.26144 - 0.0712 \log_{10} t \qquad (2.1)$$

where E is the energy expenditure rate in kcal/kg/min and t is the allowable time in minutes.

Equation (2.1) can be modified to yield the allowable time t directly, viz.,

$$t = 10^{(0.26144-E)/0.0712} \qquad (2.2)$$

Under alternating work load conditions, the rate of energy expdniture will also be alternating between two levels. Further the gradual increase in oxygen uptake would cause these levels to change when the work is prolonged. In order to take into effect these two facts, it becomes necessary to define an equivalent energy expenditure rate, $\overset{\circ}{E}$. This $\overset{\circ}{E}$ in essence would represent a constant energy expenditure rate which will be equivalent to the given alternating work load situation. The computational procedure to obtain $\overset{\circ}{E}$ from the given work profile conditions is mentioned in Chapter IV.

For any given equivalent energy rate, $\overset{\circ}{E}$, the equation (2.2) can be used to predict the endurance time limit. In this case, the endurance time limit would be given by t.

i.e. Endurance time limit or

$$ETL = 10^{(0.26144-\overset{\circ}{E})/0.0712} \qquad (2.3)$$

Figure 1 shows the relationship between logarithm of the allowable time and energy expenditure rate graphically. The X axis represents the logarithm of time in minute and the Y axis the energy
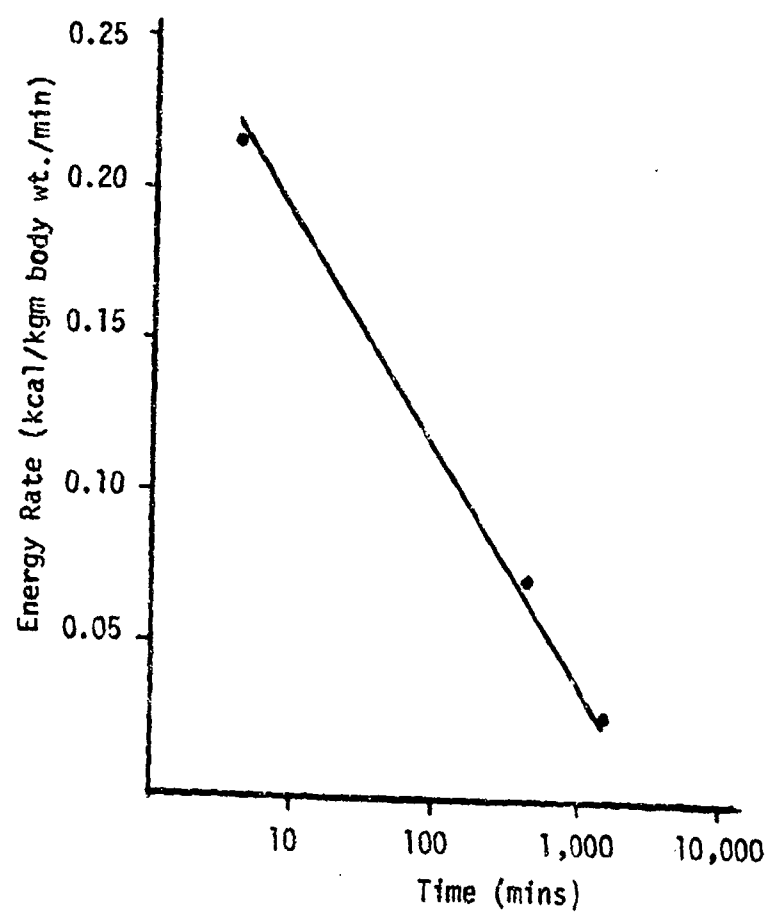
Fig. 1.-- Endurance time limit (ETL) model

expenditure rate in kcal/kg/min. The three points represent the three
constraints and the straight line is the best fitting line connecting
the three points. The area to the left of the line represents pos-
sible conditions, i.e. the subject can further continue on the task.
The area to the right of the straight line represents impossible or
fatigued condition. The worker should have stopped working earlier.
In effect the straight line represents the endurance time limit.
Figure 1 as well as equation (2.3) may be called the endurance time
limit model or ETL model for short.

The model can be used with relative ease in predicting the
endurance time limit, for any given energy expenditure rate. Substi-
tuting for $\overset{\circ}{E}$, the given value of energy expenditure rate in equation
(2.3) will yield the endurance time limit in minutes directly. Or by
drawing a horizontal line in Figure 1 across at the given $\overset{\circ}{E}$ level, to
intersect the ETL line will yield the endurance time limit. Either
technique could be adopted depending on one's choice. While using the
equation would require some computations, the answer would be exact.
Using the graph is quick and simple but would yield an answer that is
approximate, depending on how accurate the user is in drawing the line
and reading values off the graph. It should be remembered that the
results from these models refer to the normal subject as previously
defined.

The next step would be to estimate the equivalent energy
expenditure reate, given the profile of the alternating work load
situation. This could be done considering,

i) the oxygen uptake at each level of the alternating work
load

ii) the gradual increase or build up in oxygen uptake on
prolonged tasks.

Muscular Energy and Oxygen Uptake

An adequate supply of oxygen is necessary for all organisms
for normal life and activity. The oxygen is used by the cells for oxi-
dative processes in the metabolic reactions that yield energy for any
kind of activity.

When an individual performs an activity expending muscular
energy, it can be easily observed that the rate and depth of his
breathing increases. This occurs because as more energy is required,
the metabolism is increased and the need for oxygen in turn is also
increased. In order to supply more oxygen the individual breathes
more air. It is important to realize that man has very little capacity
to store oxygen in his body. The blood and lungs may store 2000 ml of
oxygen in the body of a normal adult. In addition a few hundreds of
milliliters of oxygen may be present in combination with myoglobin.
This supply is inadequate for any real physical activity considering
the fact that even an individual at rest would consume about 200 to
300 ml/min. Hence practically all the oxygen required for energy
release has to be met by adequate supply to the muscles.

When oxygen supply is available in adequate amounts, muscular
contractions are carried out by aerobic processes. When oxygen supply
is not adequate, energy is still released, but by anaerobic processes.

The exact chemical reactions involving a number of chemical constit-
uents and enzymes are highly complex and are not yet fully understood.
However, a general picture of the chemical reactions that take place
in the process of liberation of energy in man can be described as
below. (Astrand and Rothal, 1970).

1. Organic Phosphate → Inorganic Phosphate + Energy for
   muscular work

2. Glycogen → Lactic acid + Energy for resynthesis of organic
   phosphates

3. Inorganic Phosphate + Energy → Organic Phosphate

The above three reactions do not require oxygen supply from
outside and are said to comprise the anaerobic process of energy
liberation. This can last only for a short time, normally two or
three minutes at the most, by which time the stores of essential or-
ganic phosphates are depleted and lactic acid accumulation in the
working muscles require that the contractions be stopped.

If free oxygen is available, the muscle contractions can be
continued according to the following reactions.

4. $1/5$ Lactic acid $+ O_2$ → $CO_2 + H_2O$ + Energy for
   converstion of remaining Lactic acid

5. $4/5$ Lactic acid + Energy $+ O_2$ → Glycogen

The above two reactions are said to comprise the essential
features of aerobic processes. The glycogen produced in step 5 could
be used again for muscular contraction. Theoretically this can con-
tinue forever if the oxygen supply is maintained. But in skeletal
muscles the rate of accumulation of lactic acid and CO_2 is much faster

than these could be eliminated. This leads to muscle fatigue and requires stopping the activities in order to recover from the fatigue.

When an individual starts working the oxygen uptake does not immediately rise to the level of energy expenditure. It takes some time for the oxygen uptake to stabilize at the new level. During this period, the energy release is accomplished anaerobically. This is the basis of the well-known phenomenon called "oxygen debt." Similarly when the individual stops working the oxygen uptake does not immediately return to the previous level, but slowly returns to normal. During this period the excess oxygen consumed is utilized to repay the debt incurred at the start of activity. Figure 2 shows this diagrammatically. The phase during which the oxygen debt is repayed is usually known as "Recovery Process."

Response of Oxygen Uptake to Sudden Changes in Work Level

Hill, Long and Lupton (1924) measured the rate of decrease of oxygen uptake during the recovery process after running on a treadmill. On sampling at frequent intervals they found that the decrease follows a logarithmic curve in the first, fast phase of recovery. The recovery curve may be expressed in the form,

$$f(t) = AE^{-kt}$$

where

$f(t)$ = O_2 uptake at time t from the start of recovery

A = O_2 uptake at the start of the recovery

k = the velocity constant
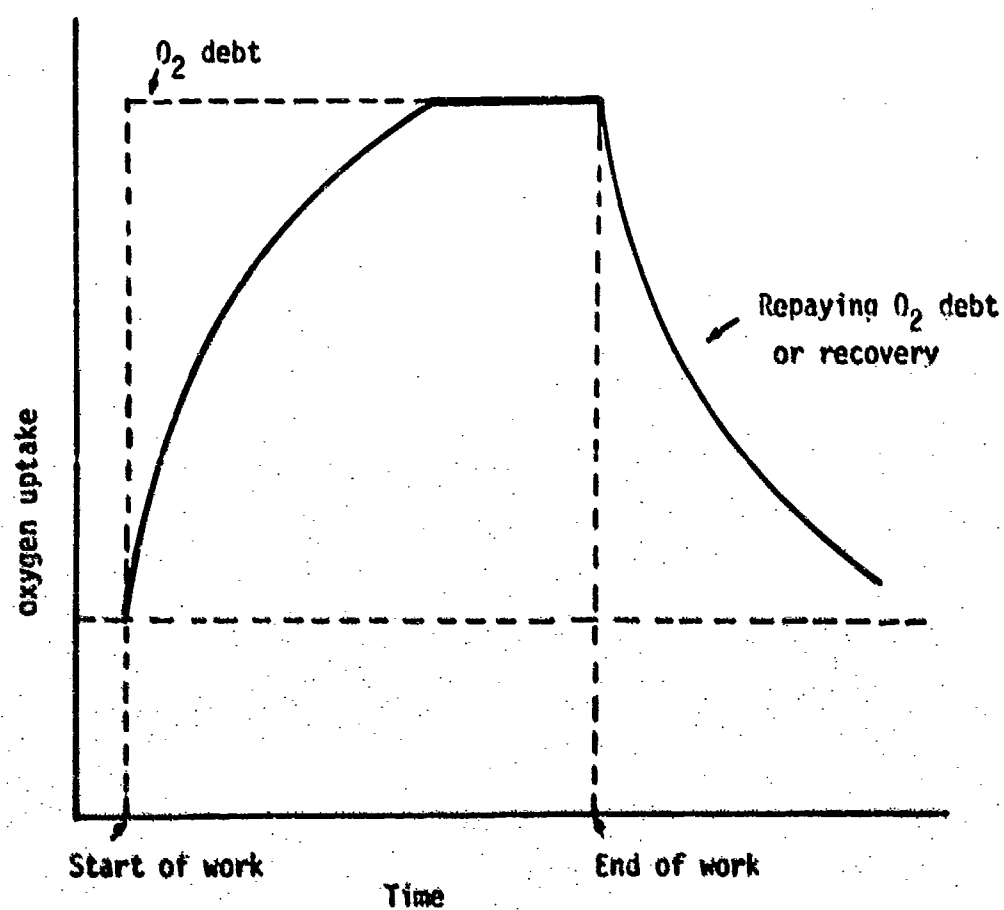
Fig. 2.--Response of oxygen uptake to sudden changes in physical work load levels

Margaria, Edwards and Dill (1933) stated that the oxygen recovery curve after strenuous exercise is composed of two exponential terms, an initial rapid component lasting a few minutes and a longer component of several hours duration depending on the exercise intensity. However, they found that after moderate exercise, the recovery curve is composed entirely of the first component.

Henry and Demoor (1950, Royce (1955), Clark and Smith (1966) also proposed more than one exponential term for describing the recovery process. Though these relationships with more than one component could be said to describe the recovery process more accurately, a single exponential term has been found to be a fairly good approximation for most practical cases. (Simonson, 1971)

Berg (1957) made a detailed study of the recovery processes of both oxygen uptake and carbon dioxide elimination on a total of 38 subjects of different ages performing step tests. He found that the recovery process could be accurately described by an exponential expression. He also computed the time required to achieve 50 per cent recovery for both oxygen uptake and carbon dioxide elimination. The half time recovery constants for oxygen uptake was on the average 31.3 seconds. For investigating the effect of work rate, he used two work rates requiring an average oxygen uptake of 790 cc/min and 1400 cc/min. The half time recovery constants were 29.7 $\pm$ 4.6 seconds and 30.3 $\pm$ 2.2 seconds respectively, with no significant effect due to work rates. The duration of exercise also had no significant effect on the half time recovery constant. The age did show a significant difference between the very young and the very old among the subjects.

Schneider et. al. (1958) conducted experiments involving six subjects walking on a treadmill requiring about 30 to 55 per cent of the subject's maximal oxygen uptake. The duration of the walk was varied as 3 minutes, 8 minutes, 14 minutes, and 25 minutes. They found a constancy of oxygen uptake and of the oxyten debt at the third minute of constant aerobic work. At any particular work load the oxygen debt was not significantly different for different work situations.

Cerretelli, Sikand and Farhi (1966) studied the oxygen uptake response at the onset of exercise and during recovery at three different walking speeds of 3.2, 4.9 and 6.8 km/hr with a constant incline of 8 per cent. They found the kinetics of oxygen uptake to be independent of the work load. At the onset of exercise the oxygen uptake appeared to rise according to a simple exponential function with a half time of about 30 seconds. For moderate work loads, the O_2 uptake both during rise at the start and during fall at the end could be described by a single exponential term. But at work loads near the maximal capacity the oxygen uptake during the recovery process appeared best comprised of several exponential terms.

Broman and Wigretz (1971) studied the transient dynamics of ventilation with step changes in work load in an experiment involving six subjects. They found that the response of ventilation to both increasing and decreasing step changes in work load could be represented by a single exponential function. Further the velocity constant of the response was independent of the initial work load. Though their findings relate to ventilation as such, these can be reasonably extended to oxygen uptake also.

Whipp (1971) used an approximate formula,

$$\text{Velocity constant} = \frac{VO_2 \text{ steady state}}{O_2 \text{ deficit}}$$

for the oxygen uptake response at the onset of exercise and compared
the results with actual values of the velocity constant as derived from
a single exponential expression. There was no significant difference
either at the light load of 300 kg/min or at the moderate load of
450 kg/min of exercise.

Davies, di Prampiro and Cerretelli (1972) studied the kinetics
of respiratory gas exchange and cardiac output on a single breath
basis in two subjects during onset and recovery, a) from rest to mild,
b) from rest to heavy, and c) from light to heavy exercise. They
found that starting from rest both for mild or heavy exercise the
half time of the process is about 30 seconds, both at the onset and
at the recovery. However, in the case of light to heavy exercise, the
half time of the process is approximately 17 to 20 seconds at the on-
set and during recovery from heavy to light, it was of the order of
40 seconds.

All of the above mentioned studies lead to the following conclusions.

1) The oxygen uptake following a sudden change in work load
can be represented by an exponential expression. The
relationships would be

$f(t) = AE^{-k_f t}$ for a fall in work load and

$f(t) = A(1 - e^{-k_r t})$ for a rise in work load, where A is

the change in work load and k_f and k_r are velocity

constants.

ii) The velocity constants, k_r and k_f in effect determine the
response process and they are independent of initial work
load or duration.

iii) The velocity constants depend on the individual's physical
condition.

Equivalent Energy Rate Model

An alternating work load is that work in which the work rate is
not constant; but alternates between two fixed levels. The work rate
is maintained at a higher level for a fixed time duration at the end
of which the work rate is suddenly reduced to a lower level for some
other time duration. At the end of the low level work period, the
work rate is again increased to the higher level and the cycle is
repeated until the task is completed. In effect there are two dif-
ferent work rates and the worker alternates between these two levels
for fixed time periods on each. However, due to the slow response
of oxygen uptake for a sudden change in work level and due to the
gradual build up in O_2 uptake over time the general profile of oxygen
uptake for an alternating work load is not identical with that of the
work load itself. Figure 3 shows the response of oxygen uptake to an
alternating work load.

If the theories of gradual increase in oxygen uptake in prolonged
work and the exponential response of oxygen uptake during sudden changes
in work load are accepted, it is then fairly easy to compute the equiva-
lent energy rate for any given alternating work profile.

Consider an alternating work load situation with the following
profile:

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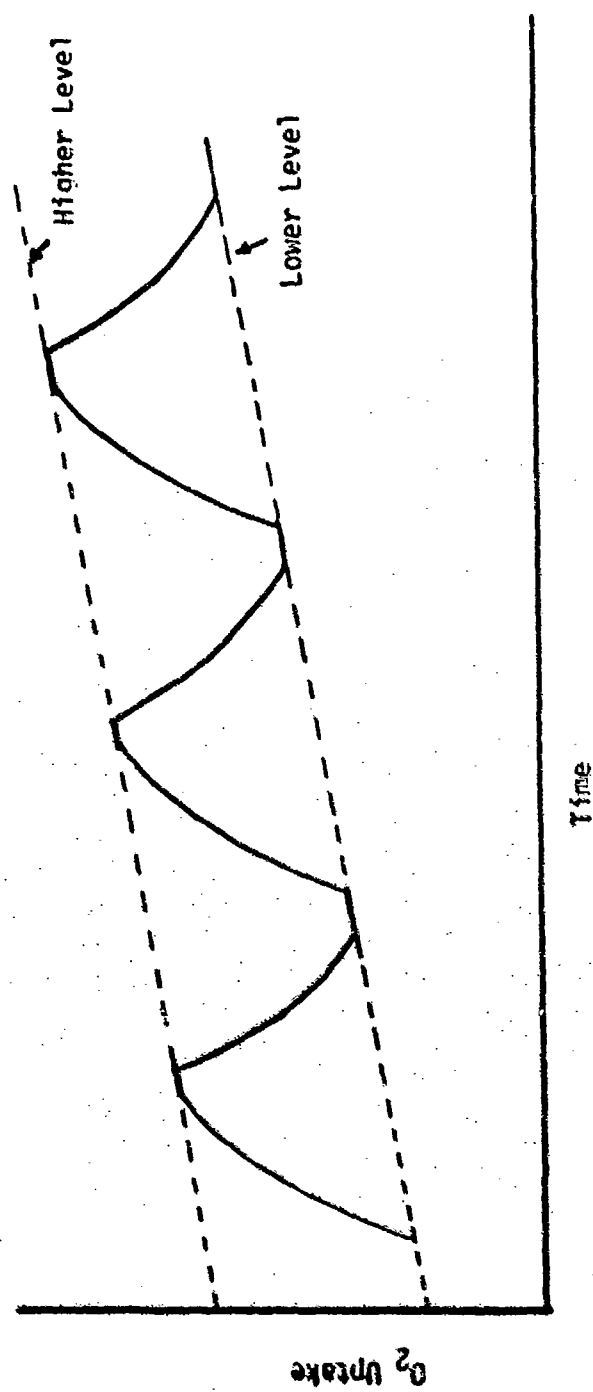
Fig. 3.--O_2 Uptake response for an alternating work load condition

H_1 = oxygen uptake requirement in liters/min at higher level during first cycle

L_1 = oxygen uptake requirements in liters/min at lower level during first cycle

t_H = work time at higher level in minutes

t_L = work time at lower level in minutes

$(t_H + t_L)$ = cycle time in minutes.

Also for the normal worker let k_r and k_f represent the velocity constants for oxygen uptake following a sudden rise and sudden fall respectively.

Assume that the oxygen uptake increases from cycle to cycle by a constant proportion, θ, of that of the first cycle and that this θ is the same at lower and higher levels.

That is, if H_i represents the oxygen uptake rate at high level during i^{th} cycle,

$$H_2 = H_1 + H_1\theta$$

$$H_3 = H_2 + H_1\theta = H_1 + 2H_1\theta \text{ and so on.}$$

In general,

$$H_i = H_1 + (i-1)H_1\theta \qquad (2.4)$$

Similarly,

$$L_i = L_1 + (i-1)L_1\theta \qquad (2.5)$$

Let n be the total number of cycles the worker can perform before stopping due to physical fatigue.

Now, the oxygen uptake during i^{th} cycle can be represented as shown in Figure 4. The time t_1 represents the time taken for oxygen uptake to stabilize following a rise in work level and t_2 represents the time taken for oxygen uptake to stabilize following a fall in work level.

The total energy released during i^{th} cycle by the oxygen consumed will be proportional to the sum of the areas under the curves, AB, BC, CD and DE.

The curve AB is given by,

$$f(t) = (H_i - L_i)(1 - e^{-krt}).$$

In the above the point A is taken to be at the level L_i, i.e., the build up in oxygen uptake is assumed to have occurred at the very end of the previous low work, shifting the oxygen uptake level suddenly from $L_{(i-1)}$ to L_i. The error introduced by making such an assumption is small and can be neglected.

Taking A as the origin and L_i as the base line, the area under the curve AB is computed as,

$$Y_1 = \int_0^{t_1} (H_i - L_i)(1 - e^{-krt})\, dt$$

The rectangular area B'BCC' is given by

$$Y_2 = (H_i - L_i)(t_H - t_1)$$

The area under the curve CD is computed with C' as the origin and L_i as the base line and is given by
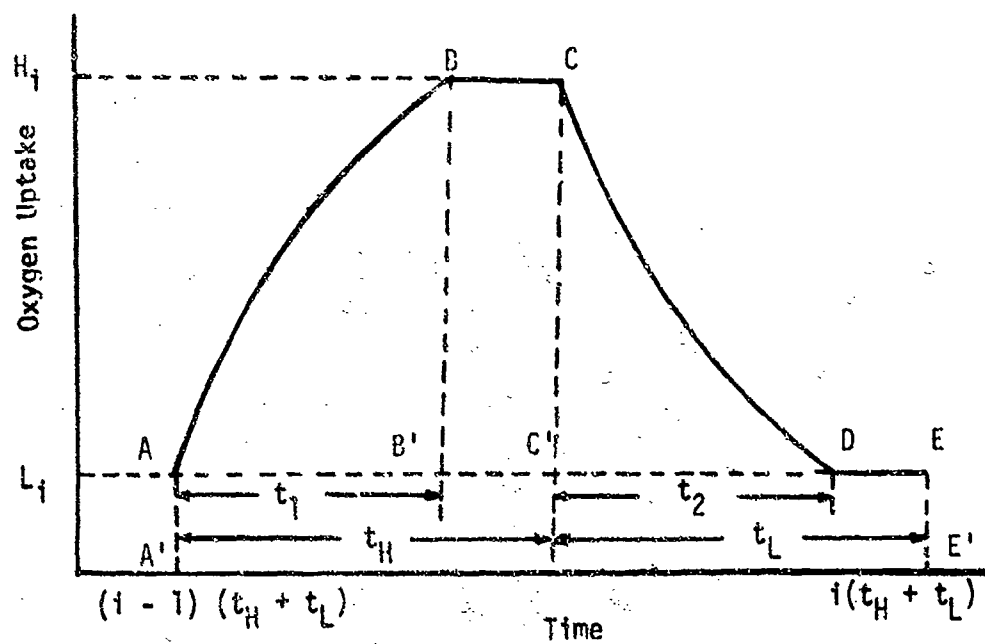
$$Y_3 = \int^{t_2} (H_i - L_i) e^{-kft}\, dt.$$

Fig. 4.--Oxygen uptake during i^{th} cycle

The rectangular area A'AEE' is given by

$$Y_4 = L_i (t_H + t_L)$$

The total oxygen uptake during the ith cycle is given by the sum $Y_1 + Y_2 + Y_3 + Y_4$.

i.e.

$$Y_i = Y_1 + Y_2 + Y_3 + Y_4$$

$$Y_i = \int_0^{t_1} (H_i - L_i)(1 - e^{-k_r t}) \, dt + (H_i - L_i)(t_H - t_L)$$

$$+ \int_0^{t} (H_i - L_i) e^{-k_f t} \, dt + L_i (t_H + t_L) \qquad (2.6)$$

The above is true only if $t < t_H$ and $t_2 < t_L$. If $t_1 \geq t_H$, then

$$Y_i = \int_0^{t_H} (H_i - L_i)(1 - e^{-k_r t}) \, dt + \int_0^{t_2} (H_i - L_i) e^{-k_f t} \, dt$$

$$+ L_i (t_H + t_L) \qquad (2.7)$$

If $t_2 \geq t_L$, then the limits of the second integral in equation (2.6) will be changed to 0 to t_L. If both $t_1 \geq t_H$ and $t_2 \geq t_L$ then the limits of the second integral in equation (2.7) will be changed to 0 to t_L.

