Factors Affecting the Mechanical Efficiency of Men Shovelling Rock in Stopes

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INTRODUCTION

The shovelling of rock in stopes is still a basic and important operation in many gold mines in the removal of gold-bearing rock from the stopes. There is, however, little factual knowledge of the factors which influence the the rates of energy expenditure and work output, and of the way in which variations in these factors, individually or in combination, affect the mechanical efficiency of the mine workers. What for example is the influence of different rates of shovelling, shovel loads and distances of throw? How does stope width and dip of the stope affect the mechanical efficiency of men shovelling rock?

Recently a simple physiological test was introduced into the gold mining industry for classifying Bantu recruits into those capable of hard, moderate and light work. If this test is used to select only those Bantu mine workers who are capable of hard work for the task of shovelling rock in stopes then the rate of energy expenditure which could be expected from these men is 1·5 litres/min for the entire period of the shift. With an adequate knowledge of the influence of the various factors which affect the rate of energy expenditure of men shovelling rock in stopes it would be possible to set work standards for Bantu mine workers in stopes. This should be done in terms of the rate of shovelling, the shovel load and the distance of throw for any combination of width of stope, dip of stope, condition of foot wall and grade of rock in such a way that the resultant energy expenditure would be the 'optimum' that could be expected from the men but would be within their capacities for physical work of an endurance nature (that is, 1·5 litres/min from the 'average' Bantu mine worker). Work standards could thereby be determined for the different stopes of a mine on a sound and systematic basis.

In order to supply the information required a study was carried out by the Human Sciences Laboratory in which the work output and energy expenditures (in terms of oxygen consumption in litres/min) were measured on six highly trained Bantu mine workers under the following conditions:

(*a*) rates of shovelling of 3, 4, 5, 6, and 10 shovels per minute.

(*b*) loads of from 9 to 18 lb on the shovel.

(*c*) distances of throw from 8 to 20 ft.

(*d*) stope width of 28 in., 42 in. and 72 in.

(*e*) dip of stopes of 0°, 15° and 30°.

(*f*) rough and smooth footwalls and various grades of rock size.

This paper gives the main results of practical importance of this study.

Method

The experiments were designed and conducted in conjunction with the Work Study Department of one Group of mines. Surface training stopes which simulated certain underground conditions such as variable stope widths, stope angle, etc., were made available in a mine Surface Training School and suitable subjects were selected from the large number of labourers being put through the training school.

Subjects

Bantu recruits who had returned to the mine for a new contract and who had previous underground experience on shovelling were considered to be suitable as subjects for the experiments. The particulars of the subjects are given in Table I.

TABLE I

PHYSICAL CHARACTERISTICS OF SUBJECTS

Subject	Weight (Kg)	Height (cm)	Surface area (sq meters)	Max O_2 capacity (Litre/minute)
A	71·5	167·3	1·80	3·5
B	61·5	162·3	1·65	2·8
C	63·0	164·1	1·69	2·4
D	66·5	167·4	1·75	2·8
E	70·2	164·6	1·77	3·0
F	77·8	173·1	1·92	3·8

Training

The method of shovelling, accepted by the Work Study Department, was demonstrated to the subjects who then practised the movements with empty shovels, under the supervision of an instructor. After the technique was mastered, the men started shovelling rock and were trained for at least four hours per day to work at the higher shovelling rates. Training was continued for three weeks to enable the subjects to achieve a reasonable degree of physical training and conditioning.

Shovelling method

In both the kneeling and standing positions the subjects faced the pile of rock, grasped the shovel in the accepted manner and pushed the blade of the shovel into the base of the pile of rock, sliding the blade between the rock and the concrete floor. In the standing position (72 in. wide stope) the back leg assisted in the movement by pushing the knee against the back of the hand holding the shovel handle. In the kneeling position the elbow was tucked into the side of the body so that the muscles of

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the trunk were used when the shovel was inserted into the pile of rock. After the blade of the shovel was inserted into the pile of rock, the shovel was lifted and swung around, the movement being initiated in the legs and followed through in the trunk and arms. The feet either remained in the same position or the back foot crossed over in a follow-through movement. In the kneeling positions the trunk twisted round with only limited movement of the knees. In the 42 in. stope the trunk was held straight and in the 28 in. stope the trunk and head were inclined forward.

Material

The rock used in these experiments consisted of fine, medium-sized and bigger rocks. The mixture was considered to be representative of an average underground rock sample. The rock was renewed frequently.

