The Physiological Cost of Muscular Work Measured by the Discharge of Carbon Dioxide. Part I.—*The Energy Output of Dock Labourers during "Heavy Work."*

[Interim Report to the Royal Society Food (War) Committee.]

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The metabolism Sub-Committee of the Food (War) Committee of the Royal Society at its first meeting considered the following two methods of inquiry for the determination of the energy output of men and women workers:—

A. The Douglas-Haldane method, by which determinations of CO_2 and of O_2 are made, was adopted for recommendation to new workers as the standard method.

B. Waller's method by which determinations of CO_2 alone are made at short frequent intervals, was to be taken on trial.

Allocations for the necessary expenses were made, and interim reports, dealing with the results obtained by both methods, were presented to and considered by the Sub-Committee at several subsequent meetings. Of these interim reports, two dealing with results of method A have recently been communicated to and published* in the 'Proceedings of the Royal Society,' and the present interim report of method B is submitted for similar publication. It deals with the CO_2 output of heavy workers, for whom the energy output has been estimated by the Food (War) Committee at 1100 to 2000 calories per 8 hours per "average man" [*i.e.*, 78 to 142 calories per square metre per hour].

Both methods A and B afford the measure of energy output by readings of the respiratory exchange. By method A the intake of oxygen and the output of carbon dioxide are measured; by method B the output of CO_2 alone.

By method A the relation quotient CO_2 plus/O_2 minus is ascertained, and its variation taken into the calculation of the final energy value of the exchange, which is expressed in calories per square metre.†

* O. Rosenheim, "A Preliminary Study of the Energy Expenditure and Food Requirements of Women Workers," 'Roy. Soc. Proc.,' No. 635, B, vol. 91, p. 44; M. Greenwood, C. Hodson, and A. E. Tebb, "Report on the Metabolism of Female Munition Workers," *ibid.*, p. 62.

† In accordance with the practice of the Carnegie Laboratory. A full account of the method is given by Cathcart in the 'Journal of the Royal Army Medical Corps,' November, 1918.

In method B, the results are directly read and expressed in terms of CO_2 output as cubic centimetres of CO_2 per second. The final energy value if required is calculated on the assumption of a normal value of the respiratory quotient $CO_2/O_2 = 0{\cdot}85 \pm 0{\cdot}05$. It is claimed that the range of error involved by A can be reduced to $\pm$ 1 per cent., in method B to $\pm$ 5 per cent. The speed with which useful data can be obtained is much greater by method B than by method A.*

Errors of Observation.

Errors of timing, of volume reading, corrections for temperature and pressure, errors of CO_2 (and O_2) readings, and clerical errors of arithmetic can occur by both methods; their detailed consideration would occupy too much space, and must be deferred. I shall assume that due care and accuracy have been given to the carrying out of both methods, and consider in detail only the error due to the assumption of a normal respiratory quotient which forms the essential difference between methods A and B.

In the first place it should be realised as being not an error of observation peculiar to method B, but an error of translation, occurring when the results measured in terms of cubic centimetres CO_2 per second are converted into calories—calories per hour, or calories per square metre per hour.

This error of translation can be evaluated from the following two considerations:

1. Its maximal (improbable) value with maximal (improbable) fluctuations of the CO_2/O_2 quotient, *e.g.*, between 0·7 and 1·0 which are its theoretical values on diets exclusively of fat or exclusively of carbohydrates.

2. Its practical (probable)† value with practical (probable) fluctuations of the CO_2/O_2 quotient.

1. Its maximal value is to be appreciated from the following Table of Equivalents of 1 c.c. CO_2:—

* With Method B, Miss De Decker's ordinary day's work on dock labourers was, for Perry, 20 readings per day (10 double readings), for King and others only 10 per day. But in the laboratory when getting out CO_2 curves, she has worked up to 80 per day. None of her hourly readings on labourers has been rejected or amended. The net expenditure of time at the docks and at Smithfield was 27 days and 6 nights, and the data collected have not involved the employment of an expert computer. By Method B, Greenwood obtained a total number of 226 readings during the period November, 1918, to March, 1919, upon 43 subjects engaged upon various kinds of work.

† Not probable error in the technical statistical sense. My data are not numerous enough for calculation of "probable error."