In any event the total oxygen uptake for the n cycles can be represented by,

$$Y_{total} = \sum_{i=1}^{n} Y_i \quad \text{liters} \qquad (2.8)$$

The equivalent rate of oxygen uptake is obtained by dividing Y_{total} by the total time elapsed.

The time elapsed $= n\ (t_H + t_L)$ minutes. Therefore,

$$\overset{o}{Y} = \sum_{i=1}^{n} Y_i\ /\ n\ (t_H + t_L)\ \text{liters/min} \tag{2.9}$$

Assuming that 1 liter of oxygen uptake is on the average equal to 4.85 kcal of energy released and that the individual weighs W kilograms, we can say that the equivalent energy expenditure rate is given by,

$$\overset{o}{E} = \frac{4.85}{W}\ X\ \overset{o}{Y}\ \text{kcal/kg/minute}$$

i.e.

$$\overset{o}{E} = \frac{4.85}{W}\ \sum_{i=1}^{n} Y_i\ /\ n(t_H + t_L)\ \text{kcal/kg/min} \tag{2.10}$$

Equation (2.10) is the equivalent energy rate model or EER model for short.

In order to predict the endurance time limit this value of $\overset{o}{E}$ can be used in the ETL model. To start with $\overset{o}{E}$ for first cycle will be computed and the corresponding endurance time limit determined from the ETL model. If this endurance time is greater than the elapsed time, i.e. $(t_H + t_L)$ minutes, it means that the activity can be continued further. Then $\overset{o}{E}$ for the first two cycles will be computed from EER model and the corresponding endurance time determine from the ETL model. This will again be checked with the elapsed time, i.e. $2(t_H + t_L)$ mins in this step. The procedure will be repeated, increasing by one cycle every time, until the endurance time and elapsed time are equal. Ideally, these two will be equal at the endurance time limit. However, in most cases these two times will not become equal; but at a certain stage, the elapsed time will become

greater than endurance time. This is because the elapsed time increases in discrete steps of $(t_H + t_L)$ minutes, while the endurance time increases on a continuous basis. In such cases the endurance time limit will occur when the elapsed time, $n(t_H + t_L)$ would just exceed the endurance time as computed from the ETL model.

The necessary computations to determine $\overset{\circ}{E}$ and endurance time limit can be carried out in successive iterations. A computer program to do this is written in Fortran IV language and is included in the Appendix A.

Modifications for Workers Other Than Normal Workers

For the purpose of developing the models a normal worker was defined earlier in the chapter. The normal worker is a male, 25 years old, of 70 kgs weight and having a maximum aerobic capacity of 45 ml/kg/min. However, in actual situations the worker involved may differ widely from the above norms. Hence it becomes necessary to provide modifying procedures for such cases.

First, the endurance time limit will be determined for the normal worker without considering the deviations. Then the necessary corrections, as outlined below, will be carried out to account for the deviations.

P. O. Astrand and Christensen (1964) report the results of an extensive study they conducted on the variation in maximum aerobic capacity of individuals of different ages and both sexes. The study covered 350 males and females of age 4 to 65. They found that in both sexes, there is a peak around 20 years of age, followed by a gradual

decline in the maximal oxygen uptake. At the age of 65 the mean value is about 70 per cent of what it is for a 25 year old individual. Further that at any age, females have a maximum aerobic capacity which is about 70 to 75 per cent of that of a comparable male. Also the physical working capacity of an older individual is considerably less than that of a younger individual. The multiplication factors given in Table 3 are to be used to correct the endurance time limit for subjects of different ages. These factors are modified from the Physical Fitness Index suggested by Chaffin (1966), by assuming an index of one for the age range 21 to 25 years and then computing the indexes for other age ranges.

TABLE 3

CORRECTION FACTORS FOR AGE DIFFERENCES

Age range (years)	Multiplying Factor
16 - 20	1.025
21 - 25	1.000
26 - 30	0.965
31 - 35	0.885
36 - 40	0.840
41 - 45	0.825
46 - 50	0.805
51 - 55	0.780
56 - 60	0.735

Note: Modified from Chaffin (1966)

If the model predicts that the endurance time limit for a given task for the normal worker is 100 minutes, some other individual of 45 years of age, all other conditions being the same, will be able to endure the same task only for 100 x 0.825 = 82.5 minutes.

Also in the event that the aerobic capacity is different from the defined 45 ml/kg/min, the endurance time will be affected proportionate to the difference. In such a case, the endurance time limit as predicted by the model will have to be multiplied by a factor $\frac{a}{45}$ where a represents the maximum aerobic capacity of the individual in terms of ml/kg/min. This correction is similar to that suggested by Chaffin (1966). Chaffin assumes a maximum physical working capacity of 16 kcal/min for an average worker and for workers differing from this norm, he suggests using a factor $\frac{A}{16}$ where A is the maximum physical working capacity of the individual.

The correction factors for differences in age and maximum aerobic capacity are included in the computer program written to take care of the computational procedures. The program in Fortran IV language is presented in Appendix A. The corrections are effected after computing the endurance time limit for the normal worker.

CHAPTER III

MODEL PARAMETERS

The equivalent energy rate (EER) model as developed in Chapter II requires that the following be known before it can be used in practice.

(i) The work profile conditions: t_H, t_L, H_1, and L_1

(ii) The gradual increase in oxygen uptake from cycle to cycle as a fraction of the oxygen uptake during the first cycle, i.e. θ.

(iii) The velocity constants: k_r and k_f.

(iv) The time durations required for the oxygen uptake to attain steady state after a change in work load: t_1 and t_2.

Of the above the work profile conditions are assumed to be known for the given task. But the other parameters are unknown at this stage. These are task as well as worker dependent.

The gradual increase or build up in oxygen uptake during prolonged work has been observed by a number of authors. In general, the increase has been found to be about 5 to 10 per cent per hour, under widely differing conditions of work (Simonson, 1971). The exact amount of increase for different work profile conditions has not been studied to date. Hence it becomes necessary as a first step to study this build up phenomenon in order that the EER model could be useful in practice. A set of experiments was conducted as a part of this research

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to obtain information on the build up in oxygen uptake under different work profile conditions.

The velocity constants k_r and k_f depend on the physical condition of the individual. Except when there is a light activity or rest during the low level, the velocity constants are independent of work load and duration of activity (Davies, et. al., 1972). Most of the studies reporting on the velocity constants (Simonson, 1972; Margaria, et. al., 1933; Berg, 1947; Henry and Demoor, 1950; Henry, 1951; Cerretelli, et. al., 1970; Whipp, 1971) concern constant work load conditions. Very little knowledge is presently available how alternating work load conditions would affect these parameters. Also as the velocity constants are dependent on the individual, it is not possible to directly apply the available data from the literature to the case of a normal worker.

Finally the steady state time for oxygen uptake to stabilize following a change in work load poses a curious problem. If it is accepted that the oxygen uptake response can be described by an exponential law, then theoretically the steady state would never occur. However, in practice it can be said that the oxygen uptake has attained a steady state level, when only a small amount of deviation from the expected steady state value exists. Such a criterion is necessary in determining the steady state times t_1 and t_2 within any reasonable limits.

In general, there is not much data available in the literature regarding the parameters mentioned above. This is especially true if the individual concerned has any effect on these, because, for the

purpose of developing the models in Chapter II, a normal worker with certain physical capacity is defined. Therefore, all the required data are obtained from experiments conducted specifically for this research. The exceptions are the data taken from published and un-published reports relative to the physical loading experiments con-ducted at the Industrial Engineering Laboratory of Texas Tech University.

Design of Experiments

The determination of the parameters for the EER model require that oxygen uptake of the worker, as he performs the alternating work load task, be known. However, the oxygen uptake itself depends on the work load conditions. Specifically the high level load, low level load, the time schedule on each level, and the duration of the task determine the oxygen uptake.

Therefore, the following were chosen as the independent variables for this research.

(i) The work load combination in each cycle.

(ii) The time schedule in each cycle.

Further it is also possible that the gradual increase in oxygen uptake depends on the duration of the task to be accomplished. That is, during different time durations the build up in oxygen uptake may occur at different rates, even when all other conditions are maintained the same. Hence a third independent variable, the time duration of activity, was also included.

Work Load Combinations

An alternating work load, by definition, involves two different work loads. The individual performing the task does the higher work load for a specified time and the lower work load for some other specified time and then goes back to the higher load. Thus he alternates between the two defined loads for specified time intervals under each load. One combination of work loads means one work load at higher level and another at lower level. It is also customary to specify the work load levels in terms of the percentage of the maximum aerobic capacity of the individual. Thus 50 per cent work load means a work load level which requires an oxygen uptake of 50 per cent of the maximum aerobic capacity of the individual. The 50 per cent is specific for the individual concerned only. For some other individual the same work load will not be 50 per cent of his maximum, unless the maximum aerobic capacity of the second individual is the same as that of the first. In other words, for individuals with the same maximum aerobic capacity, the same work load will be a constant percentage of their maximum. This makes it possible to use different subjects to represent the normal worker so long as their maximum aerobic capacity is the same as that of the normal worker.

The following four levels of work load combination were chosen.

1. 50 per cent of maximum and 20 per cent of maximum
2. 50 per cent of maximum and 30 per cent of maximum
3. 70 per cent of maximum and 20 per cent of maximum
4. 70 per cent of maximum and 30 per cent of maximum

The above were just a few of the various combinations possible. The low levels of 20 per cent and 30 per cent were chosen so that the low level activity could be maintained below the 8 hour limitation of 33 per cent of maximum. The higher loads were chosen to be 50 per cent and 70 per cent so that there could be one moderate level of activity and one heavy task. A work load higher than 70 per cent of maximum would be too difficult for an individual to sustain for long. Further it is rare that an industrial task of prolonged nature would require such heavy energy output. Other than the above mentioned criteria, the levels were chosen arbitrarily.

The experiments conducted earlier, under the THEMIS project, in this laboratory used a work load combination of about 40 per cent and 25 per cent.

The above four levels could be expressed in terms of the energy output in kcal/kg/minute as given below.

1. 0.1090 and 0.0436

2. 0.1090 and 0.0655

3. 0.1538 and 0.0436

4. 0.1538 and 0.0655

Time Schedules

The following four levels of time schedules were used.

1. 5 minutes at high load and 15 minutes at low load

2. 5 minutes at high load and 10 minutes at low load

3. 10 minutes at high load and 5 minutes at low load

4. 15 minutes at high load and 5 minutes at low load

These time schedule levels were also chosen arbitrarily. Of course, rarely do such exact schedules exist in any practical task. However, in order to keep a systematic approach, some such exact levels have to be used.

Time Duration

Two levels of time duration, viz., 2 hours and 3 hours were chosen and used in this experiment. It was felt that any time duration of longer than 3 hours will be too difficult to complete especially at high work load combinations. In fact, it was found later during actual experimentation that even 3 hours was too long for a few of the tests of heavy work load combinations and time schedules.

The experiment was so designed as to yield a 4 x 4 latin square design for each time duration. Under each time duration, there were 4 levels of work load combinations and 4 levels of time schedules, resulting in 16 test cases. Four subjects were used in each of the 16 tests with 4 tests per subject. On the whole for both the time duration levels, there were 32 tests and 8 subjects were involved with 4 tests per subject. No repetition of the same test was designed to be conducted. Tables 4A and 4B show the assignment of subjects to the particular test cell in the latin squares.

The model for the above design is

$$X_{ijkl} = \mu + R_i + C_j + S_k + T_l + E_{ijkl}$$

where

X_{ijkl} is the observation in the cell given by i^{th} row, j^{th} column

TABLES 4A AND 4B

ASSIGNMENT OF SUBJECTS FOR PARAMETER DETERMINATION EXPERIMENT
(A) 2 HOUR TEST--(B) 3 HOUR TEST (LETTERS WITHIN
THE CELL REFER TO THE SUBJECT)

	TIME SCHEDULES				
		5/15	5/10	10/5	15/5
Work Load Combinations	50/20	T.T.	R.F.	L.M.	R.K.
	50/30	R.F.	L.M.	R.K.	T.T.
	70/20	L.M.	R.K.	T.T.	R.F.
	70/30	R.K.	T.T.	R.F.	L.M.

(A)

	TIME SCHEDULES				
		5/15	5/10	10/5	15/5
Work Load Combinations	50/20	R.L.	H.H.	L.N.	B.F.
	50/30	H.H.	L.N.	B.F.	R.L.
	70/20	L.N.	B.F.	R.L.	H.H.
	70/30	B.F.	R.L.	H.H.	L.N.

(B)

and k^{th} square with subject l performing the test.

μ is the overall mean common to all the cells.

R_i is the effect due to i^{th} row

C_j is the effect due to j^{th} column

S_k is the effect due to k^{th} square

T_l is the effect due to l^{th} subject

E_{ijkl} is the random error or the error due to all uncontrolled

   factors

Methods

Eight healthy, young male subjects participated in this experiment. They were all college students accustomed to normal physical activities. The relevant data of the individual subjects are shown in Table 5. The subjects were chosen to represent the normal worker defined earlier as closely as possible in their physical capacities. The personal data of the individual was obtained by having him fill out a questionnaire at first. Then the maximum aerobic capacity of the individual was determined according to the procedure to be outlined later. Only those closely meeting the specifications of a normal worker were selected to be the subjects. All the subjects were volunteer male students and were paid at the rate of $1.75 per hour.

All experimental data were obtained with the subject walking on a motor driven treadmill manufactured by Warren E. Collins, Inc., Braintree, Massachusetts. The treadmill had an endless belt, running over two circular pulleys, providing a non slippery, smooth walking surface. The effective walking surface available was 66" long and 18" wide. The treadmill was equipped with controls to obtain any speed

TABLE 5

DETAILS OF THE SUBJECTS INVOLVED IN PARAMETER
DETERMINATION EXPERIMENT

No.	Subject	Age	Weight kg.	Maximum Aerobic Capacity	
				Liters/min	ml/kg/min
1	T.T.	23	72.9	3.310	45.4
2	R.F.	22	69.6	3.076	44.2
3	L.M.	23	73.3	3.338	45.5
4	R.K.	22	70.1	3.007	42.9
5	R.L.	23	71.3	3.029	42.5
6	M.H.	22	81.6	4.088	50.1
7	L.N.	26	70.4	3.985	56.6
8	B.F.	25	77.1	3.362	43.6

between 0 to 16 mph. The slope of the walking surface could be con-
trolled from 0 to 40 per cent inclination to the horizontal.

The oxygen uptake of the subject was automatically and con-
tinuously computed, breath by breath with an oxygen consumption com-
puter manufactured by Technology/Versatronics, Inc., Yellow Springs,
Ohio (model OCC 1000). In order to measure the oxygen uptake of the
subject, a plastic face mask was fitted snugly to his face. Two sets
of low resistance one-way rubber valves encased in plastic chambers
attached to the mask acted as inlet and outlet valves for breathing in
and out. During inspiration, the inlet valves opened and let the

atmostpheric air into the face mask. During expiration the outlet valves opened and let out the expired air into a plastic, flexible tubing of 1 1/2" diameter and 34" long. The inspired air and exhausted air were never mixed except in the small space inside the face mask. The other end of the plastic tubing was connected to the oxygen consumption transducer of the computer. The valve chamber and flexible tubing were suspended from above through a coil spring so that the subject might not feel hampered by them. The transducer of the computer in essence was an oxygen cell capable of detecting the amount of oxygen in the sample of air passing through it. The computer was previously calibrated to the atmostpheric air. Hence any depletion of oxygen in the expired air could be in effect sensed by the computer. This depletion was assumed to be equal to the oxygen used by the subject while performing the activity. The computer then converted the amount of oxygen depletion in volume at standard temperature and pressure and was integrating continuously. The computer was so set to automatically integrate up to one liter of oxygen and then reset and start again.

Rectal temperature was measured using a thermister type rectal probe manufactured by Yellow Springs Instruments, Inc., Yellow Springs, Ohio, in combination with a bridge circuit. The probe was inserted to a depth of about 6 inches inside the rectum. The bridge circuit was calibrated every time before the test started and was checked during the test at frequent intervals of at least once every 15 minutes. This was done since it was found in earlier experiments that there was a tendency for the base line to shift during the test. For some subjects

the probe was slipping out occasionally while walking and at such moments the subject was instructed to push it back in position. Each subject was assigned a thermal probe and he used only that particular one for all the tests.

Heart rate was also monitored continuously during the test. It was monitored by placing chest electrodes on the subject and using a cardiotachometer which gave an output signal directly proportional to the integrated time interval between two successive R waves. A digital counter-printer was coupled to the cardiotachometer to print out the number of heart beats every 30 seconds.

Though rectal temperature and heart rate were not used in the development of the model, they were monitored in order to insure that the subject was not overly stressed in some aspect that could not ordinarily be detected by oxygen uptake. Also it was thought that the data so collected could later be used in refining the model or for other analyses. A four channel physiograph with suitable amplifiers was used to record all the three measurements on paper continuously and simultaneously. The time was maintained by a built-in mechanism in the physiograph to make a special mark on the paper every 30 seconds. This facilitated to a large extent the data assimilation with respect to time at any convenient later time. The paper speed was maintained at 0.2 cm/sec. The room temperature was maintained at 70°F. An electric fan was used in order to effect good circulation of the air in the room.

Experimental Procedure

During the first visit of the subject, he was informed of the general course of the test and the purpose of the experiment. He was asked to fill out a questionnaire regarding his personal data such as age, food habits, medical problems, etc. Only healthy and physically fit candidates were selected. He was then given a chance to walk on the treadmill for a few minutes and familiarize himself with it. Next the subject underwent testing for his maximum aerobic capacity using submaximal test procedures. This was done twice once a day on two different days, and the average value was taken as the individuals maximum aerobic capacity. The procedure for determining the maximum aerobic capacity was similar to that outlined by P. O. Astrand and Rodahl (1970). The subject was instructed not to have any heavy food intake for at least two hours before any test was scheduled to start. He was dressed in shorts and tennis shoes. He walked on the treadmill at speeds of 3 mph and 0 per cent grade, 4 mph and 0 per cent grade, 4 mph and 4 per cent grade and 4 mph and 8 per cent grade for at least 5 minutes in each level. The steady state values of heart rate and oxygen uptake at each level were recorded. These values were used in predicting the maximum aerobic capacity. It was assumed that at the maximum aerobic capacity the heart rate is also maximum. The maximum heart rate for an individual is predicted from the following empirical relationship developed by I. Astrand (1959).

$$\text{Maximum Heart Rate} = 100 + (25 - \text{age}) \times 0.62$$

Then each subject was administered a trial test on the treadmill in order to determine the treadmill settings necessary to obtain the required percentages of the maximum aerobic capacity. Table 6 shows the various treadmill settings for each subject for each work load condition.

TABLE 6

TREADMILL SETTINGS FOR SUBJECTS USED IN PARAMETER
EXPERIMENTS FOR DIFFERENT WORK LOADS

Subject	Treadmill Settings for Work Load							
	70 per cent		50 per cent		30 per cent		20 per cent	
	Mph	Slope	Mph	Slope	MPH	Slope	MPH	Slope
1) R.L.	4	8%	4	4%	3	3%	3	0%
2) M.H.	4	8%	4	5%	3	2%	2.5	0%
3) L.N.	4	9%	4	6%	4	0%	3	0%
4) B.F.	4	8%	4	5%	3	2%	2.5	0%
5) T.T.	4	6%	4	2%	3	2%	2.5	0%
6) R.F.	4	5%	4	2%	3	2%	2.5	0%
7) L.M.	4	6%	4	2%	3	0%	2.5	0%
8) R.K.	4	6%	4	2%	3	0%	2.5	0%

On the test day the subject came to the laboratory and was informed about the work profile conditions in terms of the treadmill settings and time schedule. He then inserted the rectal thermometer himself to the length marked on the thermometer (about 6 inches). The

lead of the thermometer was fastened to the upper seam of the shorts
with adhesive tape to prevent accidental pulling off while walking.
Then three electrodes were applied to the chest of the subject after
cleaning the skin well. The face mask was then strapped to his face.
A chair was placed on the treadmill and the subject sat on it and
rested for 15 minutes. At the end of the rest period, the subject
walked for the required time as per the work profile conditions of the
particular test. Figure 5 shows schematically the work load protocol
in general for any work profile used in this experiment. The subject
always started off on higher load and completed on lower load. At the
end of the walk the subject again sat on the chair and recovered for
about 15 to 20 minutes. During the entire period of the test including
initial rest and final recovery, all of the three physiological para-
meters were continuously monitored and recorded. Change in work load
levels was brought about by manually operating the controls for speed
and elevation of the treadmill. This was done with utmost care at the
exact moment as the event marker indicated the completion of the last
minute of work.

Computational Procedures

In order to compute θ, k_r, k_f, t_1 and t_2, the oxygen uptake data
is required. Hence, first of all, this data was obtained from the
recordings of the tests.

In order to determine θ, the build up factor per cycle, the
oxygen uptake during each cycle of the entire test run was determined.
Then a regression line for the oxygen uptake against the number of
cycles was computed. In general, the equation of the line may be
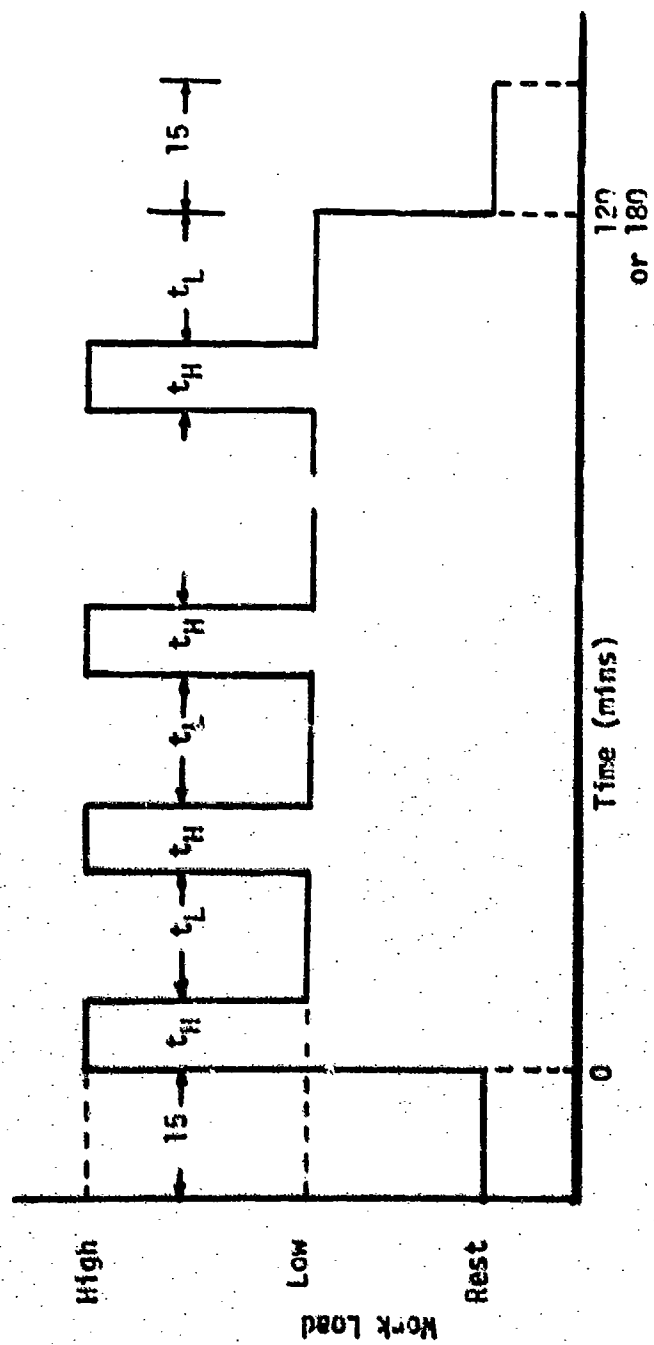
Fig. 5.--General protocol of the alternating work load

expressed as,

$$Y = \beta_0 + \beta_1 n$$

where

> Y is the oxygen uptake during one complete cycle
>
> n is the number of cycles
>
> β_0 is the y intercept
>
> β_1 is the slope of the regression or the increase in
> oxygen uptake from cycle to cycle.

A straight line was fitted to data, since it was assumed during the development of EER model that such a relationship exists between oxygen consumption and the cycle number. The straight line relationship was found to be better than higher order relationships in the experimental data conducted under the THEMIS project in the Industrial Engineering Laboratories at Texas Tech University. The build up factor per cycle, θ, was computed in the following manner.