Experiments

A fixed amount of rock (approximately one ton) had to be shovelled by each subject in turn. This operation was performed in stopes of three different widths, that is, 72 in. (standing), 42 in. (kneeling) and 28 in. (kneeling, trunk and head inclined forward). The height of the stopes could be adjusted by suspending timber barricades from the roof. The men worked at rates of 3, 4, 5, 6 and 10 shovels per minute, the work rate being controlled by an electric metronome. At the work rate of 10 shovels per minute the men worked in stopes inclined at 15° and 30°. In the 15° slope the widths were 28 in. and 42 in. and in the 30° slope the widths were 28 in. and 48 in. The subjects worked in rotation and were observed on five occasions in each of the abovementioned working conditions. Subjects were constantly encouraged to fill their shovels adequately and to throw for specified distances. The distances of throw under the various conditions were those which all the subjects could throw comfortably. Small variations between subjects were allowed, however.

To determine the effect of throwing distance on energy expenditure the subjects were required to throw the rock various fixed distances, that is, 8, 12, 16 and 20 feet in the standing position, in the 42 in. and 28 in. wide stopes. To determine the effect on energy expenditure of the material being shovelled the men shovelled sand (1½-1 in.) gravel (2-3 in.) rocks and (6-8 in.) rocks, a fixed distance. The experiments on distance and grades were repeated three times. An effort was also made to determine the effect of shovelling on a rough footwall. The rough footwall was simulated by having 6 to 8 in. diameter rocks jutting out from the concrete surface. Each subject was observed on five occasions while working on a rough floor.

Oxygen consumption measurements were made while men shovelled under the different working conditions. Subjects were connected to a Max Planck Spirometer by a 9 ft length of corrugated tubing and Edward masks. The samples of expired air were taken over a period of at least six minutes to ensure that the sample was representative. Samples of expired air were collected in butyl rubber bags and analyzed at the Laboratory on a Beckman oxygen analyzer.

Shovel load and distances. The time taken by the subjects to shovel the ton of rock was recorded. Shovelling distances were measured and a random sample of shovel loads was weighed.

FINDINGS

Influence of shovelling rate and stope width on mechanical efficiency

In Fig. 1 are given the second degree polynomial curves which were fitted to plots of mean oxygen consumption against mean work output (the work outputs are taken, arbitrarily, to be the product of the shovel load and distance of throw of the load). The data were obtained from experiments in which the men shovelled rock at 3, 4, 5, 6 and 10 shovels per minute in stope widths of 28 in., 42 in. and 72 in. on the horizontal.

The curves fitted to oxygen consumptions against work outputs obtained in stopes of 42 in. and 72 in. width are very closely similar in slope and location (Fig. 1)., i.e. the mechanical efficiency of the men (which is expressed by the oxygen consumption against work output relationship) was closely similar in stopes of these two widths. This is surprising because the postures of the men were very different in the two stopes: they shovelled from the standing position in the 72 in. stope and were kneeling in the 42 in. stope. However, even though the mechanical efficiencies of the men were the same in stopes of these two widths, the oxygen consumption and work outputs for a given rate of shovelling were higher in the 72 in. stope than in the 42 in. stope. In Tables II and III this is shown to be due to the bigger shovel load and longer distances of throw of the men in the 72 in. stope.

TABLE II

AVERAGE DISTANCES OF THROW IN DIFFERENT STOPE WIDTHS AND STOPE ANGLES

Stope width	Horizontal stope	15° slope	30° slope
72 in.	16·9′	—	—
42 in.	15·8′	18 (17·6)′	21 (18·2)′
28 in.	10·9′	15·4 (14·9)′	14·1 (12·3)′

Calculated horizontal distances given in brackets

TABLE III

THE EFFECT OF SHOVELLING RATE, STOPE WIDTH AND SLOPE ANGLE ON SHOVEL LOAD

Stope width	6 s/min horiz.	10 s/min horiz.	10 s/min 15° slope	10 s/min 30° slope
72 in.	18 lb	15·1 lb	—	—
42 in.	16 lb	13·1 lb	16·3 lb	15 lb
28 in.	15·8 lb	13·0 lb	15·9 lb	15 lb

Fig. 1 also demonstrates the fact that mechanical efficiency of the men in the stopes of 28 in. width was greatly reduced compared with the mechancal efficiencies in the 42 in. and 72 in. stopes, judged by the displacement to the left of the curve of oxygen consumption against work output. The main reason for the markedly reduced mechanical efficiency in the 28 in. stope is that the work output for a given level of oxygen consumption was much less than in the other two stopes. Tables II and III bring out the fact that the reduction in work output was due mainly to the greatly reduced distance of throw in the