Respiratory quotient CO_2/O_2.	Calories.	Kilogrammetres.	1 c.c. CO_2 per sec. signifies.
1·00	5·047	2·155	18·17 Kals per hour.*
0·95	5·317	2·270	19·14 ,, ,,
0·90	5·587	2·386	20·11 ,, ,,
0·85	5·856	2·501	21·08 ,, ,,
0·80	6·126	2·615	22·06 ,, ,,
0·75	6·396	2·731	23·02 ,, ,,
0·70	6·667	2·846	24·01 ,, ,,

* To reduce clerical mistakes, I am accustomed to write "cal" for the small or gramme calorie, and "Kal" for the large or kilogramme calorie.

by inspection of which it appears:

(1) That the maximum error between the extremes 1·00 and 0·70 is ±13·79 per cent.

(2) That the practical error between the probable range 0·90 and 0·80 is ±4·598 per cent.

I have allowed therefore as inherent to method B the practical (probable) error = ±5 per cent.

There is an error of observation inherent to short (1 to 5 min.) samples that requires particular consideration at this stage.

In forced breathing, either voluntary without other muscular exertion, or involuntary in consequence of work, there is increased ventilation and increased output of CO_2, which is pumped out of the pulmonary alveoli and blood to an exaggerated degree. It is difficult in a short sample taken during increased work to assign the shares of increased muscular action and of increased pump action in the total increase exhibited by a short sample, which therefore cannot be regarded as a fair sample indicative of increased metabolism. The objection is well founded as regards brief sampling during the period of establishment of augmented breathing, but not as regards brief sampling when the augmented *régime* has become established. During the first minute or two of increased muscular activity the increased expiration of CO_2 is partly due to increased pumping action, partly to increased muscular metabolism; but at the end of five minutes (or less) of steady work a steady *régime* of CO_2 output is established, during which the rate of output is unaffected, or inconsiderably affected by variations of pump effect. A person breathing at rest 6 litres per minute at 3 per cent. CO_2, *i.e.*, discharging CO_2 at the rate of 180 c.c. per minute or 3 c.c. per second, on commencing work at say 10 kgrm. per second exhibits at once an increased ventilation, accompanied by a rise of CO_2 percentage and a total increased output of CO_2, which during the first minute of effort is certainly the resultant of two factors,

increased pumping out of CO_2 by the lungs and increased muscular metabolism; but as time passes, the CO_2 output reaches a maximum, and a constant *régime* is established, during which the CO_2 ordinate serves as a true physiological indicator of muscular metabolism. This constant *régime* is reached very rapidly, *i.e.*, in a very few minutes—certainly in five minutes, sometimes even less—and while it lasts, the CO_2 ordinate is a faithful indicator of the internal physiological activity. During the constant *régime* of deeper breathing caused by work, the physiological order of events is (1) increased production of CO_2 causing (2) greater thoracic movements by which the increase is got rid of. With the increased ventilation there is of course increased pump action, and both these factors are equally physiological, in as much as both are excited by the state which they serve to relieve.

And so the muscular metabolism of a workman at steady work—preferably piece-work—is usefully measured by short samples of expired air from which his "CO_2 ordinate," *i.e.*, his established rate of CO_2 discharge, is ascertained. The procedure has two principal advantages: (1) The interruption of work is trifling; it is, *e.g.*, cheerfully tolerated by piece-workers, to whom time is money; (2) The sampling is taken under actual conditions of work, and as nearly as possible during work. Work done in a respiration chamber, or for a few minutes for the sake of affording a sample, cannot be regarded as normal or as affording a fair sample of the respiratory activity obtaining during normal work.

As is shown in this preliminary report, the constant *régime* during work is established at the beginning of work and disestablished at the end of work with surprising rapidity. Samples should not be taken during either of these periods of change. They should be taken if possible without interruption of work in progress, or if this should be impossible, with least interruption for the shortest practicable periods—20 to 30 seconds—immediately after the load or tool has been dropped as, *e.g.*, in the carrying of coal or grain or meat, which form the hardest labour going on in the London docks. An obvious drawback to short sampling is, of course, the possible error arising from turning the tap at beginning and end of say 30 seconds during different phases of respiration. This error is to be avoided by turning the tap on and off at the same phase, *i.e.*, immediately after expiration. In the mouthpiece which I prefer, the expiratory valve click is easy to follow, and I have not found any disturbance of the subject to be caused by the valve clicking, as has been reported by some observers. For a subject breathing say 15 per minute, it is 2 to 1 against the tap being closed during the expiratory movement; but if this should happen, a considerable error, amounting to perhaps 10 per cent., might be made in a half-minute sample.