> Oxygen uptake during cycle number 1, $= \beta_0 + \beta_1$
>
> The increase in oxygen uptake in every cycle $= \beta_1$.

Therefore,

$$\theta = \frac{\beta_1}{\beta_0 + \beta_1} \quad . \tag{3.1}$$

Figure 5 shows the build up in oxygen uptake and the basis for the above computation. However, since θ represents the build up per cycle, it will not be possible to directly compare the build up under
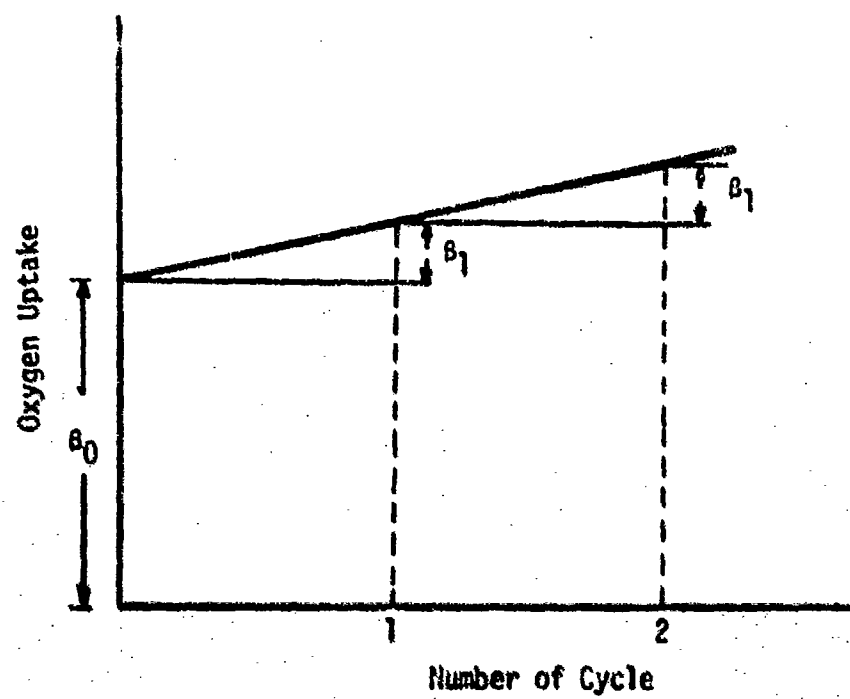
Fig. 6.--Showing the build-up in oxygen uptake

time schedules with different cycle times. For example θ for a 15/5 schedule and 10/5 schedule cannot be directly compared even if the work load combination was the same in both cases. This is because the cycle times are 20 minutes and 15 minutes respectively. Hence another quantity, the build up per hour was computed using the θ value. Thus,

$$\theta' = \theta \times n' \times 100 \ldots \qquad (3.2)$$

where

θ' = the build up in oxygen uptake per hour expressed as percentage of the oxygen uptake during first cycle

n' = number of cycles per hour.

It must be remembered that while θ is required in order to be used in the EER model, θ' is required in order to make a comparison of the build up under different time schedules on a common time basis.

The velocity constant k_f was computed in the following manner. The oxygen uptake response curve for a sudden fall in work load was represented by

$$f(t) = A e^{-k_f t}$$

now

Y_1 = the oxygen uptake during the interval 0.5 minute to 1.0 minute

and

Y_2 = the oxygen uptake during the interval 1.5 minutes to 2.0 minutes.

Therefore at t = 1 min,

$$f(1) \;=\; Y_1 \;=\; A\,e^{-k_f} \;\ldots \tag{3.3}$$

and at t = 2 min,

$$f(2) \;=\; Y_2 \;=\; A\,e^{-2k_f} \;\ldots \tag{3.4}$$

Dividing (3.3) by (3.4) we have

$$\frac{Y_1}{Y_2} \;=\; \frac{e^{-k_f}}{e^{-2k_f}}$$

i.e.

$$\frac{Y_1}{Y_2} \;=\; e^{k_f} \;\ldots \tag{3.5}$$

Y_1 and Y_2 are determined directly from the recordings. Hence k_f can be calculated from equation (3.5).

For example, let the oxygen uptake during the time interval 0.5 to 1.0 minute and 1.5 to 2.0 minutes be 130 ml. and 40 ml. respectively.

i.e.

$$Y_1 \;=\; 130$$
$$Y_2 \;=\; 40$$

Hence

$$e^{k_f} \;=\; \frac{Y_1}{Y_2} \;=\; \frac{130}{40} \;=\; 3.25$$

Therefore

$$k_f = 1.18$$

The velocity constant k_r cannot be determined as readily since the relationship is a little more complex. The oxygen uptake response for a sudden increase in work load was represented by the relationship,

$$f(t) = A(1-e^{-k_r t}).$$

Now at time $t = 1$ min

$$f(1) = Y_1 = A(1-e^{-k_r}) . \qquad (3.6)$$

and at $t = 2$ min

$$f(2) = Y_2 = A(1-e^{-2k_r}) . \qquad (3.7)$$

Dividing (3.6) by (3.7) we have

$$\frac{Y_1}{Y_2} = \frac{A(1-e^{-k_r})}{A(1-e^{-2k_r})}$$

i.e.

$$\frac{Y_1}{Y_2} = \frac{1-e^{-k_r}}{1-e^{-2k_r}} . \qquad (3.8)$$

Put $p = e^{-k_r}$ and $\frac{Y_1}{Y_2} = C_1$ in equation (3.8).
Now, we have

$$C_1 = \frac{1-p}{1-p^2} .$$

Cross multiplying and rearranging,

$$C_1 - C_1 p^2 - 1 + p = 0$$

i.e.

$$C_1 p^2 - p - (C_1 - 1) = 0.$$

Put $C_2 = C_1 - 1$. Then we have,

$$C_1 p^2 - p - C_2 = 0 \tag{3.9}$$

Equation (3.9) is a quadratic equation in p of the form $ax^2 + bx + c = 0$, whose roots are given by,

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}.$$

Hence the two roots of the equation (3.9) are given by,

$$p = \frac{-1 \pm \sqrt{1 - 4C_1 C_2}}{2C_1}. \tag{3.10}$$

Of the above two roots one will be negative and the other will be positive. A negative value for p means a negative value for k_r which is not possible in this case. Hence only the positive root will be used in calculating k_r.

For example, let the oxygen uptake during the intervals 0.5 to 1.0 min and 1.5 to 2.0 mins be 420 ml and 600 ml respectively. Then

$$Y_1 = 420$$
$$Y_2 = 600$$

$$c_1 = \frac{Y_1}{Y} = \frac{420}{600} = 0.7$$

$$C_2 = (C_1 - 1) = (0.7 - 1) = -0.3$$

Substituting the above values in equation (3.10), we have

$$p = \frac{-1 \pm \sqrt{1 - 4(0.7)(-0.3)}}{2(0.7)}$$

$$= \frac{-1 \pm \sqrt{1 + 0.84}}{1.4} = \frac{1 \pm 1.356}{1.4}$$

$$= \frac{0.356}{1.4} \quad \text{or} \quad -1.683$$

Selecting only the positive root, we have

$$p = 0.253$$

i.e.

$$e^{-kr} = 0.253$$

Therefore,

$$k_r = 1.37$$

Figures 7A and 7B show diagrammatically the oxygen uptake values used in the computations.

The time constants t_1 and t_2 are dependent on the velocity constants and the magnitude of work load change. When the oxygen uptake following a change in work load reached a level of 25 mls of difference from the expected steady state level the time constants t_1 and t_2 were determined. This procedure was adopted because for the assumed exponential relationship the steady state would never occur. Figures
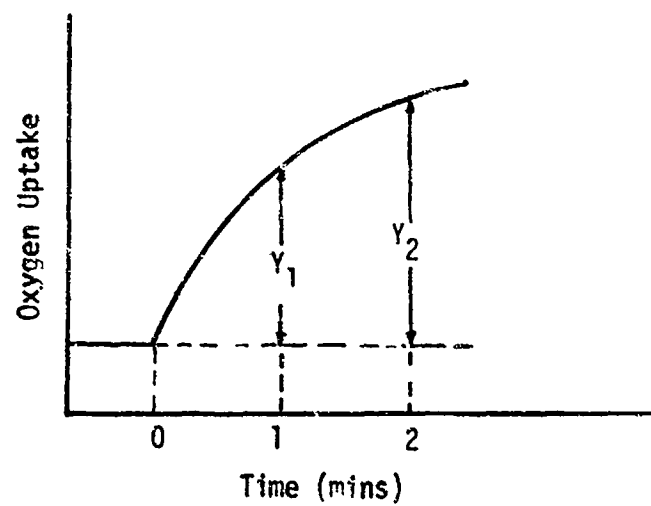
Fig. 7A.--Showing the O_2 uptake values used in k_r computation
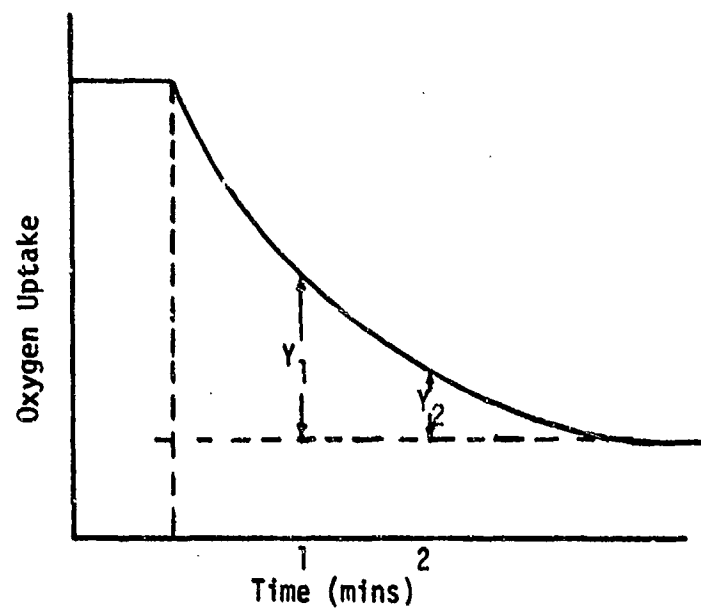
Fig. 7B.--Showing the O_2 uptake values used in k_f computation

8A and 8B show the above stated condition for t_1 and t_2 in relation with oxygen uptake. The error introduced in either case is small and is shown in the figure. This amount of error could be neglected without affecting the results significantly.

Results

The various results of experiments conducted for the specific purpose of determining the parameters of the EER model are discussed below. These results were obtained according to the computational procedures mentioned in the previous section.

First, in order to determine the build up factors θ and θ', regression lines were fitted to the amount of oxygen uptake in liters per cycle to the cycle number for every test. The sum total of the oxygen uptake during a higher work load followed by a lower work load is the oxygen uptake for that particular cycle. Figures 9A through 9P show the regression lines for all the 32 tests. The figures also show the 95 per cent confidence interval lines for the corresponding regression lines. In the case of a few 3 hour tests, the particular subject could not complete the task but terminated somewhere in the middle. In such cases the regression lines are based on the data up to the last complete cycle. These are shown as "Termination" in the corresponding graph. Tables 7A and 7B present the regression line data for 2 hour and 3 hour tests respectively. The correlation coefficients 'or 2 hour tests vary from a low of 0.611 to 0.983. The same for 3 hour tests vary from a low of 0.612 to 0.982. In general, it can be said that for both 2 hour and 3 hour tests the oxygen uptake increases linearly as the cycle numbers increase.
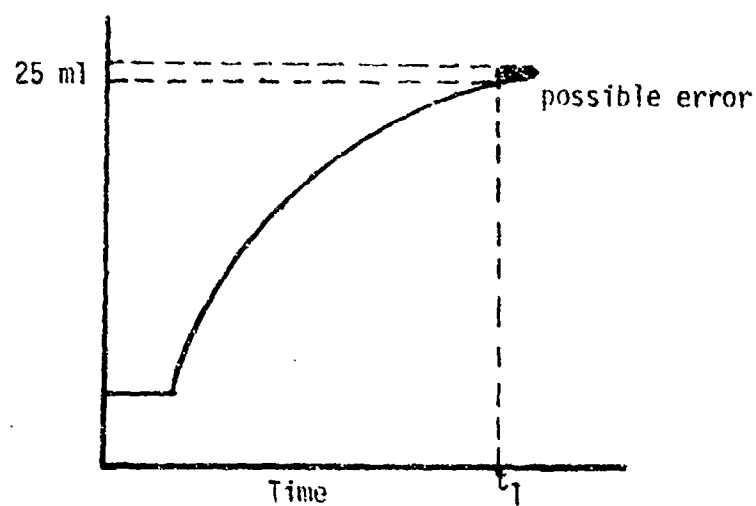
Fig. 8A.--Showing the criterion to determine the time constant, t_1 and the possible error
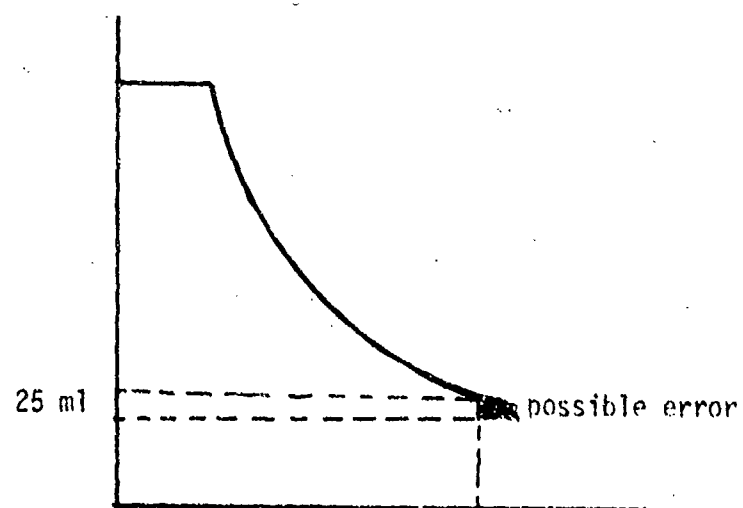
Fig. 8B.--Showing the criterion to determine the time constant, t_2, and the possible error

Fig. 9A.--Regression lines for 2 hour tests. Subject - T.T. Top: Work load combination - 50/20, Time schedule - 5/15. Bottom: Work load combination - 50/30, Time schedule - 15/5.

Fig. 9B.--Regression lines for 2 hour tests. Subject - T.T.
Top: Work load combination - 70/20, Time schedule - 10/5. Bottom:
Work load combination - 70/30, Time schedule - 5/10.

