A BIOCHEMICAL ESTIMATION OF EFFICIENT ENERGY EXPENDITURE DURING THE PERFORMANCE OF ARDUOUS MANUAL EFFORTS.

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PREFACE.

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CHAPTER I.

INTRODUCTION.

The common labourer in the gold mining industry of the Republic of South Africa has become such an integral part of the daily mining procedure that he cannot be replaced by industrial mechanization. Every machine needs an operator, but no machine can install a pack or remove a hydraulic prop, and lashing on which production largely depends cannot be done so thoroughly by any machine. Thus an efficient mining procedure in this country requires the employment of several thousands of labourers per annum.

This large labour force is comprised of local Bantu labourers and is supplemented by labourers from neighbouring states. Due to the contract of labourers, a 100% turnover of the labour force per annum has become the practice. Efficient use of this labour force calls for a successful method of "placing the right man in the right job as soon as possible".

All underground tasks require a physical effort, some more intensive than others. For the estimation of a worker's abilities, therefore, a sound physiological constitution should be kept in mind, whatever method of estimation is proposed. The estimation of maximum capacity in man has been proposed by various authors. Such an estimate would enable the stronger man to be selected for a task requiring a bigger physical effort, and vice versa, Working men could then be classified into groups for various tasks.

Labourers would then be safeguarded against working too hard in their jobs, for the supervisor would know exactly what to expect from every man. This would lessen the medical services required by these people in general, and more efficient

work performances may be expected from a healthy worker than from a sick, over worked man. A labourer can also be encouraged to work at his maximum output by the application of an incentive bonus system. The management by knowing a man's capabilities, can now judiciously allot the bonus money. If a group of men, however, are already working at maximum output per unit time, the production could be more successfully increased by an additional labour force than by increasing the bonus money.

The psychological and mental components are ignored in this study, which is mainly concerned with the physiological and biochemical aspects of physical effort.

Statement of the problem.

This study is mainly concerned with a dual investigation. Firstly, it includes a mental extrapolation to construct from the findings of many authors, working under various conditions, a general view of the lactic acid, excess lactate and pyruvic acid metabolism during exercise. This task was rendered nearly impossible due to the divergent techniques employed in the past. This was found to be the main reason for the controversy among authors.

The literature, reviewed in Chapter II, revealed that scanty researches were conducted during the period of exercise, and that the available literature is limited by the different blood sampling times and techniques in current use. The different types of exercise employed and the inability to define work stress accurately have limited the useful and comparable data available even further.

Secondly, the more specific aims of this investigation were:-

1. The application of a method of analysis, proposed in Chapter II, to the data of a large group of subjects so as to investigate the general trends of lactic acid, pyruvic acid and excess lactate relative to time for different percentage of the maximum oxygen intake values. A comparison was then made of that stage in metabolism at which each of these metabolic parameters started to accumulate excessively, and also those stages at which the "primary rises" disappeared.

2. The relationship of the maximum heart rate values to the optimum percentage of the maximum oxygen intake at which work could just be sustained for 1 hour only, was also tested.

3. A Criterion was proposed for the evaluation of work stress:-

   a) In Industry.

   b) In exercise physiology, which is badly in need of a physiologically sound and universally applicable criterion.

The average excess lactate values and heart rate values at each of the proposed levels were also investigated.

Limitations.

The value of this study might be reduced on account of the following limitations:-

Analysis of the data necessitates the grouping of experimental runs into different percentages of the maximum oxygen intake value. These groups were 5% apart from each other, having been allowed a scatter of ± 2% in all cases, except at 95% which has been allowed ± 3% due to fewer observations having been recorded in that region. The allowance of ± 2% in nearly all cases might now amplify the scatter of lactic acid, pyruvic acid and excess lactate concentration around the actual percentages discussed.

Also, due to the length of time devoted to experimentation on each subject, it was impossible to control the outside activities of the subjects, especially over week-ends. This might contribute to a deviation of results from the true values.

A slight error in results might occur due to the experimental runs being done in the post-prandial stages of nutrition (T.E. Friedemann et al. 1945).

Blood samples, collected from the prewarmed fingertip, were used in the analyses for lactic acid and pyruvic acid concentrations. These might not resemble the values obtained from arterial blood samples (D.P. Barr and H.E. Himwich 1923). In this study, however, at least 72 separate blood samples were collected over a period of 18 working days from each subject. This large number of blood samples, collected over such a long period, made the collection of blood samples by means of an indwelling needle impracticable

Significance of this study.

This study has proposed and applied a method by which the results of lactic acid, pyruvic acid and excess lactate of any subject could be compared to that of any other subject or group of subjects. A valid summation of the results of different subjects was unheard of in the past.

A physiologically sound criterion for the evaluation of work stresses is also proposed in this study. The precise evaluation, which considers and treats all men on the same basis, has made possible the well defined and clear-cut description of the work performed by either subject or labourer.

It seems that the higher the maximum heart rate value the lower will the optimum percentage of the maximum oxygen intake be, at which work can be sustained for a unit time and vice versa. This finding will aid the selection

of atheletes and soldiers when volunteers of the same capacities are to be chosen for emergency jobs.

CHAPTER II.

REVIEW OF LITERATURE.

Living matter is considered to be a thermodynamic unstable system which depends on a continuous supply of energy for its maintenance and the performance of its every-day tasks. This energy is supplied by the in vivo oxidation of various organic substances to water and carbon dioxide. It is thus clear that the utilization of oxygen is of vital importance to the animal body. However, in animal tissues there is available another energy-yielding process known as glycolysis or lactic acid fermentation by means of which a glucose molecule can be split into 2 molecules of lactic acid in the complete absence of oxygen. The vital importance of such an emergency mechanism for the supply of energy to the animal tissue needs no emphasis, if it is kept in mind that almost all arduous tasks are performed under partly anaerobic conditions.

A. BLOOD LACTATE, PYRUVATE AND OXYGEN.

1. Lactate concentrations in blood.

The accumulation of blood lactic acid is undoubtedly due to the muscle metabolism being conducted in an oxygen deficient "milieu interieur". This finding was first demonstrated by W.M. Fletcher and F.G. Hopkins (1907), while working on isolated muscle fibres. They observed that lactic acid, accumulated under anaerobic conditions, disappeared on the administration of oxygen.

This remarkable correlation between oxygen and the lactic acid accumulation has became a matter of extensive interest. O. Jervell (1928), A.V. Hill (1923) and others retested this correlation in vivo with considerable success.

A.V. Hill (1923) found that:-

> "if the oxygen supply be adequate, a 'steady state' is reached in which the rate of lactic acid production is balanced by the rate of its oxidative removal, and its concentration remains constant in the muscle as long as exercise at that speed is maintained".

O. Jervell (1928) on the other hand contradicted A.V. Hill's finding when he found that the highest lactic acid concentration reached in blood during an experimental run was during the first few minutes of exercise and the lowest value in the last minute of exercise.

A.V. Hill et al. were later supported by G. Lundin and G. Ström (1946) who claimed that:-

> "The rise from the rest value to the steady state value was found to have a certain inverse proportional relation to the partial pressure of oxygen of the inspired gas mixture".

O. Bang (1936), working on trained subjects, found the highest lactic acid concentration to occur during approximately the 5th minute of exercise. This prominent elevation was referred to as the "primary rise". However, he differed from O. Jervell (1928) by not finding the lowest lactic acid concentration in the last minute of exercise, but claimed to have recorded a "secondary rise" during the latter stages of exercise, which does not bear any constant relationship to time.

According to G. Lundin et al. (1947), P.P. Eskildsen (1945) stated that:-

> "The blood lactic acid concentration will reach a steady state after a temporary rise above this level at the beginning of the work".

E. Asmussen (1950) found a gradual increase in the lactic acid concentration relative to time.

The existence of the primary elevation was also confirmed by E.V. Flock et al. (1939), who described a transitory production of lactic acid in rats indulding in exercise not resulting in continuous lactic acid accumulation.

P. Harris et al. (1962) found that the "primary rise" occurred between the 5th and 10th minutes of exercise, while R.E. Johnson and H.T. Edwards (1937) and J. Tepperman and H.M. Tepperman (1947) found the highest lactic acid concentration between the 5th and 15th minutes of exercise.

B. Pernow and J. Wahren (1962) found the lactate and pyruvate concentrations of arterial and deep venous blood to differ significantly during rest. During work lasting ± 4 minutes, elevated lactate and pyruvate concentrations occurred in both arterial and venous blood samples.

In spite of E. Asmussen's (1950) claim that a fairly precise picture of the lactic acid relative to time curve has been established during the period of work, the above review of the literature clearly points to the fact that all has not yet been agreed upon. Controversy still exists, both about the existence of the "primary rise" and the cause of the lactic acid concentration curve relative to time during the latter stages of exercise.

2. Blood sampling times and methodology.

Many different blood sampling times, techniques, exercises and subjects were used by different investigators in the past. This seems to have made comparison of data very difficult, because a blood sample taken during the peak of a "primary rise" will most definitely differ from a sample taken after the "primary rise" has disappeared. The following are some of the different techniques employed:-

P.O. Åstrand (1952) collected blood samples from the

pre-warmed fingertip 1-2 minutes and also 4-5 minutes after exercise had stopped. The treadmill run lasted from 4-6 minutes, and the work load chosen was one which would exhaust the subject in the mentioned time. Lactic acid concentrations were determined.

P.O. Åstrand et al. (1963) collected blood samples from skiers after performances. The hand of the skier was washed for 3 minutes before the fingertip was punctured.

J. Tepperman and H.M. Tepperman (1948) also collected blood after exercises of short duration. Work loads of moderate and severe intensities were done on a bicycle ergometer.

R.E. Johnson and H.T. Edwards (1937) collected blood after treadmill running at a high work rate was completed.

P. Harris et al. (1962) used an indwelling needle in the brachial artery for the collection of blood samples. Work loads of various intensities were investigated for a period of 10 minutes, after which the recovery period was followed for 20 minutes.

O. Bang (1936) studied trained and untrained men on a stationary bicycle ergometer. Blood samples were collected during and after exercise. The work loads done by the subjects were chosen at random and noted in the write-ups. However, the physical characteristics and maximum oxygen intake of the subjects were not stated.

T.E. Friedemann et al. (1945) collected blood samples from subjects after work of a low intensity was performed, such as office and laboratory work.

E. Asmussen (1950) investigated lactic acid and pyruvic acid concentrations during and after heavy muscular work. An ergometer was pedalled for 20-30 minutes in each

case.

G. Lundin and G. Ström (1946) collected blood samples during exercise from subjects, who were fit and fully fimiliar with the experimental procedure. The experimental runs lasted 45-50 minutes each.

3. Pyruvate concentrations in blood.

The scanty research available on this metabolite can be attributed either to the small quantities present in blood or to the very sensitive method of analysis of relatively large quantities of blood. The importance of the pyruvic acid concentration for an understanding of the oxygen debt concept has been stressed (W.E. Huckabee 1958). It was also pointed out that pyruvic acid is the immediate precursor of lactic acid during anaerobic conditions (E. Asmussen 1950).

T.E. Friedemann et al. (1945) showed an increased resting pyruvate level after ingestion of both carbohydrate and protein. Neither the ingestion of fat, even in large quantities, nor light muscular exercise have had any influence on the blood pyruvate level. By climbing up steps at a rate representing a load of 650 kilogrammeter/min. the blood pyruvate level was increased over the resting values. This finding was confirmed by E. Asmussen (1950) who found that the pyruvate and lactate levels increased excessively only after work loads with oxygen consumption rates of 2.5 L/min. had been surpassed. He found that the pyruvate concentration of blood reached its maximum value during the first few minutes of recovery from heavy muscular exercise, the lactic acid concentration again decreased immediately after exercise stopped.

P. Harris et al. (1962) found that the pyruvate concentration in blood increased throughout the entire 10 minutes of exercise, reaching its maximum concentration

2½-5 minutes after exercise had stopped. Sometimes, however, there occurred a peak during exercise and also a peak after exercise. This peak in the pyruvate concentration, during the recovery from exercise, was reached later than the peak in lactic acid concentration (R.E. Johnson and H.T. Edwards 1937).

J. Tepperman and H.M. Tepperman (1947) found that the maximum pyruvic acid concentration in blood occurred approximately 15 minutes after the beginning of exercise, while the lactic acid's maximum concentration always occurred before that of pyruvic acid.

In general it was concluded that the maximum pyruvate concentration is reached later than that of lactate, because of an oxidative conversion of lactate to pyruvate in the non-exercising tissues (liver).

4. Lactate and Pyruvate diffusion and removal rates.

W.E. Huckabee (1956) investigated, "The control of concentration gradients of Pyruvate and Lactate across cell membranes in Blood". It was pointed out that, by assuming arterial plasma pyruvate concentrations to be equal to that of arterial blood, an error of 22% has been made. The plasma pyruvate values also averaged 130% higher than those of cells, and the lactate values 37% higher. These inequalities are in the same direction across the cell membrane. Correction factors have then been proposed to convert the whole blood values to plasma values, by means of the multiplication of lactic acid and pyruvic acid concentrations by 1.08 and 1.22 respectively. Thus the concentrations in blood water were significantly lower than those in plasma water, this was also the finding in each individual set of determinations.

Whether this relationship, found in membranes of erythrocytes, exists in other cells is a possibility that has not

been ruled out, because of the very active and unstable nature of lactic acid in the tissues removed from the body.

A.F. Hartmann and M.J.E. Senn (1932) injected sodium-r-lactate into the blood. Over a period of 30 seconds the blood lactate concentration was elevated to ± 300-500 mgm./100 cc. After 15 minutes of the injection 90% of the lactate had been removed and the lactate concentration in blood was between 30-65 mgm./100 cc. After 30 minutes the lactate concentration was still slightly elevated, but after 60 minutes it was back to normal. At the end of 2 hours, however, subnormal levels seemed to occur.

These authors then suggested that the initial rapid fall in blood lactic acid concentrations was due to:-

a) Diffusion into body fluid.
b) Oxidation and conversion into glycogen.
c) Excretion into urine.

The latter more gradual fall seems chiefly due to the metabolism of the lactate radicle, and this was also indicated by glucose and bicarbonate concentrations in blood.

By working on resting frog muscles, A. Ghaffer (1935) found that only one third of the muscle water appears to be involved in the diffusion process concerning d-lactate, the rest is shut off by membranes impermeable to lactate. These portions have been called "interspaces" and "cells". The fatigued, heat rigored and excited muscles seems to differ in this respect. These authors then concluded that:-

> "The intact animal possesses some mechanism by which a relationship, between the concentration of 'cells' and 'interspaces' is maintained".

H.G. Eggleton and C.L. Evans (1930) found the lactic acid concentration in tissue to be less than that in blood plasma both during rest and recovery from exercise. Muscle, however, does not come into equilibrium with other tissue or

blood until 10 minutes after the end of exercise. At equilibrium then the muscle lactate was lower than that of the arterial blood.

The above review of the diffusion of lactate ions has still not been agreed upon and seems to be a field in which anything can be revealed in the future. In studies of lactic acid the pyruvate concentrations must not be omitted (W. Huckabee 1956).

The removal of lactate from blood was found to be due to a rapid diffusion into the total body water, a small amount being excreted in the urine and the rest oxidized and converted to glycogen. Evidence for the oxidative removal of lactic acid was found in both glucose and bicarbonate levels of blood (A.F. Hartmann and M.J.E. Senn 1932).

M.G. Eggleton and C.L. Evans (1930) found the site of lactic acid production to be in the active muscle. The resting inactive muscle and the liver possess the ability to convert lactate from the blood circulation into glycogen. The lungs on the other hand had no part in the lactic acid removal during recovery from exercise. Lactic acid is removed from the blood during recovery at a rate of 2 mg./100cc. per minute.

A.F. Hartmann and M.G.E. Senn (1934) investigated the complete metabolism of sodium-r-lactate in subjects with impaired liver and kidney functions. It was found that, in the four cases of acute catharral jaundice studied, there was a delay in the complete metabolism of lactate.

N.R. Alpert and E. Trager (1956), while working on barbitalized dogs, found the same excess consumption of oxygen before and after complete hepatectomy and evisceration. The lactate levels of normal dogs rapidly returned to control values, whereas those of operated animals remained elevated.

In the normal, intact and lightly anesthetized dog, W.T. Goodale et al. (1948) found a consistently high coronary A-V[x] difference of oxygen, pyruvic acid and lactic acid. If the coronary blood flow was considered, a very high myocarcial utilization rate of these metabolites could be pointed out. For 40-60% of the total cardiac oxygen utilized must be consumed, to ensure the complete breakdown of cardial lactic acid and pyruvic acid to H_2O and CO_2.

In the air ventilated heart-lung preparation, C.L. Evans et al. (1934 a & b) found that a heart weighing 90-100 gm. was able to remove approximately 7 mg. of glucose and 234 mg. of lactic acid from the blood in 1 hour. Adrenaline and iodoacetic acid caused an output of sugar from the heart, while iodoacetic acid either did not change or resulted in an increased uptake of lactic acid. The origin of lactate in the heart-lung preparation was due to glycolysis in both blood and lungs, while the lactic acid consumed by the beating heart originated from both sources. No large amounts of lactic acid were removed by the lungs.

D.P. Barr and H.E. Himwich (1923) found that lactic acid escaped from the exercised muscle even 3 minutes after exercise stopped:-

> "At the same time the less active tissues are removing it rapidly as the blood passes through them".

5. <u>The contraction of an oxygen debt</u>.

Muscle fibres, contracting under anaerobic conditions, will accumulate lactic acid which can be removed by the administration of oxygen (W.M. Hopkins and F.G. Fletcher 1907). Since the above observation was made, many investigations have been conducted to retest this in vitro phenomenon in the in vivo environment.

x Arteriovenous

A.V. Hill and H. Lupton (1923), A.V. Hill, C.N.H. Long and H. Lupton (1924) found that, after a physical effort, the oxygen consumption remained elevated above the basal level for a time depending on the intensity of exercise. The extra oxygen used, while the body seemed to be at rest, was conveniently called an "oxygen debt". It was also assumed that the excess oxygen was entirely used for the oxidative removal of lactic acid. Firstly the lactic acid was removed from the muscle where it was formed and secondly, the lactic acid which had,had time to diffuse away from the muscles was then removed. The removal of the lactic acid from these two sites then resulted in a rapid phase, and in a more prolonged phase of the recovery oxygen consumption curve, respectively.