First Observation (Tuesday, December 3rd, 1918).

Labourer No. 1, age 51, weight 84 kgrm., height 1·71 metre.

A regular labourer (building and concrete laying) at the East Surrey Docks. Work begins at 7.30 A.M., ends at 4.30 P.M., with dinner hour from 12 to 1, during which he walks ¼ mile home and back.

The work in progress was of varied character consisting in the preparation for the laying of a concrete floor—carrying tools and materials, shovelling and wheeling gravel, mixing concrete, spreading, levelling, "tapping" and "trowelling."

Weight of tapper 12 to 14 lb., height of lift about 18 in., 20 to 25 blows per minute.

"Tapping" is considered by the men as heavy work, but does not amount to more than 1 kgrm.-metre per second.

Time.	Time of collection, secs.	Ventilation.		CO_2.	
		Litres.	C.c. per sec.	Per cent.	C.c. per sec.
Luncheon hour 12-1 ...	—	—	—	—	—
1 h. 0 m.	37	14	378	2·0	7·56*
2 m.	35	13	354	2·0	7·08*
2 h. 0 m.	30	14	446	3·0	13·98
2 m.	30	11	366	2·2	7·32
2 h. 30 m.	30	15	500	3·0	15·00
32 m.	60	10	333	2·6	8·65
3 h. 0 m.	16	16	533	3·4	18·12
3 m.	12	12	200	2·9	5·80

* *Régime* not established.

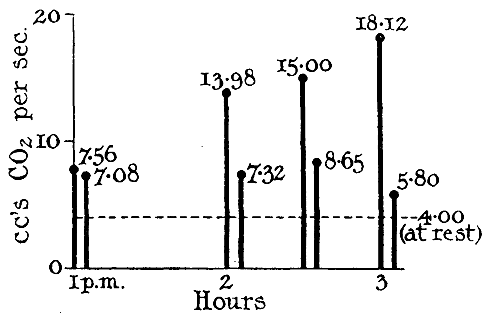
This was an orientation observation, by which the system of sample collection was shown to the labourer for the first time. No difficulty in the use of the apparatus was experienced and no serious interruption of work occurred. Serviceable data were obtained at once. The effect of a brief rest for two or three minutes was evident, also the gradually increasing output of CO_2 during the afternoon. Three last readings were 13·98, 15·00, and 18·12 c.c. CO_2 per second, *i.e.*, an average output of 15·7 c.c. (gross) per second (= 319·7 Kalories per hour).

I quote this first observation in order to show that the collection of "first observations on a reasonably large" number of subjects under their normal conditions of work is a legitimate task and likely to afford serviceable data.

From inspection of the work in progress it appeared to me that the operation known as "tapping" (in which a known weight is lifted to a regular height at a regular rhythm) is one that lends itself best to a direct mechanical

estimation. But the detailed study of this particular form of work was foreign to my present purpose, which is to make good the method of estimating the cost of work of unknown mechanical equivalence in terms of CO_2 discharged.

The next step in the enquiry was to take hourly observations of the CO_2 discharge for the complete day's work and for several days.



Labourer No. 1.—Age 51. Weight (clothed)* 84 kilos.; height 1·71 M. (Surf. 1·96 M^2.) Wednesday, December 4, 1918.

Time.	Time of collection, secs.	Litres.	C.c. per sec.	CO_2 per cent.	CO_2 c.c. per sec.	Remarks.
7 h. 30 m..	60	11	183	2·4	4·39	After ¼ hour walk followed by 5 min. sitting.
8 h. 30 m.	45	12	266	2·8	7·48	Laying concrete floor. "Trowelling" and "tapping."
33 m.	60	13	216	2·3	4·96	
9 h. 30 m.	42	14	333	3·2	10·65	
34 m.	60	12	200	2·8	5·60	
10 h. 30 m.	40	17	425	3·5	14·86	"Tapping."
34 m.	60	14	233	3·0	7·00	
11 h. 30 m.	45	20	444	3·4	15·09	Trowelling on his knees.
34 m.	60	11	183	2·8	5·12	
1 h. 0 m.	55	15	272	3·0	8·16	Immediately after ¼ mile walk, fast.
2 h. 0 m.	43	18	418	2·8	11·70	"Trowelling" and "tapping."
3 m.	60	14	233	2·2	5·12	
3 h. 0 m.	45	20	444	3·2	14·20	
4 m.	60	17	283	2·4†	6·79	
4 h. 0 m.	43	21	488	3·8	18·54	
4 m.	60	18	300	2·6	7·80	

* Four kilos. allowed for weight of clothes.