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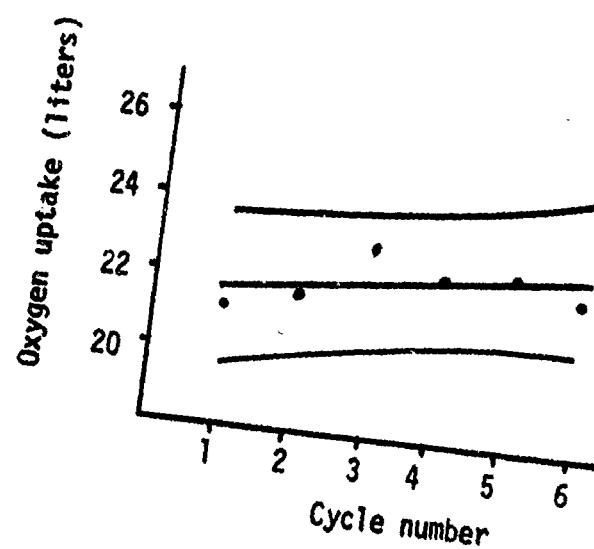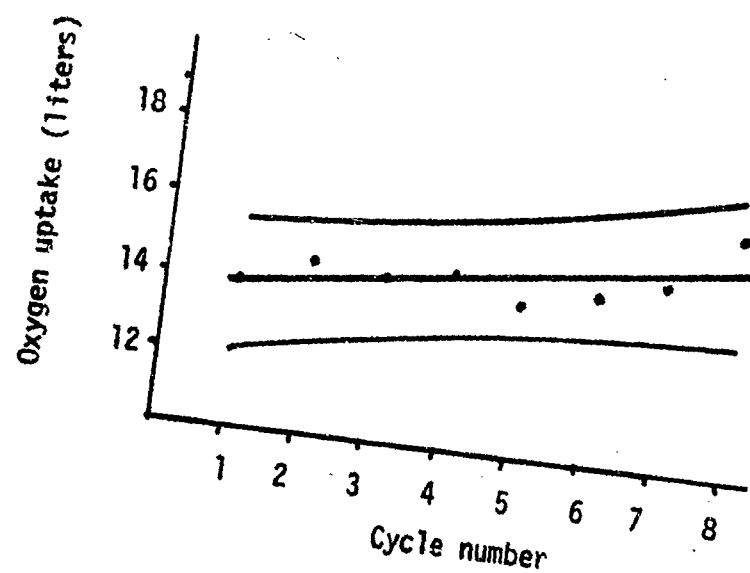
Fig. 9C.--Regression lines for 2 hour tests. Subject - R.F.
Top: Work load combination - 50/20, Time schedule - 5/10. Bottom: Work load combination - 50/30, Time schedule - 5/15.
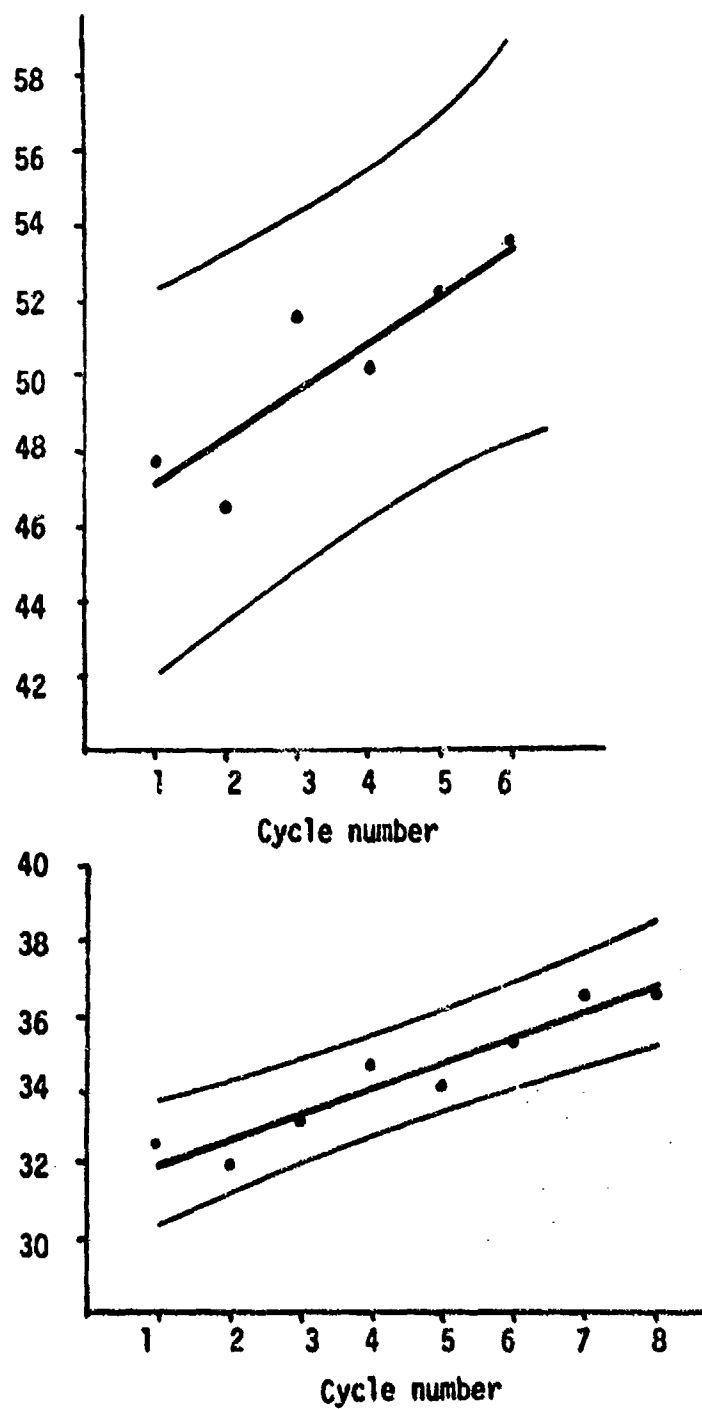
Fig. 9D.--Regression lines for 2 hour tests. Subject - R.F.
Top: Work load combination - 70/20, Time schedule - 15/5. Bottom:
Work load combination - 70/30, Time Schedule - 10/5.
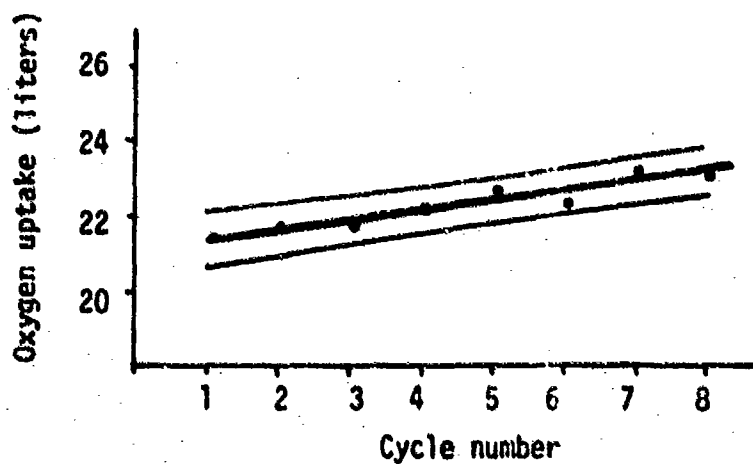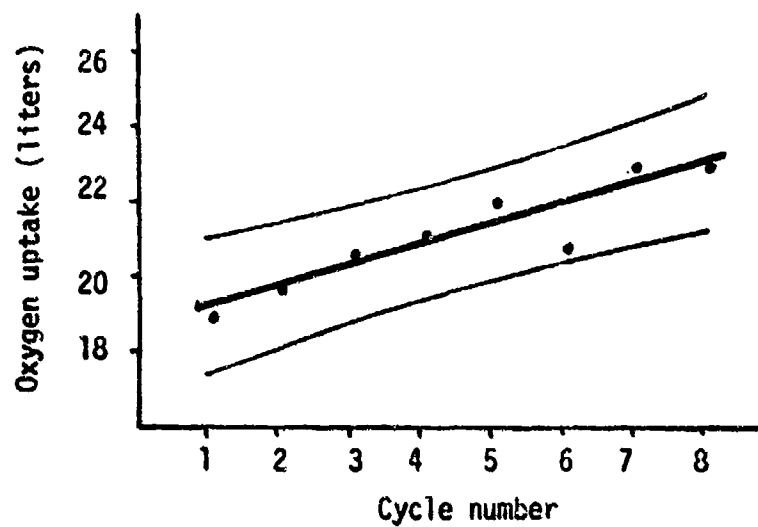
Fig. 9E.--Regression lines for 2 hour tests. Subject - L.M.
Top: Work load combination - 50/20, Time schedule - 10/5. Bottom:
Work load combination - 50/30, Time schedule - 5/10.
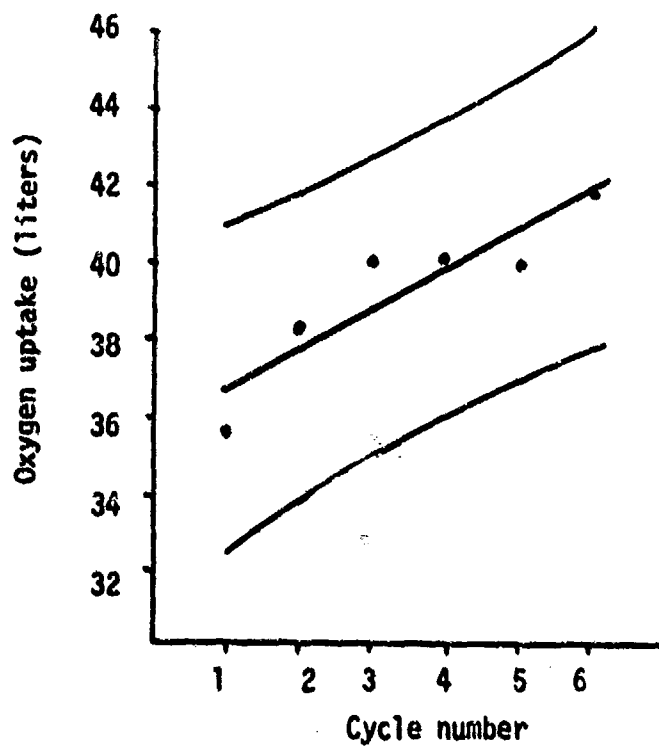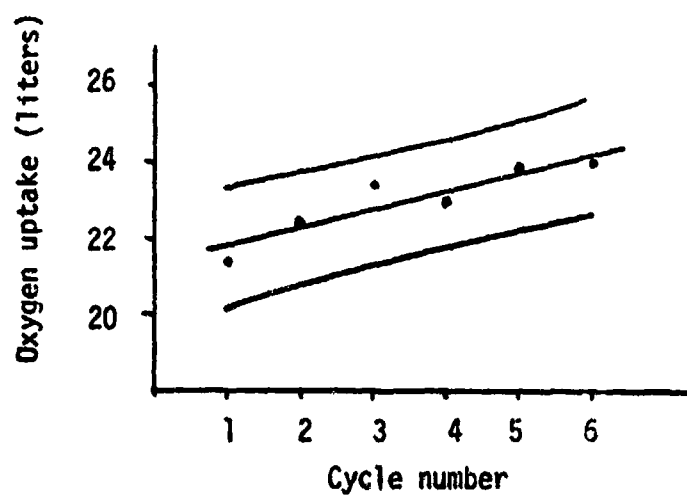
Fig. 9F.--Regression lines for 2 hour tests. Subject - L.M.
Top: Work load combination - 70/20, Time schedule - 5/15. Bottom:
Work load combination - 70/30, Time schedule - 15/5.
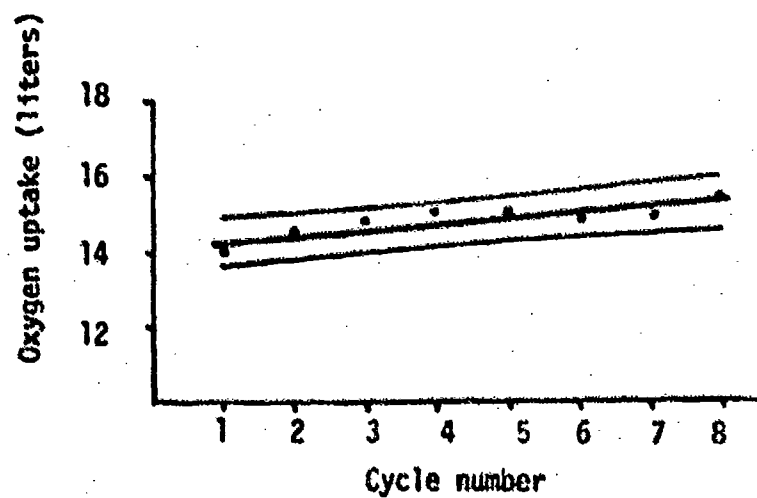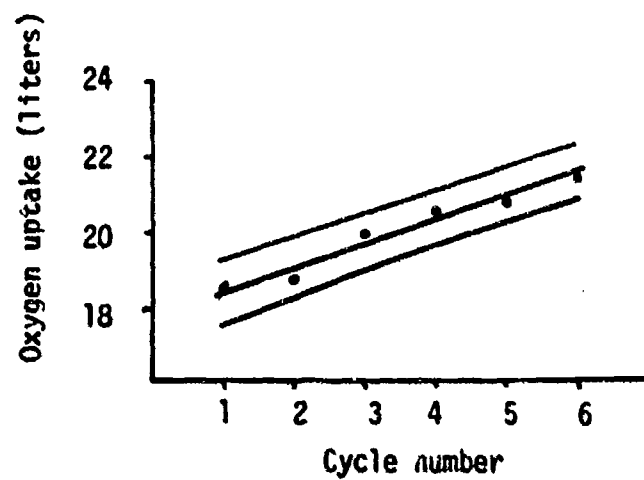
Fig. 9G.--Regression lines for 2 hour tests. Subject - R.K.
Top: Work load combination - 50/20, Time schedule - 15/5. Bottom:
Work load combination - 50/30, Time schedule - 10/5.
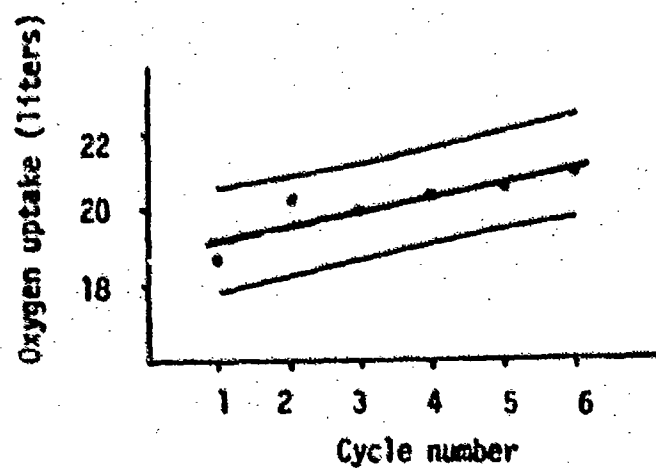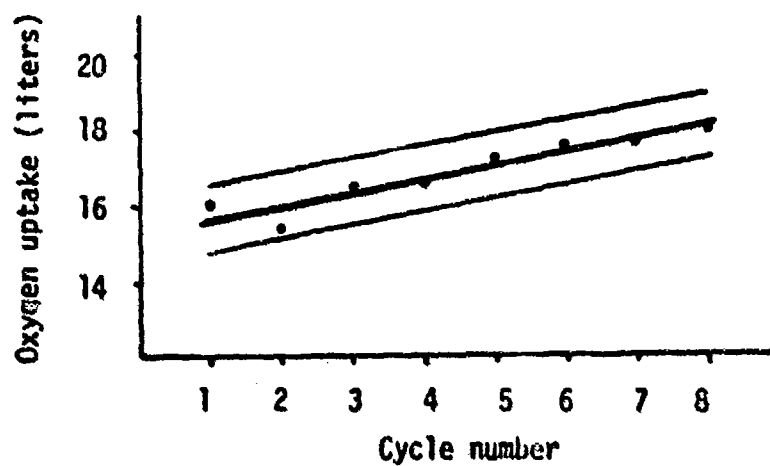
Fig. 9H.--Regression lines for 2 hour tests. Subject - R.K.
Top: Work load combination - 70/20, Time schedule - 5/10. Bottom:
Work load combination - 70/30, Time schedule - 5/15.
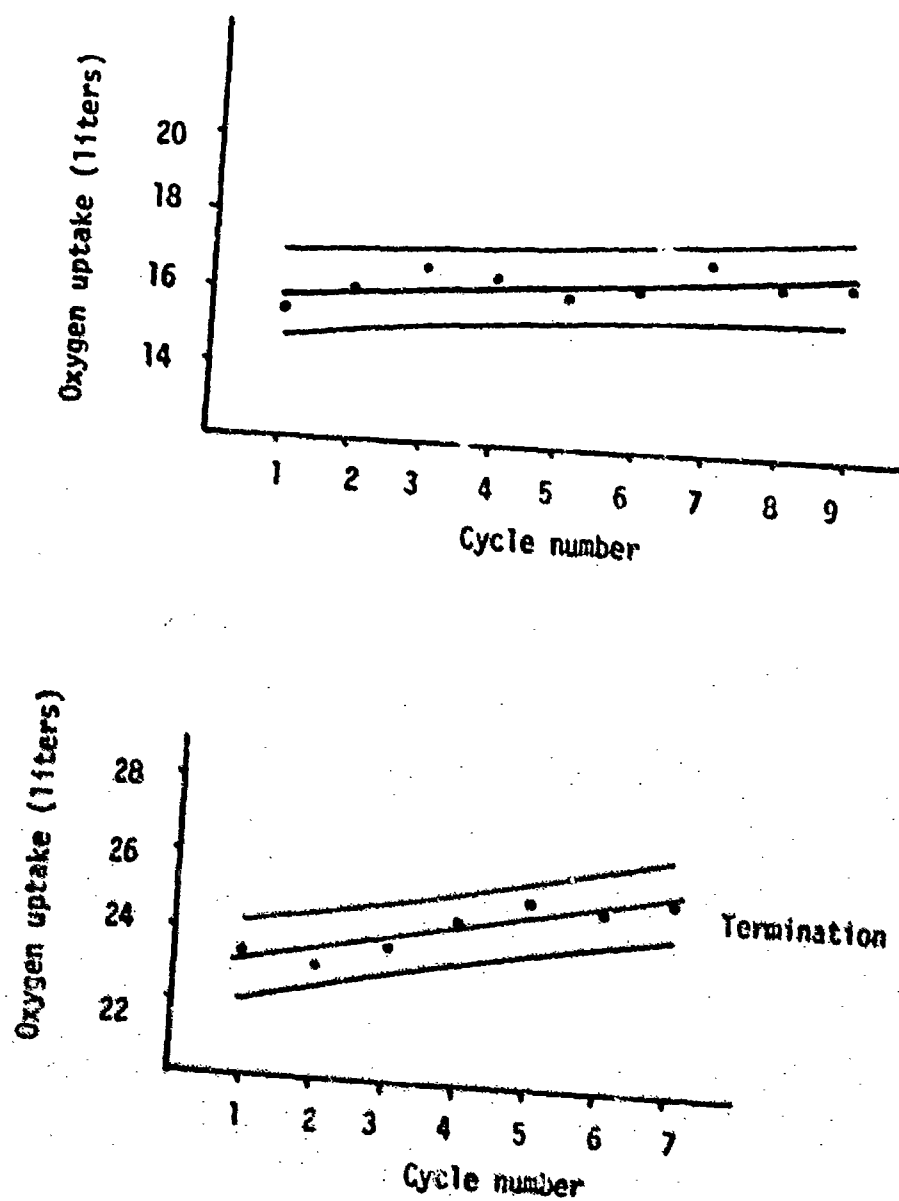
Fig. 91.--Regression lines for 3 hour tests - Subject - R.L.
Top: Work load combination - 50/20, Time schedule - 5/15. Bottom:
Work load combination - 50/30, Time schedule - 15/5