O. Jervell (1928) claimed, after A.V. Hill et al. (1924), that:-

> "The calculated oxygen debt and that actually found are fairly concordant".

R. Margaria, H.T. Edwards and D.B. Dill (1933) divided the oxygen debt into an alactacid and a lactacid phase. The former had a velocity constant of 0.6 and was 50% completed in 30 seconds, while the latter had a velocity constant of 0.02 and was a function of time. These authors considered only the prolonged phase to be due to the oxidative removal of lactic acid from blood, for they have measured an oxygen debt of 2.54 litre without any lactic acid being accumulated.

D.B. Dill and B. Sactor (1962) stated as a fact that:-

> "The rate of removal of lactic acid does not run parallel to the payment of the oxygen debt".

NB.

These two phases in the extra oxygen consumed during the recovery from exercise have in general been agreed upon. The first and rapid phase, or the oxygen deficit

seems to be due to the depletion of high energy phosphates in muscle cells, resulting in an increased oxygen consumption (D.C. Pearl et al. 1956). During the first minute of exercise there was found to be a depletion of glycogen, phosphocreatine and adenosinetriphosphate, while an increased inorganic phosphate and hexosemonophosphate have been observed (E.V. Flock et al. 1939).

The second and more prolonged phase of recovery was then called the oxygen debt and was assumed to be entirely due to the oxidative removal of lactic acid from the blood water (A.V. Hill et al. 1923 and R. Margaria et al. 1933).

W.E. Huckabee (1958) introduced the "excess lactate" concept, which is a function of both changes in pyruvate and lactate. In experiments over a wide range of work loads, he found that excess lactate accumulated at all intensities of work and that it correlated remarkably well with the oxygen debt contracted. This conclusion was reached upon by writing the lactic dehydrogenase system into the mass action form:-

$$\left[\text{Lactate}\right] = \left[\text{Pyruvate}\right] \times K \left[\frac{\text{DPNH}}{\text{DPN}}\right]$$

H.G. Knuttgen (1962) could not confirm the above finding, for in his study excess lactate did not increase excessively until a critical work load was surpassed, and:-

> "the O_2 debt surpassed in quantity the O_2 equivalents of the maximum increases in total lactate and to an even greater extent, the O_2 equivalents of excess lactate".

From the above findings it is more than obvious that fundamental research remains to be done as far as oxygen debt and oxygen deficit are concerned.

6. The maximum oxygen intake and its physiological meaning.

If consecutive work loads are to be done on a subject, each of a higher intensity than the former, a linear relationship of oxygen consumption relative to work load will be found. The maximum oxygen intake will be reached gradually, at first biassing to and then tending towards an asymptotic maximum. At this stage no increase in oxygen consumption per unit time will occur by further increasing the work load.

C.H. Wyndham et al. (1959) claim that:-

> "The maximum levels of oxygen intake and maximum heart rate of trained men studied over 4 months is remarkably constant, having average coefficients of variation of 4.3% and 3.5% respectively".

The size of the bias observed was 0.34, which means an underestimate of the asymptotic maximum when the maximum value on the linear curve was used (P.O. Åstrand et al. 1954). It was also pointed out that the:-

> "horizontal asymptote is not significantly different from the mean measured O_2 intakes at the three levels of work".

This maximum oxygen intake value per kg. of body weight is 29% higher in adult males than in adult females (P.O. Åstrand 1952).

The maximum oxygen intake was decreased during conditions of semi-starvation (A. Keys et al. 1950).

No significant differences could be found between the maximum capacities of subjects working under heat stress conditions and those working in comfortable conditions (C.G. Williams et al. 1962).

A training regime on the other hand resulted in an increased maximum oxygen intake value (L.E. Morehouse and A.T. Miller 1959). An increase of 6% or 7% in the transport

of oxygen to the tissues during exhausting work were recorded by C.A. Knehr et al. (1942) and also by S. Robinson and P.M. Harmon (1941 b). The percentage increase in the maximum oxygen intake value will depend on the physical state of training of the subjects, prior to the training regime.

a) Lactic acid accumulation point and the maximum oxygen intake.

The lactic acid accumulation point was found to be at a work load resulting $\pm$ $^2/_3$ of the maximum metabolic rate (R. Margaria et al. 1933).

C.H. Wyndham et al. (1956) found that the "excess lactate" increased rapidly after a work load presenting 55.3% of the maximum oxygen intake had been surpassed.

The significant occurrence of lactate at lower levels of work in hot, rather than in comfortable conditions, has been explained by more blood being shunted to the skin for heat dissipation purposes and less blood then being available for the transport of oxygen to the active muscles (C.G. Williams et al. 1962).

b) The physiology of the maximum oxygen intake.

For the maximum efficient oxygen transfer from atmospheric air to the blood circulation and from there to the active "muscle machine", it is essential to have a smooth linkage and operation of various physiological mechanisms.

The transport of oxygen in blood is made possible by its bondage to hemoglobin. Correlation coefficients of 0.97 and 0.94 for males and females respectively have been reported between the maximum oxygen intake and total hemoglobin (P.O. Åstrand 1952). An increased blood volume was found to be due to physical training (S. Robinson et al. 1937); however, the hemoglobin concentration remained constant. This increased total hemoglobin explains in part the higher

maximum oxygen intake after a training regime.

To satisfy the demand for oxygen, made by the tissues, an increased intra-capillary oxygen tension will result. This increased oxygen tension will be achieved by the influence of a raised temperature and a change in pH on the decomposition of oxyhemoglobin. More capillaries will also be opened up to make a shorter diffusion distance possible from the blood to the tissues demanding oxygen.

Observations made by E.H. Christensen (1932 and 1950) revealed that each different type of exercise has its own maximum oxygen intake value, depending on the size of the active muscle mass.

An algebraic presentation of the parameters of oxygen consumption and cardiac output have been given by C.H. Wyndham et al. (1959) as follows:-

$$\frac{O_2 \text{ intake}}{\text{Cardiac output}} = \frac{\text{heart rate x stroke vol. x A-V diff.}}{\text{heart rate x stroke vol.}}$$

The stroke volume reaches its maximum at $\pm$ 120 heart beats/min. (B. Asmussen and M. Nielsen, 1955) after which the cardiac output will be dependent on the heart rate alone. At the maximum heart rate now the oxygen consumption can only be increased by an increment in the A-V difference.

L.B. Morehouse and A.T. Miller (1959) concluded that the:-

> "Minute volume of breathing is unlikely to be a limiting factor in exercise".

While J.H. Mitchell et al. (1958) regarded this:-

> "As not being ruled out".

The pulmonary diffusion capacity is in general expected to increase with exercise (R.L. Riley et al. 1954 and R.H. Shephard 1956).

c) Maximum heart rate values.

L.E. Morehouse and A.T. Miller (1959) mentioned a heart rate of 320 beats/min., while P.O. Åstrand (1952) found heart rates of 194 and 198 beats/min. in males and females respectively. C.H. Wyndham et al. (1959) recorded an average maximum heart rate of 178 beats/min. on subjects doing bicycle ergometry. E.H. Christensen and P. Högberg (1950) found heart rates of 240 beats/min. in an age group of 14-16 years, while indulging in ski-ing.

A.V. Bock et al. (1928) concluded that the heart rate is not limited by the venous return, but rather copes with it.

B. ANALYTICAL PROCEDURE.

During the above survey of the literature it was observed that the investigators of lactic acid, pyruvic acid and excess lactate in blood had great difficulty with the problem of usefully comparing their data. Such a comparison is necessary in order to detect general trends and formulate or prove theories. Unfortunately the comparison of data was found to be impossible, due to the many different ways in which the investigations had been made and the different types of subjects used. The major reason why they failed to establish a common approach and comparable results can be attributed to the following facts:-

1. A common oxygen consumption or work rate cannot be used.

The lactic acid and pyruvic acid concentrations, accumulated in blood at a specific work load, will differ from one subject to another. Even the layman knows that a small man will find a certain task almost impossible to perform, while the big, robust man will easily complete this same task, being only slightly exhausted. The small man will accumulate a higher lactic acid concentration than the

big man for this specific task. The data of these two men cannot be compared and the general trend of each subject's results could only be discussed.

Admittedly this is an extreme case, but it emphasizes very well the errors made by many investigators in this field, for slight differences between the work capacities of subjects will also contribute to errors like this.

In a preliminary investigation, C.H. Wyndham et al. (1962) found the oxygen consumed by a physically fit subject, at the point where excess lactate begins to accumulate in the blood, to be ± 55.3% of the maximum oxygen intake of that subject.

It seems that the accumulation point of excess lactate is dependent very largely on the maximum oxygen intake value and the physical condition of the subject. The physiological parameters influencing the maximum oxygen intake value in comfortable environmental conditions, will also effect the excess lactate accumulation point.

2. Environmental conditions.

Lactate occurred at significantly lower levels of work in heat than in comfortable conditions (C.G. Williams et al. 1962). However, the maximum oxygen intake values under hot conditions did not differ significantly from those under comfortable conditions. The working muscle is more anoxic in heat, as a larger amount of blood is being shunted to the skin for heat dissipation purposes. Therefore in a hot environment the working muscle sooner goes on to anaerobic metabolism.

3. Sampling times.

From the investigation of O. Bang (1936) the blood

sampling times were found to be important. He found that the lactic acid concentration was at its highest during the period 5-10 minutes after commencement of exercise. After this "primary rise" a continual drop in lactic acid relative to time was observed with a "secondary rise", recorded during the latter stages of exercise, which does not bear any relation to time.

The lactic acid and pyruvic acid concentrations, accumulated in blood during recovery, differ from those in the active muscle (E. Asmussen 1950 and O. Bang 1936).

The importance of the sampling times was overlooked by many investigators.

4. Severity of work loads.

Referring to work loads as light, moderate or heavy puts the severity of exercise on a rather arbitrary basis. Definite criteria have not yet been established for these terms to be of significance in this field.

E.H. Christensen (1953) has attached to light, moderately heavy, heavy, very heavy and unduly heavy, the following oxygen consumptions 0.5, 1.0, 1.5, 2 & 2.5 l/min respectively for the population in general. For the comparison of individual trends this is unsatisfactory, and more limited and precise criteria are needed to compare a small and big man. For an oxygen consumption of 1.5 litre/min. will be moderate exercise for one subject, while it may already be heavy exercise for another.

5. Training.

a) Maximum loads.

During exhausting exercise the maximum lactic acid concentration accumulated in blood varies from one subject

to another and this may be independent of the individuals maximum oxygen intake. The degree to which the subject extends himself may, however, be the major contributory factor. C.H. Wyndham et al. (1959) pointed out that:-

> "The high level of blood lactic acid merely eliminates the man who is so poorly motivated for these experiments that he has not even extended himself up to levels of work at which anaerobic metabolism occurs".

Motivering!

The better motivated and conditioned man will urge himself much more to work at higher rates for longer periods than his less motivated companion.

b) Sub-maximum work loads.

If the same work load should be done on a subject before training and again after training, it would be found that the lactic acid concentration accumulated in blood has dropped significantly over this period of training (O. Bang 1936, H.T. Edwards, L. Brouha and R.E. Johnson 1940, L.E. Morehouse and A.T. Miller 1959). At sub-maximum work loads no endurance work is performed and therefore no motivation will be needed and the lactic acid concentration completely depends on the performance of exercise.

?

C. CONCLUSIONS.

From a consideration of the research projects of leading authors in the exercise physiology an attempt is now made to put the basic ideology for this type of data on to a more scientific basis for the purpose of comparing data from subject to subject. The following points of absolute importance should always be considered:-

1. Data of one subject may only be compared with that of another, if both subjects are doing work loads requiring the same percentage of their maximum oxygen values.

2. The data obtained during exercise may not be compared with that obtained during the recovery period.

3. More correct comparisons of data may only be achieved if the blood sampling times correspond.

4. Subjects to be used in a study must be at "optimum" fitness where possible, if not a "training effect" may influence the data obtained.

5. More than one experimental run, each on a different day, should be done under the same conditions so as to include daily variations.

CHAPTER III.

METHODOLOGY AND APPARATUS.

It was considered necessary to conduct this experiment in the following way:-

A. SELECTION AND TRAINING OF SUBJECTS.

The 19 subjects used for this experiment were all young African mine workers, selected at random from new recruits to the Gold Mining Industry in South Africa. From Table I it is clear that these subjects differed widely in physical characteristics. The average age was between ± 18 and 34 years. Estimation of age is, however, a problem, because these people do not keep records of their birthdays. After they were selected, it was brought to their attention that they would be working for a monthly bonus in addition to their pay. This was found to have a very good motivating effect on all the subjects.

On the first day of training the maximum oxygen intake of each subject was determined by means of a step test (see Method). Thereafter, training was based on this "maximum oxygen intake", and this value determined the required work rates during the following training routine:-

1. Mornings.

The subjects were requested to pedal bicycle ergometers at work rates which required oxygen consumptions equivalent to 55% of their maximum oxygen intakes. These work loads were pedalled for 3 hours every morning of a 6-day week. Heart rates were counted while using a stethoscope, and were plotted on a graph to see when a stable state in heart rate had been reached.

2. Afternoons.

The subjects were trained on consecutive days at work rates requiring oxygen consumptions of 80% and 100% of their maximum oxygen intakes on alternate days. These work rates were pedalled for as long as possible and the time recorded.

The above mentioned training programme lasted for a minimum of one month, and the experiment commenced only if the subjects were considered to be at optimum physical fitness in terms of certain physiological changes.

B. EXPERIMENTAL PROGRAMME.

At 5 a.m. the subjects came from the compound to the laboratory where they rested in the supine position and pre-prandial state of nutrition. After 3 hours rest, samples of their basal expired air, basal lactic acid and basal pyruvic acid were taken.

The experimental runs all lasted for a maximum of 60 minutes, or until fatigue compelled the subject to stop. All runs lasted longer than 30 minutes, however. Either the 60 minutes sample or the sample taken at the end of the run was used as the final observation.

Gas samples were collected for a period of 3 minutes at the 6th, 26th and 56th minutes of each experimental run. These samples were collected by connecting a Douglas bag to an Edwards mask by means of corrugated rubber tubing. The mask was fitted to the subject one minute before the gas sample was taken to allow the mask to be washed out of all atmospheric air. The espired air was then collected in a Douglas bag, which had first been flushed with expired air.

Maximum oxygen intakes were recorded over a period of 3 days from about the 10th to the 13th day of the experiment

or otherwise in the afternoons after completion of the morning's experimental programme.

Blood samples for lactic acid and pyruvic acid analysis were collected at the 6th, 26th and 56th minutes of the experimental run. If fatigue compelled the subjects to stop before the last samples were collected, the samples were collected immediately before they stopped, and the time recorded.

Heart rates were recorded at rest and the 5th, 10th, 15th 30th, 45th and 60th minutes during the run, using a portable Sanborn electrocardiograph.

C. SELECTION OF WORK RATES.

If the work rate is progressively increased for normal young subjects from, say, 3,000 ft. lbs./min. no lactic acid will accumulate in the blood before a certain critical work rate is reached. In this study three work loads below this point and three work loads above this point were selected, and each work load was repeated three times.

D. METHODS OF ANALYSIS AND APPARATUS.

1. Arterial blood samples from the fingertip.

Ten ml. aliquots of a 10% (w/v) aqueous solution of trichloro-acetic acid were measured into glass weighing-bottles by means of a burette. To minimize evaporation, the lids of these bottles were lightly greased before being closed and weighed.

The subject's hand was pre-warmed for at least 5 minutes in a water bath at $49^{\circ}C \pm 0.5^{\circ}C$. The fingertip was then dried, greased, and a deep cut made into it with an automatic spring stilletto. Blood was collected straight

into the pre-weighed glass bottle, while the finger was lightly squeezed in a distal direction to aid blood flow. The bottle was gently agitated to ensure complete mixing of blood and acid, because remaining clots of blood can influence the lactate values through continued anaerobic glycolyses. The bottle was immediately closed and weighed to determine the weight of blood collected. For the purpose of lactic acid determination 4 drops of blood (0.1-0.2gm.) and for pyruvic acid determination 10 drops of blood (0.25-0.35gm.) were collected. This blood mixture was then centrifuged for 10 minutes, after which the deproteinized supernatent solution was set aside for analysis.

Blood was also collected in pre-weighed crucibles while taking basal samples, and also at the end of each experimental run. This blood was dried in an electric oven, to constant weight and by calculating the weight loss, the percentage blood water was determined (see Method).

2. Analysis of lactate in blood.

The analysis of lactate in blood was done by the method of S.B. Barker and W.H. Summerson (1941) as modified by R.P. Hullin and R.L. Noble (1953).

a) Preparation of lactate standard.

U.S.P. lactic acid (85%) was diluted with an equal volume of water and a few drops of phenol red indicator were added. Saturated 20% lithium hydroxide solution was added from a pipette to slight excess as indicated by the phenol red. The solution was then heated to boiling point and was then cooled and filtered through a sintered glass filter. Four volumes of 96% alcohol were added and the solution was cooled overnight in a refrigerator. The crystals were then filtered through a Buchner funnel and washed thoroughly with

96% alcohol. The crystals were recrystallized from water and dried at 100°C. Lithium lactate was preferred because of its anhydrous and non-hygroscopic properties.

Of this pure lithium lactate, 0.2133 gm. was dissolved in 100 ml. water in a 1 litre volumetric flask. To this was added 1 ml. of concentrated sulphuric acid (Analar) and the volume was made up to the mark with water and the solution thoroughly mixed. This was the stock solution and contained 1 mg. of lactic acid per 5 ml.