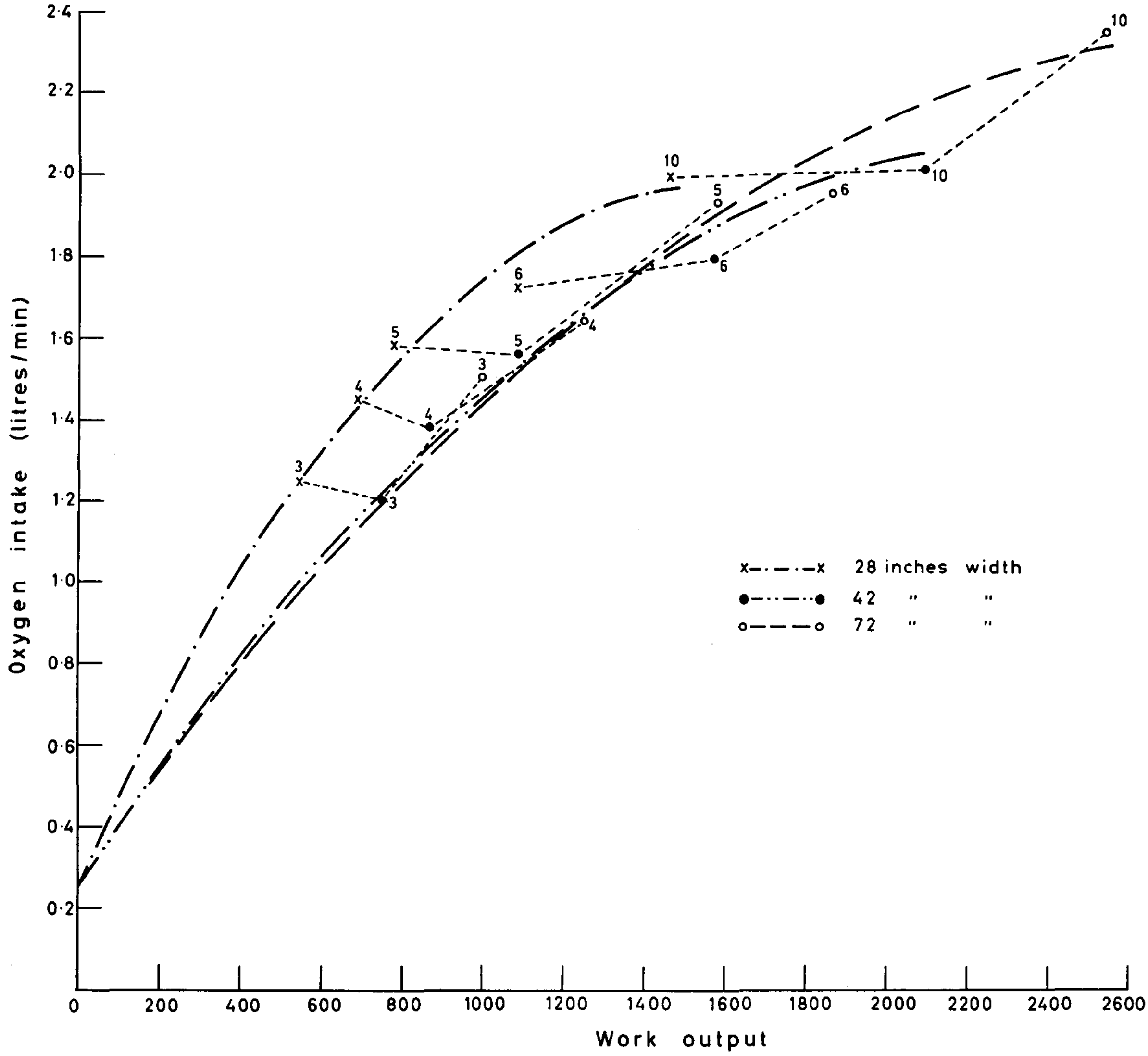

Fig. 1—Plots of mean oxygen consumption against mean work output at various rates of shovel loads per minute

28 in. stope; the shovel load was not decreased. The reduction in the distance in throw appears to be due both to the cramped posture of the men which did not allow them a free swing with the shovel when throwing the load and to the fact that the hanging wall was too low for them to get the trajectory needed for the same distance of throw as in the 42 in. and 72 in. stopes.

Influence of dip of stope on mechanical efficiency

When the angle of the stope dips below the horizontal the main effect is to increase the distance of the throw as shown in Table II and to increase the shovel load as seen in Table III. The net effect in the 42 in. and 28 in. stope widths is that work output was increased by 23 per cent and 54 per cent respectively when the dip of the stope was increased from 0° to 15° from the horizontal as shown in Fig. 2.

A further increase in the dip of the stope from 15° to 30° below the horizontal had the opposite effect on the work output in the two stope widths. In the 42 in. stope work output was increased to 50 per cent compared with the work output in the horizontal stope. In the 28 in. stope the work output was actually decreased because the distance of throw could not be increased (this was due to the fact that the rock struck the hanging wall and fell onto the footwall; although the rock continued to roll for a short distance, the distance of throw was taken to be the point at which the rock fell onto the footwall).