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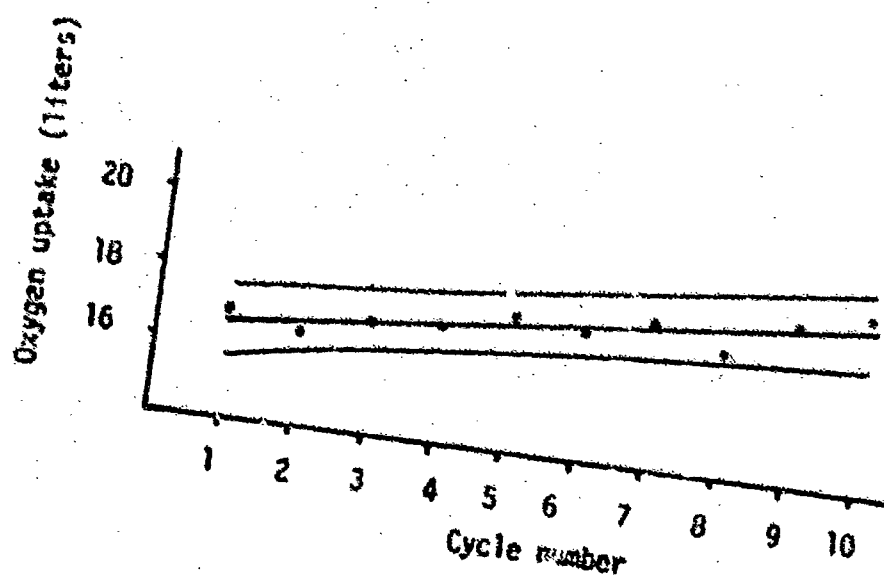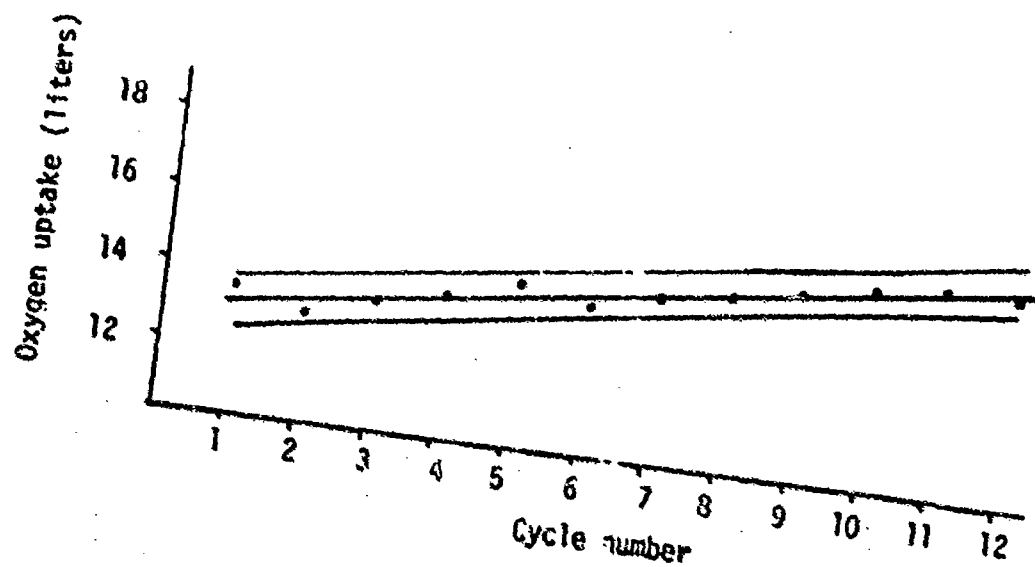
Fig. 9J.--Regression lines for 3 hour tests. Subject - R.L.
Top: Work load combination - 70/20, Time schedule - 10/5. Bottom:
Work load combination - 70/30, Time schedule - 5/10.
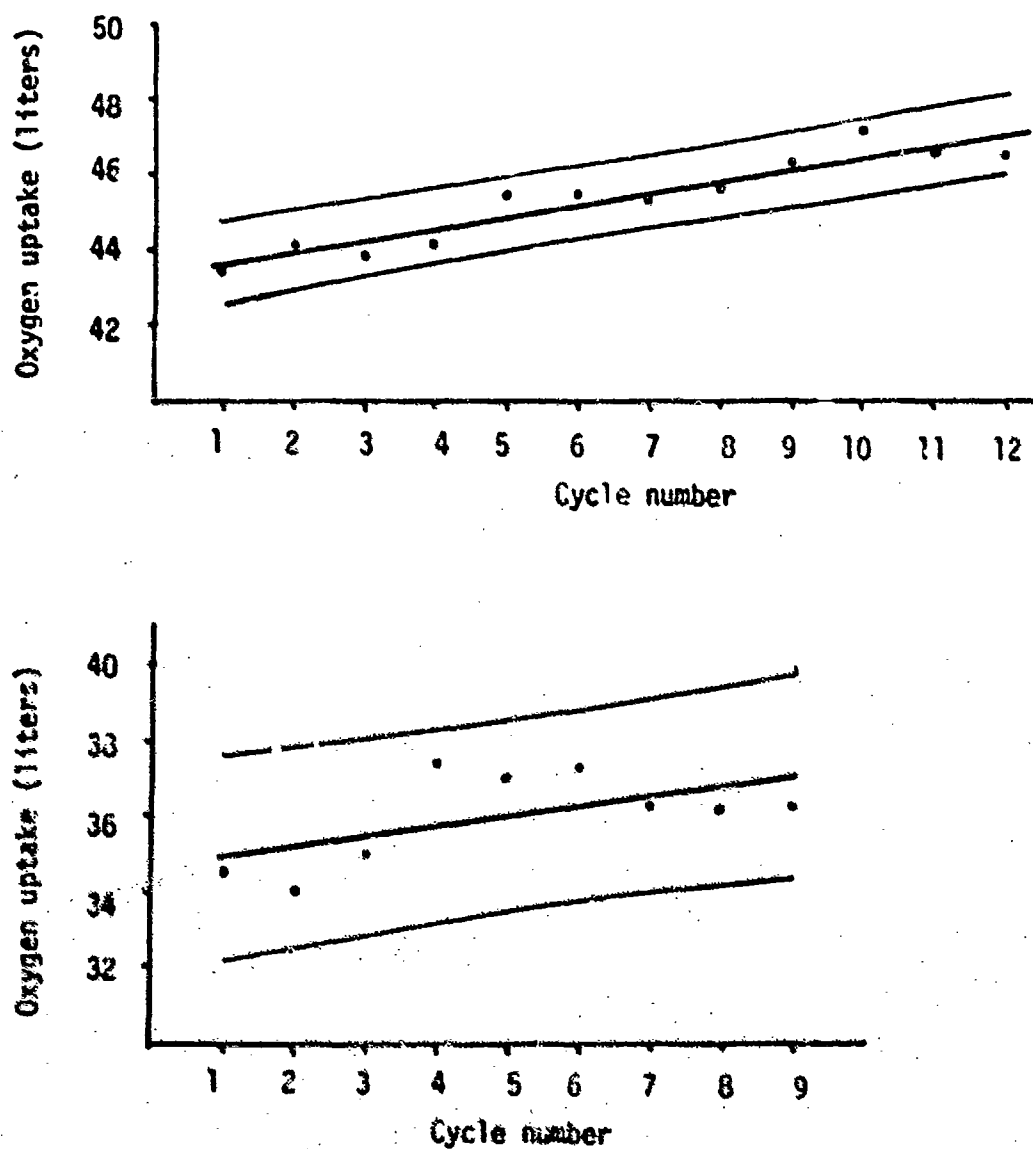
Fig. 9K.--Regression lines for 3 hour tests. Subject - H.H.
Top: Work load combination - 50/20, Time schedule - 5/10. Bottom:
Work load combination - 50/30, Time schedule - 5/15.
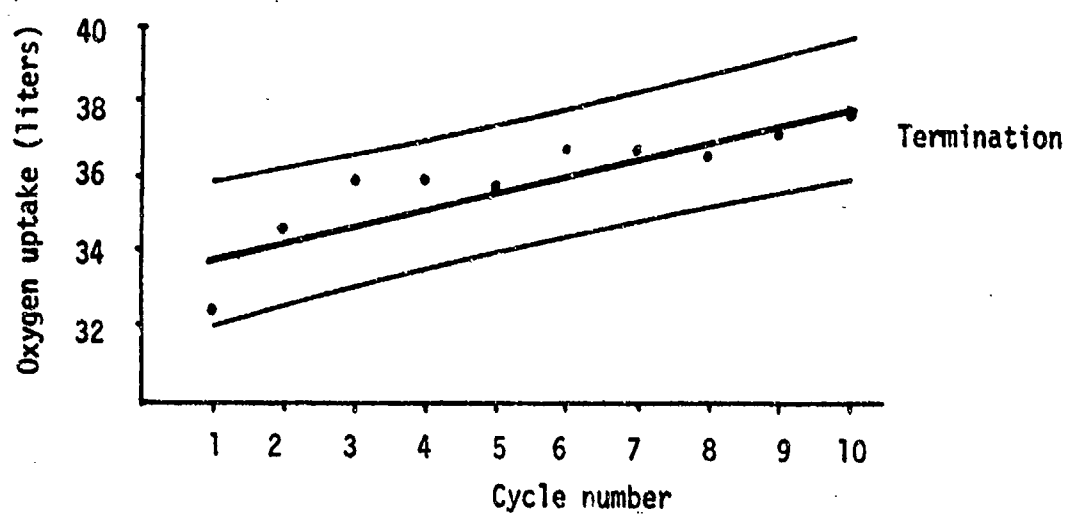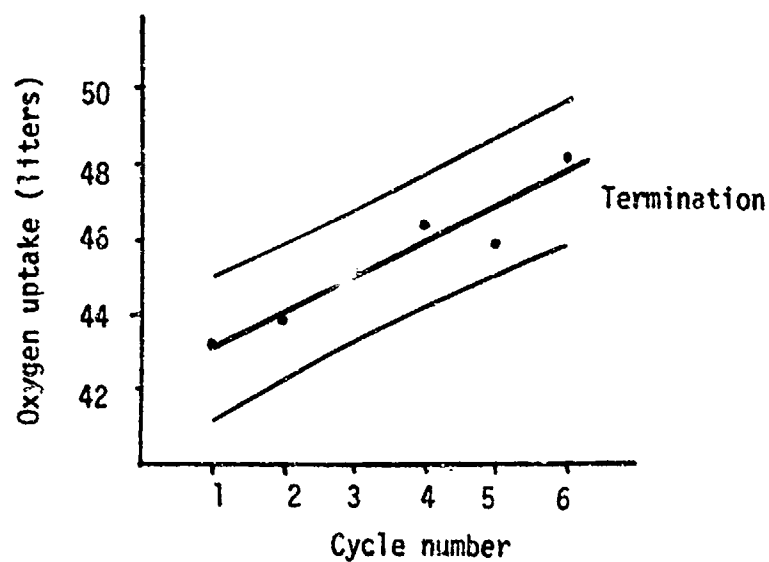
Fig. 9L.--Regression lines for 3 hour tests. Subject - M.H.
Top: Work load combination - 70/20, Time schedule - 15/5. Bottom:
Work load combination - 70/30, Time schedule - 10/5.
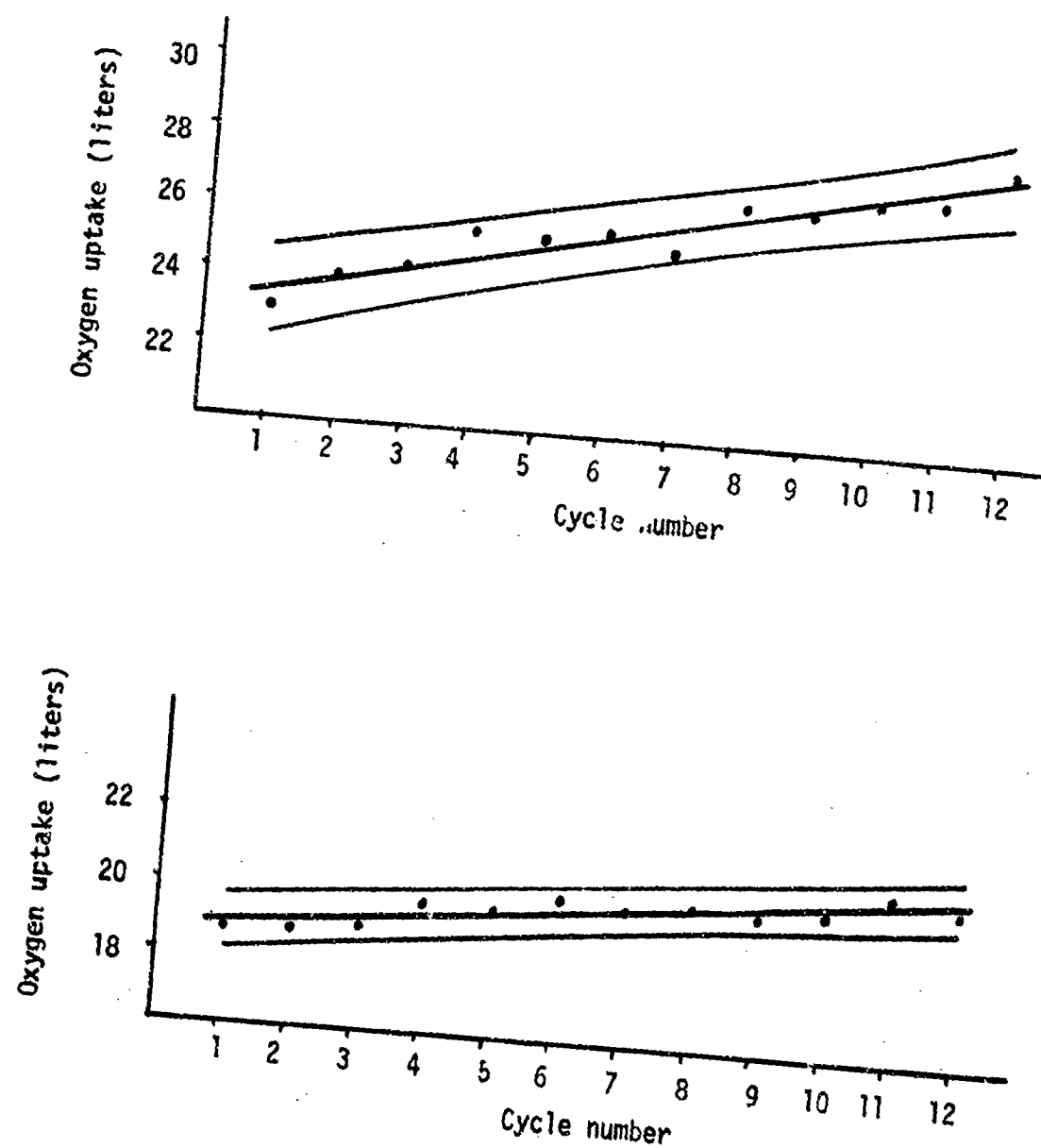
Fig. 9M.--Regression lines for 3 hour tests. Subject - L.N.
Top: Work load combination - 50/20, Time schedule - 10/5. Bottom:
Work load combination - 50/30, Time schedule - 5/10.
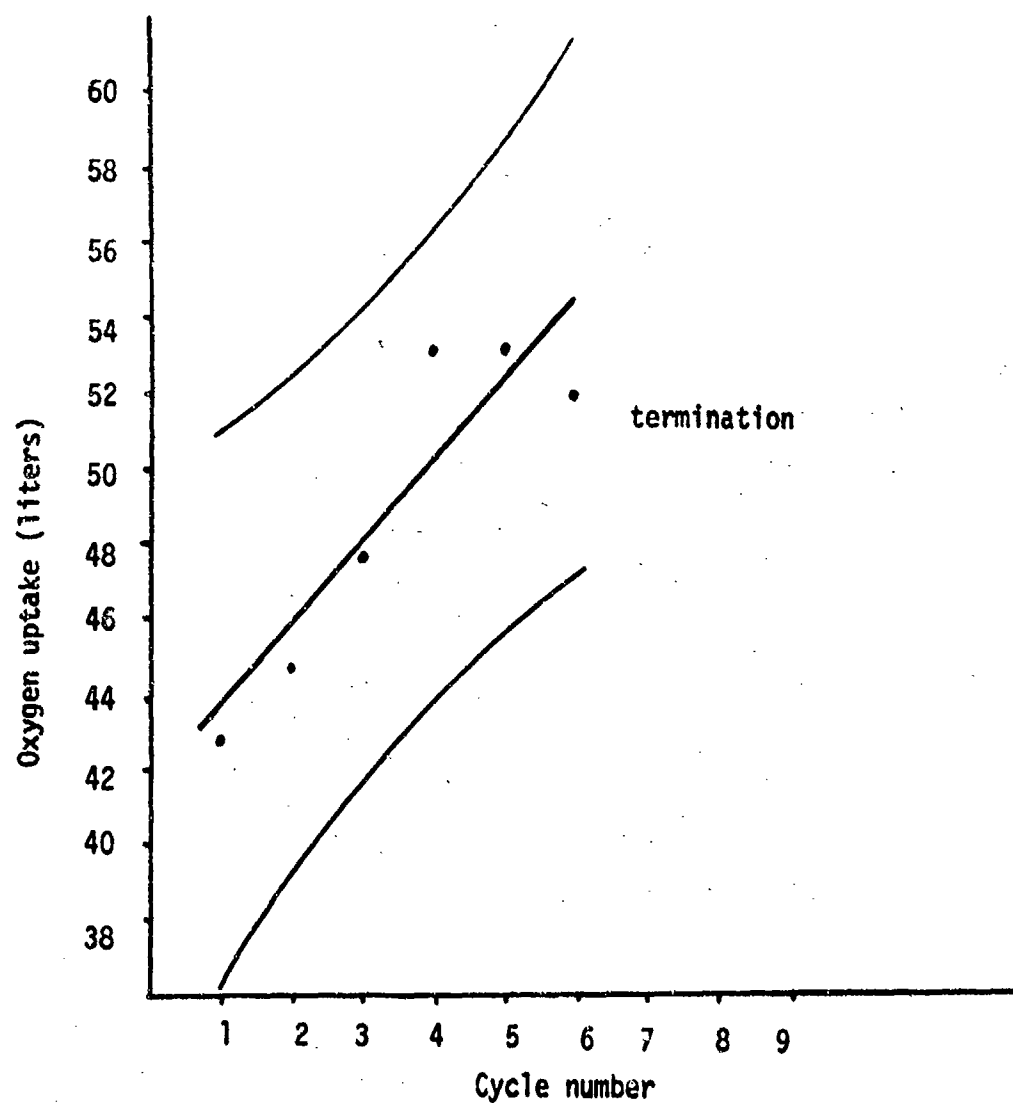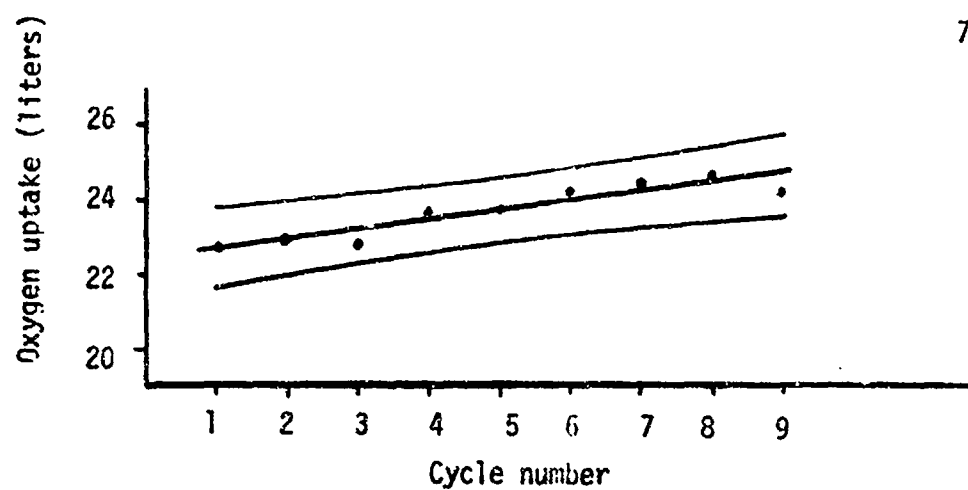
Fig. 9N.--Regr   sion lines for 3 hour tests.   Subject - L.N.
Top: Work load combination - 70/20, Time schedule - 5/15.   Bottom:
Work load combination - 70-30, Time schedule - 15/5.
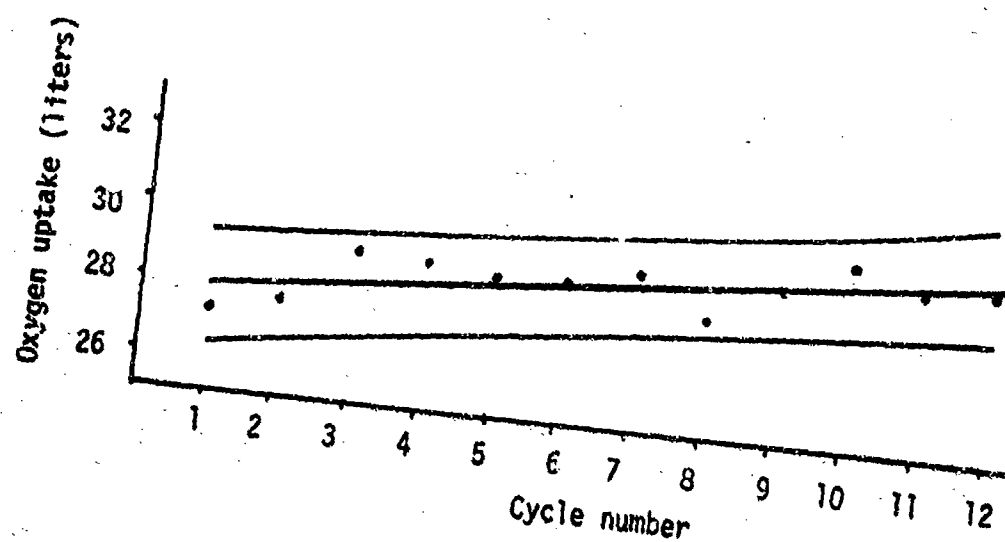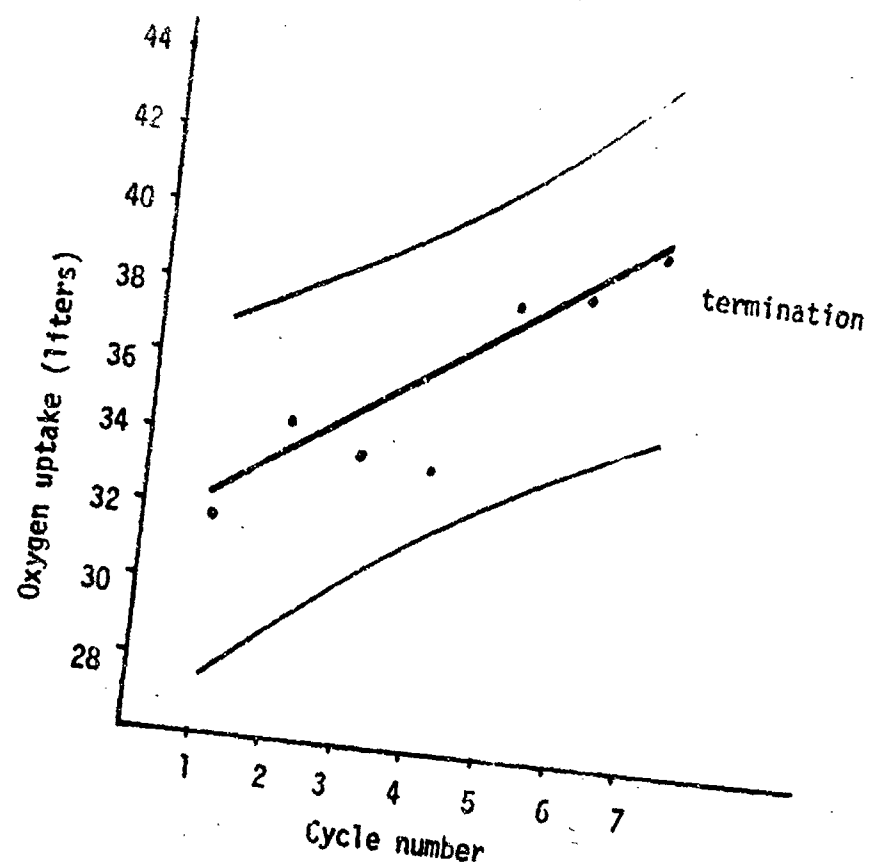
Fig. 90.--Regression lines for 3 hour tests. Subject - B.F.
Top: Work load combination - 50/20, Time schedule - 15/5. Bottom:
Work load combination - 50/30, Time schedule - 10/5.
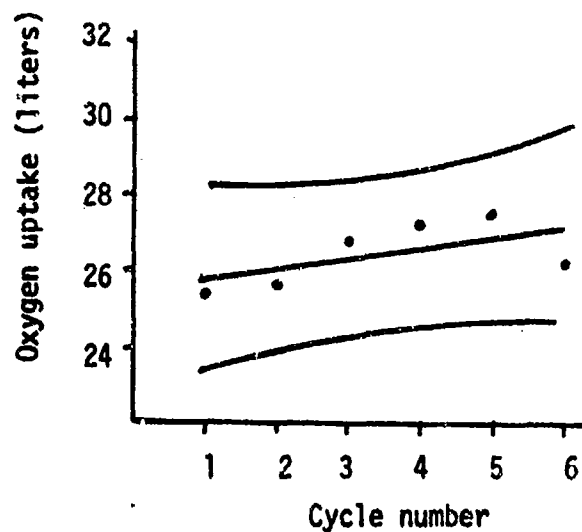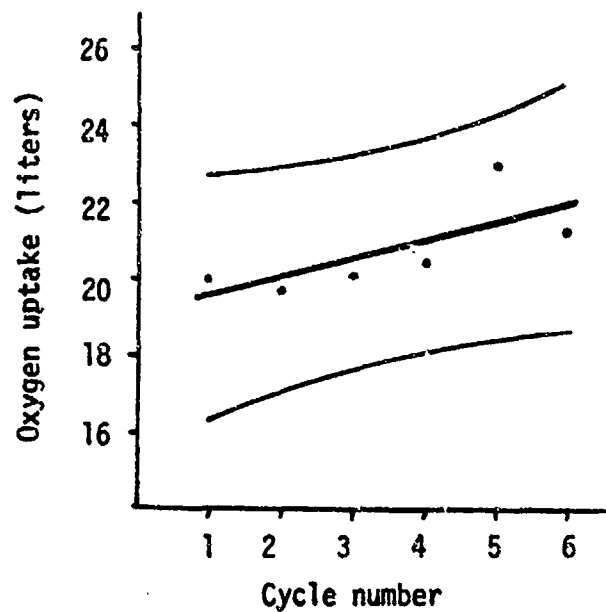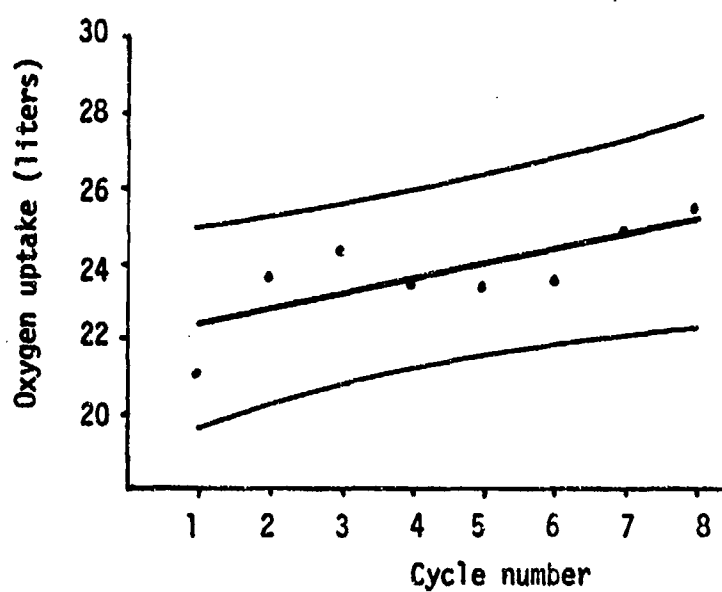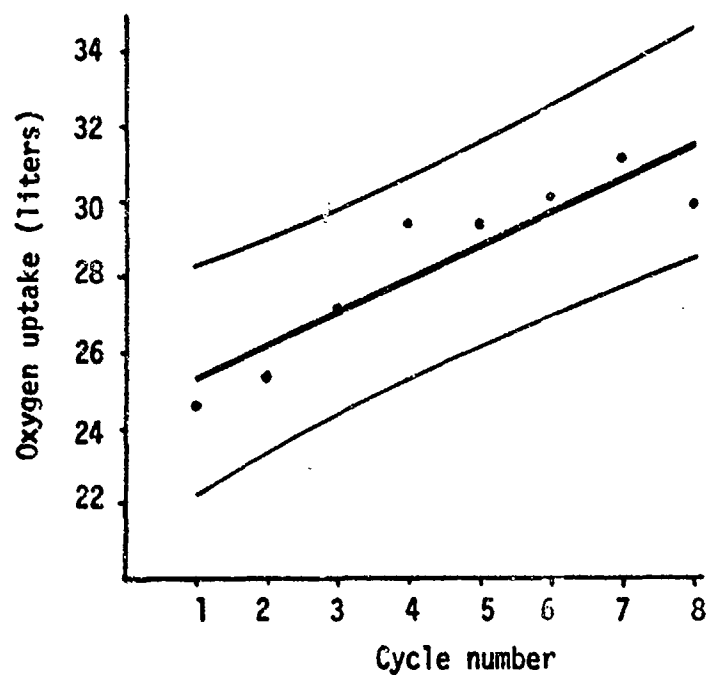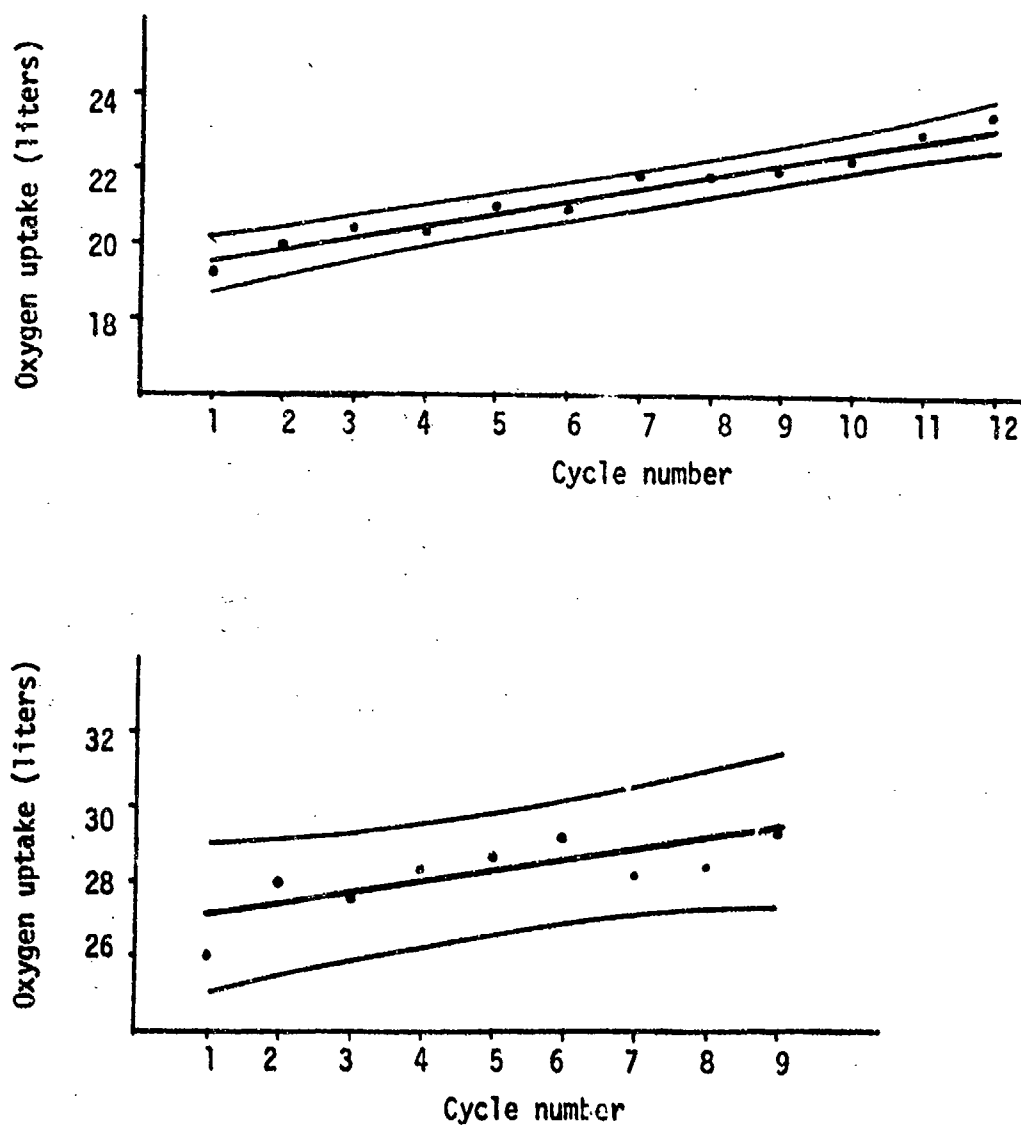
Fig. 9P.--Regression lines for 3 hour tests. Subject - B.F.
Top: Work load combination - 70/20, Time schedule - 5/10. Bottom:
Work load combination - 70/30, Time schedule - 5/15.

TABLE 7A

REGRESSION LINE DATA FOR 2 HOUR TESTS

Work load Combination	Time Schedule	Regression Line Data		
		Constant Term β_0	Slope Term β_1	Correlation coeff. r
50/20	5/15	19.043	0.488	0.738
	5/10	13.529	0.259	0.764
	10/5	18.646	0.552	0.921
	15/5	17.793	0.634	0.983
50/30	5/15	21.483	0.228	0.654
	5/10	21.184	0.252	0.939
	10/5	14.152	0.155	0.890
	15/5	25.512	0.267	0.611
70/20	5/15	21.307	0.408	0.919
	5/10	15.330	0.352	0.951
	10/5	24.408	0.804	0.916
	15/5	45.895	1.253	0.864
70/30	5/15	18.793	0.394	0.894
	5/10	21.938	0.395	0.749
	10/5	31.372	0.674	0.954
	15/5	35.719	1.038	0.871

TABLE 7

REGRESSION LINE DATA FOR 3 HOUR TESTS

Work load Combination	Time Schedule	Regression Line Data		
		Constant Term β_0	Slope Term β_1	Correlation coefficient
50/20	5/15	15.844	0.116	0.646
	5/10	21.321	0.316	0.940
	10/5	23.331	0.379	0.956
	15/5	31.078	1.209	0.882
50/30	5/15	24.680	0.267	0.612
	5/10	18.818	0.161	0.924
	10/5	27.715	0.191	0.769
	15/5	22.814	0.346	0.923
70/20	5/15	22.464	0.247	0.892
	5/10	21.178	0.340	0.982
	10/5	12.836	0.249	0.965
	15/5	42.244	0.930	0.959
70/30	5/15	26.781	0.290	0.785
	5/10	16.494	0.180	0.866
	10/5	33.490	0.438	0.886
	15/5	41.319	2.174	0.905

The results of the build up factor calculations are shown in Tables 8 and 9. Table 8 shows the factor θ, which is the build up in oxygen uptake per cycle expressed as a fraction of the oxygen uptake during the first cycle. Table 9 shows the build up factor θ', which is the build up in oxygen uptake per hour expressed as a percentage of that of the first cycle.

For the 3 hour tests the θ values range from 0.0069 to 0.0478. For the 2 hour tests these values range from 0.015 to 0.0345. The θ' values for 3 hour tests range from 2.18 per cent to 14.37 per cent and for 2 hour tests they range from 3.11 per cent to 12.76 per cent. The θ' values obtained from the present study compare favorably with those calculated from the data of Ayoub et. al. (1972). In their study, on the average, θ' value for 2 hour tests was 4.10 per cent and for 3 hour tests was 5.66 per cent under 40/25 work load combination and 15/5 time schedule. Under the same work load combination but with 10/10 time schedule the corresponding values were 6.84 per cent for 2 hour tests and 2.733 per cent for 3 hour tests. Each of these values were the average of 10 tests involving 5 subjects. Further Saltin and Stenberg (1964) observed that over a 3 hour period with in between rests, the oxygen uptake of subjects working at about 75 per cent of their maximum aerobic capacity rose on the average about 5 per cent. Also Ekelund and Holmgren (1966) reported an increase of about 8 per cent over a 50 minute period at a constant work load. The large range found in the present study is due to the fact that different work load combinations and time schedules were employed.

TABLE 3

θ VALUES FOR 2 HOUR AND 3 HOUR TESTS

Work Load Combination	Time Schedule	2 Hour Test		3 Hour Test	
		Subject	θ	Subject	θ
50/20	5/15	T.T.	0.0250	R.L.	0.0073
	5/10	R.F.	0.0188	M.H.	0.0146
	10/5	R.K.	0.0288	L.N.	0.0160
	15/5	L.M.	0.0345	B.F.	0.0375
50/30	5/15	R.F.	0.0105	M.H.	0.0107
	5/10	R.K.	0.0118	L.N.	0.0085
	10/5	L.M.	0.0108	B.F.	0.0069
	15/5	T.T.	0.0104	R.L.	0.0149
70/20	5/15	R.K.	0.0188	L.N.	0.0109
	5/10	L.M.	0.0225	B.F.	0.0158
	10/5	T.T.	0.0319	R.L.	0.0190
	15/5	R.F.	0.0266	M.H.	0.0215
70/30	5/15	L.M.	0.0205	B.F.	0.0105
	5/10	T.T.	0.0177	R.L.	0.0108
	10/5	R.F.	0.0210	M.H.	0.0129
	15/5	R.K.	0.0270	L.N.	0.0478

TABLE 9

θ' VALUES FOR 2 HOUR AND 3 HOUR TESTS

Work Load Combination	Time Schedule	2 Hour Test		3 Hour Test	
		Subject	θ	Subject	θ
50/20	5/15	T.T.	7.51	R.L.	2.18
	5/10	R.F.	7.53	M.H.	5.84
	10/5	L.M.	11.50	L.N.	6.40
	15/5	R.K.	10.34	B.F.	11.24
50/30	5/15	R.F.	3.16	M.H.	3.21
	5/10	L.M.	4.36	L.N.	3.38
	10/5	R.K.	4.33	B.F.	2.80
	15/5	T.T.	3.11	R.L.	4.48
70/20	5/15	L.M.	5.63	L.N.	3.27
	5/10	R.K.	8.99	B.F.	6.30
	10/5	T.T.	12.76	R.L.	7.60
	15/5	R.F.	8.09	M.H.	6.47
70/30	5/15	R.K.	6.16	B.F.	3.22
	5/10	T.T.	7.08	R.L.	4.32
	10/5	R.F.	8.42	M.H.	5.16
	15/5	L.M.	8.20	L.N.	14.37

An analysis of variance was performed on these θ' values. For the purpose of analysis the subjects were used as treatments. Two 1 tin squares of 4 x 4 x 4 size corresponding to each time duration, i.e. 2 hours or 3 hours were used. The results are presented in Table 10.