The working standard was prepared by diluting 10 ml. of stock standard to 200 ml. with water in a volumetric flask. This solution contained 0.01 mg. lactic acid per ml. (10 mic. gm. lactate/1 ml.).

b) Lactate Analysis.

Five ml. of concentrated sulphuric acid (Analar) was pipetted into each of a series of ground-glass stoppered test tubes, the drainage time (± 15 seconds) being carefully controlled with the aid of a stopwatch. Two drops of a 20% (w/v) aqueous solution of cupric sulphate was added and the contents were then treated as follows:-

The test tube was placed in crushed ice to prevent the contents from becoming too hot and 1 ml. of the supernatent liquid from one of the weighing bottles was pipetted into it. The test tube was then quickly shaken and returned to the ice to ensure that the deproteinized blood solution was well mixed with the sulphuric acid. The stoppered test tube was then placed in a waterbath at 60°C (± 0.5°) for exactly 30 minutes, after which it was cooled in crushed ice for 4½ minutes. Three drops of a 1.5% (w/v) solution of p-hydroxy-diphenyl in 2% sodium hydroxide were then added and the contents of the tube carefully shaken once more to disperse the precipitated

p-hydroxy-diphenyl in the concentrated sulphuric acid. The test tubes were then transferred to a waterbath at 30°C for a period of 20 minutes, during which time it was shaken twice. The test tube was then placed in rapidly boiling water for exactly 90 seconds, after which it was once more cooled in ice for 3 minutes. The percentage transmittency of this violet coloured solution was then read in a Beckman DU spectrophotometer at a wavelength peak of 560 mμ. Each blood sample was analysed in duplicate.

In addition a set of reagent blanks and standard solutions of known concentration were prepared and treated exactly as above. In the blanks 1 ml. of 10% trichloroacetic acid solution was used and for the standards 1 ml. each of a 3 microgm./ml. a 5 microgm./ml. and an eight microgm./ml. of lithium lactate solution were used. These standard were prepared by taking 0.3, 0.5 and 0.8 ml. of the working standard described earlier and making the volumes up to 1 ml. in each case with 10% trichloroacetic acid.

By dividing the percentage transmittency of the solution into the mean percentage transmittency of the reagent blanks, the optical density of the standards and unknown solutions were determined. A calibration curve was then drawn by plotting the log of the optical densities of the standard solutions against their known lactate concentrations. This curve took the form of a straight line passing through the zero point, and from it the lactate concentrations of the unknown solutions could be read off. These concentrations were then related to the known weights of the original blood samples and the results expressed as mM lactate per litre of blood water. Explanations of the various calculations will follow later.

3. Analysis of pyruvate in blood.

This estimation of T.E. Friedemann et al. (1943) also demands a set of reagent blanks and a set of standards for the purpose of drawing a calibration curve.

a) 2-4 Dinitrophenol hydrazene was obtained in powdered form. Of this powdered substance 0.25 gm. were grinded very fine in a mortar and then dissolved in 100 cc. of concentrated hydrochloric acid in a 500 ml. flask. The volume was then made up to the mark with distilled water and filtered through a Whatman no. 40 filterpaper. This solution was kept in a refrigerator.

b) Distilled water, was prepared with an "Elgastat" de-ionizer.

c) 10% Thrichloroacetic acid was made up by dissolving 10 gm. of the crystals in H_2O(dist) in a 100 cc. flask. The volume was then brought up to the mark with H_2O(dist).

d) Xylene reagent was filtered to remove all waterdrops left in it.

e) Sodium carbonate was prepared by dissolving 90 gm. of powder in distilled water in a 1 litre flask. The solution was left standing overnight for complete dissipation of heat caused by the dissolving powder, and only the following morning was the volume made up to the mark with water.

f) Soduim hydroxide solution was prepared by dissolving 20 gm. in 500 cc. of distilled water.

The reagent blanks were prepared by pipetting 3 ml. of a 10% trichloroacetic acid solution into the test tubes.

The standards were prepared by dissolving 0.1249 gm. of sodium pyruvate, obtained from Messrs. L. Light & Co. Ltd., England, into 20 ml. distilled water. One ml. of this

solution was then transferred to a 1 litre flask and the volume made up to the mark with distilled water. This working solution then had a concentration of 5 mic.gm./ml., the impurities of the reagent being taken into consideration. The standard concentrations used in this analysis were 5, 10, and 15 mic.gm./3 ml. respectively. These were made up by taking 1, 2, and 3 ml. of the working standard solution and making it up to 3 ml. with 10% trichloroacetic acid respectively.

Three ml. aliquots of the supernatent solution set aside for analysis were pipetted into test tubes and analysed. All the above mentioned test tubes were subjected to the following test procedure:-

Two ml. aliquots of a 2-4 dinitro-phenol-hydrazene solution were pipetted into each tube. After five minutes standing, 4 ml. xylene was added to each tube by means of a burette. The contents was then bubbled for one minute with nitrogen gas, flowing at a rate of 3 litres per minute. After the fluid layers had been re-established, the bottom layer was sucked off and discarded. To the remaining portion in the tube 5 ml. sodium carbonate was added and again bubbled with nitrogen gas at the same constant rate of flow. The bottom layer was then sucked out and transferred to another test tube. To the original test tube 4 ml. of xylene and 2 ml. sodium carbonate were added and again bubbled under the same conditions as mentioned above. The bottom layer was added to the contents of the tube that had not been bubbled. From this test tube 4 ml. were pipetted into a centrifuge tube containing 1 ml. of sodium hydroxide. After this, the centrifuge tube was toppled for complete mixing and it was centrifuged for three minutes. The contents of this tube were then read against distilled water on a Beckman DU spectrophotometer at a wavelength peak of 520 mμ.

A calibration curve was then fitted for the standards in exactly the same way as that mentioned for lactate above, and the concentrations for the unknown samples related to their original weights. The results were also expressed as mM pyruvate per litre of blood water.

4. Calculations.

a) Blood water.

This was determined in the basal state and at termination of exercise every day. A blood sample was collected in a pre-weighed crucible and was again weighed immediately after collection of the sample. This sample was then dried in an oven to constant weight, cooled in a desiccator to room temperature and reweighed.

(i) Crucible alone = a.
(ii) Crucible + blood (wet) = b.
(iii) Crucible + blood (dry) = c.

$$\% \text{ blood } H_2O = \frac{\text{weight lost}}{\text{wet blood weight}} \times 100$$

b) mM Lactate and mM Pyruvate per litre of blood water.

From the calibration curve fitted to the log of the optical densities relative to the known concentration of the standards, the amount in micro gram present in the unknown supernatent blood sample could be determined. The lactate values obtained were then multiplied by 10 and the pyruvate value with 3.33. These values were the amount in micro. gram. present in the blood water of the blood sample taken in the trichloroacetic acid. From the blood water determination in (a) above, the total amount of blood water in the blood sample could be calculated. Thus, this blood water contained the

above total micro gram of lactate (or pyruvate). Using this blood water and micro gram present the micro gram per 1 litre of blood water could be calculated. By dividing this value by 88 in the case of pyruvate and 90 in the case of lactate, the final values could be expressed as mM/L of blood water.

c) Calculation of Excess Lactate.

$$XL = (Ln - Lo) - (Pn - Po)\frac{Lo}{Po}$$

XL = excess lactate

Ln = lactate concentration

Lo = basal lactate concentration

Pn = pyruvate concentration

Po = basal pyruvate concentration

mM = milli moles

d) Calculation of Oxygen Consumption.

SUBJECT ..... 61336 DATE .....12-12-63.....

HEIGHT ..... 5' 10" CORRECTED BAROM PRESSURE (mm/H

.....628.06.....

SPIROMETER TEMPERATURE .22.2

CORRECTION FACTOR ..7397...

WORK LOAD: Bicycle ergometer 10,000 ft. lbs./min.
Gas ..... (26 - 29) min.

CALCULATIONS

FIRST READING 7660.x.20:93.÷.16:03

SECOND READING 8075.x.20:93.÷.16:90

VOLUME AIR EXPIRED 71:70 VOLUME CORRECTED 53:04/3

% O_2 in sample .....16:03 % CO_2 in sample .5:15..

% N_2 in sample 78:82

Corrected inspired O_2 = 20:87
% O_2 absorbed = .4:84
Ventilation = 53:04
O_2 consumption/min. = .2:5671 litre/min.

5. Maximum Aerobic Capacity.

a) Step Test Procedure (Indirect method)

This test consisted of stepping up and down adjustable stepping blocks at fixed rates of stepping. For the first work load the subject stepped six times up and down a block of 12" high in one minute. The second and third work loads consisted of stepping up and down the same block at rates of 12 and 24 steps/min. respectively. The last work load was stepping 15" high at a rate of 24 steps/min.

These work loads lasted for 15 minutes each and expired gas samples were collected from the 6th to 9th minutes. Heart rates were recorded in the last minute.

Oxygen consumptions were plotted relative to corresponding heart rates for all four work loads and a straight line was fitted to these four points. Where the extrapolated line intersected a heart rate of 180 beats/min. the maximum oxygen intake was read off.

b) Bicycle ergometer (Direct method)

The first three work loads employed were of sub-maximum order, and a straight line could be fitted to the data of oxygen consumption relative to work load. The next three work loads were done in triplicate. The line fitted to the maximum work loads tended towards its asymptote and this was taken to indicate the maximum oxygen intake value (Asymptotic maximum). The calculated average oxygen values of the asymptotic maximum was shown not to differ significantly from that indicated by the fitted curve (C.H. Wyndham et al. 1959).

Gas samples were collected from the 6th to 9th minutes or during the last minute of exercise, if the exercise could not be done for 9 minutes. Heart rates were recorded

over the last 15 seconds of the gas sampling period.

E. APPARATUS.

1. Constant load ergometer.

A constant load ergometer was constructed by the Research Lab., Transvaal and Orange Free State Chamber of Mines, Johannesburg, South Africa (A.R. Atkins and J.D. Nicholson 1963).

This ergometer was the key to the study of blood lactate, which mostly depends on a constant work load.

2. Beckman Paramagnetic oxygen analysers.

Oxygen is paramagnetic in nature due to its unique molecular structure. As a result of this property, a characteristic of the oxygen molecule, it has become possible to determine its partial pressure in a gas sample of mixed gasses. Basically this method depends on the gas mixture being passed through the analysis chamber of the instrument, the magnetic susceptibility of the oxygen atom being measured with a magnetic torsion balance.

With a modification of the gas sample mixture the CO_2 content could also be determined with this apparatus.

3. Collins Spirometer.

Ventilation volumes were measured by means of a Collins spirometer of 350 litre maximum capacity.

4. Electrocardiograph.

Heart rates were recorded with a cardiomat machine. Chest electrodes were attached throughout the exercise and "contacta electroden papier" from Germany was used instead of

electrode-paste.

5. Barometer.

The barometric pressure was recorded with a mercury barometer, fixed with a nonuis scale for accuracy.

6. Thermometers.

Both room and spirometer temperatures were recorded with mercury thermometers.

7. Edward masks and valves.

These were used because of the findings of C.H. Wyndham et al. (1959) of the need for low resistance valves. Gas was collected by the conventional Douglas-bag method.

8. Avery scale and an anthropometer.

These were used to record the weights and heights respectively of each subject.

9. Water baths.

Three self constructed water baths were fitted with temperature regulating thermostats to maintain water temperatures at 49°C, 30°C, and 60°C.

10. Automatic Spring Stilletto.

This apparatus was used to make a deep cut in the fingertip of the subject.

11. Spectrophotometer.

The beckman DU spectrophotometer operates by means

of a system of mirrors, lamps and prisms by which the standard solutions and unknown solutions could be compared with distilled water at any chosen wavelength peak.

CHAPTER IV.

RESULTS.

A. INDIVIDUAL DATA.

The results of one subject presented here is an example of the work done on each individual subject. The data in Table VI(A) are also graphically presented in graphs 10 and 11. These two graphs are the oxygen/work load and heart rate/work load relationships up to the maximum level of the subject. The actual oxygen intake and maximum heart rate values were calculated by drawing the mean value of the recordings obtained at 3 different work loads on the asymptotic maximum. In two cases, however, of which one is presented here, the subjects could not work at work loads sufficiently high enough to have 3 different work loads on the asymptotic maximum. In these two cases then the means were drawn from the number of work loads worked at on the asymptotic maximum.

The average oxygen consumption value at each work load was then expressed as a percentage of the maximum oxygen intake value. Each work load could then be substituted by a corresponding percentage of the maximum oxygen intake value.

Average heart rate values presented in Table VI(B) were plotted relative to time in graph 9 and the percentages of the maximum oxygen intake value worked at noted next to each individual graph.

The average lactic acid, pyruvic acid and excess lactate concentrations given in Tables VI(C), VI(D) and VI(E) are also presented relative to time in graphs 6, 7, and 8 respectively. Corresponding percentages of the maximum oxygen intake value are also noted next to each individual graph.

B. GROUPED DATA.

The lactic acid, pyruvic acid, excess lactate and heart rate data of all the subjects were grouped together into different percentages of their maximum oxygen intake values. These groups ranged from 40-95% and are 5% ± 2% apart from each other, except at 95% where ± 3% was allowed due to the relatively few observations made in this percentage range.

Calculated averages drawn from the grouped data are tabulated into Tables V(A), V(B), V(C) and IV and are also graphically presented in graphs 1, 2, 3 and 4 respectively. Next to each individual graph are given the corresponding percentage of the maximum oxygen intake worked at and in brackets the number of subjects grouped together at each percentage group.

(1) a) Lactic acid concentration relative to time.

From graph 1, it is obvious that in general the following progressive change occurred in the lactic acid concentration curve relative to time as the work load was increased.

(i) As the work load was increased, the "primary rise" became more prominent; however, in the range of 40-60% of the maximum oxygen intake value the lactic acid concentrations returned to the basal value after the primary elevation.

(ii) At a certain critical work load, which resulted in an oxygen consumption of 60-65% of the maximum oxygen intake, there was in addition to the "primary rise" an elevation of the nearly plateau like curve found between the 26th and 56th minute observations to levels well above the basal value. This type of curve was obvious for the next 20%.

(iii) With a work load resulting an oxygen consumption of ± 90% of the maximum oxygen intake value the lactic acid concentration curve was nearly a plateau over its entire range.

(iv) At work loads resulting in oxygen consumptions of more than 90% of the maximum oxygen intake value the primary elevation moved over to the 56th minute observation, which is also the period immediately before termination of the experimental run. This primary elevation moved from the first few minutes of exercise to the last minute in a matter of ± 10% of the maximum oxygen intake value.

(v) In Table III are accumulated the optimum percentages of the maximum oxygen intake values at which each subject could just sustain work for 1 hour only. The mean value of ± 83% falls roughly together with the lactic acid concentration curve which is a plateau over its entire range.

b) Scatter.

In graph 5 are presented the total scatter about the mean for 13 subjects working at 65% ± 2% of their maximum oxygen intakes. The average scatter about the mean at the 6th, 26th and 56th minute observations being 2.6 mM lactic acid per litre of blood water.

2. Pyruvic acid concentration relative to time.

In graph 2 are presented the pyruvic acid concentrations relative to time for different percentages of the maximum oxygen intake value. The graphs differ by 5% ± 2% from each other and range from 40-95% of the maximum oxygen intake value. The following progressive changes occurred in the general trend of the curve with increasing work loads.

a) In the performance of work loads resulting in oxygen intakes of 40-60% of the maximum oxygen intake, a

"primary rise" occurred at the 6th minute observation in each set of data. After this primary elevation, however, the pyruvic acid concentrations returned to the basal value.

b) At a critical work load resulting in an oxygen consumption of 60-65% of the maximum oxygen intake, there was in addition to the primary elevation an elevation of the nearly plateau like level found between the 26th and 56th minute observations to a level well above the basal value. With each increment in work load, then, the corresponding levels moved higher above the basal value. This type of curve was obvious from 65% to 80% of the maximum oxygen intake value.

c) At work loads resulting in oxygen consumptions of 85-90% of the maximum oxygen intake value the "primary rise" was abolished and the curve was a plateau like over its entire range.

d) When work loads resulted in oxygen consumptions of more than 90% of the maximum oxygen intake, the curve of pyruvic acid concentrations relative to time had an ever increasing tendency.

e) Table III presents the optimum percentages of the maximum oxygen intake at which work could just be maintained for 1 hour only. The mean value of ± 83% falls together with the curve in which the pyruvic acid concentrations relative to time is a plateau for the entire period of exercise.

3. Excess lactate concentrations relative to time.

The analysis of graphs 1, 2 and 3 revealed that in all 3 cases the concentrations, of those metabolic parameters, in blood varied close around a mean value. Above 60%, however, pronounced differences made themselves apparent with each increment in work stress. The first large difference

from the usual mean value was considered to be that stage in metabolism at which the accumulation became excessive.

The excess lactate concentrations, presented relative to time in graph 3, follow roughly the same general pattern as that of lactic acid. Below 65%, however, the excess lactate concentrations, after a "primary rise", returned to practically zero values whereas the lactic acid concentrations returned to approximately basal values. The netto accumulation of excess lactate at corresponding points was also much less than that of lactic acid.

4. The average heart rate values at submaximum levels.

In graph 4 are presented the calculated average heart rates relative to time. Corresponding percentages of the maximum oxygen intake worked at, and also the number of subjects in each group, are noted next to each separate graph. The average heart rate values over the last 30 minutes of exercise were:-

60	percent	=	127	beats/min.
65	"	=	136	" "
90	"	=	169	" "
100	"	=	177	" "

5. Physical characteristics.

In Table I are accumulated the heights and average weights of all the subjects over the period of experimentation. The heterogeneous character of this sample, taken at random from the mining industry of South Africa, is also clear from this table. Heights ranged from 62" - 69.25" and weights from 118 - 161 lbs.

6. Maximum oxygen intake values.

In Table II are given the individual maximum oxygen intake values. These values ranged from 2.62 - 3.84 litres/min. and have an average of 49.9 ml. oxygen/kg. of body weight which is also tabulated in the same table.