† Sample analysed by small Haldane apparatus CO_2 = 2·5 per cent., O_2 = 2·3 „ „ R.Q. = 1·09.

The points of note in this observation are:—

1. The hourly increase of CO_2 discharge during each period of work.
2. The restorative effect of the dinner-hour.
3. The rapid fall of CO_2 during a rest pause of three or four minutes,

showing that it is necessary to take samples with least possible delay. The average discharge for the last three hours of forenoon was 13·53: of afternoon 14·78.

4. The maximum discharge is greater at the end of the afternoon than of the forenoon.

The volume of ventilation and the percentage of CO_2 were both higher in the first sample, taken immediately after the labourer had dropped tools than in the second sample, taken after a pause of three minntes.

There is, as may be seen throughout the protocols, a general correspondence between volume of ventilation and amount of CO_2 per second, so that it is allowable, with due reservation, to make use of ventilation alone as a guide to work done. I have found this guide of value in prolonged observations, and when it was not possible to take samples by bag quickly enough to follow the change of output of CO_2 that takes place at the beginning and end of a spell of work. For this purpose I have adapted a Verdin spirometer as a litre recorder of expired air during rest and during certain kinds of work. The results obtainable by this means will be reported upon later.

Labourer No. 1.—Thursday, December 5, 1918.

Time.	Time of collection in secs.	Litres.	C.c. per sec.	CO_2 per cent.	CO_2 c.c. per sec.	Remarks.
7 h. 30 m.	60	12	200	2·5	5·0	After ¼ mile walk followed by 5 min. rest.
9 h. 0 m.	40	22	555	2·8	15·54	Trowelling and tapping.
3 m.	60	23	383	1·7	6·51	
10 h. 0 m.	42	21	500	3·0	15·00	Moving tools to another part of the building.
3 m.	60	18	300	2·8	8·40	
11 h. 0 m.	40	22	550	3·1	17·05	Moving gravel, etc., and other building materials.
3 m.	60	17	233	2·9	6·75	
11 h. 45 m.	40	23	575	3·6	20·70	
48 m.	60	19	316	3·0	9·48	
1 h. 0 m.	60	18	300	2·8	8·40	After ¼ mile fast walk.
2 h. 0 m.	40	21·5	537	3·0	16·11	Work rather heavier than usual.
3 m.	60	20	333	2·6	8·65	
3 h. 0 m.	40	23	575	3·5	20·12	
5 m.	60	19	316	3·2	10·11	
4 h. 0 m.	40	22	550	3·5	19·80	Trowelling floor.
4 h. 3 m.	60	10	333	3·0	10·00	

The time of collection of samples was chosen as one minute when the subject was at rest, but when he was at work it was necessary to collect for a shorter period; the beginning and end of each period was made by sharply turning the tap at the end of an expiration, as indicated by the valve click. No disturbance by reason of this click was experienced by any of the subjects; it

served to count the respirations, which, however, were of such constant frequency under conditions of work and rest that no attempt was made to take systematic frequency counts.

Points of Note.—The hourly increase of CO_2 discharge during the morning and the afternoon; average discharge for last three morning hours = 17·58, for the afternoon hours 18·67; the restorative effect of the dinner hour and of short rests.

Labourer No. 1.—Friday, December 6, 1918.

Time.	Time of collection in secs.	Litres.	C.c. per sec.	CO_2 per cent.	CO_2 c.c. per sec.	Remarks.
7 h. 30 m.	60	14	233	2·2	5·12	After ¼ mile walk and 10 min. rest.
8 h. 0 m.	50	22	440	2·8	12·32	Tapping and trowelling.
3 m.	60	18	300	2·4	7·20	
9 h. 0 m.	40	21	525	2·8	14·70	
3 m.	60	20	333	2·5	8·32	
10 h. 0 m.	40	22	555	3·0	16·65	
3 m.	60	18	300	3·0	9·00	
11 h. 0 m.	40	24	600	2·9	17·40	
3 m.	60	20	333	2·7	9·00	
12 h. 0 m.	40	23	575	3·0	17·00	
3 m.	60	19	316	2·8	8·80	
1 h. 0 m.	60	21	350	2·8	9·8	Immediately after ¼ mile walk.
2 h. 0 m.	45	22	488	3·0	14·64	Tapping and trowelling.
3 m.	60	19	316	2·7	8·53	
3 h. 0 m.	40	20	500	3·3*	16·50	
3 m.	60	16	266	3·1*	8·24	
4 h. 0 m.	40	23	575	3·4	19·50	
3 m.	60	20	333	3·0	10·00	