TABLE 10

ANOVA TABLE FOR θ'

Source	D.F.	S.S.	M.S.	F-Ratio
Work Load Combination	3	73.204	24.401	3.979*
Time Schedule	3	73..``	24.400	3.979*
Subject	3	2.643	0.880	0.143
Time Duration	1	22.712	22.712	3.704
Residual	12	79.094	6.132	

* Significant at 0.05 level.

Effect of Work Load Combinations

The work load combinations were found to have a significant effect on the build up of oxygen uptake. This is reasonable, because a hard work load combination such as 70/30 should certainly result in a build up different from the one computed of a lighter work load combination like 50/30, when all other things are maintained the same.

Figure 10 shows the build up factor θ' against the work load combinations. Each point in the graph is the average of all the 8 tests under that particular work schedule. One interesting feature
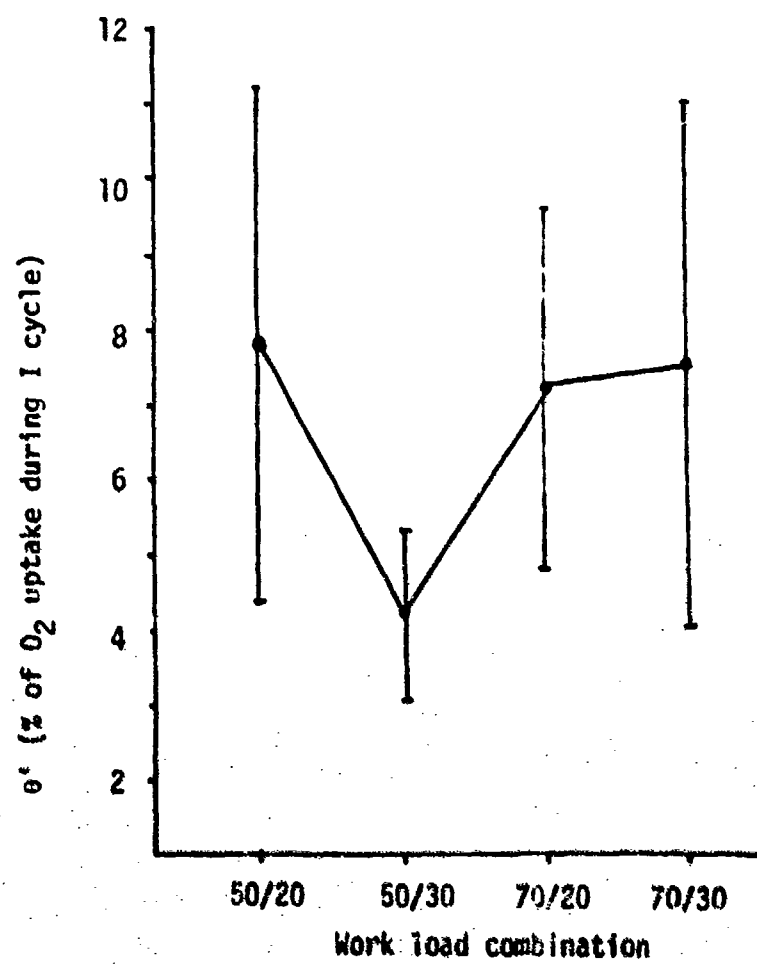
Fig. 10.--θ' vs. work load combination

to note is the combination 50/30 seer to result in the least build
up overall. In other words the combination 50/30 seems to be the
best of the four combinations tested, as the build up had the lowest
average and smallest standard variation. The exact reason for this
phenomenon is not known. However, it is suspected that the speed of
walk for this level of work load might have some part to play in
causing this effect. Referring to Table 6, it is observed that in
order to attain 30 per cent work load, most of the subjects had to
walk at a speed of 3 mph where as the 20 per work load the most common
speed of walk was 2.5 mph. It is quite possible, therefore, that the
3 mph walk keeps the physiological system in a better balanced con-
dition than 2.5 mph, yielding higher mechanical efficiency. Also
from Figure 11, it can be seen that the work load combination 50/30
results in lease variation in θ' among all the work load combinations.
This low build up was found even in the case of the subject who was
working under 50/30, 15/5 and 3 hour tests who found that he could
not continue after 140 minutes. The θ' value for this test was only
4.48 per cent. As opposed to this, the subject under 50/20, 15/5 and
3 hour tests, who also had to quit after 140 minutes, experienced a
build up of 11.24 per cent per hour. This suggests that the lower work
load of 30 per cent is better than 20 per cent since it results in a
sm ar θ' value even when the subject is stressed to the limit.

However, looking at the combinations 70/20 and 70/30 under 15/5
time schedule one gets a different picture. Both the subjects quit
after 120 minutes. The 70/30 subject experienced a build up of 14.27
per cent per hour as opposed to 6.47 per cent by the 70/20 subject.
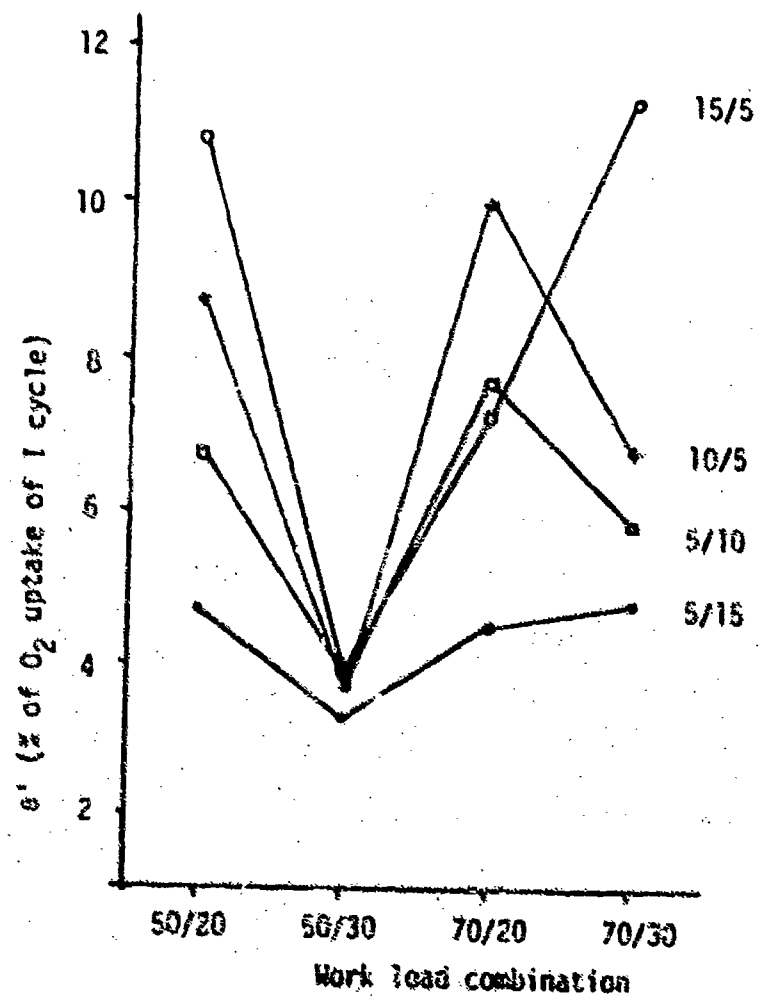
Fig. 11.--θ' vs. work load combination, according to time schedules

But again going back to Table 6, it can be seen that the 70/30 subject
was walking at a speed of 4 mph while all the others were walking at
3 mph to attain a 30 per cent work load. Also at 10/5 and 5/10 time
schedules, the θ' factors were smaller when the lower work load was
30 per cent than when it was 20 per cent, irrespective of the higher
load. At 5/15 schedule such an effect is not seen. This may be be-
cause it is such a light schedule that a physiological stress high
enough to bring about that effect is not encountered. On the whole,
it may be possible that the speed of walking has certain effects on
the build up in oxygen uptake in addition to the work load as such.

Effect of Time Schedule

The time schedules also had a significant effect on the build up
of oxygen uptake. The relationship between the average θ' values and
the time schedules is shown in Figure 12. As is reasonable to expect
the time schedules 5/15, 5/10, 10/5 and 15/5 result in increasing θ'
factors in that order. Figure 13 shows these build up factors against
time schedules and according to the work load combinations. It can be
observed that at the moderate time schedules of 5/10 and 10/5, the
θ' factors for 70/20 and 50/20 are higher than those of 70/30. Also
for any given work load combination the build up in oxygen uptake is
larger as the time schedule becomes harder. The only exception is at
70/20 work load combination at 15/5 time schedule. The average θ'
value during these tests was less than that during 70/20, 10/5 tests.
The reason for this effect is not known.
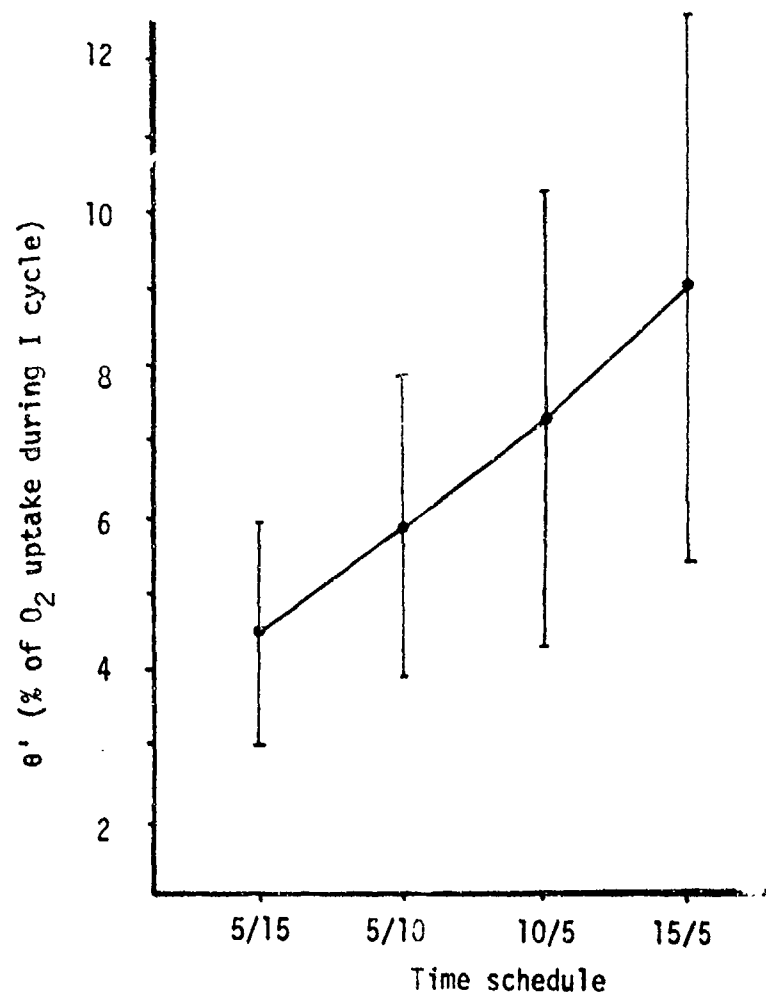
Fig. 12.--θ' vs. time schedule
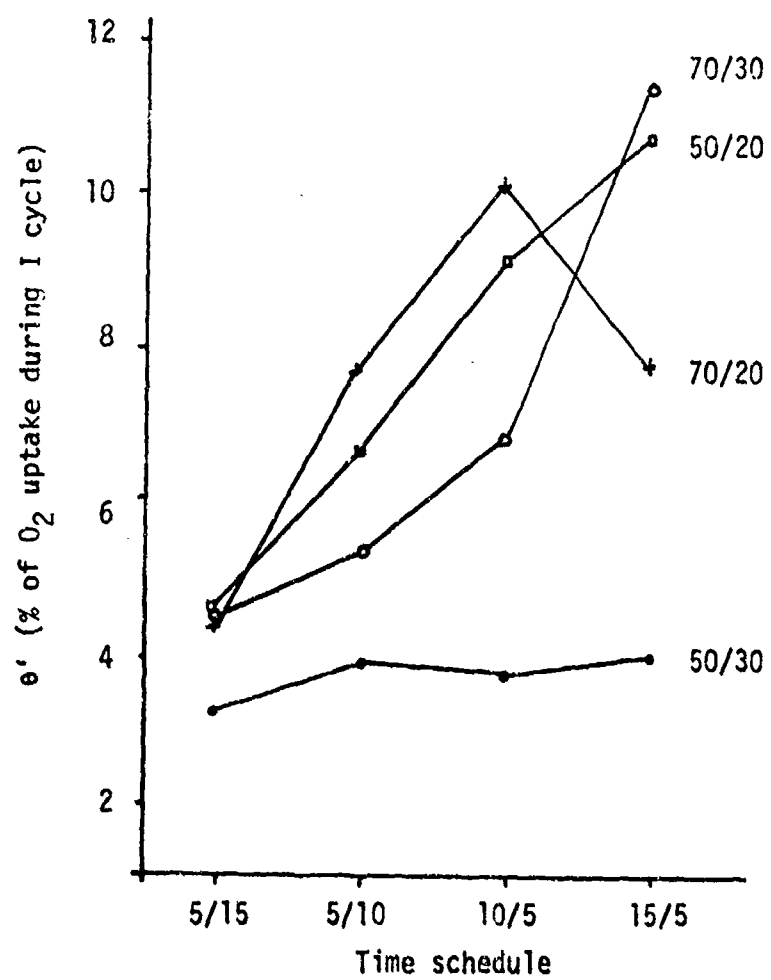
Fig. 13.--θ' vs. time schedule, according to work load combination

Effect of Time Duration

The time duration spent on the task does not seem to have a very significant effect in the cases tested in this research. Specifically, whether it is a 2 hour test or 3 hour test, the oxygen uptake build up per hour seems to be almost the same. However, the high F ratio of 3.704 (Table 10) warrants further study in this direction. This ratio makes the factor of time duration significant at 0.10 level. Also physiologically it is possible that the linear increase in oxygen uptake may change. As far as the present study is concerned, this change did not seem to have occurred. It could very well happen that such a change from linear increase may be observed if the work is prolonged more than 3 hours. Of course, it will be necessary to work at a higher work profile if it is to be prolonged longer.

Effects of Individual Subjects

Based on the analysis of variance the individual subjects had no effect on the amount of build up in oxygen uptake. This does not mean that the factor θ' is independent of the individual. On the contrary, it is very much dependent on the individual. This is not brought out in this experimentation because the subjects involved were more or less identical in their physical working capacity. They were all chosen to represent the normal worker as close as possible. The 8 subjects chosen specifically for this experimentation had an average maximum aerobic capacity of 46.35 ml/kg/min (standard deviation = 4.77). If individuals of widely different physical working capacities were used, the inter-individual differences would have been brought out.

A Regression Model for θ'

The θ' factors determined from this research would apply only to a few of the large number of work profiles possible in practical situations. It then becomes necessary that in order to predict the θ' factors for new work profile situations, some technique must be developed employing the information from the presently available data For this reason a regression model was developed.

In developing this regression model, in addition to the information obtained from the experiments conducted specifically for this purpose, data from the studies of Ayoub, et. al. (1972) and also from some unpublished studies from the experiments conducted in the laboratories of the Industrial Engineering Department of Texas Tech University were also utilized. Table 11 shows the additional data used.

TABLE 11

θ' VALUES FROM OTHER SOURCES USED IN THE PRESENT RESEARCH

Work Load Combination	Time Schedule	Test Duration	Number of Tests	θ' Value	Source
40/20	10/10	2 hrs.	10	6.84	Ayoub, et. al., 1972
40/20	10/10	3 hrs.	10	2.73	"
40/20	15/5	2 hrs.	10	4.10	"
40/20	15/5	3 hrs.	10	5.66	"
40/25	15/5	3 hrs.	1	5.66	Unpublished
40/25	15/5	3 hrs.	1	4.10	"

For any given individuals, the build up factor θ' can reasonably be assumed to be a function of the work profile conditions.

i.e.

$$\theta' = f(t_H, t_L, H_1, L_1) \quad . \tag{3.11}$$

A multiple regression model built from the data available and including the above factors resulted in the following model.

$$\theta' = 0.166 \text{ (Higher load per cent)} - 0.30227 \text{ (Lower}$$
$$\text{load per cent)} + 0.231i2 \text{ (High time-min)} -$$
$$0.18493 \text{ (Low time-min)} \quad . \tag{3.12}$$

The above model certainly will not yield reasonable results for all cases. For some work profile conditions, it will yield a negative θ' factor which is not reasonable. Further while the negative coefficient for low time can be explained by reasoning that longer times at lower levels would result in lesser build up the same cannot be said about the negative coefficient for lower work load. The negative coefficient for lower load occurs because it was found that the 30 per cent work load at low level resulted in lesser build up than the 20 per cent work load at low level. It is uncertain whether it can be extended to other lower work loads as well. It is questionable whether a lower work load of 40 per cent would result in lesser build up than 30 per cent. Also it is not certain whether this pehnomenon of 30 per cent lower work load being better than 20 per cent is peculiar to walking situations only or whether it will be the same for other work situations, like material handling, bicycling and cranking, as well. Therefore, it was

thought that the model selected shoul be more general in nature so
that a universal applicability be insured. A number of different com-
binations of the relevant factors were used. By trail and error, it
was found that a model containing only the following two factors yielded
the satisfactory results.

1. The total oxygen uptake at high level in one cycle, i.e.,
    the product, t_H x H_1 x Aerolic capacity.

2. The total oxygen uptake at low level in one cycle, i.e.,
    the product, t_L x L_1 x Aerolic capacity.

Both the above factors were expressed in units of militers per
kilogram body weight.

Such a model built on the presently available data is given
below:

$$\theta' = \text{Aerobic capacity } (0.1901 \times t_H \times H_1 + 0.1205$$
$$\times\ t_L \times L_1)\ . \tag{3.13}$$

The results of the analysis of variance conducted for the above
regression model is presented in Table 12. It shows a highly signifi-
cant regression. Further the multiple correlation coefficient about
the origin was 0.9103 and the standard error of estimate of θ' factor
was 2.9192.

The only objection to this model is that it does not consider the
rate of energy expenditure as a factor. It is quite possible that the
rate of energy expenditure has some effect on the build up in oxygen
uptake. However, this had to be sacrificed so that the model would not
give unreasonable negative values for θ' for some work profile conditions.

TABLE 12

ANOVA TABLE FOR THE REGRESSION MODEL FOR θ'

Source	D.F.	S.S.	M.S.	f-Ratio
Regression	2	1484.41	742.207	87.093
Residual	36	306.79	8.522	

The velocity constants k_r and k_f were computed using the equations (3.5) and (3.10) mentioned earlier. The Y_1 and Y_2 values to be used in these equations were computed as the average of the values determined from two different cycles, one at the beginning of the test and the other at the end of the test. The resulting values of k_r and k_f are presented in Tables 13A and 13B. These values do not differ very much among the subjects, the work combinations, or the time schedules. The results of analysis variance conducted on these velocity constants are shown in Tables 14A and 14B. For the purpose of analyzing the variance, the k_r and k_f values for 2 hour and 3 hour tests were pooled together.

The values of velocity constants obtained in this research are very much comparable with those reported by other investigators. Hill, Long and Lupton (1923) found the k_f value in their study to vary from 1.1 to 1.73. Henry and Demoor (1950) report that for a 2 term exponential formula for recovery after bicycle work of 690 kg/min the k_f values were on the average 1.059 and 0.125, while the same for 920 kg/min work were 1.107 and 0.144. The half time constants of 30 seconds

TABLE 13A

VALUES OF VELOCITY CONSTANTS, k_r AND k_f FOR 2 HOUR TESTS

Work Load Combination	Time Schedule	k_r	k_f
50/20	5/15	1.56	1.35
	5/10	1.25	1.40
	10/5	1.47	1.19
	15/5	1.69	1.27
50/30	5/15	1.28	1.17
	5/10	1.51	1.58
	10/5	1.66	1.32
	15/5	1.23	1.41
70/20	5/15	1.19	1.61
	5/10	1.70	1.19
	10/5	1.44	1.37
	15/5	1.47	1.18
70/30	5/15	1.26	1.52
	5/10	1.37	1.43
	10/5	1.51	1.16
	15/5	1.53	1.29

TABLE 13B

VALUES OF VELOCITY CONSTANTS, k_r AND k_f FOR 3 HOUR TESTS

Work Load Combination	Time Schedule	k_r	k_f
50/20	5/15	1.37	1.28
	5/10	1.72	1.32
	10/5	1.45	1.60
	15/5	1.38	1.45
50/30	5/15	1.20	1.70
	5/10	1.33	1.35
	10/5	1.26	1.56
	15/5	1.55	1.11
70/20	5/15	1.67	1.21
	5/10	1.16	1.38
	10/5	1.52	1.30
	15/5	1.38	1.47
70/30	5/15	1.52	1.39
	5/10	1.60	1.24
	10/5	1.19	1.48
	15/5	1.39	1.20

TABLE 14A

ANOVA TABLE FOR k_r VALUE

Source	D.F.	S.S.	M.S.	f-Ratio
Work Load Combination	3	.049	0.016	0.205
Time Schedule	3	.029	0.010	0.119
Subject	3	.035	0.012	0.146
Residual	13	.025	0.002	

TABLE 14 B

ANOVA TABLE FOR k_f VALUE

Source	D.F.	S.S.	M.S.	f-Ratio
Work Load Combination	3	.022	0.007	0.114
Time Schedule	3	.054	0.018	0.277
Subject	3	.027	0.009	0.138
Residual	13	.042	0.003	

as reported by Berg (1947), Margaria, et. al. (1965), Cerrotelli, et. al. (1966) correspond to a velocity constant value of 1.39. Whipp (1971) found that for light (300 kg/min) and moderate (450 kg/min) works the k_r values were 1.35 with no significant difference between the two work loads. But Davies, et. al. (1972) report that these values differ significantly when a light work was used instead of

complete rest. They found that going from light to heavy work the
half time constant was about 20 seconds corresponding to a k_r value
of 2.1 and that going from heavy work to light work the half time
constant was about 40 seconds corresponding to a k_f value of 0.45.
The present study was not show any such tendency for the velocity con-
stants to differ. The average values obtained in this study were k_r =
1.431 and k_f = 1.357.

Rectal Temperature Effects

The maximum increase in rectal temperature in each test was
determined from the recordings. Table 15 shows these values. No
recording was available in the case of the 50/20, 10/5 test for 3
hours duration. The rectal thermometer in this particular subject
was constantly slipping. For the subsequent tests for the same sub-
ject, a new type of thermometer probe with a bent end was used to
prevent slipping while walking.

An analysis of variance was performed on the rectal temperature
increments and the results are presented in Table 16. The analysis
of variance showed no significant effect of either the work load com-
binations or time schedules.