7. Maximum heart rate values and endurance times.

The maximum heart rate value of each subject and the calculated average value of 176.8 beats/min. are presented in Table III. The optimum percentages of the maximum oxygen intake value at which work could just be sustained for 1 hour only are also given. The calculated average of 82.9% was found to fall approximately together with that stage in the pyruvate metabolism at which the pyruvate/time relationship is a plateau over the entire range of exercise.

There seems to be a relationship between the maximum heart rate value and the optimum percentage of the maximum oxygen intake. The relationship between these two variables appears to be curvilinear and the equation of the curve presented in graph 12 is:-

$$xy - 100x - 211.45y + 20635 = 0$$

From the transformed data in graph 13 a correlation coefficient of 0.70, which is significant at the 5% level, was calculated.

It should be stressed, however, that this curve merely gives an indication of the functional relationship, because the curve could not be satisfactorily established due to the large scatter and few observations made.

CHAPTER V.

DISCUSSION.

A. LACTIC ACID.

1. Scatter.

The investigators of lactic acid in blood, for many years previous to this study, have been facing the problem of plotting on the same graph the results of more than one subject without a large scatter about the mean, immaterial of whether these subjects worked under the same conditions or not.

In the present study a work load, which resulted in an oxygen consumption of 65% of the maximum oxygen intake value, was regarded as of moderate intensity. At this percentage of the maximum oxygen intake the average human body has just surpassed that stage of exercise at which the lactic acid accumulation becomes excessive (graph 1).

Graph 5 represents the results of 13 subjects all doing exercise of a moderate intensity. The very small scatter of 2.6 mM lactic acid per litre of body water over a wide percentage range of 4% and such a big group of subjects points to the success achieved in grouping results together at the same percentage of the maximum oxygen intake value. Compared with the data of S. Robinson and P.M. Harmon (1941) the scatter about the mean in graph 5 is $\pm$ 43.5% less, although 31% more subjects were studied and a 4% allowance about the exact percentage was made for grouping these results together. The larger scatter of the results of S. Robinson and P. Harmon (1941) could be due to the fact that in the past no precise physiological criteria were established for different working stresses (light, moderate or severe). It might thus be that

the subjects did not all work at the same degree of their maximum capacities and thus did not experience the same degree of stress.

The results presented by S. Robinson and P.H. Harmon (1941) are the only available results of an attempt to group together the results of different subjects. Many other authors also had the problem of grouping or comparing results from one subject with that of another and in the past this had been dealt with by merely discussing the results of one subject at a time and thus masking the above problem to a large extent.

2. Lactic acid concentrations relative to time.

The general trends in the lactic acid concentration relative to time for various percentages of the maximum oxygen intake are presented in graph 1 of this study. The graphs also display the existence of a "primary rise" at the 6th minute observation; however, at levels below 65% of the maximum oxygen intake the lactic acid concentration returns to approximately basal value. The existence of the "primary rise" in this range might be due to the exercise in the early stages being performed mainly by anaerobic means. When the circulation of oxygen to the active muscles has been adapted so as to satisfy the entire metabolic demand, the production of lactic acid ceases. The accumulated blood lactic acid is then removed by the inactive tissues and the lactic acid concentrations in the blood returns to the basal level.

Above 60% the lactic acid concentration relative to time curve is exactly the same except for the "plateau" found between the 26th and 56th minutes observations now being elevated well above the basal level. Thus from 60-65% a major change in the active muscle's metabolism tends to occur when the accumulation of lactic acid in blood has become

excessive. This excessive accumulation of lactic acid after a critical work load has been surpassed is in agreement with the findings of O. Jervell (1928), R. Margaria (1963), B. Rikki (1963) and C.H. Wyndham (1962). It seems as if the oxygen supply to the active muscle tissue becomes insufficient and that part of the energy utilized for exercise is supplied by means of anaerobic metabolism, resulting in a continuous production of lactic acid in the active muscles. The accumulated lactic acid is then transported via the blood circulation to inactive tissues where it is removed. An elevated blood lactic acid concentration will thus be sustained for the entire period of exercise. This curve is characteristic in the range of 65-85% of the maximum oxygen intake. Thus if 60% of the maximum oxygen intake has been surpassed the lactic acid accumulation becomes excessive and points to an energy supply by means of anaerobic metabolism. The oxygen intake still rises up to the maximum oxygen intake and this points to aerobic metabolism. Thus we have aerobic and anaerobic metabolism proceeding at the same time, when work loads beyond 60% of the maximum oxygen intake are performed.

The appearance of the "primary rise" during the first few minutes of exercise seems to be due to a large production of lactic acid in the active muscles under partly anoxic conditions. The lactic acid so produced diffuses into the bloodstream with an elevated blood lactic acid concentration as a result. The return to a "plateau" like level after this "primary rise" seems to be due, not to a breakdown of lactic acid in the inactive tissue, but rather to the diffusion of the produced lactic acid throughout the total body water. (A.F. Hartmann and M.J.E. Senn (1932). The existence of the "primary rise" during the first few minutes of exercise were confirmed by O. Bang (1936), E. V. Flock et al. (1939), and many others. According to

O. Jervell (1928), the accumulation of lactic acid on a certain work load is of higher magnitude during the onset of exercise than in the doubling of the work load during the latter stages of exercise. If the sudden drop in lactic acid concentration after the "primary rise" was due to the breakdown of lactic acid by the inactive tissue, this same tissue should have the ability to metabolise all the lactic acid in the blood circulation. This would result in lactic acid concentrations of basal value during the latter stages of exercise. This, however, did not occur when the work load resulted in an oxygen consumption of more than 60% of the maximum oxygen intake. At these work loads, part of the energy supply depends on anaerobic metabolism and this will have a continuous production of lactic acid as a result. From the active muscles lactic acid diffuses into the blood circulation, which transports the lactic acid to inactive parts of the body, where it diffuses throughout the entire body water. The higher work load will result in a larger production of lactic acid in the active muscle, which means that more lactic acid has to be transported in the blood per unit time and thus higher blood lactic acid concentrations will result.

The "plateau" found between the 26th and 56th minute observations, has a slight slope indicating the removal of lactic acid from the blood. This removal might be due to the inactive muscle tissue's metabolism of blood lactate. In all graphs this slope seems to be of the same magnitude, irrespective of the intensity of exercise. The same type of exercise, being employed in all cases, now seems to point out that the same amount of inactive tissue existed when the body was active in each case. This then might result in the same amount of lactic breakdown in each case, which could be true, because the slope in all the graphs is approximately

the same, and thus the same amount of lactate is being removed by the same amount of inactive tissue.

The higher the percentage of the maximum oxygen intake worked at, the less prominent becomes the "primary rise", until at ± 90% where it completely disappears and the entire graph follows the course of a "plateau". At this stage the lactic acid production in the active muscles takes place to an extent which exceeds the removal of lactic acid from the blood stream by means of both the inactive tissue and the buffer action of the total body water. Thus at ± 90% of the maximum oxygen intake value, the maximum ability of the components removing lactic acid from the body water has been reached.

At work loads resulting in oxygen consumptions of more than 90% of the maximum oxygen intake value, the highest blood lactic acid concentration will occur at the end of exercise. Within 10% of the maximum oxygen intake, the "primary rise" has thus moved from the first few minutes of exercise to the last minute of exercise. The lactic acid concentration curve of an ever increasing tendency has called for the explanation of a large continuous production of lactic acid by the active tissues. The lactic acid accumulates rapidly and the total time that the exercise could be sustained will determine the magnitude of the lactic acid concentration accumulation. Thus we conclude that the better motivated subject will urge himself to work for longer periods and thus accumulate higher blood lactic acid concentrations. This finding was first suggested by C.H. Wyndham et al. (1959).

During the latter stage of exercise O. Bang (1936), sometimes in addition to a "primary rise", also found a "secondary rise", while P.P. Eskildsen (1945) claims to have found a plateau after a transitory rise, while the results

of O. Jervell (1928) and those of J. Tepperman and H.M. Tepperman (1947) support the findings of the present study. The magnitude of the slope found between the 26th and 56th minute observations is so small that it might have been over looked by P.P. Eskildsen (1945). O. Bang (1936) on the other hand only did one experimental run at each work load, thus the "secondary rises" were not extensively investigated. From a survey of O. Bang's (1936) data, the "secondary rises" seem more likely to occur during the very late stages of exercise, thus this could be due to the subjects, who are in a state of fatigue, being compelled to change their exercising technique during the discomfort of blood sampling. These changes in pedalling technique will result in the incorporation of new muscle groups for the performance of exercise and will also result in an additional production of lactic acid.

A curve, which was a "plateau" over its entire course, has been classed by O. Bang (1936) as not typical. However, when the lactic acid concentrations accumulated are compared to the findings of this study, it was revealed that this curve falls within the 90% range, which has a "plateau" like trend for the entire period of exercise. From the available literature it seems that all the investigators in the past have overlooked this type of curve, which occurs only in a very small percentage range of the maximum oxygen intake value.

A.V. Hill (1923), G. Lundin and G. Ström (1946) found the lactic acid concentration relative to time curve to follow the course of a "plateau", similar to the oxygen consumption relative to time. E. Asmussen (1950) again claims to have found a curve with an increasing nature.

The controversy among authors, as to the exact time of exercise at which the "primary rise" reaches its

maximum, can be explained in terms of the finding that the "primary rise" moves from the first few minutes of exercise to the last minute of exercise, as the work load is increased. This suggests that, if results are to be compared, it is absolutely essential to state the percentages of the maximum oxygen intakes worked at and the blood sampling times for each subject, and to make comparisons only at the same sampling times and corresponding percentages of the maximum oxygen intake values.

In Table III are presented the optimum percentage of the maximum oxygen intake at which each subject was just able to sustain exercise for a maximum period of 60 minutes. The lactic acid concentration curve relative to time, which is a "plateau" over its entire range, falls roughly together with the calculated average of ± 83% of the maximum oxygen intake value. This is also that stage of exercise at which the lactic acid production proceeds at a rate which just exceeds the sum total of the components removing lactic acid from the blood.

It can thus be concluded that the continuous production of lactic acid, at a rate which equals or exceeds the lactic acid removal from blood, is one of the parameters contributing to the experience of the sensation commonly known as fatigue.

B. PYRUVIC ACID CONCENTRATIONS RELATIVE TO TIME.

A comparison made of graph 1 and 2 revealed that the changes in blood pyruvic acid concentrations relative to time follow roughly the same pattern as those of blood lactic acid.

In the range of work loads which resulted in oxygen consumptions of 40-60% of the maximum oxygen intake, the

existence of a "primary rise" in the pyruvic acid concentrations was due to anaerobic metabolic activities. This conclusion was drawn after observing a concomitant increase in the lactic acid concentrations. It is not clear, however, what is the origin of the accumulated pyruvic acid, for this might be formed either by the oxidative removal of lactic acid in the resting tissues or by the excessive formation of pyruvic acid in, and the rapid diffusion from, the anoxic muscle.

The finding that the accumulation of both lactic acid and pyruvic acid concentrations become excessive at the same oxygen consumption is in agreement, with the findings of E. Asmussen (1949) and C.G. Williams (1960). After conducting this present study the occurrence of this critical point was coined to a work load which resulted in an oxygen consumption of 60-65% of the maximum oxygen intake value. Within 5% of the maximum oxygen intake, the circulation of oxygen to the active muscles became limited and the supply of energy to the muscles started to depend on partly anaerobic metabolism. At work loads above 60% of the maximum oxygen intake, the elevated "plateau" like level, found between the 26th and 56th minute observations points out a continuous production of both pyruvic acid and lactic acid. The slight slopes of these nearly "plateau" like levels indicate an increased efficiency in the removal of both lactate and pyruvate with time. This efficiency remains constant for lactate, while decreasing for pyruvate as the work load increased. These slopes, however, are of a very small magnitude and could nearly be regarded as insignificant.

At oxygen intake values of 90% and 85% of the maximum oxygen intake value, the rates at which lactic acid and pyruvic acid respectively are produced and removed from the blood are in equilibrium. This balance, struck between the

production of these metabolites and those parameters removing these metabolites, is also that stage in metabolism at which the "maximum capacities" of the parameters removing these metabolites are in operation. Above these percentages, the "maximum removing capacities" of these parameters have been surpassed and these metabolites accumulated rapidly in the blood.

Now that relatively large amounts of both metabolites are present in the total body water, it is obvious that the pyruvic acid concentrations accumulated in blood have already exceeded those parameters removing it, while lactic acid is still being removed after the "primary rise" occurred. This could not be attributed to differences in the diffusion rates of these metabolites, because if the findings of W. Huckabee (1956) on erythrocytes are assumed to be the same in tissues, the opposite result would occur. Thus, it was concluded that while working under anaerobic conditions, there is firstly a production and accumulation of lactic acid, while the accumulation of pyruvic acid seems to follow later. Due to the very active nature of the lactate/pyruvate reaction, the concomitant increase in pyruvic acid might seem to occur at the same time as that of lactic acid. These observations, however, were made on the "turning points" of these metabolites, where relatively very small amounts of these metabolites were present. Major difficulties were encountered in determining the exact point where the working concentrations started to differ significantly from the basal and light exercise values.

The mean value for the optimum percentages of the maximum oxygen intake at which work could just be sustained for 1 hour only, is given in Table III as $\pm$ 83%. This percentage correlates remarkably well with the "plateau" like pyruvic acid curve found at 85%. It is also that stage in

metabolism, where the production and removal rates of pyruvic acid from blood, balance one another. Higher work loads will rapidly tire the subject and result in an excessive accumulation of pyruvic acid. Thus it "might" be that the accumulation of blood pyruvic acid plays a more prominent roll in fatigue than lactic acid, because pyruvic acid concentrations have already became ever increasing relative to time, while that of lactic acid is still being removed effectively.

The comparison of a sedentary and physically active group made by L.A. Cobb et al. (1963) revealed that the higher pyruvic acid concentrations were accumulated in the sedentary group. From the results presented in graph 2, it is obvious that subjects with different maximum oxygen intake values could not all be subjected to the same work load and the data accumulated then compared from one subject to another. Physically active subjects will have higher maximum oxygen intake values than sedentary people, therefore a work load of moderate intensity for a physically active man will be of a very heavy intensity for the physically inactive man. This then accounted for the finding of L.A. Cobb et al. (1963).

C. EXCESS LACTATE CONCENTRATIONS RELATIVE TO TIME.

The existence of a primary rise in the excess lactate concentration time curve presented in graph 3 did not confirm the finding of H.D. Thomas et al. (1964) who, when doing work loads lasting 10 minutes only, found the curve to be of a plateau like nature. The finding of L.A. Cobb et al. (1963), however, was to some extent confirmed, for this author only on a few occasions found a "primary rise" during the early stages of exercise that lasted up to 60 minutes.

D. PHYSIOLOGICALLY SOUND EVALUATION OF WORK STRESS.

A close correlation, found between the oxygen equivalents of excess lactate and the actual oxygen debt incurred, is assumued to be correct (W. Huckabee 1958). According to some critical points in the accumulation of excess lactate in blood, this study attempted to lay down well defined and physiologically sound criteria for the universal evaluation of work stress. This evaluation might then be used by the gold mining industry of South Africa for the efficient application of their labour force. These well defined criteria will also enable the exercise physiologist to state the exact work stress of each work load that the human body is subjected to. The comparison of data from one subject to another will now be possible, even those results from different investigations will be comparable.

Work stress.	% of max. O_2	Heart rates.
Light	50	± 110 beats/min.
Moderately heavy	65	± 136 " "
Heavy	90	± 169 " "
Very heavy	100	± 177 " "

The corresponding average excess lactate values were as follows:-

Work stress.	6 min.	26 min.	56 min.
Light	0.420	0.029	0.023
Moderately heavy	1.128	0.587	0.657
Heavy	4.398	4.081	4.132
Very heavy	Not investigated.		

For light exercise no well defined criterion could be proposed except for an arbitrarily chosen work load which would result in an oxygen consumption of ± 50% of the maximum

oxygen intake. Work loads of this intensity will have an average heart rate of ± 110 beats/min.

Moderately heavy exercise on the other hand was defined to that stage in metabolism at which the cardio-respiratory mechanism is supplying oxygen to the human tissues at a rate "just" insufficient to satisfy the entire metabolic demand. Partly anaerobic metabolism has commenced from 60-65% of the maximum intake value. This major change-over in the energy supplying mechanism of tissues seems also to be that stage in the metabolism at which the muscles can operate for 8 hours per working day without any ill effect on the health of a labourer. The average values found in this study are ± 5% higher than those found by C.H. Wyndham et al. (1962). Moderately heavy exercise is accompanied by an average heart beat of ± 136/min. At this heart rate the maximum stroke volume has also been surpassed (E. Asmussen, and M. Nielsen 1955). It seems that major physiological changes have occurred at this point in the metabolic pattern.

At ± 90% of the maximum oxygen intake value the removal of the calculated excess lactate from blood is balanced by the production thereof, no large accumulation of this metabolite will result and the concentration will remain constant for the entire period of exercise. The time for which an effort of this intensity could be maintained will be less than 1 hour. An average heart rate of ± 169 heart beats/min. will result at a work load of this intensity.

Very heavy muscular work could be defined to 100% of the maximum oxygen intake value. This work load corresponds to heart rates of 176.8 beats/min. and a maintenance time of 3-4 minutes only.

The criteria proposed above might seem to be an

over estimation; however, the daily mining procedure is of an intermittent nature. Recovery will take place from time to time throughout the whole shift.

For scientific purposes these criteria are also valuable, for they cover a large working range of each subject and give a fairly concise view of what might be expected from each subject.

The success in applying the above evaluation effectively will depend on increasing the maximum oxygen intake value of each labourer as much as possible. This could be achieved by directing the week-end interests of labourers into the participation in well organized sport. The labourer will be well motivated and at the same time the industry will benefit from the increased maximum oxygen intake values.