* Two samples of each of these two bags were collected at once by mercury displacement and handed over to Dr. Pembrey for independent analysis. His report was as follows :—

	CO_2.	O_2.	R.Q.
Sample I	3·16	2·96	1·04
Sample II	2·99	2·97	1·00

The noteworthy points are as on the first two days, viz., the progressive hourly increase of CO_2, and the restorative effect of the dinner hour and of short rests.

Average hourly discharge of CO_2 : forenoon, 17·02 ; afternoon, 16·88.

The mean hourly discharge of CO_2 (gross expenditure) for the three days was :—

Forenoon, 17·02 Afternoon, 16·88.

General hourly mean for three days = 16·41

"Resting CO_2" = 4·00

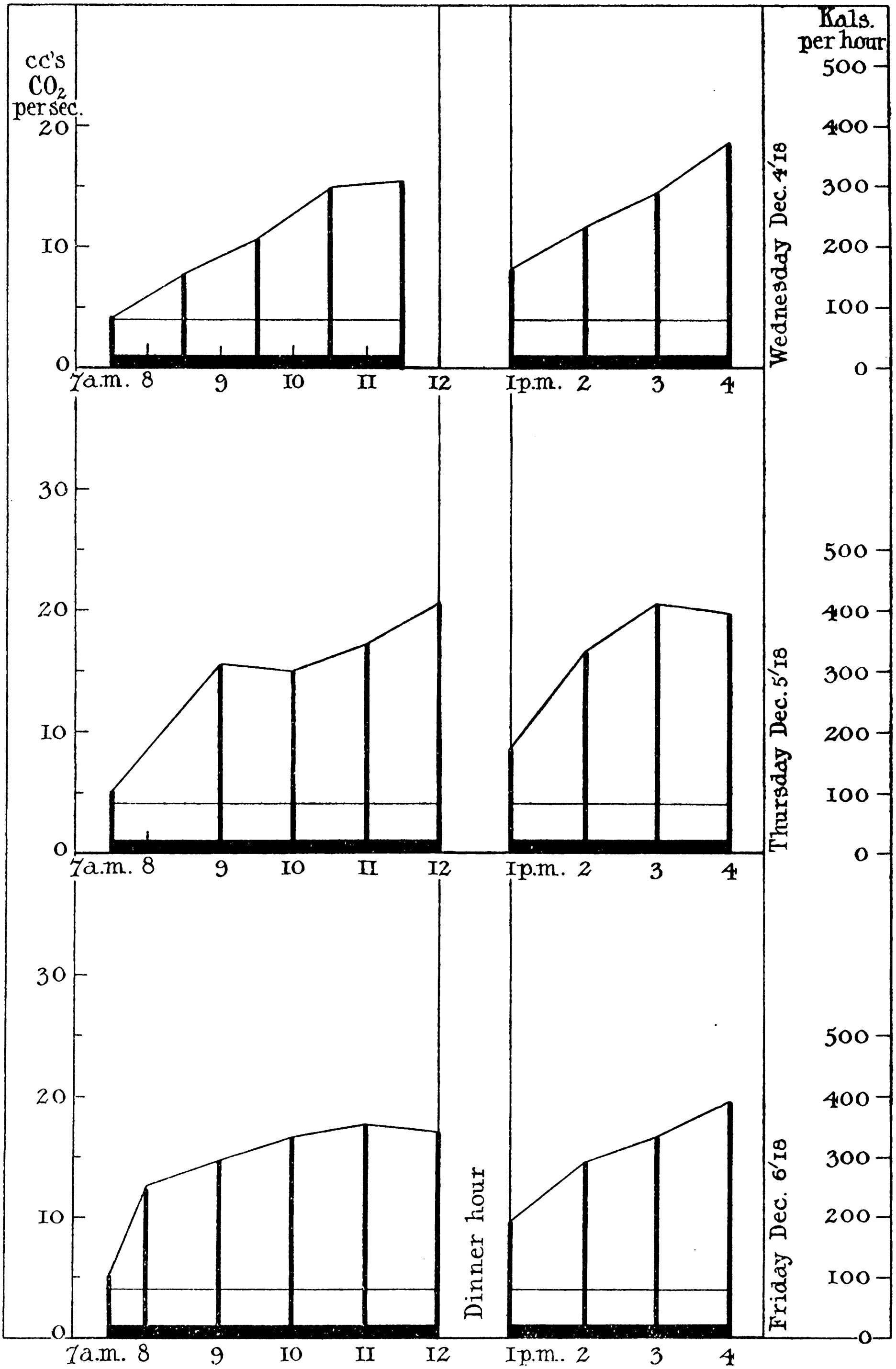
Net cost of work = 12·41 c.c. CO_2 per sec.