The commonly accepted theory is that during prolonged constant
work load situations, the body temperature starts to rise a few minutes
after the onset of work and continues to rise until a new equilibrium
is reached. The resultant increase in temperature is proportional to
the metabolic rate. (Lind, 1963; Nielson, 1966; Astrand and Rodahl,
1970). However, for an intermittent work (30 seconds work, 30 seconds

TABLE 15

INCREASE IN RECTAL TEMPERATURE ($\Delta T_{rec.}$) IN $\overset{o}{C}$

Work Load Combination	Time Schedule	2 Hour Test		3 Hour Test	
		Subject	ΔT_{rec} $\overset{o}{C}$	Subject	ΔT_{rec} $\overset{o}{C}$
50/20	5/15	T.T.	0.45	R.L.	1.35
	5/10	R.F.	0.85	M.H.	0.85
	10/5	R.K.	1.60	L.N.	NA
	15/5	L.M.	0.85	B.F.	0.80
50/30	5/15	R.F.	1.00	M.H.	1.00
	5/10	R.K.	0.85	L.N.	0.75
	10/5	L.M.	1.20	B.F.	1.20
	15/5	T.T.	1.00	R.L.	1.30
70/20	5/15	R.K.	1.00	L.N.	1.00
	5/10	L.M.	0.90	B.F.	1.05
	10/5	T.T.	0.75	R.L.	1.25
	15/5	R.F.	1.60	M.H.	1.35
70/30	5/15	L.M.	1.20	B.F.	1.15
	5/10	T.T.	1.00	R.L.	1.00
	10/5	R.F.	0.90	M.H.	1.10
	15/5	R.K.	1.35	L.N.	1.55

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TABLE 16

ANOVA TABLE FOR THE INCREASE IN RECTAL TEMPERATURE
(AVERAGE FOR 2 HOUR AND 3 HOUR TESTS)

Source	D.F.	S.S.	M.S.	f-Ratio
Work Load Combination	3	0.035	0.012	0.154
Time Schedule	3	0.272	0.091	1.203
Subject	3	0.081	0.027	0.358
Residual	6	0.453	0.075	

rest) of about 60 per cent of maximal aerobic capacity, Ekblom, et. al. (1971) found that the increase in rectal temperature was about 21 per cent higher than that during continuous work load. They suspected that the higher rectal temperature was due to reduced circulatory efficiency resulting in decreased evaporative loss in the case of intermittent work.

In the present research the increase in temperature does not seem to follow any particular pattern. This is evident from Figures 14 and 15. However, it can be seen that the time schedule 5/10 seems to result in the least increase in rectal temperature for any work load combination, even though there is no significant difference among the time schedules. If this was really an effect of the time schedule, it means that 10 minutes of low work is better than 15 minutes of low work, when all other conditions remain the same. No reasonable explanation can be given for this effect at present.
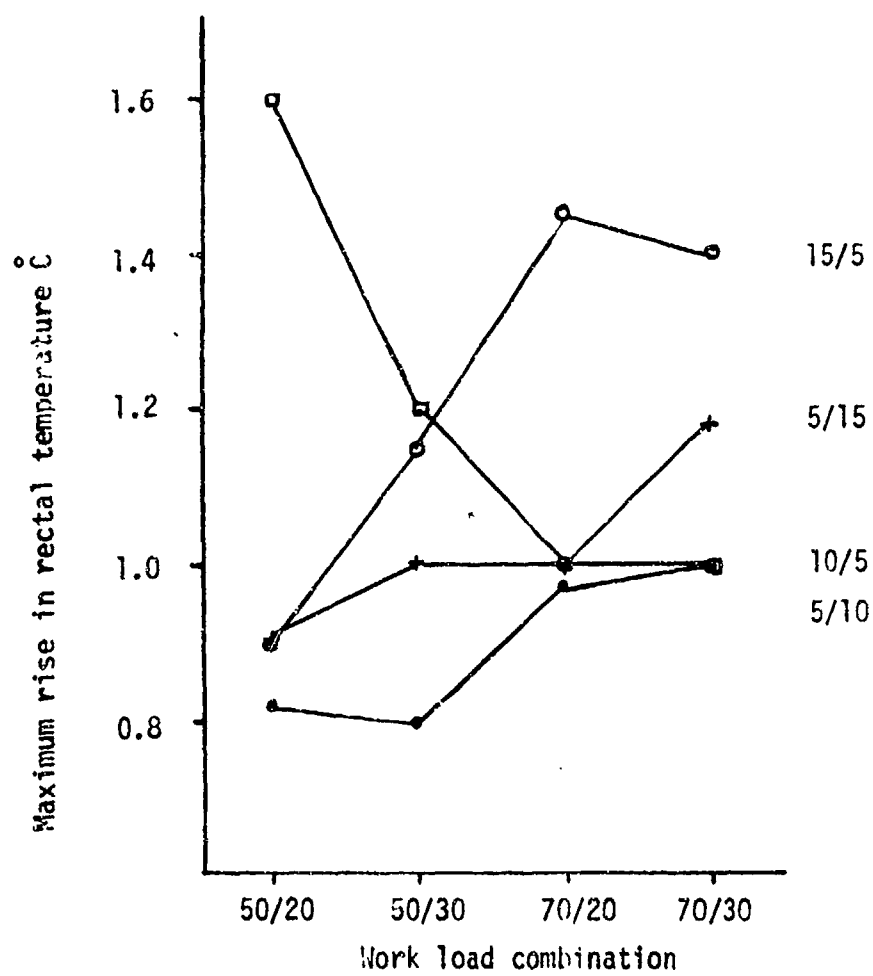
Fig. 14.--Maximum rise in rectal temperature vs. work load combination
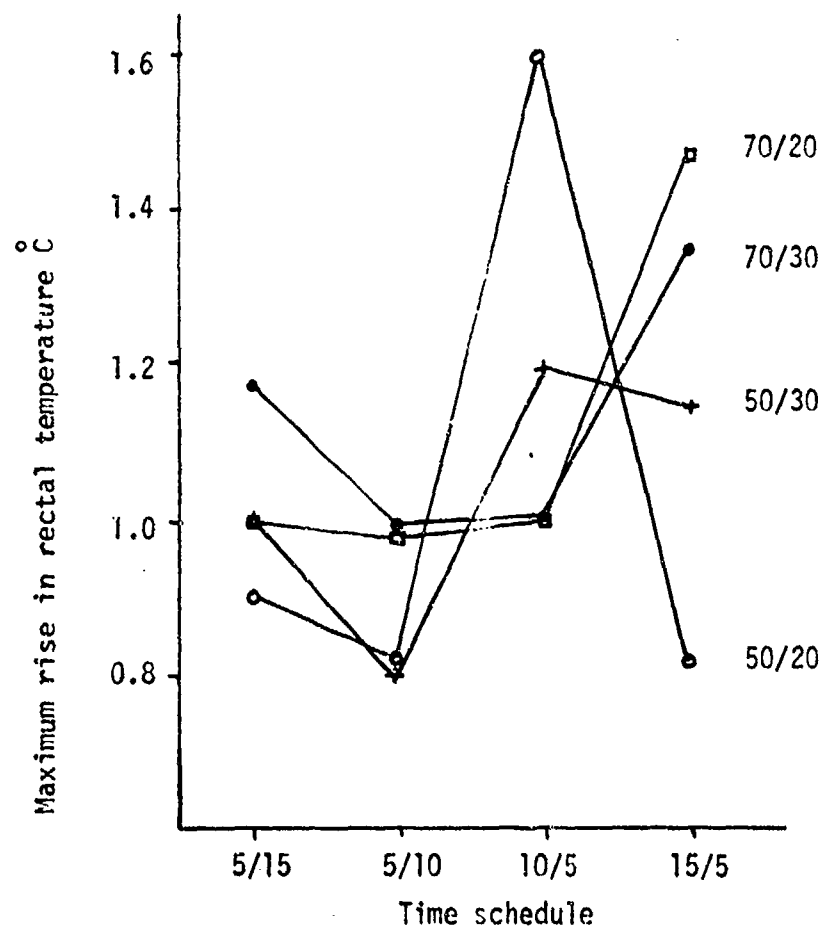
Fig. 15.--Maximum rise in rectal temperature vs. time schedule

CHAPTER IV

MODEL TESTING

The model is completed in all respects when the parameters θ, k_r, k_f, t_1, and t_2 are known directly or indirectly in terms of other known parameters. No model, mathematical or otherwise, is of any practical significance unless it can be said that it represents the actual situation as far as possible in the relevant aspects. The models developed in this research were tested for their accuracy in predicting the endurance time by comparing with actual results from experiments.

These experiments were specifically designed and conducted for testing the models. The methods and experimental procedures for this set of experiments were essentially the same as in the earlier experiments. The variations in the design, methods and procedures are mentioned below.

First of all, it was decided to include some new work load combinations and time schedules along with a few of those used in parameter determination. The following levels of these factors were chosen. Work Load Combinations:

1. 70 per cent of maximum and 20 per cent of maximum

2. 50 per cent of maximum and 30 per cent of maximum

3. 60 per cent of maximum and 40 per cent of maximum

The first two levels in this factor were already employed in earlier experiments. The 60/40 work load combination was a new level.

Time Schedules:

1. 15 minutes at high level and 5 minutes at low level

2. 10 minutes at high level and 5 minutes at low level

3. 10 minutes at high level and 10 minutes at low level

4. 5 minutes at high level and 5 minutes at low level

In this case also the first two time schedules were employed in the earlier experiments. The last two were new schedules.

It was also decided not to use any of the subjects who were involved in the earlier experiments, but to get new individuals as subjects for this experimental series. Further one subject was to be used in only one test. This meant that for the various combinations of work load and time schedules, 12 different new individuals were to be used as subjects. However, the subjects chosen in this case were of varying aerobic capacities instead of uniform capacity to represent the normal worker. The relevant details of the subjects are presented in Table 17.

The maximum aerobic capacity tests, the trial tests to determine the treadmill setting, etc., were carried out exactly in the same way as in the earlier experiments. But in the actual testing, the subject was informed to walk on the treadmill as long as he can. He could stop at any time whenever he felt that he was tired and wanted to rest. The length of time the subject walked before stopping was taken to indicate the endurance time limit of that individual under the particular work profile conditions.

TABLE 17

DETAILS OF SUBJECTS FOR MODEL TESTING

Subject	Age	Weight kg	Maximum Aerobic Capacity ml/kg/min.
C.T.	24	76.5	42.55
J.H.	21	82.6	46.82
W.D.	23	95.5	37.46
J.S.	22	83.3	36.82
J.R.	20	105.0	31.60
T.D.	22	81.0	42.32
T.C.	22	81.6	38.10
T.M.	22	79.4	44.08
K.C.	23	69.1	32.30
M.W.	22	70.4	41.20
D.G.	22	72.5	38.16
M.C.	22	84.8	36.90

All the subjects used in this set of experiments were volunteers except the subject J.S. who was paid at the rate of $1.75 per hour. The other subjects were students in P.E. 531 and participation in this experimentation was required of them. They were informed of the importance of exerting their best effort. The results of the tests are presented in Table 18. These are the actual endurance time limits as determined by how long the subjects were able to walk before wanting to stop.

TABLE 18

ACTUAL ENDURANCE TIME

Subject	Work Load Combinations	Time Schedule	Actual Endurance Time Minutes
C.T.	70/20	15/5	90
J.H.	60/40	15/5	100
W.D.	50/30	15/5	106
J.S.	70/20	10/10	132
J.R.	60/40	10/10	90
T.D.	50/30	10/10	155
T.C.	70/20	10/5	120
T.M.	60/40	10/5	105
K.C.	50/30	10/5	120
M.W.	70/20	5/5	160
D.G.	60/40	5/5	120
M.C.	50/30	5/5	140

The predicted endurance time limit computed from the models was arrived at according to the following procedure.

1. Calculate the expected build up in oxygen untake per hour for a normal worker, i.e., c' factor for the given work profile conditions using equation (3.13).

2. Determine the θ factor by dividing θ' by the number of cycles per hour. The time schedules used in this research were such that there will be an integer number of cycles per hour. In cases where this is not the situation, the nearest integer number may be chosen.

3. Determine the time constants t_1 and t_2 for the given work load combination and using the values $k_r = 1.431$ and $k_f = 1.357$. Also use the criterion that a difference of 25 ml of oxygen uptake from the expected steady state is the required condition for determining the time constants.

4. Compute the areas under the curves in Figure 3 as per equation (2.6), using the work profile conditions, the velocity constants and the time constants for the first cycle.

5. Determine the equivalent energy rate as per equation (2.10).

6. For the equivalent energy rate determined in step 5, compute the endurance time limit from the PWC model.

7. Compare this endurance time limit against the elapsed time, i.e., the product of cycle time and number of cycles.

8. If endurance time is greater than the elapsed time by at least one cycle time, repeat steps 4 through 7 for one more cycle. If not, use the endurance time determined in step 6 as the endurance time limit for the normal subject for the given work profile conditions.

9. Make corrections for the aerobic capacity and age of the individual depending on how much these differ from the aerobic capacity and age of the normal worker. For differences in aerobic capacity multiply the endurance time limit of the normal worker by a factor $\frac{a}{45}$ where a represents the aerobic capacity of the individual. For differences in age use multiplying factor from Table 3.

The endurance time limit as obtained from the above computations is the predicted time. Such predicted times for each of the 12 work profile conditions with the corresponding subjects, maximum aerobic capacity and age were determined. The computer program given in the Appendix was used for this purpose.

The predicted time and actual time along with the error in each case is given in Table 19. The errors were calculated according to the formula,

$$\text{Fractional Error} = \frac{\text{Predicted Time} - \text{Actual Time}}{\text{Actual Time}} \times 100.$$

The minimum error was 0.10 per cent for 60/40, 15/5 test and the maximum error was 31.25 per cent. The mean error was 14.38 per cent with a standard deviation of 9.88 per cent. It can also be noted that the error is always negative suggesting that the predicted time is always less than the actual time. In other words the models always under predict the endurance time limit. Figure 15 shows the predicted values against the actual values. A regression line of the form, Predicted Time $= B_0 + B_1 \times$ (Actual Time) was fitted to these points. The values of the coefficients were found to be,

TABLE 19

COMPARISON OF ACTUAL TIME WITH PREDICTED TIME (CORRECTED
FOR AEROBIC CAPACITY DIFFERENCES)

Work Load Combination	Time Schedule	Predicted Time Minutes	Actual Time Minutes	Fractional Error
70/20	15/5	73.2	90	-18.67
60/40	15/5	99.9	100	- 0.10
50/30	15/5	104.1	106	- 1.81
70/20	10/10	109.5	132	-17.05
60/40	10/10	83.0	90	- 7.78
50/30	10/10	146.0	155	- 5.81
70/20	10/5	82.5	120	-31.25
60/40	10/5	97.6	105	- 7.05
50/30	10/5	93.8	120	-21.80
70/20	5/5	120.6	160	-24.75
60/40	5/5	92.8	120	-22.67
50/30	5/5	120.8	140	-13.86

$$B_0 = 17.0687$$

$$B_1 = 0.7087$$

and the correlation coefficient = 0.8253.

The regression line and 95 per cent confidence interval lines
are also shown in Figure 16. In an ideal case the predicted time
should have been equal to the actual time in every case and all the
points should have been on the broken line shown in the figure.
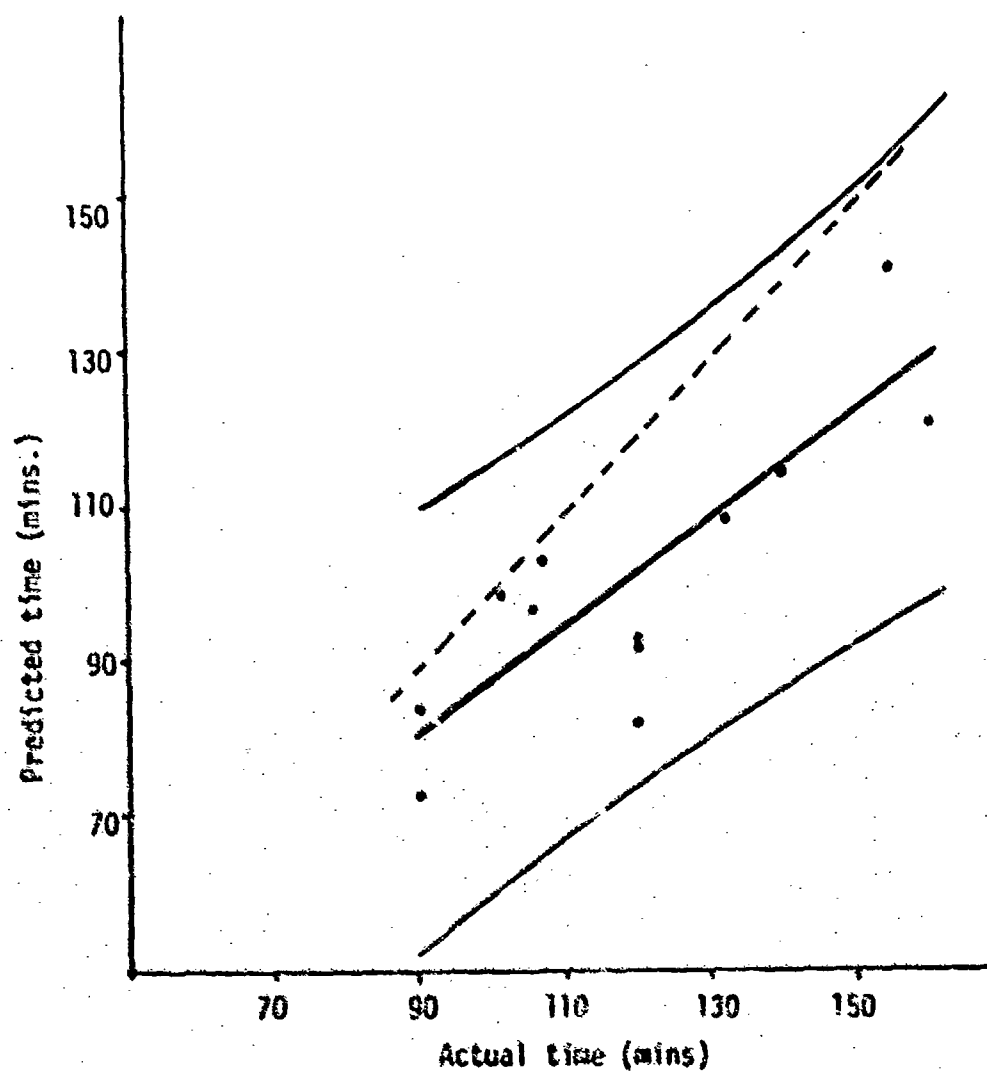
Fig. 16.--Predicted time (corrected) vs. actual time

As the errors were always negative, it was thought that the correction factor for the maximum aerobic capacity differences possibly had too much effect. Therefore, the predicted time for the normal subject (not corrected for the aerobic capacity differences) was compared with the actual time. Table 20 presents these comparisons along with the errors for each test. The minimum error was 0.15 per

TABLE 20

COMPARISON OF ACTUAL TIME WITH PREDICTED TIME (NOT CORRECTED)

Work Load Combination	Time Schedule	Predicted Time Minutes	Actual Time Minutes	Fractional Error
70/20	15/5	77.36	90.0	-14.04
60/40	15/5	96.04	100.0	- 3.96
50/30	15/5	125.10	106.0	+13.02
70/20	10/10	133.80	132.0	+ 1.36
60/40	10/101	118.50	90.0	+31.67
50/30	10/10	155.23	155.0	+ 0.15
70/20	10/5	97.50	120.0	-18.75
60/40	10/5	99.60	105.0	- 5.14
50/30	10/5	130.70	120.0	+ 8.92
70/20	5/5	131.75	160.0	-17.66
60/40	5/5	109.40	120.0	- 8.93
50/30	5/5	153.68	140.0	+ 9.77

cent and the maximum error was 31.67 per cent. The mean error was
11.52 per cent with a standard deviation of 9.0 per cent. Figure 17
shows this comparison in a graphical form along with the regression
line, the confidence intervals and the ideal line. The regression
line in this case had the following coefficients:

$$B_0 = 26.7829$$

$$C_1 = 0.7689$$

Correlation Coefficient = 0.7478.

From this it is difficult to say whether there was any over
correction for the aerobic capacity differences.

Further among the 12 subjects, there were 5 individuals with
more or less the same aerobic capacity (45 ml/kg/min) as the normal
worker. Table 21 presents the predicted and actual times for these
five subjects. It may be noted that now the error is much reduced.
In this case the variation in error is from a low of 0.15 per cent to
a high of 17.66 per cent. The mean error is found to be 8.19 per
cent and the standard deviation 14.08 per cent. Further all except
one have negative error.

In general, the predicted times are found a little less than the
actual time. This might be due to the competitive spirit that existed
among the subjects. Most of the subjects were students in a particu-
lar class and each one wanted to equal if not exceed the other. At
any rate a reasonable under prediction is better than an over pre-
diction. This is especially true if the industrial world has to be
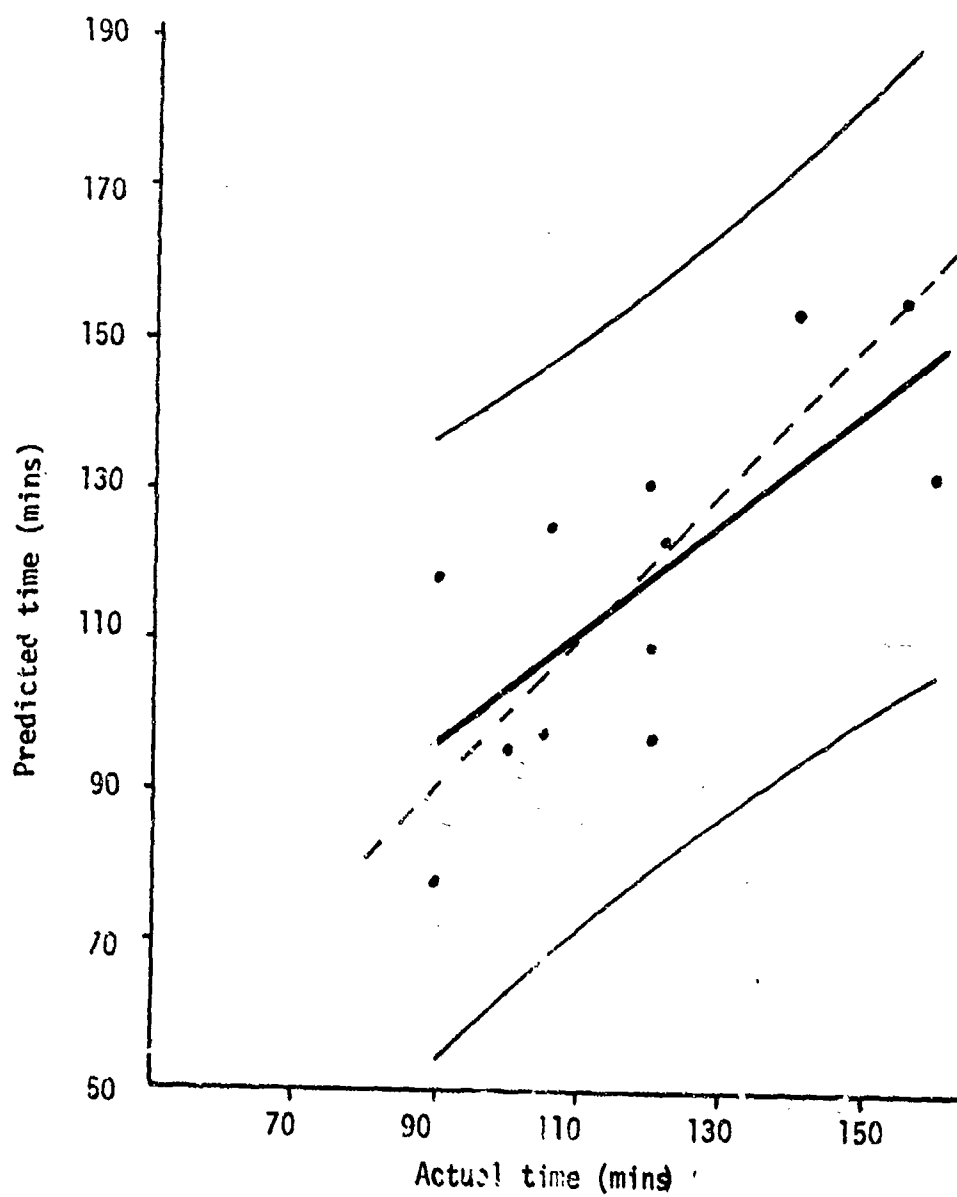
Fig. 17.--Predicted time (not corrected) vs. actual time

convinced of the usefulness of any technique, since the factor "safety margin" is a necessity in most practical situations.