Long distance atheletes will benefit from this study by knowing that they are able to run at 60% of the maximum oxygen intake for long periods without any ill effect on their health. At 83% of their maximum oxygen intake value on the other hand, exercise can be sustained for $\pm$ 60 minutes. This will largely be dependent on motivation.

The defence force will also be able to calculate the rate at which men could be moved over a long stretch without harming the health of the men for combat. They will also be in the position to calculate the rate of moving men rapidly over a short distance.

The physiological evaluation of workers, proposed by E.H. Christensen (1953), seems to be an arbitrarily chosen set of oxygen consumptions based on experience only. This evaluation made no allowance for distinguishing between men of different somato types. If a man of 4 litres maximum oxygen intake capacity performs a work load requiring an

oxygen consumption of 2 litres, he will only be working at 50% of his capacity and will not even make a demand on his anaerobic metabolic stores. A man of 3 litres maximum oxygen intake capacity on the other hand, when doing the same work load, will extend himself up to 67% of his capacity and will be dependent on a continuous supply of energy from anaerobic sources. These two men could definitely not be regarded as performing the same work stress.

The comparison made of excess lactate in sedentary and physically active subjects (L.A. Cobb et al. 1963) revealed that even in recent investigations the comparison of excess lactate data from 1 subject or group of subjects with others has still not been put on to a sound physiological basis. All the subjects, whether big or small and sedentary or physically active, were subjected to the same work load and did thus not all experience the same degree of stress. This was also confirmed by the differences in the time that each sedentary subject could sustain work. In the physically active group, it seems that with the exception of 3, all the subjects worked at loads not even high enough for the production of excess lactate. This fact then accounted for the remarkable reduction in scatter on the results of the physically active group. If the subjects were all worked at the same percentages of their maximum oxygen intake values, the scatter would be much smaller and it would be valid to draw averages of the excess lactate, lactate and pyruvic acid concentrations accumulated.

E. RELATIONSHIP BETWEEN THE MAXIMUM HEART RATE AND THE OPTIMUM PERCENTAGE OF THE MAXIMUM OXYGEN INTAKE AT WHICH WORK COULD BE SUSTAINED FOR ONE HOUR.

There appears to be a relationship between these two variables. However, this matter should be reinvestigated on a better basis and with more observations. Thus if 2 men of the same capacity should be chosen from as far as endurance work is concerned there is a high probability that the man with the lower maximum heart rate value will be the more suitable.

This finding is directly applicable to the defence force and athletes.

CHAPTER VI.

CONCLUSIONS.

1. A valid comparison of the lactic acid, pyruvic acid and excess lactate data from one subject or group of subjects with those of another subject or group of subjects can only be achieved if:-

   a) The percentages of the maximum oxygen intake, worked at, are the same.

   b) The blood sampling times exactly correspond.

2. The accumulation of lactic acid, pyruvic acid and excess lactate in blood becomes excessive when a work-stress of 60-65% of the maximum oxygen intake value has been surpassed. This is also that stage in metabolism at which a continuous anaerobic energy supply to the active muscles makes its self apparent.

3. The maximum capacities of the components removing blood lactic acid and excess lactate is reached at a work stress resulting in ± 90% of the maximum oxygen intake value. The capacity of the components removing blood pyruvic acid on the other hand was found to be ± 5% sooner.

4. The maximum capacity of the components removing blood pyruvic acid was found to correspond well with the 82.9% value of the maximum oxygen intake at which work could be sustained for one hour only. Thus it might be that pyruvic acid accumulation contributes to fatigue.

5. Existence of a "primary rise" during the first few minutes of exercise was confirmed in lactic acid, pyruvic acid and excess lactate concentrations relative to time.

At ± 85% of the maximum oxygen intake value, this rise was abolished for pyruvic acid, while for lactic acid and excess lactate it only disappeared at ± 90%.

6. It seems that a man with a lower maximum heart rate value will be able to work at a higher percentage of the maximum oxygen intake value for the same time interval than a man with a high maximum heart rate value.

7. The following work-stress criterion was proposed for industry:-

Work stress.	% of max. O_2	Heart rates.
Light	50	± 110 beats/min.
Moderately heavy	65	± 136 " "
Heavy	90	± 169 " "
Very heavy	100	± 177 " "

The corresponding average excess lactate values were as follows:-

Work stress.	6 min.	26 min.	56 min.
Light	0.420	0.029	0.023
Moderately heavy	1.128	0.587	0.657
Heavy	4.398	4.081	4.132
Very heavy	Not investigated.		

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TABLE I.

PHYSICAL CHARACTERISTICS.

Group	Subject.	Heights		Weights.	
		in.	cm.	lbs.	Kg.
1	88366	69.25	175.9	156	70.9
	88609	67.00	170.2	140	63.6
2	132969	67.50	171.5	138	62.7
	134554	62.00	157.5	131	59.6
3	17620	69.25	175.9	161	73.2
	27111	66.00	167.6	134	60.9
	17442	65.00	165.1	143	65.0
4	62626	67.50	171.5	135	61.4
	61336	66.75	169.5	147	66.8
	63576	63.50	161.3	130	59.1
5	108499	65.25	165.7	133	60.5
	105570	64.00	162.6	124	56.4
	133108	69.00	175.3	139	63.2
6	102512	64.00	162.6	118	53.6
	100366	66.75	169.5	139	63.2
	98655	65.75	167.0	138	62.7
7	117927	63.00	160.0	127	57.7
	114359	66.75	169.5	159	72.3
	118613	69.00	175.3	153	69.6
AVERAGES.		66.17	168.1	139.2	63.3

TABLE II.

MAXIMUM OXYGEN CAPACITIES.

Group	Subjects	Maximum oxygen capacity l/min.	Maximum oxygen intake in ml. per kg.
1	88366	3.84	54.16
	88609	3.05	47.80
2	132969	3.08	49.12
	134554	2.62	43.96
3	17620	3.71	50.68
	27111	3.35	55.01
	17442	3.16	48.62
4	62626	3.32	54.07
	61336	3.05	45.66
	63576	2.89	48.90
5	108499	3.45	57.02
	105570	3.16	56.03
	133108	3.31	52.37
6	102512	2.72	50.75
	100366	3.05	48.26
	98655	2.69	42.90
7	117927	2.66	46.10
	114359	3.62	50.07
	118613	3.23	46.41
AVERAGES.		3.16	49.89

TABLE III.

MAXIMUM HEART RATES AND ENDURANCE TIMES.

Groups	Subjects	Maximum Heart rate values in beats/min.	% of max. oxygen intake.
1	88366	172.4	80.2
	88609	164.5	86.2
2	132969	186.2	78.3
	134554	180.4	86.3
3	17620	182.1	80.9
	27111	173.8	88.4
	17442	187.6	76.9
4	62626	187.1	82.8
	61336	163.7	89.5
	63576	173.8	83.7
5	108499	170.8	73.3
	105570	185.6	71.2
	133108	178.9	87.9
6	102512	179.2	74.6
	100366	177.9	82.0
	98655	176.7	87.0
7	117927	183.3	86.5
	114359	169.3	90.1
	118613	165.6	90.7
AVERAGES.		176.8	82.9

TABLE IV.

AVERAGE HEART RATES IN BEATS/MIN. AT VARIOUS PERCENTAGES OF THE MAXIMUM OXYGEN INTAKE VALUE.

n	%	MINUTES					
		5	10	15	30	45	60
6	40	103.3	102.3	102.0	104.9	105.1	106.7
11	45	105.1	104.9	105.2	108.5	107.1	110.0
3	50	104.1	106.0	109.1	108.2	109.1	110.4
11	55	115.0	116.4	117.2	120.9	119.6	121.1
6	60	120.0	123.1	121.2	126.7	124.3	129.9
13	65	125.0	128.4	130.0	135.5	134.5	138.0
11	70	133.2	137.8	138.2	145.2	144.2	149.1
15	75	139.3	142.6	142.8	150.3	149.8	155.2
12	80	142.8	148.3	149.1	156.5	158.0	160.0
12	85	149.6	156.2	157.6	165.5	167.3	167.0
7	90	152.9	160.0	160.8	168.0	169.9	168.0
5	95	155.3	164.1	167.6	175.8	176.6	176.5

TABLE V(A).

THE AVERAGE 6th MIN. OBSERVATIONS FOR ALL THE SUBJECTS AT CORRESPONDING PERCENTAGES.

n	% ± 2% of the max. O_2 intake.	6th min. Observations		
		PA	LA	KL
6	40	0.178	1.529	0.150
11	45	0.183	1.584	0.289
3	50	0.212	1.960	0.420
10	55	0.190	2.314	0.663
6	60	0.201	1.783	0.354
13	65	0.235	3.009	1.128
11	70	0.253	3.673	1.736
15	75	0.275	4.822	2.567
12	80	0.291	5.232	2.983
12	85	0.302	6.464	4.229
7	90	0.324	7.040	4.398
6	95 ± 3	0.363	8.697	5.992

TABLE V(D).

THE AVERAGE 26th MIN. OBSERVATIONS FOR ALL THE SUBJECTS AT CORRESPONDING PERCENTAGES.

n	% ± 2% of the max. O_2 intake.	26 th min. Observations.		
		PA	LA	KL
6	40	0.150	1.168	0.062
11	45	0.143	1.134	0.116
3	50	0.176	1.470	0.029
10	55	0.164	1.798	0.379
6	60	0.174	1.299	0.079
13	65	0.208	2.293	0.537
11	70	0.224	2.604	0.931
15	75	0.253	4.148	2.040
12	80	0.271	4.293	2.176
12	85	0.308	6.150	3.778
7	90	0.330	6.687	4.081
6	95 ± 3	0.386	10.033	6.371

TABLE V(C).

THE AVERAGE 56th MIN. OBSERVATIONS FOR ALL THE SUBJECTS AT CORRESPONDING PERCENTAGES.

n	% ± 2% of the max. O_2 intake.	56th min. Observations.		
		PA	LA	XL
6	40	0.159	1.063	-0.034
11	45	0.142	1.178	0.187
3	50	0.147	1.308	0.023
10	55	0.155	1.634	0.313
6	60	0.158	1.266	0.152
13	65	0.192	2.185	0.657
11	70	0.208	2.470	0.860
15	75	0.246	4.190	2.203
12	80	0.266	4.113	2.050
12	85	0.297	6.637	4.343
7	90	0.321	6.724	4.132
6	95 ± 3	0.393	10.843	7.686

TABLE VI(A).

SUBJECT No. 133108

Work rate	Heart rates in beats/min.	Oxygen intake in litres/min.
2500	81	0.95
	80	0.89
	97	0.93
5000	107	1.56
	121	1.61
	116	1.50
7500	141	2.26
	136	2.21
	138	2.16
10000	173	3.00
	164	3.00
	170	2.95
11000	181	3.18
	175	3.18
	174	3.10
12000	183	3.22
	178	3.24
	174	3.05
13000	178	3.17
	176	3.38
	179	3.38
14000	185	3.41
	184	3.29
	180	3.24

HEART RATES IN BEATS/MIN.

Work rate	%	Minutes.					
		5	10	15	30	45	60
3000		112 113 97	114 105 94	108 103 95	108 99 93	104 92 93	105 95 93
AVERAGE	31.4	107.3	104.3	102.0	100.0	96.3	97.6
4000		104 107 109	99 115 102	99 106 103	104 110 105	101 106 101	103 109 107
AVERAGE	37.8	106.6	105.3	112.6	106.3	102.6	106.3
5000		102 113 109	103 107 111	105 105 109	111 107 113	113 105 105	117 113 111
AVERAGE	46.2	108.0	107.0	106.3	110.3	107.6	119.6
6000		113 121 123	113 121 123	113 120 123	119 121 123	117 124 131	121 127 133
AVERAGE	54.4	119.0	119.0	118.6	124.0	124.0	127.0
7000		141 141 130	138 138 131	140 141 129	146 145 135	150 143 137	156 150 141
AVERAGE	66.8	137.3	136.0	136.6	142.0	143.3	149.0
8000		143 141 143	144 141 141	142 143 142	151 146 145	151 146 149	157 155 156
AVERAGE	76.4	142.3	142.0	142.3	147.3	148.6	156.0
9000		155 156 151	157 159 156	160 162 158	163 171 169	168 177 171	167 --- 173
AVERAGE	87.9	154.0	157.3	160.0	167.6	172.0	170.0

TABLE VI(C).

SUBJECT NO. 133108.

6th MIN. OBSERVATIONS.					
Work rate	%	PA	LA	XL	O_2
3000		0.220 0.193 0.116	1.417 1.462 1.189	0.000 0.219 0.422	1.142 1.054 0.956
AVERAGE	31.4	0.176	1.356	0.214	1.051
4000		0.230 0.227 0.148	1.441 1.914 1.361	-0.040 0.452 0.408	1.215 1.194 1.288
AVERAGE	37.8	0.202	1.572	0.273	1.232
5000		0.369 0.193 0.202	2.015 1.355 1.871	0.040 -0.124 0.170	1.524 1.474 1.434
AVERAGE	46.2	0.255	1.747	0.029	1.477
6000		0.175 0.259 0.185	2.528 3.748 3.023	1.154 1.769 0.825	1.777 1.660 1.720
AVERAGE	54.4	0.206	3.100	1.249	1.719
7000		0.272 0.315 0.281	4.230 5.857 2.971	1.708 2.640 1.656	2.109 2.158 2.146
AVERAGE	66.8	0.289	4.353	2.001	2.138
8000		0.314 0.442 0.335	5.795 6.132 5.677	3.021 3.184 2.164	2.373 2.421 2.432
AVERAGE	76.4	0.364	5.845	2.790	2.409
9000		0.384 0.319 0.270	9.114 8.560 6.813	6.753 5.612 5.028	2.791 2.707 2.786
AVERAGE	87.9	0.324	8.172	5.798	2.761

SUBJECT NO. 133108.

26th MIN. OBSERVATIONS.					
Work rate	%	PA	LA	XL	O_2
3000		0.203 0.132 0.121	1.240 1.222 1.154	-0.067 0.372 0.375	1.049 0.964 0.997
AVERAGE	31.4	0.152	1.205	0.227	1.003
4000		0.180 0.116 0.148	1.483 1.158 1.294	0.324 0.411 0.341	1.279 1.241 1.253
AVERAGE	37.8	0.148	1.312	0.359	1.258
5000		0.216 0.172 0.182	1.335 1.532 1.892	0.178 0.214 0.053	1.506 1.464 1.501
AVERAGE	46.2	0.190	1.586	0.148	1.490
6000		0.134 0.206 0.186	1.528 2.569 3.398	0.476 0.995 1.188	1.754 1.807 1.731
AVERAGE	54.4	0.175	2.498	0.886	1.764
7000		0.271 0.293 0.365	4.110 4.428 3.086	1.597 1.810 1.378	2.189 2.249 2.205
AVERAGE	66.8	0.310	3.875	1.595	2.214
8000		0.312 0.365 0.337	7.280 5.894 6.638	4.593 3.459 3.104	2.537 2.418 2.401
AVERAGE	76.4	0.338	6.604	3.719	2.452
9000		0.461 0.387 0.300	10.432 11.578 9.232	7.561 8.002 6.903	2.892 2.832 2.842
AVERAGE	87.9	0.383	10.414	7.489	2.855

TABLE VI(E).

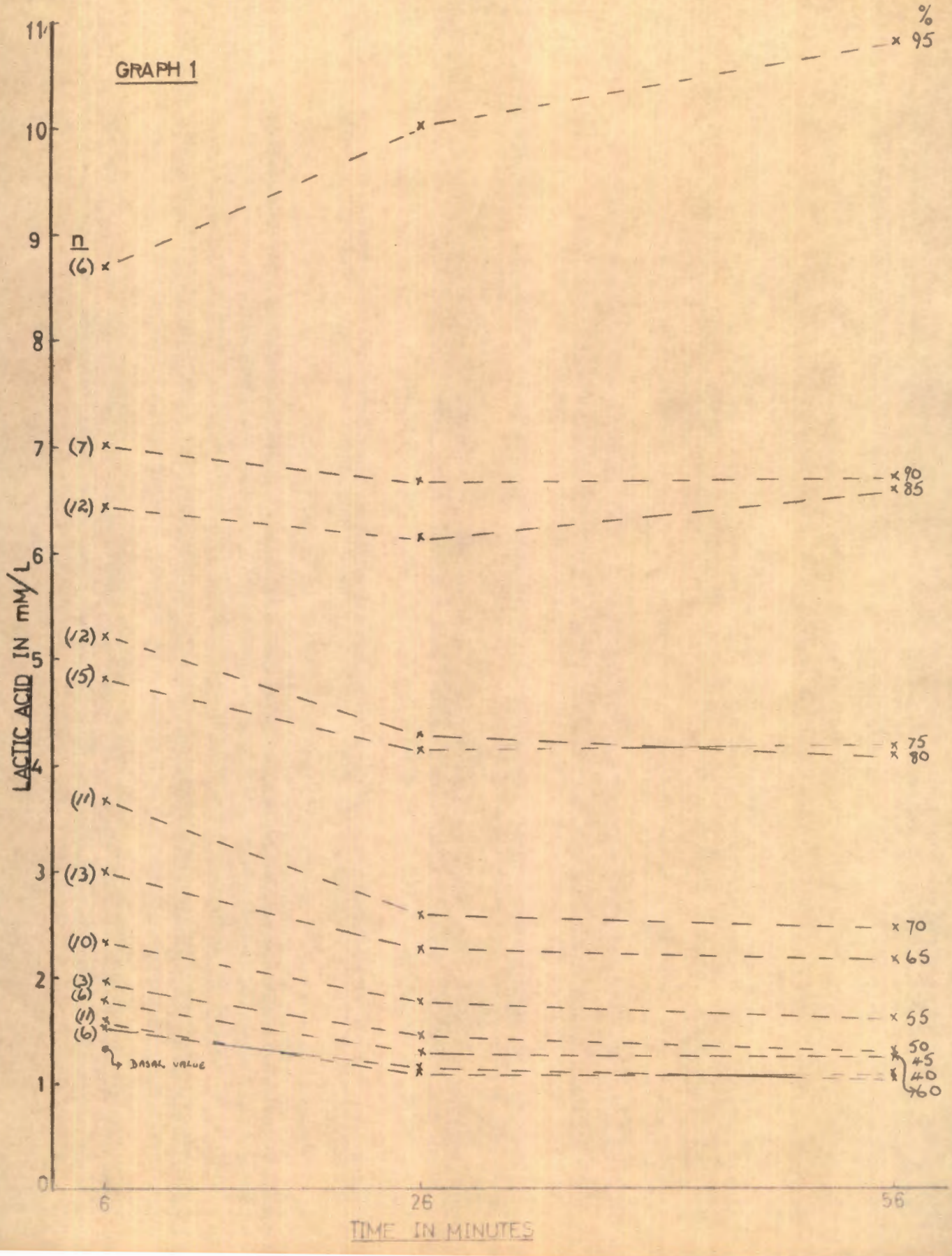
SUBJECT NO. 133108.