= 248·2 Kals per hour.

Labourer No. 1.—Age 51. Weight (clothed), 84 kilos.; height, 1·71 metre (surface calculated = 1·96 sq. metre), East Surrey Docks. Three days' continuous observation.

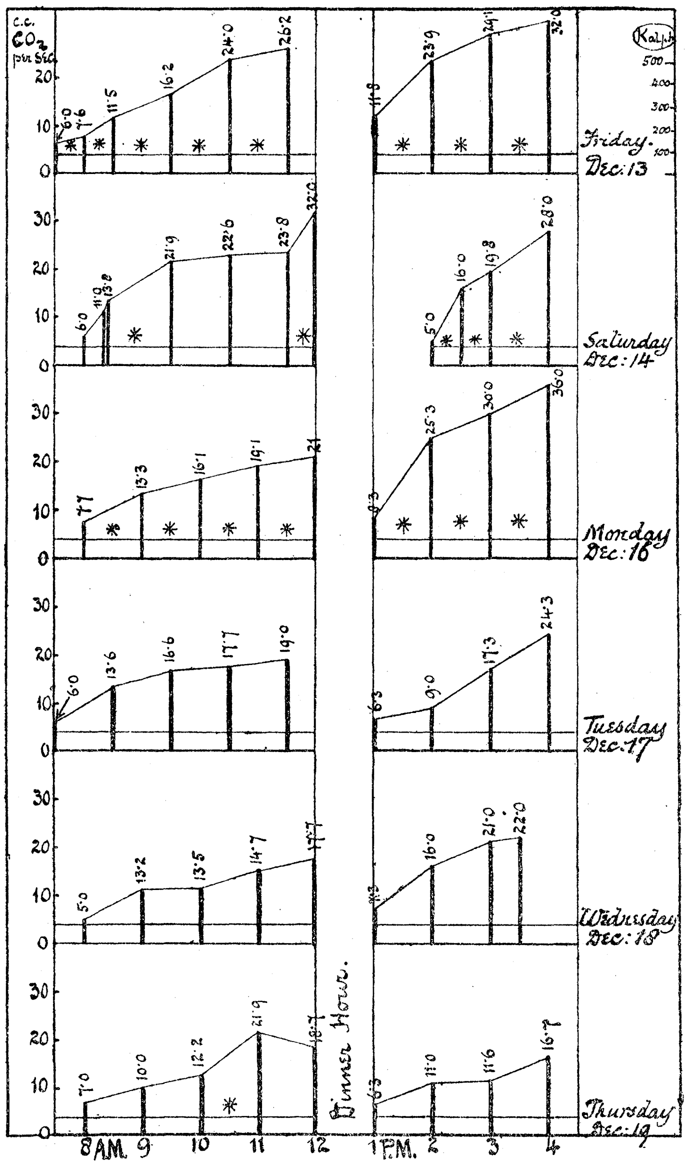
Time.	Time of sampling in seconds.	Ventilation in litres.	Ventilation in c.c. per sec.	CO_2 per cent.	CO_2 in c.c. per sec.	Remarks
						Wednesday December 4, 1918.
7.30	60	11	183	2·4	4·39	After ¼ mile walk followed by 5 mins. rest.
8.30	45	12	266	2·8	7·48	Laying a concrete floor. Chiefly "tapping" and trowelling.
8.33	60	13	216	2·3	4·96	
9.30	42	14	333	3·2	10·65	
9.33	60	12	200	2·8	5·60	
10.30	40	17	425	3·5	14·86	
10.34	60	14	233	3·0	7·00	
11.30	45	20	444	3·4	15·09	
11.34	60	11	183	2·8	5·12	
1.0	55	15	272	3·0	8·16	Immediately after ¼ mile fast walk.
2.0	43	18	418	2·8	11·70	"Tapping" and trowelling.
2.3	60	14	233	2·2	5·12	
3.0	45	20	444	3·2	14·20	
3.4	60	17	283	2·4	6·79	
4.0	43	20	448	3·8	18·54	
4.4	60	18	300	2·6	7·80	
						Thursday, December 5.
7.30	60	12	200	2·5	5·00	After ¼ mile walk and 5 mins. rest.
9.0	40	22	555	2·8	15·54	Finished with concrete floor at 10, when moved tools to another place, and prepared to lay another floor. Moving gravel and other building materials.
9.3	60	23	383	1·7	6·51	
10.0	42	21	500	3·0	15·00	
10.3	60	18	300	2·8	8·40	
11.0	40	22	550	3·1	17·05	
11.3	60	17	233	2·9	6·75	
11.45	40	23	575	3·6	20·70	
11.48	60	19	316	3·0	9·48	
1.0	60	18	300	2·8	8·40	After ¼ mile fast walk.
2.0	40	21·5	537	3·0	16·11	Laying concrete floor. Work rather heavier than usual.
2.3	60	20	333	2·6	8·65	
3.0	40	23	575	3·5	20·12	
3.5	60	19	316	3·2	10·11	
4.0	40	22	550	3·5	19·80	
4.3	60	20	333	3·0	10·00	
						Friday, December 6.
7.30	60	14	233	2·2	5·12	After ¼ mile walk and 5 mins. rest.
8.0	50	22	440	2·8	12·32	Laying concrete floor.
8.3	60	18	300	2·4	7·20	
9.0	40	21	525	2·8	14·70	
9.3	60	20	333	2·4	8·30	
10.0	40	22	555	3·0	16·65	
10.3	60	18	300	3·0	9·00	
11.0	40	24	600	2·9	17·40	
11.3	60	20	333	2·7	9·00	
12.0	40	23	575	3·0	17·00	
12.3	60	19	316	2·8	8·80	
1.0	60	21	—	2·8	9·80	Do.
2.0	45	22	—	3·0	14·64	
2.3	60	19	—	2·7	8·53	
3.0	40	20	—	3·3†	16·50	
3.3	60	16	—	3·1	8·24	
4.0	40	23	—	3·4	19·50	
4.3	60	20	—	3·0	10·00	