TABLE 11

COMPARISON OF ACTUAL TIME WITH PREDICTED TIME FOR THE
5 SUBJECTS RESEMBLING THE NORMAL WORKER

Subject	Maximum Aerobic Capacity ml/kg/min	Work Load Combination	Time Schedule	Predicted Time Minutes	Actual Time Minutes	Fractional Error
C.T.	42.57	70/20	15/5	77.36	90	-14.04
J.H.	46.82	60/40	15/5	96.04	100	- 3.96
T.M.	44.08	60/40	10/5	99.60	105	- 5.14
T.D.	42.32	50/30	10/10	155.23	155	+ 0.15
M.W.	41.20	70/20	5/5	131.75	160	-17.66

CHAPTER V

CONCLUSIONS

The present research was an attempt to develop a mathematical technique which could be used in industrial and other fields to predict the endurance time limit for individuals working on physical tasks of alternating nature. The results of this investigation lead to the following conclusions:

1. During prolonged muscular work of alternating nature, the oxygen uptake increases gradually over time for the same rate of work output. The reason for this build up in oxygen uptake is not known. It is suspected that a deterioration in mechanical efficiency combined with the possibility of more and more proportion of fat being utilized as the primary source of energy for muscular contraction, might cause this effect.

2. This gradual build up in oxygen uptake is linear over the time durations tested.

3. Among the work combinations tested, the combination 50/30 (expressed as percentage of the maximum aerobic capacity), resulted in the least build up per hour. This effect, is is suspected, may wholely or partly be due to the walking speeds employed.

4. The time schedules tested also inf .ed the build up in oxygen uptake. Among the time schedules, the build up in oxygen uptake was increasing in the order 5/15, 5/10, 10/5 and 15/5.

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5. Individuals of about the same aerobic capacity as the normal worker experience a similar amount of build up when the work profile conditions are the same.

6. The oxygen uptake response following a sudden change in work load can be represented by an exponential formula. Individuals of similar work capacity have more or less similar oxygen uptake response.

7. The velocity constants for the above mentioned exponential formulae were found to be independent of the work load combinations or time schedules. The average value of the velocity constant for rise in work load was found to be 1.431 and the same for a fall in work load was 1.357 for the subjects tested.

8. In the cases tested the increase in rectal temperature did not show any particular pattern. However, the time schedule of 5/10 resulted in the least increase in rectal temperature under all the four work load combinations.

9. The endurance time limit for an individual performing any alternating work load can reasonably be predicted by the ETL model in conjunction with the EER model as developed in the present research.

10. In order to maximize the total work done, the normal worker will have to maintain an equivalent energy rate of 0.13022 kcal/kgm/min (about 65 per cent) and will be able to endure this work for at least 90 minutes.

In general the phenomenon of oxygen uptake build up over time under alternating muscular work load situations is established. However, the factors causing this are not determined yet. There are also numerous other interesting questions raised as a result of this and other similar

investigations. These are outlined in the following section as suggestions for future research.

Suggestions for Future Research:

The present investigation opens up a number of other interesting possible studies in the general areas of work physiology and industrial work design.

First of all, the factors responsible for the observed build up in oxygen uptake are not yet known. It would be desirable to know the exact reasons so that the build up can be maintained at a low level. If it was due to more and more of fat being utilized for energy supply, the respiratory quotient (R.Q.) should have a simultaneous decrease. Determination of R.Q. combined preferably with muscle biopsy tests for glycogen content of working muscles at frequent intervals would be necessary to determine the change in the primary source of energy.

The increase in oxygen uptake under different environmental temperatures is also worth investigating. It is possible that under elevated temperatures, this build up in oxygen uptake may not be the same since the cardiovascular system would be stressed much more. This may impose a limitation on the oxygen supply to the working muscles. As a result early fatigue might set in.

For the work durations employed in the present study, the oxygen uptake has been found to increase in a linear fashion. If the work durations were further prolonged, this may or may not be the case.

The effect of least oxygen build up at 50/30 work load combination among those tested is another interesting aspect. At present it is not

known whether it is really due to work load combination or due to the effect of walking speeds. This question certainly deserves further investigation. If it was really due to work load combinations, the physiological reasons for such an effect will have to be found out.

Similarly, the least increase in rectal temperature during 5/10 time schedule is a phenomenon which merits further work in that direction.

The velocity constants have been found to be independent of work load combinations and time schedules. However, the effect of differences in work capacity on these constants are not known yet. It is guessed that a decrease in work capacity would decrease the value of these constants.

Further, the effects of differences in aerobic capacity and age on the endurance time limit under alternating work load situations require more investigations. The presently used factos are derived from experimental investigations as well as experience of some authors under constant work load situations only.

Finally, the optimum energy expenditure rate for maximum work done also has to be experimentally proved. If such an optimum rate really exists, then this expenditure rate can be arrived at with a number of different work profiles under alternating work load situations. The relationship between this optimum rate (about 65 per cent of maximum capacity) and the work load combination 50/30 which resulted in least build up in oxygen uptake is also worth investigating.

To conclude, it is hoped that the development of scientific techniques to predict endurance time limit would attract much interest

among the industrial work designers and work physiologists. It is also hoped that in future more and more attempts will be made in this direction under a wide variety of environmental and task conditions.

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APPENDIX A

COMPUTER PROGRAM DOCUMENTATION

```
C          TH,TL,HI,RL1 DEFINE WORK PROFILE
           READ(5,50) TH,TL,HI,RL1,AERCAP,WEIGHT,IAGE
50         FORMAT(2F4.1,2X,2F7.5,3X,F6.2,2X,F6.2,3X,I2)
           NPERHR = 60.0/(TH+TL)
           THETFN = ((0.01901*TH*HI) + (0.01205*TL*RL1))*(1000./4.85)
           THETA = THETFN/(NPERHR*100.0)
           RKR = 1.43
           RKF = 1.357
           CYCTIM = TH+TL
C COMPUTE THE TIMES FOR STEADY STATES AFTER A CHANGE IN WORK LOAD
           ST1 = (ALOG((.025*4.85)/((WEIGHT)*(HI-RL1))))/(-RKR)
           ST2 = (ALOG((.025*4.85)/((WEIGHT)*(HI-RL1))))/(-RKF)
           WRITE(6,51)TH,TL,HI,RL1,WEIGHT,AERCAP,IAGE,NPERHR,THETA,
      1    THETFN,ST1,ST2
51         FORMAT(1H1,15X,10HHI TIME = ,F4.1,11X,10HLOTIME = ,F4.1,
      1    //,16X,10HHI WORK = ,F7.5,8X,10HLO WORK = ,F7.5,//,17X,
      1    9HWEIGHT = ,F6.2,3X,16HAERO CAPACITY = ,F6.2,
      1    //,20X,6HAGE = ,I2,10X,13HCYCLES/HR. = ,I3,
      1    //,18X,8HTHETA = ,F6.4,5X,14HTHETA PRIME = ,F6.3,
      1    //,20X,5HT1 - ,F6.3,16X,5HT2 - ,F6.3)
           WRITE (6,52)
52         FORMAT(1H0,///,15X,6HCYCLE ,3X,10HENERGY       ,10HE DOT
      1        ,2X,14HENDURANCE TIME)
C          COMPUTE EDOT THE EQUIVALENT ENERGY EXPENDITURE RATE
           OENCYC = 0.
           ENCYC = 0.
           HI = HI
           RLI = RL1
           DO 100 N=1,100
           HI=HI+(N-1)*HI*(THETA)
           RLI=I+(N-1)*RL1*(THETA)
           IF(ST1.GE.TH) GO TO 501
           T1=ST1
           A2=(HI-RLI)*(TH-T1)
           GO TO 509
501        T1=TH
           A2=0.0
509        A1 = (HI-RLI)*T1+((HI-RLI)/RKR)*(EXP(-RKR*T1)-1.0)
           IF(ST2.GE.TL) GO TO 511
           T2=ST2
           GO TO 512
511        T2=TL
512        A3 = ((HI-RLI)/RKF)*(1.0-EXP(-RKF*T2))
           A4=RLI*(TH+TL)
           ENCYC=A1+A2+A3+A4
           OENCYC=OENCYC+ENCYC
           CUTIM = N*(TH+TL)
           EDOT=OENCYC/CUTIM
```

```
C          COMPUTE ENDURANCE TIME LIMIT FOR THE EDOT. CHECK WITH CUMULATIVE
           TIME ON THE JOB
           ENDTL=10**((.26144-EDOT)/.0712)
           WRITE (6,53)N,ENCYC, EDOT,ENDTL
  53       FORMAT(1H0,15X,I3,5X,F5.3,4X,F7.5,9X,F7.2)
           DIFTIM = ENDTL-CUTIM
           IF(DIFTIM.LT.CYCTIM) GO TO 200
 100       CONTINUE
 200       NLIM=N
           AENDTL = ENDTL*(AERCAP/45.)
           DIMENSION F(55)
           DATA F/15*0.0,5*1.025,5*1.0,5*.965,5*.885,5*.840,
     1     5*.805,5*.780/
           RESULT = AENDTL*F(IAGE)
           WRITE(6,55)RESULT
  55       FORMAT(1H0,//,20X,33HENDURANCE TIME LIMIT (MINUTES) = ,
     1     F6.1)
  10       CONTINUE
           CALL EXIT
           END
```

PROGRAM   FLOW CHART

```
                      ╭─────────────╮
                      │    Start     │
                      ╰──────┬──────╯
                             │
                    ╱────────┴────────╲
                   ╱   Read Parameters  ╲
                   ╲_____╱
                             │
                 ┌───────────┴───────────┐
                 │  Compute THETA, CYCTIM,│
                 │      ST1, and ST2      │
                 └───────────┬───────────┘
                             │
                 ┌───────────┴───────────┐
                 │   OENCYC = 0           │
                 │                        │
                 │   ENCYC  = 0           │
                 └───────────┬───────────┘
       ╱─────────╲           │
      ╱           │          │
     │    100     ├──────────┤
      ╲           │
       ╲─────────╱           │
                 ┌───────────┴───────────┐
                 │  Compute HI, RLI       │
                 │        T1 and T2       │
                 └───────────┬───────────┘
                             │
                       ╱─────┴─────╲
                       │     1      │
                       ╲_____╱
```

```
                        ┌──────┐
                        │  2   │
                        └──┬───┘
                           │
              ┌────────────┴────────────┐
              │  DIFTIM = ENDTL - CUTIM │
              └────────────┬────────────┘
                           │
                        ╱──┴──╲
                      ╱    I    ╲
                    ╱             ╲
                  ╱  DIFTIM. LT. CYCTIM ╲── NO ──⟨ 100 ⟩
                    ╲       ?       ╱
                      ╲          ╱
                        ╲──┬──╱
                           │
                          YES
                           │
              ┌────────────┴────────────┐
              │ Compute AENDTL and RESULT│
              └────────────┬────────────┘
                           │
                   ╱───────┴───────╲
                   │  Print RESULT  │
                   ╲───────┬───────╱
                           │
                      (  Call EXIT  )
```
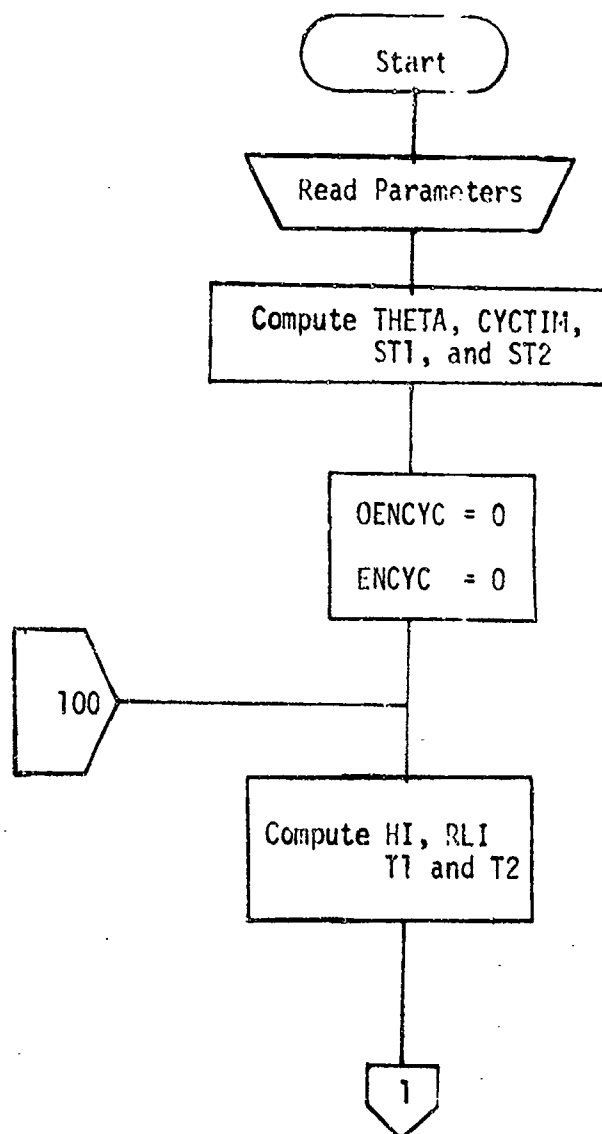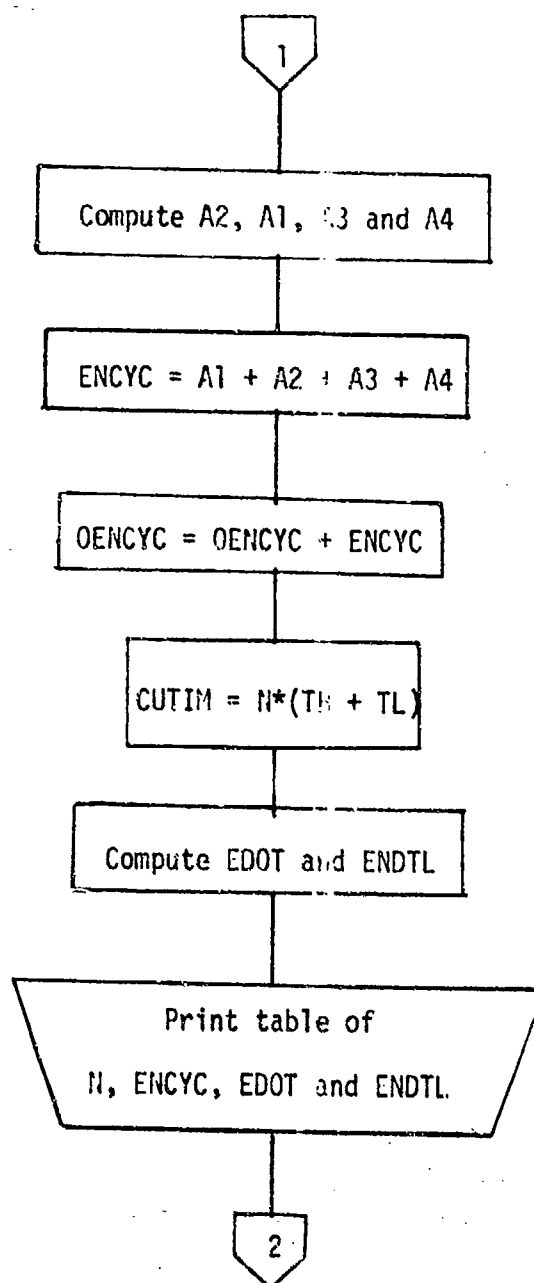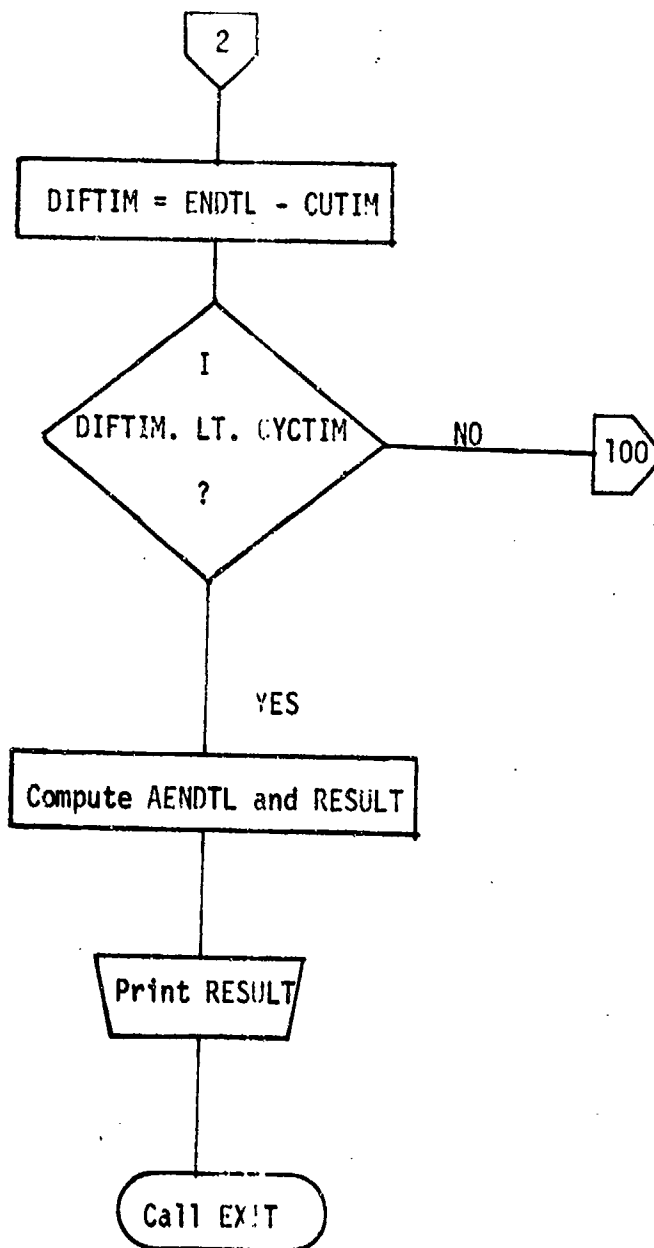
SAMPLE OUTPUT

HI TIME = 15.0   LO TIME = 5.0

HI WORK = 0.14277   LO WORK = 0.04366

WEIGHT = 76.54   AERO CAPACITY = 42.55

AGE = 24   CYCLES/HR. = 3

THETA = 0.0298   THETA PRIME = 8.936

T1 = 2.892   T2 = 3.048

CYCLE	ENERGY	EDOT	ENDURANCE TIME
1	2.364	0.11818	102.83
2	2.434	0.11994	97.14
3	2.575	0.12287	88.35
4	2.786	0.12698	77.36

ENDURANCE TIME LIMIT (MINUTES) = 73.2

APPENDIX C

BUILD UP FACTORS FOR HEART RATE, EXPRESSED

AS PERCENTAGE OF I CYCLE

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TABLE 22

θ' VALUES FOR HEART RATE

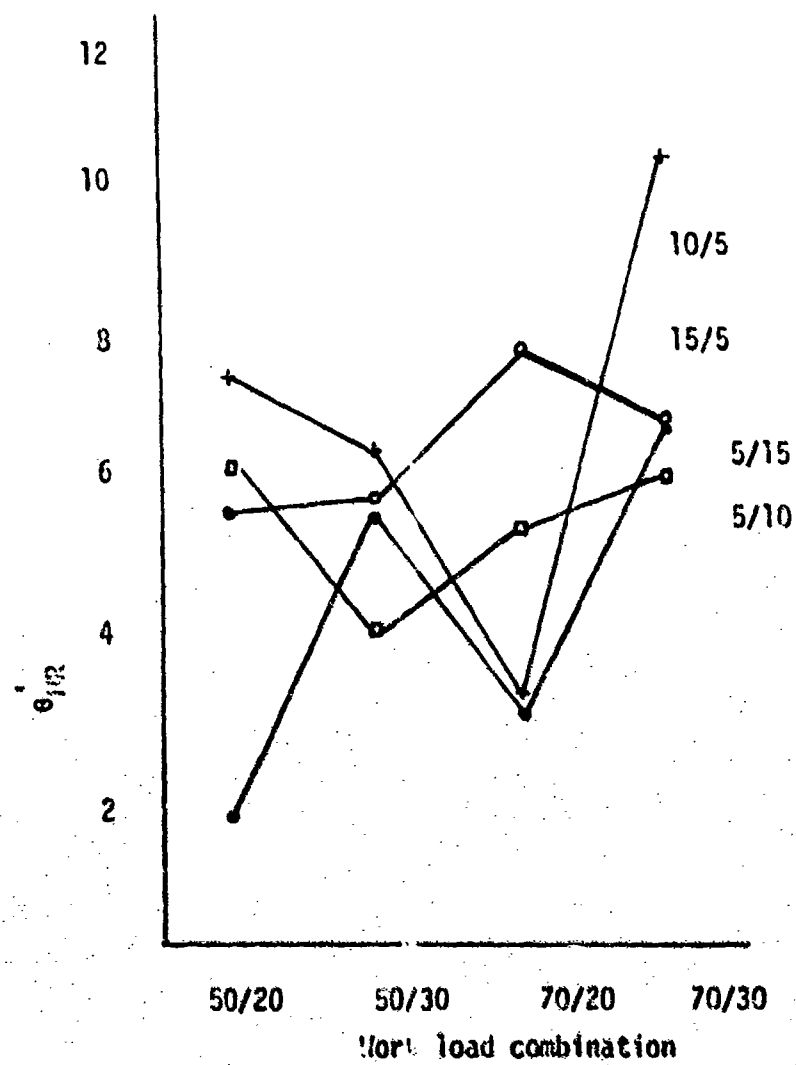| Work load Combination	Time Schedule	Build Up Factor, θ'	
		2 Hr. Test	3 Hr. Test
50/20	5/15	1.1	2.0
	5/10	2.7	9.7
	10/5	7.7	7.1
	15/5	3.4	6.3
50/30	5/15	9.6	12.1
	5/10	6.1	1.8
	10/5	7.4	5.6
	15/5	6.5	5.0
70/20	5/15	3.2	2.6
	5/10	9.7	1.1
	10/5	3.0	3.7
	15/5	4.7	11.1
70/30	5/15	11.3	2.0
	5/10	7.0	5.2
	10/5	10.4	10.1
	15/5	6.6	7.6

Fig. 18.--θ'_{HR} vs. work load combination according to time schedule
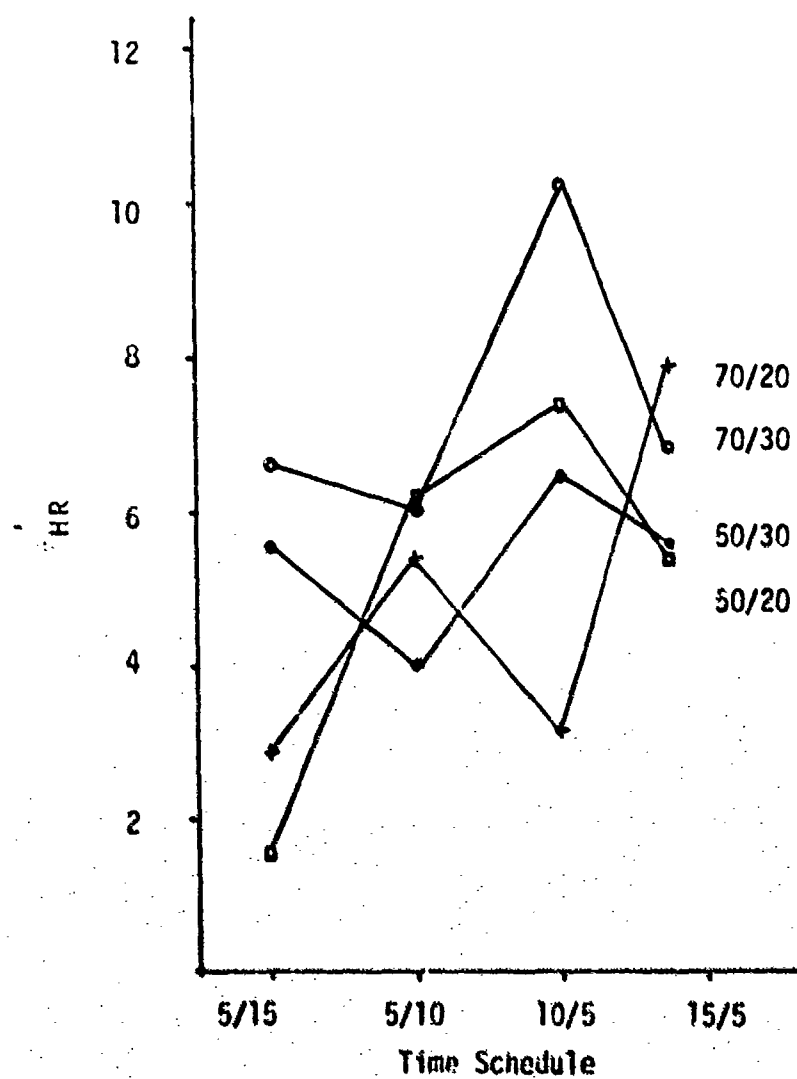
Fig. 19.--θ_{HR} vs. time schedule according to work load combination