56th MIN. OBSERVATIONS.					
Work rate.	%	PA	LA	XL	O_2
3000		0.182 0.137 0.151	1.361 1.379 1.147	0.189 0.497 0.175	1.103 0.989 1.026
AVERAGE	31.4	0.157	1.296	0.296	1.039
4000		0.153 0.089 0.133	1.156 1.216 1.299	0.171 0.643 0.443	1.240 1.236 1.260
AVERAGE	37.8	0.125	1.224	0.419	1.245
5000		0.231 0.162 0.123	1.767 1.381 1.738	0.530 0.140 0.495	1.604 1.478 1.509
AVERAGE	46.2	0.172	1.629	0.388	1.530
6000		0.167 0.207 0.201	1.974 1.976 2.706	0.662 0.394 0.318	1.806 1.802 1.792
AVERAGE	54.4	0.192	2.219	0.458	1.800
7000		0.225 0.285 0.302	4.570 5.190 2.953	2.484 2.643 1.540	2.195 2.230 2.200
AVERAGE	66.8	0.271	4.238	2.222	2.208
8000		0.329 0.397 0.255	6.753 6.515 5.817	3.920 3.867 3.143	2.560 2.494 2.527
AVERAGE	76.4	0.327	6.362	3.643	2.527
9000		0.495 0.360 0.289	13.149 11.388 9.349	10.066 8.062 7.106	2.916 2.904 2.908
AVERAGE	87.9	0.381	11.295	8.411	2.909

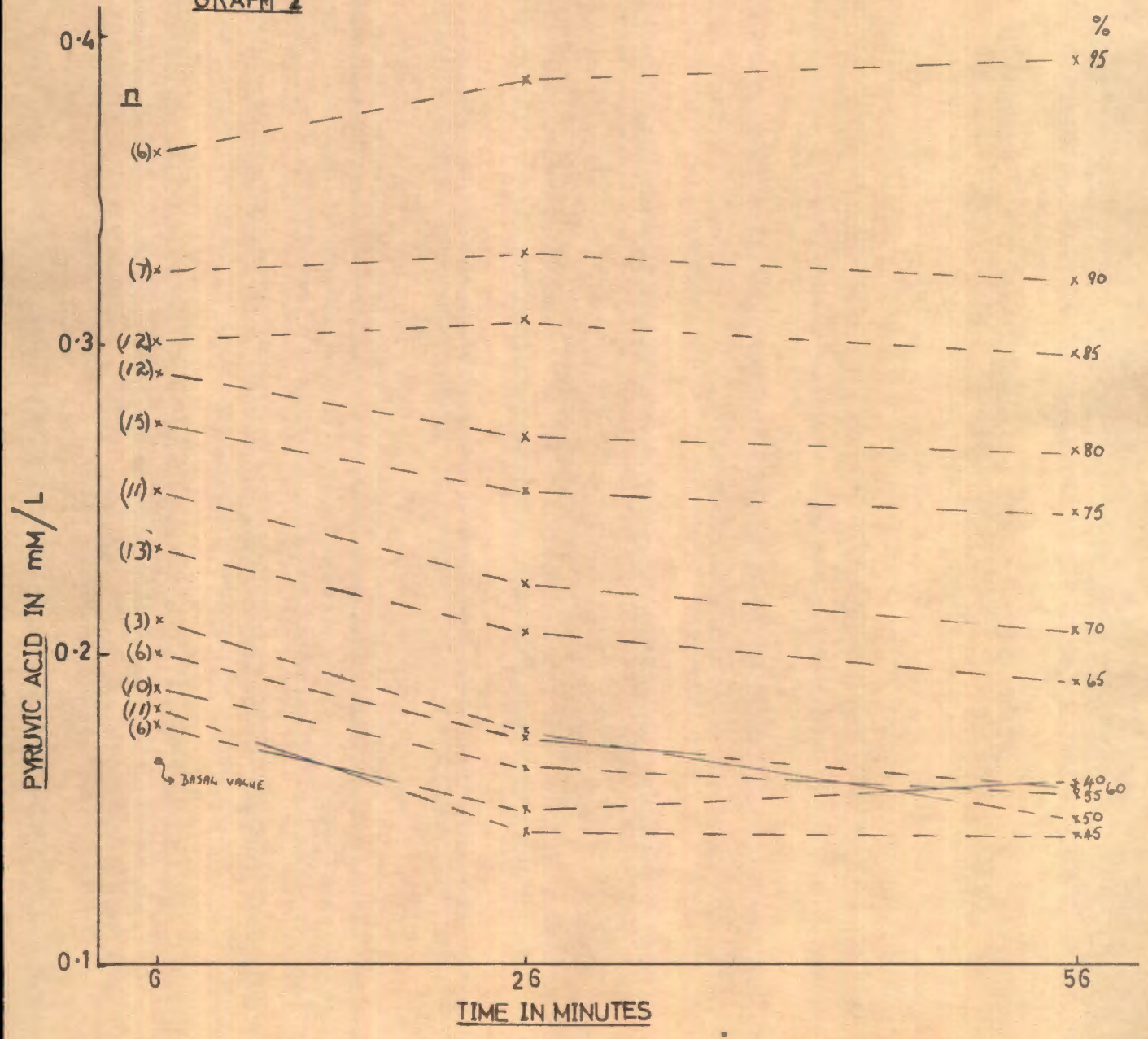
TABLE VII.

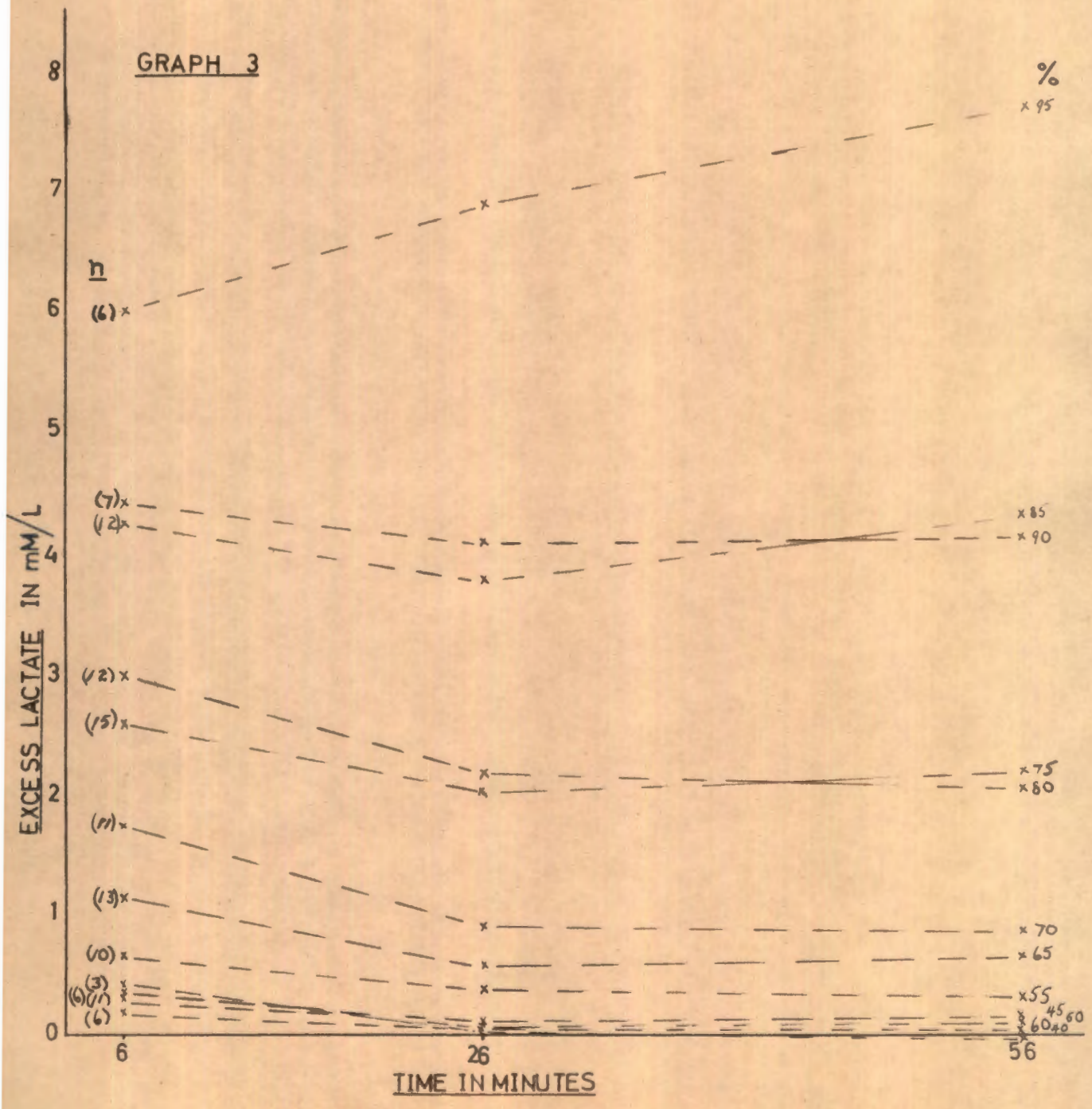
TOTAL SCATTER ON THE LACTIC ACID DATA OF 13 SUBJECTS WORKING AT 65% OF THEIR MAXIMUM OXYGEN INTAKE VALUE.

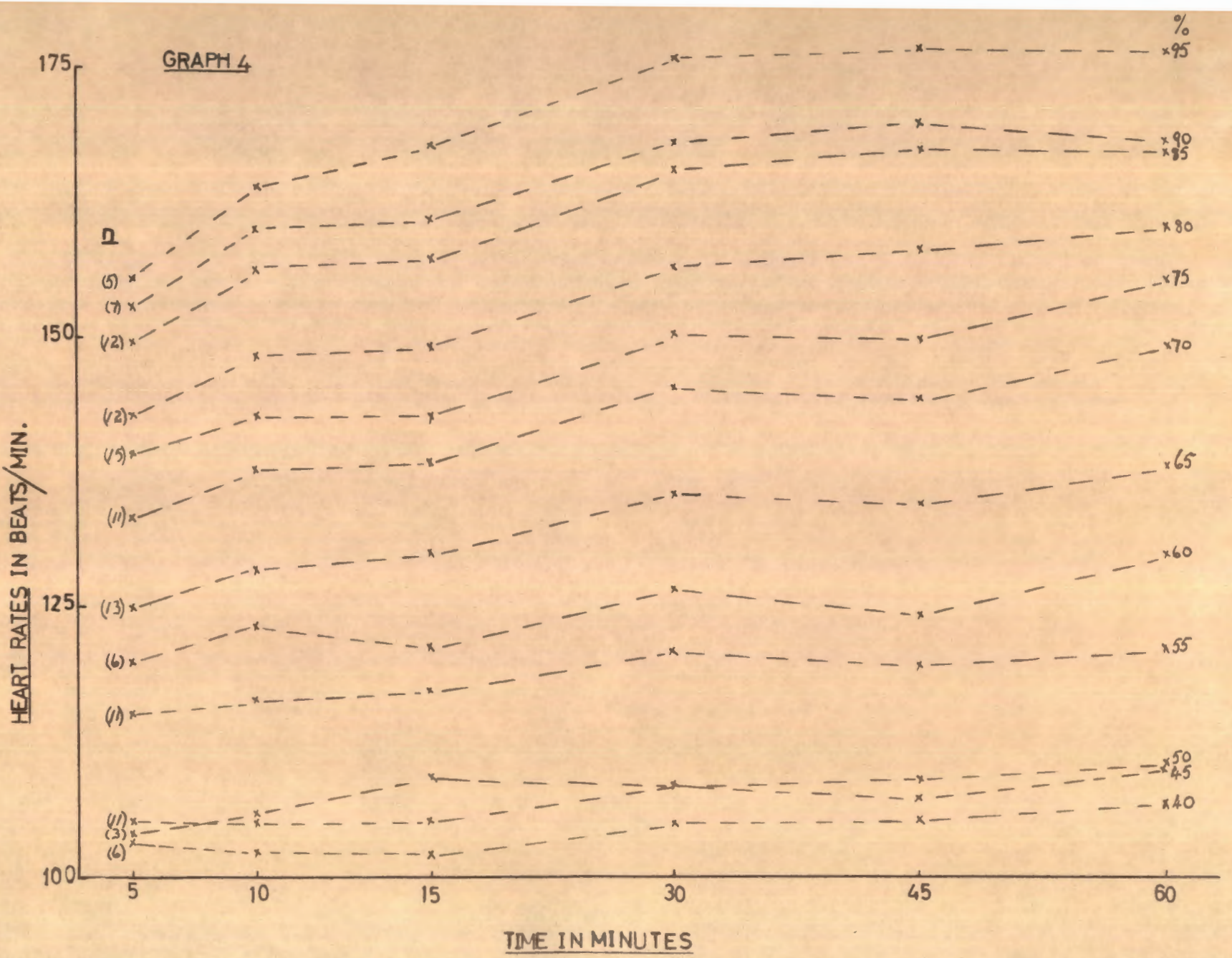
6th min.	26th min.	56th min.
2.475	1.780	1.584
4.090	2.672	2.149
2.075	2.009	1.962
2.890	1.908	2.288
2.684	2.379	1.959
2.230	1.327	1.469
4.353	3.875	4.238
4.369	3.284	2.984
3.442	2.566	2.029
2.476	1.716	1.783
2.398	1.583	1.491
3.486	2.586	2.168
2.154	2.124	2.300
	AVERAGE	
3.009	2.293	2.185
	SCATTER	
2.29	2.55	2.77

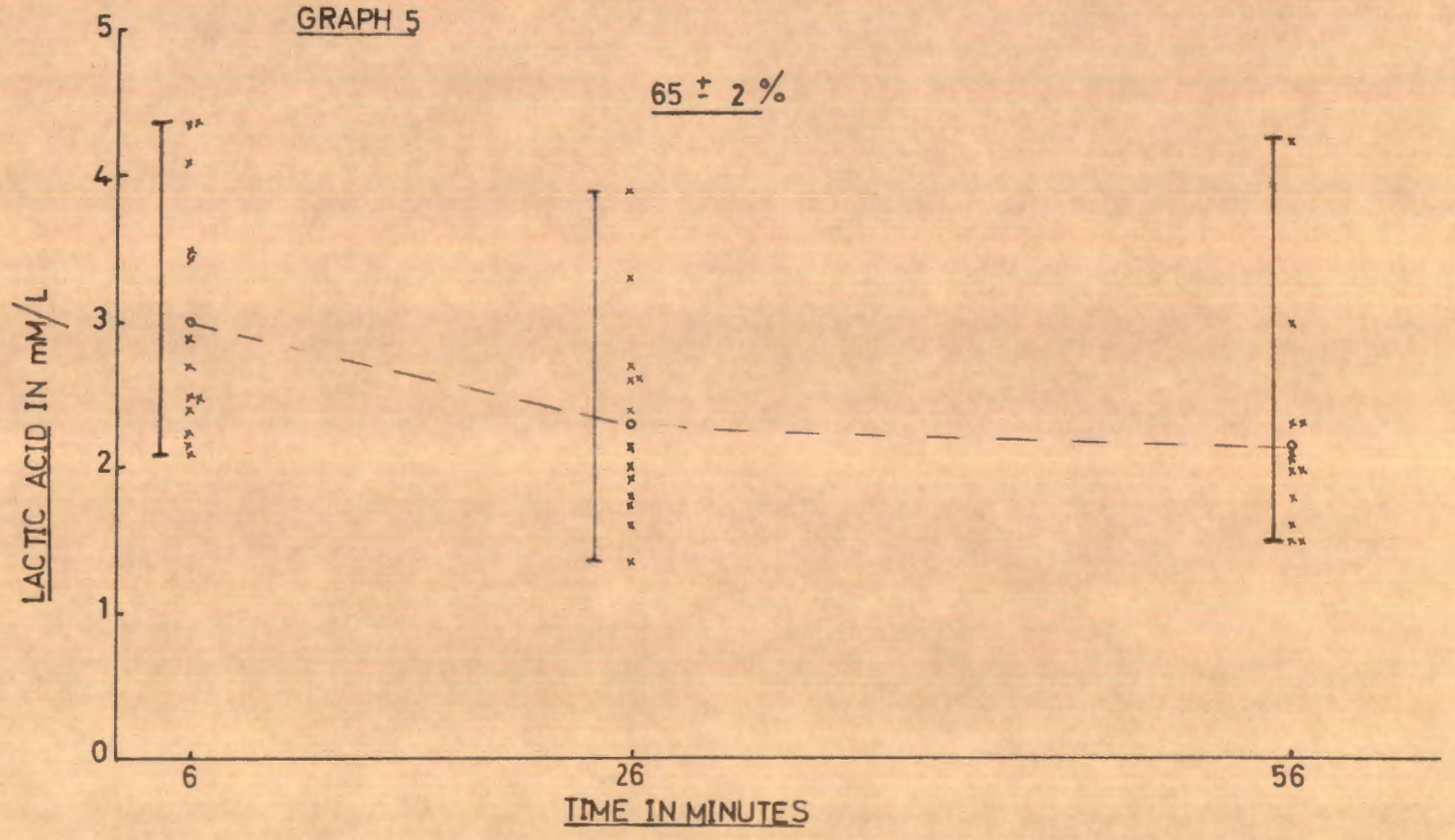

GRAPH 1
LACTIC ACID IN mM/L
TIME IN MINUTES
n
%
(6)
95
(7)
90
(12)
85
(12)
(15)
75
80
(11)
(13)
70
(10)
65
(3)
(6)
(11)
(6)
55
50
45
40
60
BASAL VALUE
0
1
2
3
4
5
6
7
8
9
10
11
6
26
56