The rates of energy expenditure in shovelling rock in the stopes in which the dip was below the horizontal were less than in the horizontal stope but the differences were not significant.

The net effect on the mechanical efficiency of the Bantu mine worker of a dip in the stope below the horizontal is a marked increase when the dip is increased from 0° to 15° but when the dip increases further from 15° to 30°, mechanical efficiency is increased only in stopes of 42 in. in width and wider.

Influence of distance of throw and shovel load on energy expenditure

The influence on oxygen consumption of the distance of throw at a shovel rate of 10 shovels per minute and load of 16-18 lb is given in Fig. 3 for the three stope widths 28 in., 42 in. and 72 in. The figure contains the

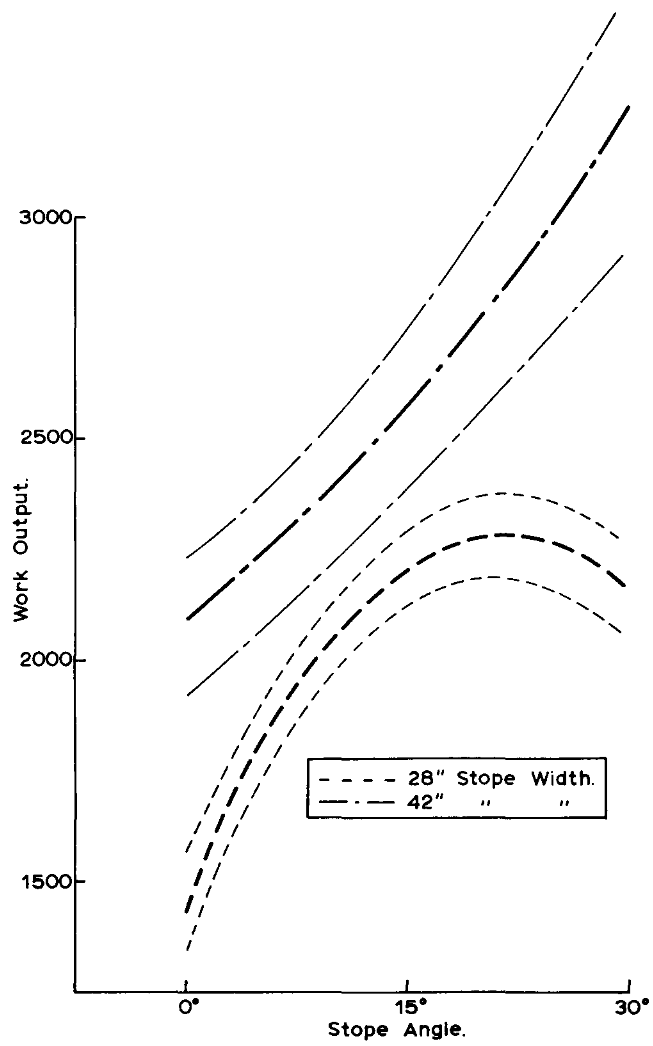

Fig. 2—Influence of dips of stope on mechanical efficiency

regression lines fitted to plots of mean oxygen consumptions (mean of six men) against distance of throw from 8 to 20 ft. Ninety per cent confidence limits have been calculated to the regression lines and are also given in the figure. Where adjacent limits do not overlap, one can be 95 per cent sure that the two regression lines are significantly different.

In general, there is no significant difference between the regression lines. The slopes of the regression lines are different with a distinct trend with change of stope width. From the regression lines in Fig. 3, the differences in oxygen consumption for a 1 ft change in throwing distance in the range 6 ft to 20 ft were as follows:

Stope width	Change in oxygen consumption
72 in.	0·03 litre/min ≃ 1·5%
42 in.	0·05 litre/min ≃ 2·5%
28 in.	0·07 litre/min ≃ 3·5%

The influence on oxygen consumption of the shovel load at a shovelling rate of 10 shovels per minute and distance of throw of 16-18 ft is given in Fig. 4 for the three stope widths. The figure contains the regression lines fitted to plots of mean oxygen consumption against mean shovel loads between 9 and 19 lb for the three stope widths of 28 in., 42 in. and 72 in., together with 90 per cent confidence limits. Here again the regression lines are not significantly different, as judged by the overlapping of the 90 per cent confidence limits, but the slopes of the regression lines are different and show a systematic trend of decreasing oxygen consumption with decrease in stope width such that a *1 lb change in shovel load* in the range 8·8 lb to 19 lb gives the following difference in oxygen consumption:

Stope width	Change in oxygen consumption
72 in.	0·09 litre/min ≃ 4·5%
42 in.	0·07 litre/min ≃ 3·5%
28 in.	0·05 litre/min ≃ 2·5%