No. 1. Timework.



Labourer No. 2.—Age 58. Weight, 89 kgrm.; height, 1·75 M. Body Surface, 2·05 M². Six days' continuous observation.

Time.	Time of sampling (seconds).	Ventilation (litres).	Ventilation (c.c. per sec.).	CO_2 per cent.	CO_2 (c.c. per sec.).	—
Friday, December 13, 1918 (Piece-work).						
7.30	60	20	333	1·8	6·00	*Coaling, *i.e.*, heavy work against time.
8.0	50	19	380	2·0	7·60	
8.30	45	20	444	2·6	11·54	
9.30	40	23	575	3·0	16·25	
10.30	30	24	800	3·0	24·00	
11.30	35	23	657	4·0	26·20	
12 to 1 P.M. Dinner hour.						
1.0	60	22	367	3·2	11·74	*Coaling.
2.0	35	24	685	3·5	23·97	
3.0	30	23	766	3·8	29·10	
4.0	30	24	800	4·0	32·00	
Saturday, December 14.						
8.0	60	18	300	2·0	6·00	
8·30	30	15	500	2·2	11·00	Samples taken immediately before and after carrying a sack of coal.
8.32	30	16	533	2·6	13·80	
9.30	30	22	733	3·0	21·90	*Coaling; carried 21 sacks, 112 lbs. each, during the hour 8.30 to 9.30, distance about 10 yards downwards, 1/20.
10.30	30	20	667	3·4	22·70	
11.30	30	21	700	3·4	23·80	
12·0	30	24	800	4·0	32·00	*Coaling.
12 to 1 P.M. Dinner hour. Felt tired and took an extra hour off duty at midday.						
1.0	—	—	—	—	—	
2.0	60	15	250	2·0	5·00	
2.30	40	20	500	3·2	16·00	Heavy work. Preparing ground for building. Pounding. (Time scale.) Feels "very tired."
3.0	35	21	600	3·3	19·80	
4.0	30	24	800	3·5	28·00	
Monday, December 16 (Piece-work.) Still not feeling well.						
8.0	60	21	350	2·2	7·70	*Coaling.
9.0	30	20	667	2·0	13·34	
10.0	30	21	700	2·3	16·10	
11.0	30	23	767	2·5	19·15	
11.45	30	21	700	3·0	21·00	
1.0	60	20	333	2·5	8·32	*Coaling.
2.0	30	19	633	4·0	25·32	
3.0	30	21	700	4·4	30·00	
4.0	30	24	800	4·5	36·00	