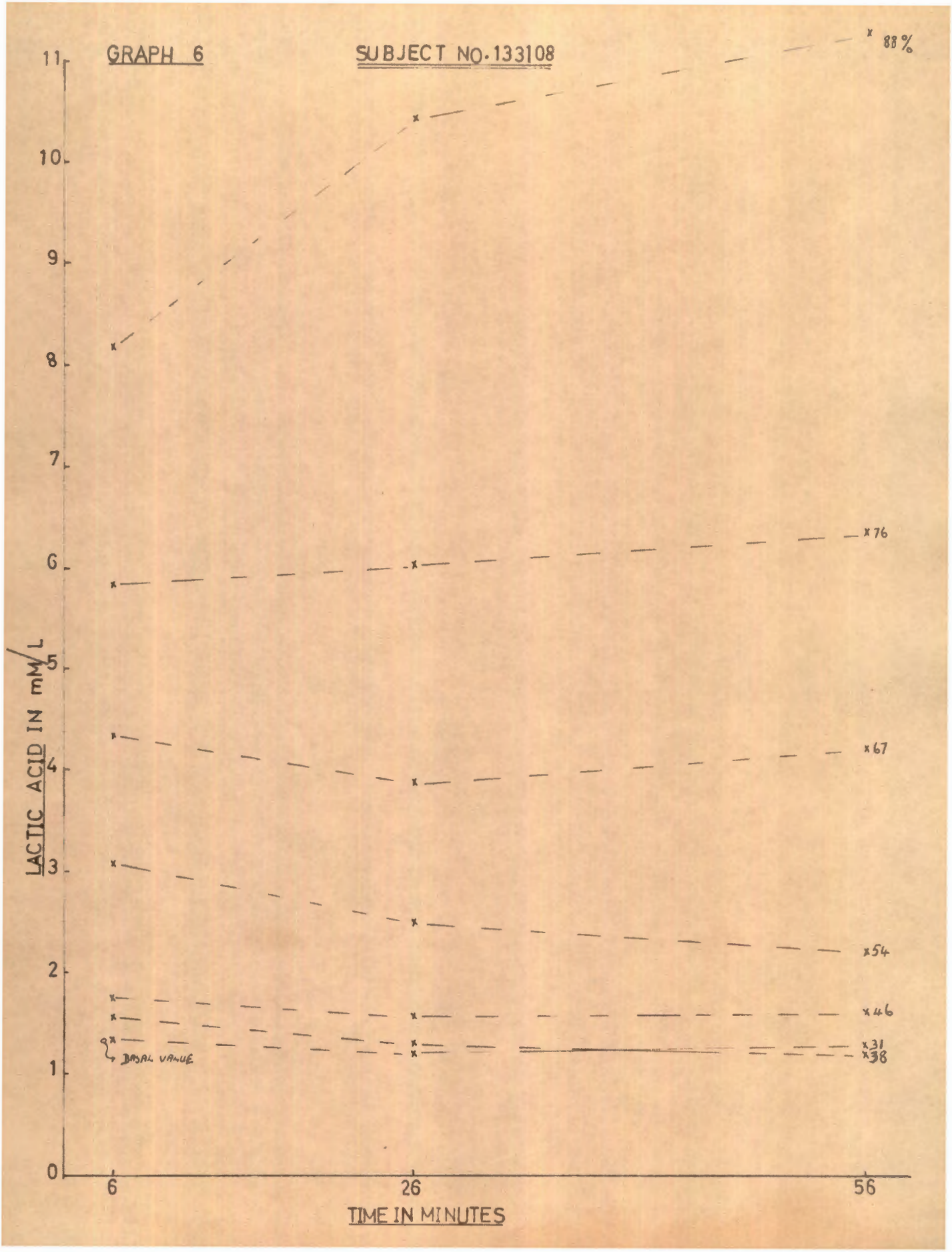
GRAPH 2


%
n
0·4
0·3
0·2
0·1
PYRUVIC ACID IN mM/L
(6)
(7)
(12)
(12)
(15)
(11)
(13)
(3)
(6)
(10)
(11)
(6)
BASAL VALUE
95
90
85
80
75
70
65
60
55
50
45
40
6
26
56
TIME IN MINUTES


GRAPH 3
%
h
95
85
90
75
80
70
65
55
60
45
40
50
(6)
(7)
(12)
(12)
(15)
(11)
(13)
(10)
(3)
(6)
(11)
(6)
EXCESS LACTATE IN mM/L
0
1
2
3
4
5
6
7
8
6
26
56
TIME IN MINUTES

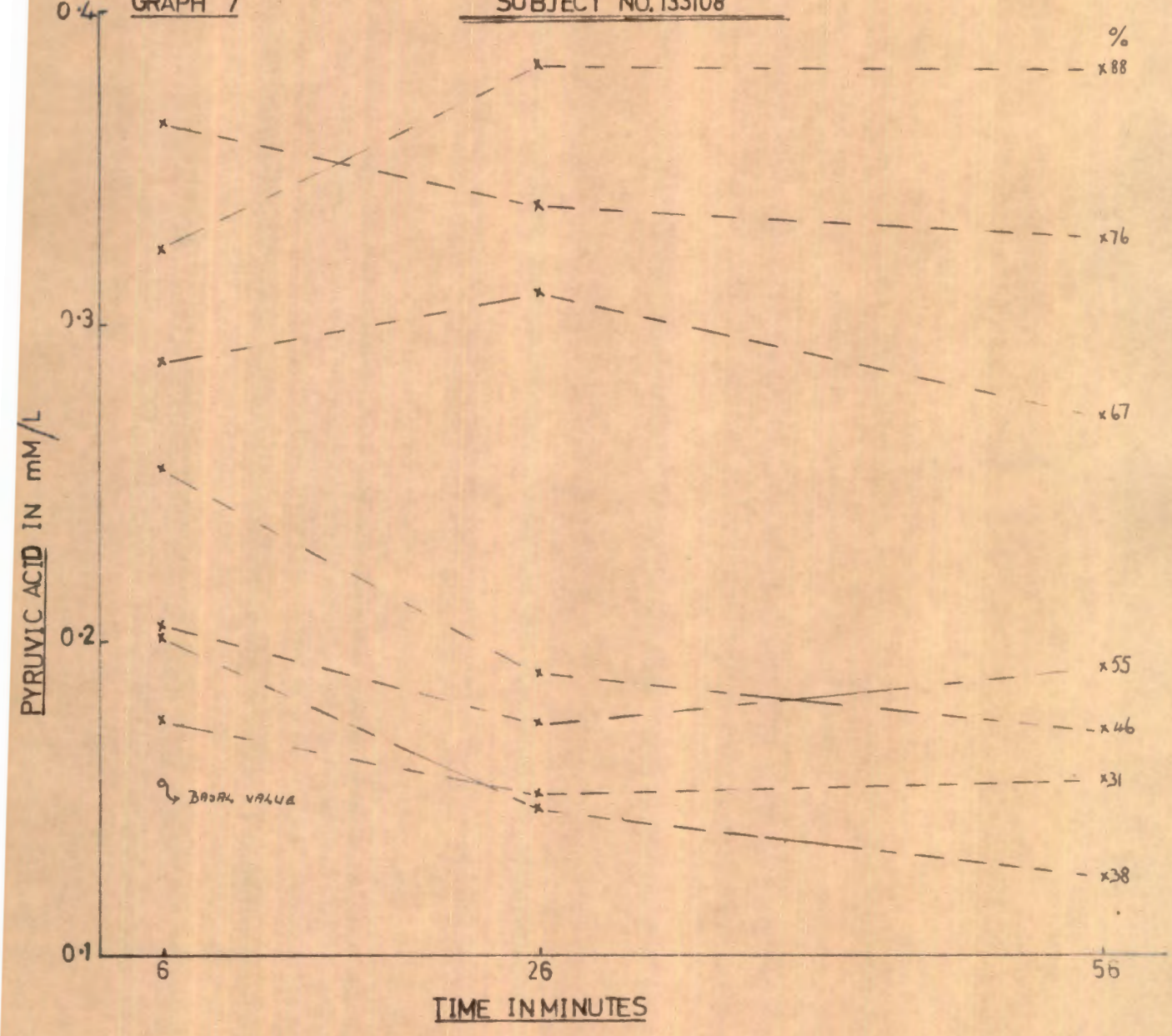

GRAPH 4
%
95
90
85
80
75
70
65
60
55
50
45
40
175
150
125
100
HEART RATES IN BEATS/MIN.
5
10
15
30
45
60
TIME IN MINUTES


GRAPH 5
65 ± 2 %
LACTIC ACID IN mM/L
5
4
3
2
1
0
6
26
56
TIME IN MINUTES


GRAPH 6
SUBJECT NO. 133108
88%
76
67
54
46
31
38
BASAL VALUE
LACTIC ACID IN mM/L
TIME IN MINUTES
0
1
2
3
4
5
6
7
8
9
10
11
6
26
56