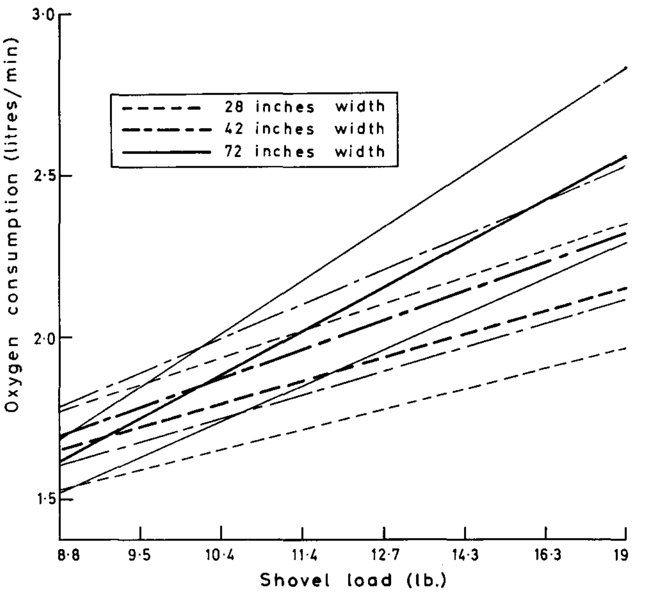

Fig. 4—Influence on oxygen consumption of shovel load

The rate of oxygen consumption for a 1 ft difference in throwing distance and for a 1 lb difference in shovel load from the values given in Tables II and III can be determined from Fig. 1 for any combination of shovel load and distance of throw in stope widths of 28, 42 and 72 in., by means of the two sets of corrections given above in this section.

Influence on energy expenditure of roughness of footwall and size of rock

In order to assess the influence of the characteristics of the footwall on the energy expenditure of the man when shovelling rock, a study was made of proportions of the total energy expended in the various components of the shovelling operation. It was found that the effort of loading the shovel, that is, the pushing of the shovel blade into the pile of rock and the lifting of the shovel blade out of the pile takes a considerable proportion of the total amount of energy used in shovelling.

The average rate of oxygen consumption of the men when they merely performed the loading action at 10 shovels per minute was 1·23 litres/min. This is 56 per cent of the energy expenditure, of 2·20 litres/min, in the full cycle of the operation.

The accepted method of shovelling is to slide the shovel blade on the footwall and insert it into the bottom of the pile of rock. It was expected, therefore,

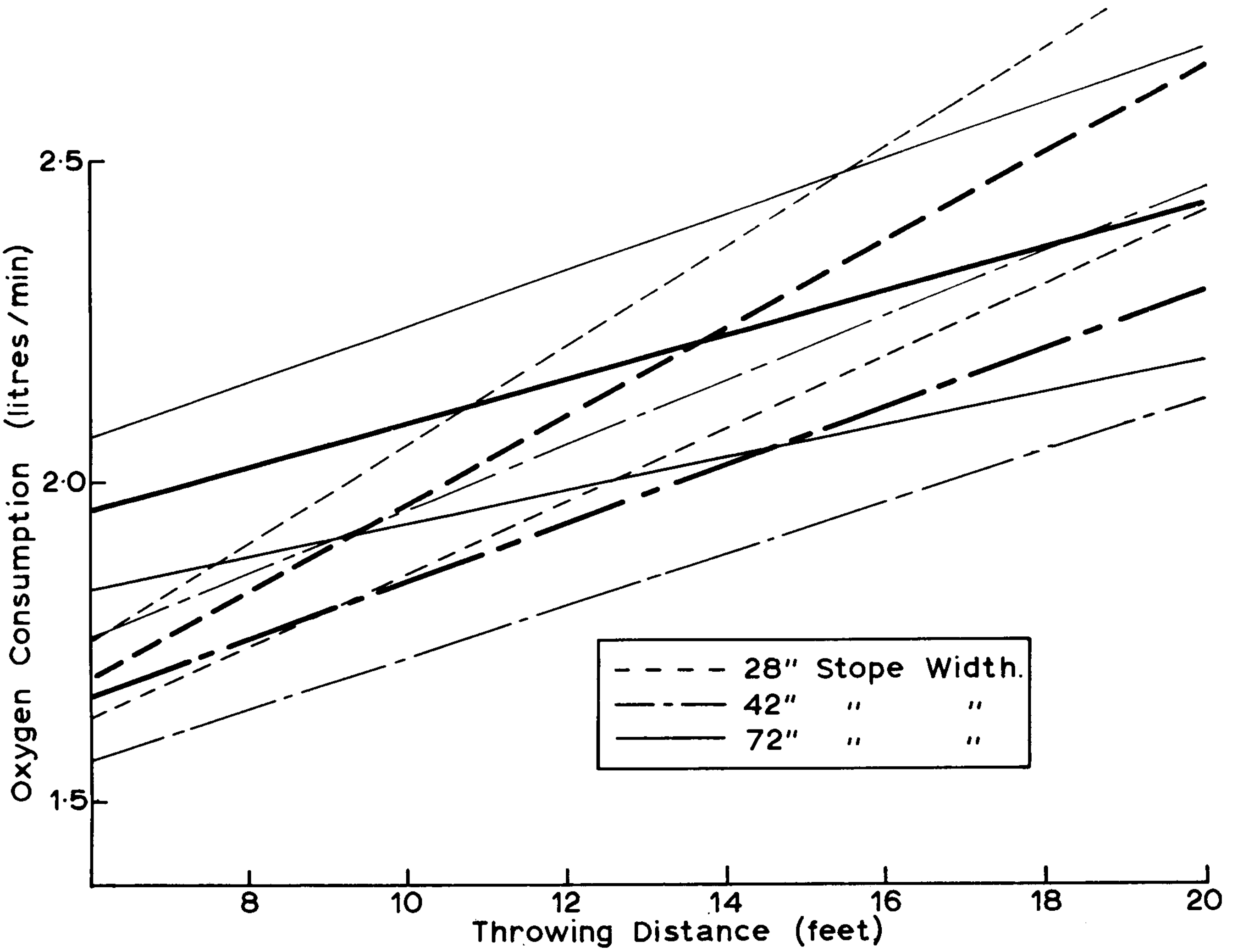

Fig. 3—Influence on oxygen consumption of distance of throw

that the effort of loading the shovel, particularly inserting the shovel blade into the pile of rock, would be influenced by the condition of the footwall and the grade of rock. A smooth footwall would be expected to facilitate this movement. However, it was found in these experiments that there was no significant difference between the mean oxygen consumptions in conditions of a smooth footwall and a moderately rough footwall. This was probably due to the fact that the fine rock levelled the rough surface of the footwall and produced a relatively firm and smooth surface.

In Fig. 5 is given a representative example of the oxygen consumptions of three of the six men when shovelling rock of four different grades in size, namely sand, $\frac{1}{2}$ to 1 in., 1 to 2 in. and 6 to 8 in. This shows clearly that the rate of oxygen consumption increased with size of rock up to the 1 to 2 in. grade but decreased for the large size rock. The differences between the mean oxygen consumptions for the different grades of rock was found to be significant at the 5 per cent level. However, it should be stated that the piles of rock and sand used in the experiment were loosely packed and probably differ in this respect from the underground situation where the rock from the blast might be firmly pressed together.

Difference between trained mine workers in mechanical efficiency

Apart from the external factors, discussed above, which influence the rate of energy expenditure and work output of the Bantu mineworkers when shovelling rock, differences between the men in certain physiological and anatomical characteristics could, from previous research in our laboratory[1], be expected to result in differences between them in the rates of oxygen consumption for a given level of work output. In order to examine this question the mechanical efficiency of the individual performing the task was expressed as the work output of the individual per unit of energy expenditure. The differences between individuals in mean mechanical efficiency at the various shovelling rates, in the stope widths of 28, 42 and 72 in., were found to be highly significant, with subject C consistently showing the highest efficiency and subject A showing the lowest mechanical efficiency, as is also indicated in Fig. 5. This result suggests that because of natural or acquired ability or skill some individuals are consistently more mechanically efficient than others.

A detailed examination of the two subjects A and C brought out certain factors which might be associated with the differences between these men in mechanical