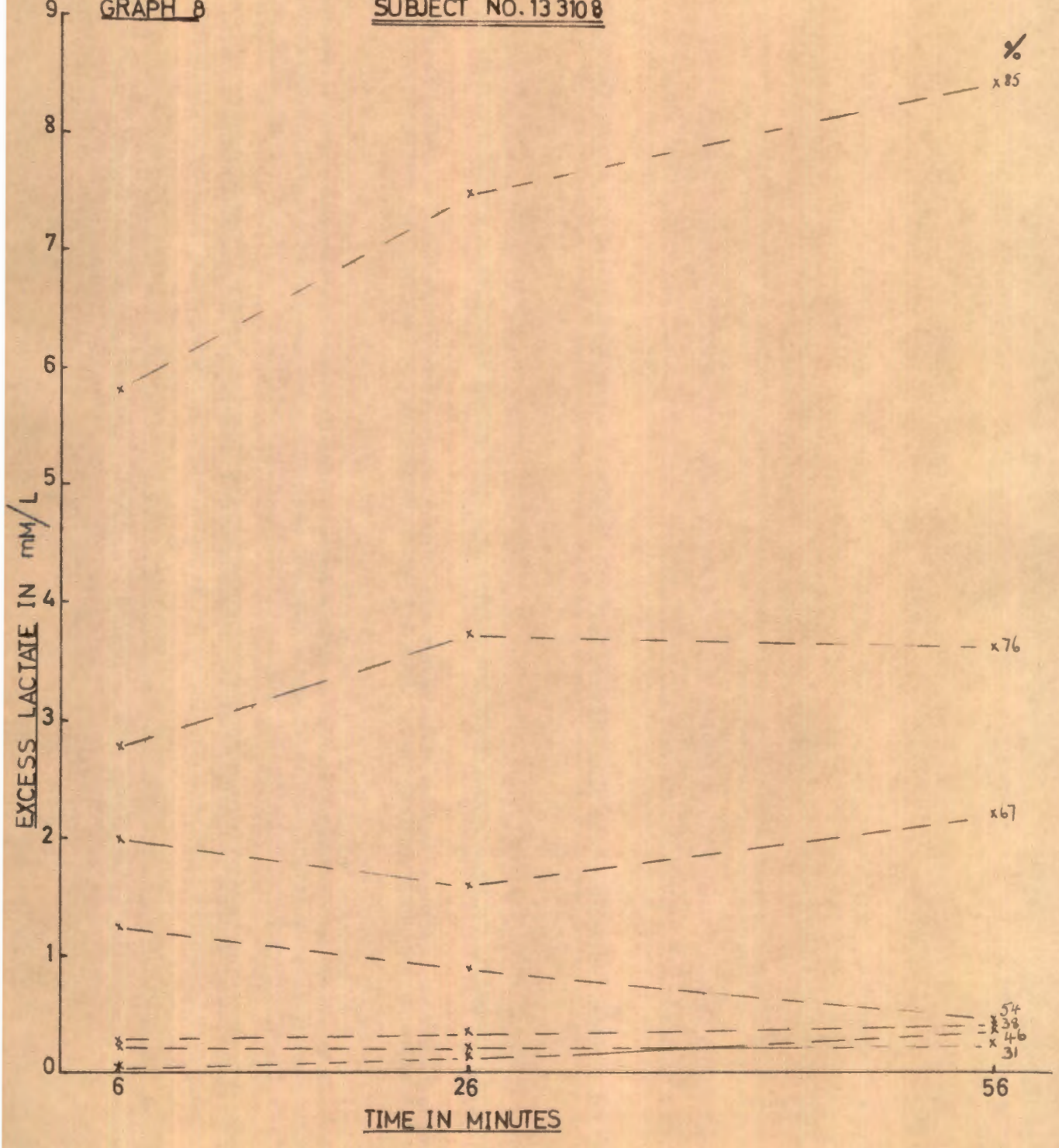
GRAPH 7

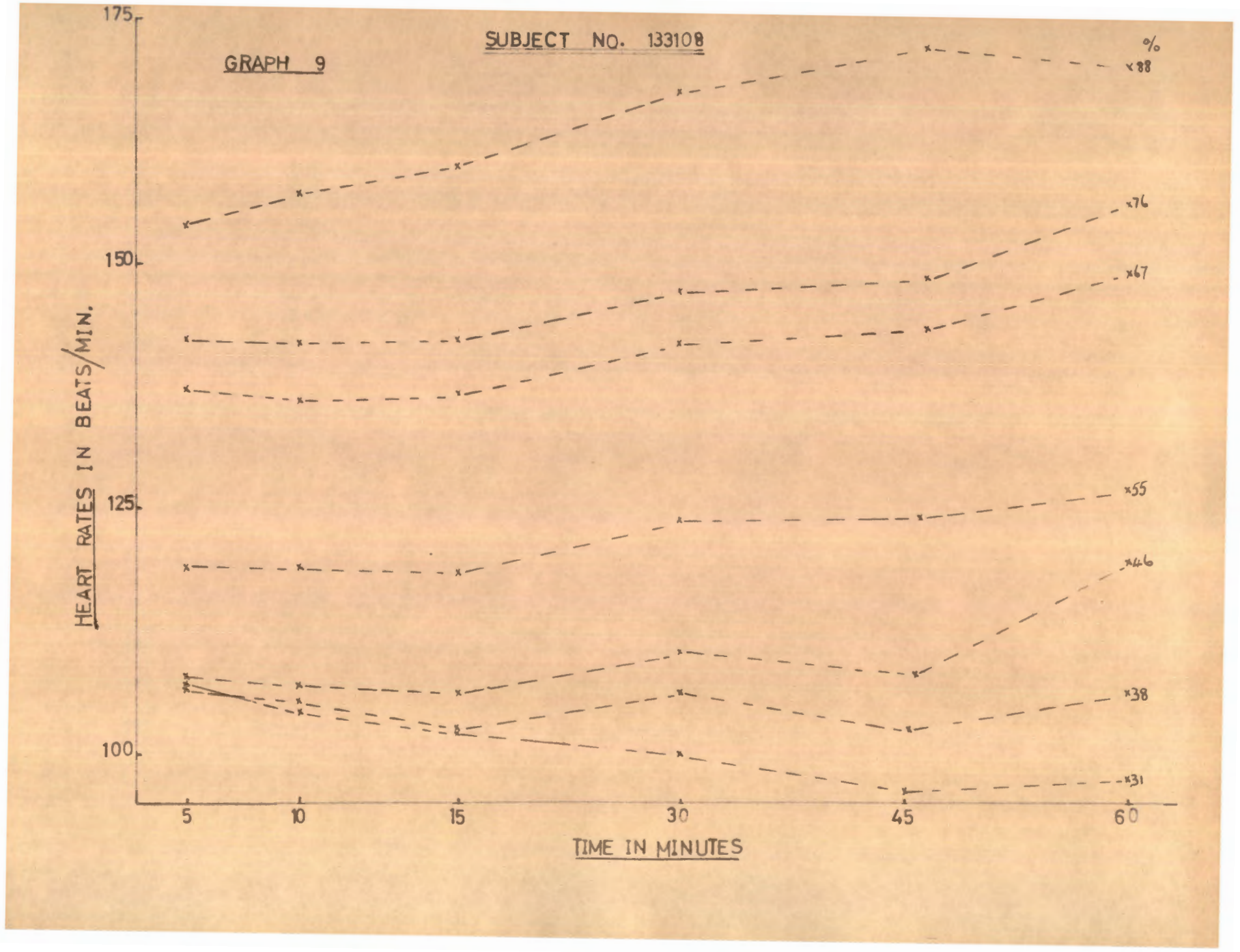
SUBJECT NO. 133108



GRAPH 8

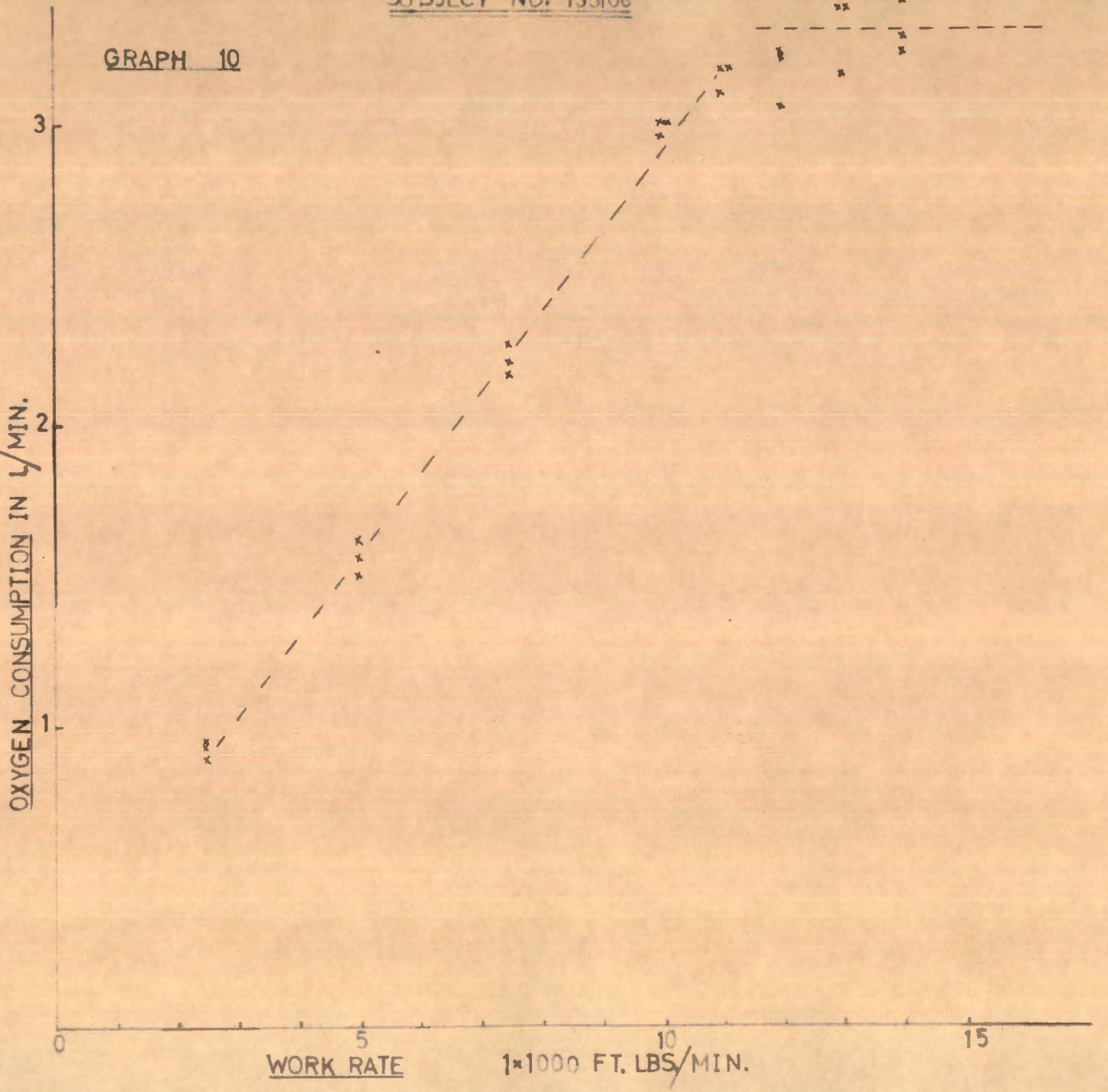
SUBJECT NO. 133108



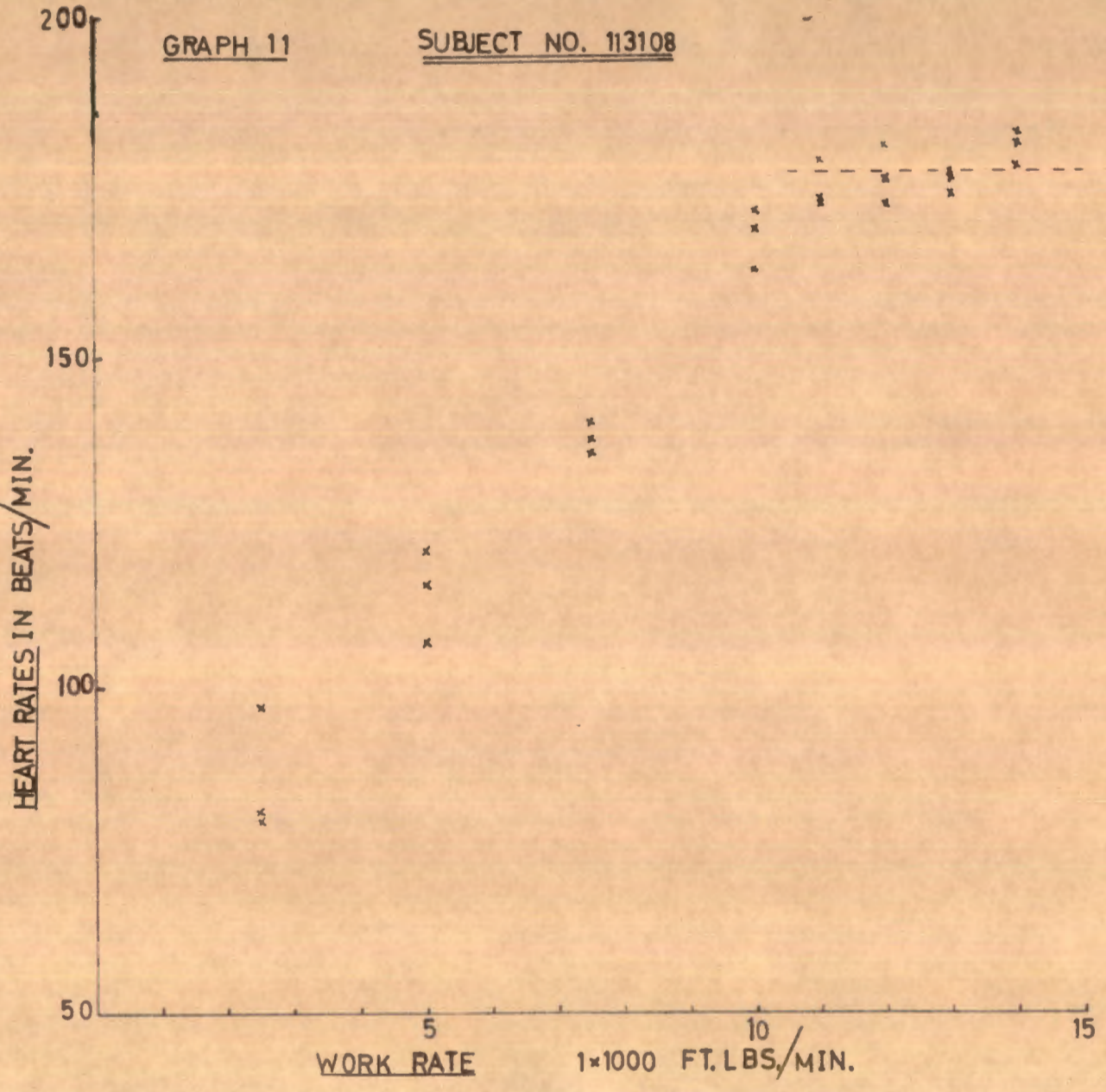

SUBJECT NO. 133108
GRAPH 9
%
88
76
67
55
46
38
31
175
150
125
100
HEART RATES IN BEATS/MIN.
5
10
15
30
45
60
TIME IN MINUTES

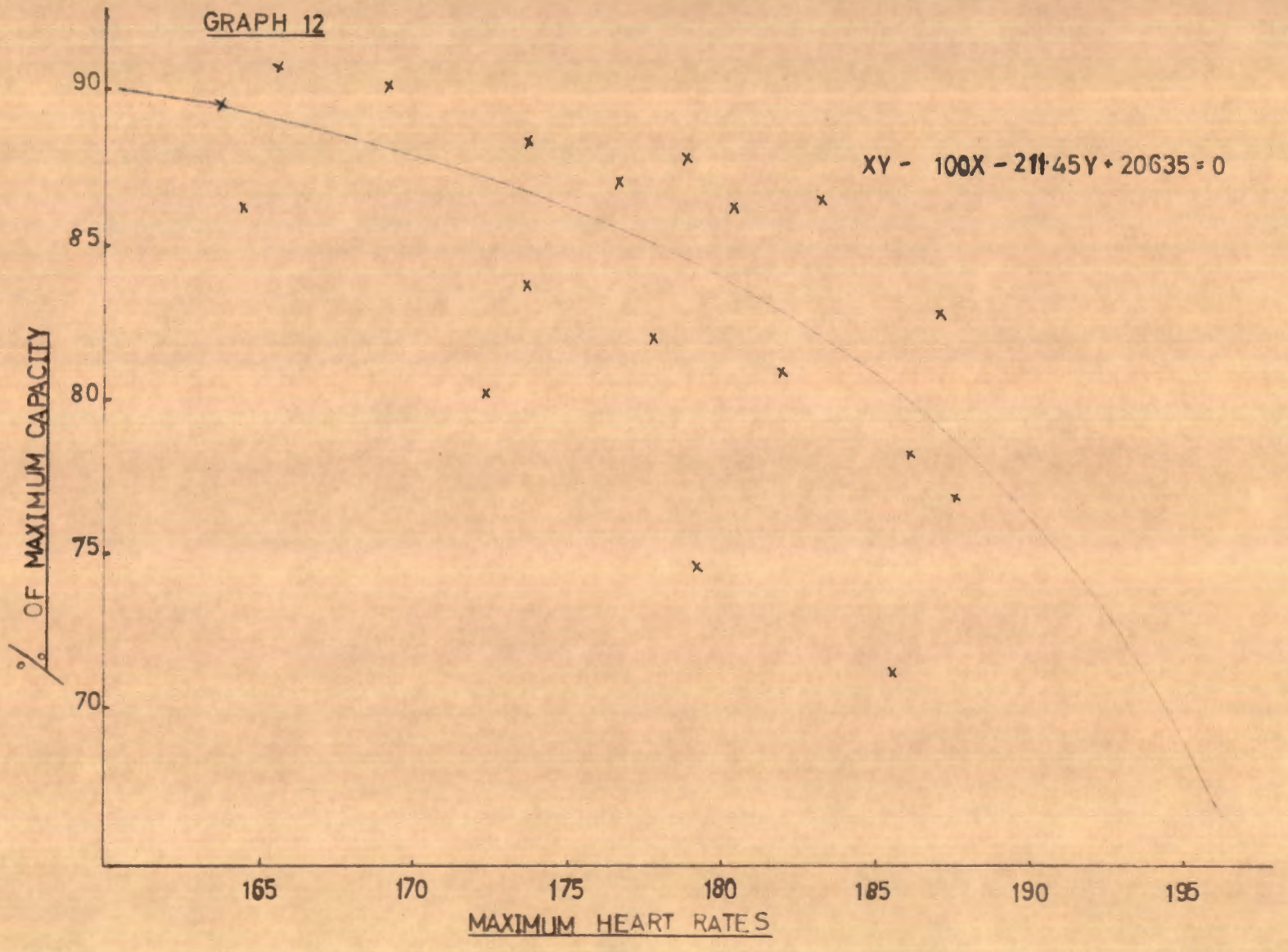
SUBJECT NO. 133108

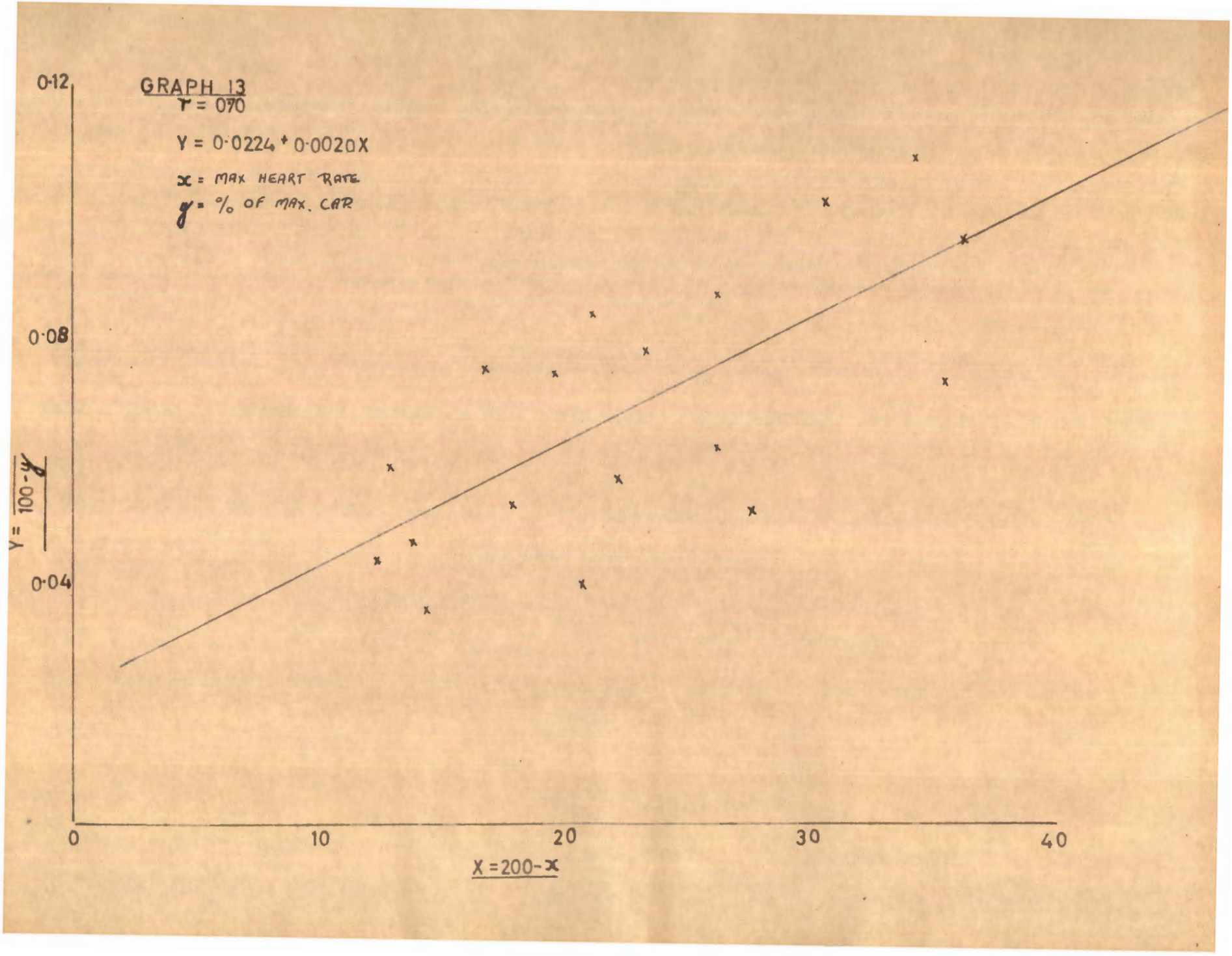
GRAPH 10



GRAPH 11 SUBJECT NO. 113108




GRAPH 12
XY - 100X - 211·45Y + 20635 = 0
90
85
80
75
70
% OF MAXIMUM CAPACITY
165
170
175
180
185
190
195
MAXIMUM HEART RATES


GRAPH 13
r = 0·90
Y = 0·0224 + 0·0020X
x = MAX HEART RATE
y = % OF MAX. CAR
0·12
0·08
0·04
Y = 100-y / y
0
10
20
30
40
X = 200-x

APPENDIX A.

AN EXAMINATION OF THE RELATIONSHIP BETWEEN MAXIMUM HEART RATE VALUES AND THE OPTIMUM PERCENTAGES OF THE MAXIMUM OXYGEN INTAKE AT WHICH WORK COULD BE SUSTAINED FOR A MAXIMUM PERIOD OF 1 HOUR ONLY.

INTRODUCTION:

Eighteen subjects whose maximum oxygen consumption and maximum heart rates had been estimated previously, worked for 1 hour on the bicycle ergometer. The work load of the ergometer was increased when necessary in order to ensure that each subject was working at the highest rate that he was able to sustain for the period.

The average oxygen consumption was determined for each man and was expressed as a percentage of his maximum oxygen consumption.

It was required to investigate whether any relationship exists between the percentage of maximum oxygen consumption used and maximum heart rate.

ANALYSIS AND DISCUSSION:

In graph 12 the percentage of maximum capacity was plotted as a function of maximum heart rate. It can be seen that there is an indication that the percentage of maximum capacity decreases as the maximum heart rate increases, i.e. men with lower maximum heart rates appear to be able to sustain a higher percentage of their maximum oxygen output than men with higher maximum heart rates. The relationship between the two variables appears to be curvilinear, although in view of the wide scatter and the small number of observations this could not be established statistically.

The transformation

$$X = 200 - x$$
$$Y = \frac{1}{100 - y}$$

where x and y are the original variables, transformed the data into a linear form as shown in graph 13. The correlation coefficient was calculated for the transformed data and a correlation of .70 which is significant at the 5% level was obtained. This indicates that there is a high probability that there exists an association between the original variables x and y. No precise statement can be made about the form of this association. However, an indication may be obtained by fitting a straight line to the transformed data (by means of least squares) and reverting back to the original units obtaining the curve shown in graph 12. The equation of the curve is

$$xy - 100x - 211.45y + 20635 = 0.$$

The hyperbola has asymptotes at $x = 211.45$ and $y = 100$.

It should be emphasized that this curve merely provides an indication of the form of the functional relationship with a given observed x (Max HR), and x.

APPENDIX B.

GRAPHS THAT OVERLAPPED.

The concentrations of lactic acid, pyruvic acid and excess lactate plotted in graphs 1, 2 and 3 reveal that below 65% of the maximum oxygen intake there is no progressive increase in these metabolites as the percentage of the maximum oxygen intake is gradually increased. No satisfactory explanation can be offered for this phenomenon. Above 65% some of the figures overlap slightly. This can be attributed to the very small gap of 1% allowed between the different percentage groups. The oxygen equivalent to 1% is smaller than the daily variation in oxygen consumption and also much smaller than the errors made in estimating oxygen consumptions. This may have resulted in the slight overlap encountered.