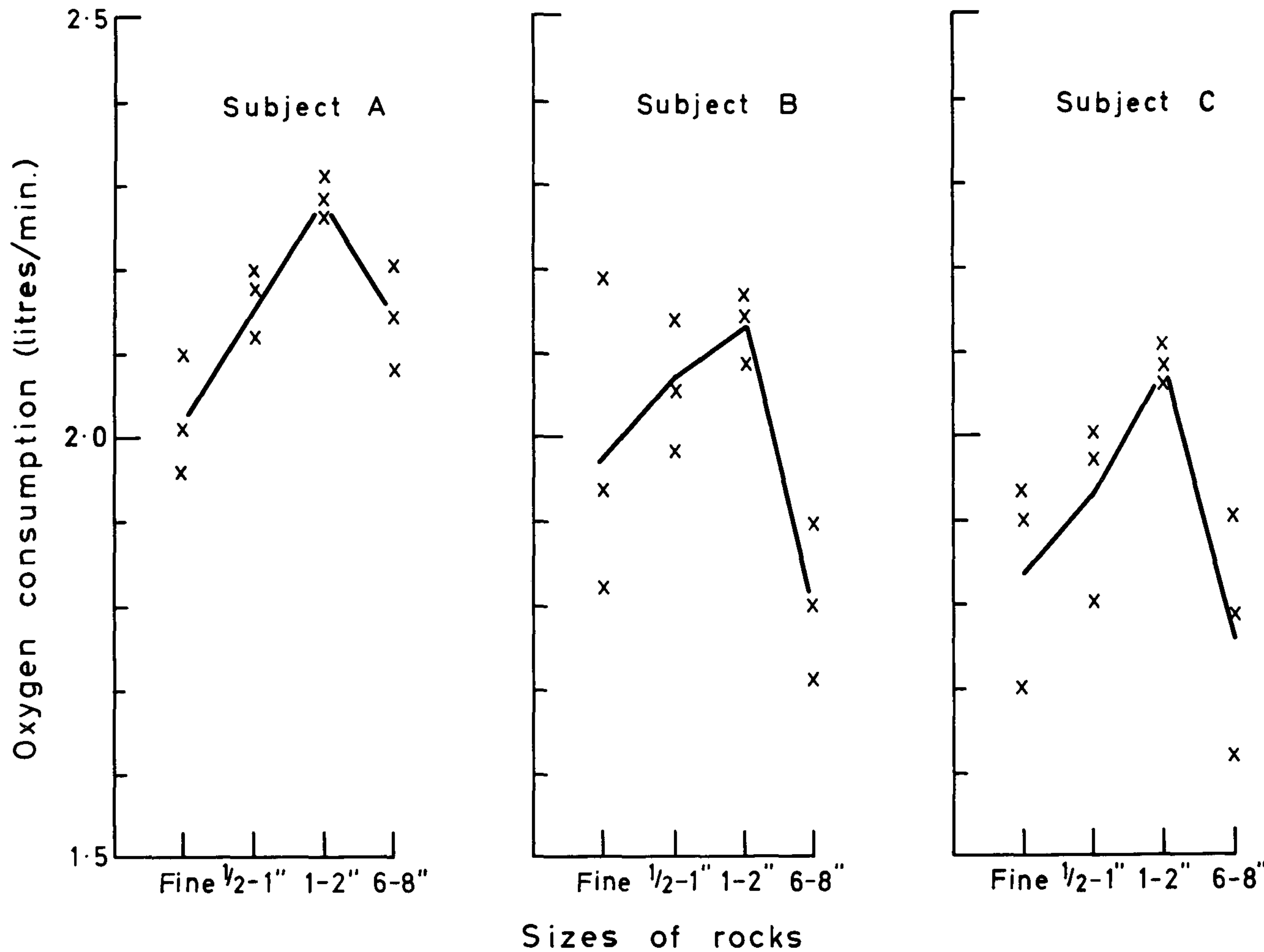

Fig. 5—Oxygen consumption when shovelling different sizes of rocks

efficiency. Subject A was 18 lb heavier than subject C, which may be one of the reasons for the former's lower efficiency[1]. His greater body weight was associated with a higher physical work capacity and he therefore had no reason to economise in his movements. His movements in loading were unnecessarily forceful and the rock was flung in a low trajectory and scattered over a wide area. The movement was followed through, the grasp by the lower hand often being released. In contrast, subject C with five years shovelling experience and a lower work capacity showed great economy in his movements. Instead of using force he eased the shovel blade into the pile of rock and the throwing movement performed was without a follow-through. Because of a higher trajectory, the rock was deposited in a heaped-up pile. It appeared that this subject, being very well motivated, compensated for his lower work capacity by developing a greater mechanical efficiency.

Observations made during the training period of these subjects indicated that it takes at least three to four weeks before men reach a reasonable level of competence in shovelling. Generally not a great deal of attention is given to the training of shovelling boys. It appears that a more intensive training in shovelling with the objective of teaching of correct methods would contribute to a more competent and efficient labour force.

"Optimum" levels of output for stope shovelling

Men selected for shovelling rock in stopes should be able to maintain an oxygen consumption of 1·5 litres/min throughout the shift (which is 50 per cent of the maximum oxygen intake of the "average" Bantu mine workers). From Fig. 1 it can be seen that, *for a stope of 72 in. width*, a shovelling rate of 3 shovels per minute (average shovel load of 18 lb and distance of throw of 17½ ft) gives an oxygen consumption of 1·5 litres/min. It can also be seen that, *for stopes of* 28 *in. and* 42 *in. width*, a shovel rate of between 4 and 5 shovels/min (with an average shovel load of 16 lb and a distance of throw of 15 and 10½ ft respectively) gives a rate of oxygen consumption of 1·5 litres/min. The work output of a Bantu mine worker shovelling at these rates would be 2·2 tons per hour in the 28 in. and 42 in. stopes and 1·7 tons per hour in the 72 in. stope.

However, it was found in underground studies of shovelling rock in stopes, that the average shovel load in stope shovelling was 15 lb and that the distance of throw was much less than those given in the last paragraph. With these lighter shovel loads, the distances of throw could be reduced (Fig. 1) to 8, 11 and 14 ft respectively in the 28, 42 and 72 in. stopes (decreasing the rates of oxygen consumption by 0·22, 0·27 and 0·37 litre/min—Fig. 4) when shovelling at 6 shovels/min in the 28 in. and 42 in. stope widths and at 5 shovels/min in the 72 in. stope width to give a mean oxygen con-consumption of 1·5 litres/min. The work output of the men in the 28 in. and 42 in. stopes would under these conditions be 2·7 tons per hour and 2·3 tons per hour in the 72 in. stope.

Although it had been suggested to us by the work study engineers that a shovel rate of 10 shovels per minute should be investigated (and even 14 shovels per minute), such a rate of shovelling in stopes in the gold mines is quite unphysiological. A shovelling rate of 10 shovels per minute (with an average shovel load of 13 lb in the 28 in. and 42 in. stopes and 15 lb in the 72 in. stopes and throwing distances of 8, 11 and 14 feet respectively) would require an oxygen consumption of 1·8 litres/min in the 28 in. and 42 in. stopes and 2·2 litres/min in the 72 in. stope (Fig. 1). At these rates of oxygen consumption the "average" Bantu mine worker would be well above 50 per cent of his maximum oxygen intake and would be in anaerobic metabolism. He would require longer rest pauses in order to recuperate. If he did not have long rest pauses he would become unduly fatigued and would be prone to accidents. It is probably for this reason that Moss[2] found that men shovelling coal at a slow, but steady pace had a higher output than men who work faster but in spurts.

In stopes inclined 15° and 30° below the horizontal, the distances of throw would be increased by 2 and 5 feet respectively in a 42 in. stope and by 4·4 and 3 ft respectively in a 28 in. stope without there being any significant difference in oxygen consumption from that in the horizontal stope.

SUMMARY

This study brings out the following facts:

(i) The mechanical efficiency of men shovelling rock, at various rates from 3-10 shovels per minute, is the same in a 42 in. and a 72 in. stope width but it falls off markedly in a stope of 28 in. width.

(ii) When the dip of the stope is 15° below the horizontal the mechanical efficiency in both the 42 in. and 28 in. stope widths is increased but with a further increase in the dip to 30°, mechanical efficiency is increased only in 42 in. stope width.

(iii) A one-ft alteration in the distance of throw of a 16-18 lb shovel load results in an 0·03 litre/min change in oxygen consumption in a 72 in. stope, in an 0·05 litre/min change in a 42 in. stope and in an 0·07 litre/min change in a 28 in. stope; a one-lb alteration in shovel load which is thrown 16-18 ft results in an 0·09 litre/min change in oxygen consumption in a 72 in. stope, in an 0·07 litre/min change in a 42 in. stope and in an 0·05 litre/min change in a 28 in. stope.

(iv) Significant differences in mechanical efficiency were found between individuals and these appeared to be associated with the economy of movement during shovelling.

(v) On the basis of these studies "optimum" levels of production for the "average" Bantu mine worker can be set for shovelling rock in stopes. They are:

  (*a*) 6 shovels/min, with 15 lb load, thrown 8 ft and 11 ft respectively in a 28 in. and 42 in. stope width.

  (*b*) 5 shovels/min, with a 15 lb load, thrown 14 ft in a 72 ft stope.

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1. Williams, C. G., Wyndham, C. H. and Morrison, J. F. 'The influence of weight and stature on the mechanical efficiency of man.' *Int. Z. angew. Physiol.* 23: 107-124, 1966.
2. Moss, K. M. 'Some effects of high air temperatures and muscular exercise on colliers.' *Proc. Roy. Soc. B.* 95: 181-200 1924.

Book Review

Sedimentary Ores—Ancient and Modern (Revised), edited by C. H. James. Proceedings of the 15th Inter-University Geological Congress. University of Leicester, December, 1967. Special Publication No. 1, Department of Geology, University of Leicester, February, 1969. Obtainable from: Leicester University Bookshop, May's Walk, Leicester LE 17 RD. Price: 42s. Postage and packing, 3s. 6d.

This volume should be of interest to economic geologists and students in this field. A number of illustrated papers on the genesis of ores in sediments are presented; the authors include experts such as Prof G. C. Amstutz, Dr K. C. Dunham, Prof D. Williams and W. G. Garlick. The papers deal mainly with sulphide deposits, but the late Prof J. H. Taylor's contribution concerns ores of iron and manganese.

Brief references to the Witwatersrand ores represent the only discussion of South African deposits.

With the notable exception of W. G. Garlick's paper on Zambian copper deposits, the Abstracts given are inadequate, necessitating thorough reading of the papers to extract the important matter.

R.J.O.