c.c. CO2 per Sec.
Friday. Dec: 13
Saturday Dec: 14
Monday Dec: 16
Tuesday Dec: 17
Wednesday Dec: 18
Thursday Dec: 19
Dinner Hour.
8 AM. 9 10 11 12 1 P.M. 2 3 4

Labourer No. 2—*continued.*

Time.	Time of sampling (seconds).	Ventilation (litres).	Ventilation (c.c. per sec.).	CO_2 per cent.	CO_2 (c.c. per sec.).	—
Tuesday, December 17 (Time work).						
7.30	60	18	300	2·0	6·0	Miscellaneous building work.
8.30	30	17	567	2·4	13·61	Shovelling, barrow-wheeling, brick-loading.
9.30	30	20	667	2·5	16·67	
10.30	30	19	633	2·8	17·72	
11.30	30	22	733	2·6	19·05	
1.0	60	20	333	2·2	6·32	Do.
2.0	30	18	667	3·0	9·00	
3.0	30	20	600	2·6	15·60	
4.0	30	23	767	3·2	24·54	
Wednesday, December 18 (Time-work).						
8.0	60	15	250	2·0	5·00	Building work. Concreting door-heads.
9.0	30	18	600	2·2	13·20	
10.0	30	15	500	2·7	13·50	
11.0	30	17	567	2·5	14·17	
11.45	30	19	633	2·8	17·72	
12 to 1 P.M. Dinner hour.						
1.0	60	20	333	2·2	7·32	Do.
2.0	30	15	500	3·2	16·00	
3.0	30	18	600	3·5	21·00	
3.45	30	18	600	3·8	22·80	
Thursday, December 19.						
8.0	60	21	350	2·0	7·00	Building work.
9.0	30	15	500	2·0	10·00	
10.0	30	16	533	2·3	12·26	
11.0	30	22	733	3·0	22·00	*Coaling from 11 to 12.
11.45	30	28	667	2·8	18·68	
12 to 1 P.M. Dinner hour. Says that the work has been easier and that he feels all right.						
1.0	60	18	300	2·1	6·30	Building work.
2.0	30	15	500	2·2	11·00	
3.0	30	14	467	2·5	11·67	
4.0	30	19	633	2·4	15·19	

The most remarkable "new fact" brought out in these observations is the progressive increase of the CO_2 ordinate in successive hours, which must be

due to one or other of two alternatives, viz., increasing labour or decreasing efficiency.

In view of its gradual progression from hour to hour, it cannot be attributed to a discharge of accumulated CO_2, but is to be regarded as a true expression of the fact that the rate of internal production of CO_2 progressively increases. A progressively increasing discharge of CO_2 for such long periods, otherwise than in consequence of its increased production, is inconceivable, whereas it is quite reasonable to imagine that the animal machine at constant work loses efficiency with lapse of time, *i.e.*, does its work at an increasing cost, as expressed by its discharge of CO_2. Unless, of course, it should be due to increasing work.

Between the two possible causes, (1) increase of work, (2) decrease of efficiency by fatigue, I am inclined towards the second as the more probable. The root fact in fatigue is a consumption of material, presumably of carbohydrate in first instance, also of fat and of protein; subjective fatigue is felt when a certain degree of waste has been incurred. Objective fatigue commences long before its subjective aspect is experienced; it begins, indeed, with the beginning of work, with increased metabolism, of which increased discharge of CO_2 is the indicator and measure, and in the progress of the expenditure there is no line of demarcation to be drawn between a state of freshness and a state of fatigue; these terms are statements of the subjective states associated with the filled and unfilled reservoir of fuel. Moreover, the progressive increase takes place with piece-work under conditions where the work is of steady value.

For reasons that will be more fully developed, I hope, in a future report, I regard the slowly increasing ordinate during presumably constant work as a sign of the increasing cost of such work, *i.e.*, of the decreasing efficiency of the worker.

The hourly rise of CO_2 during a continuous spell of work has been in my experience a rule without exception under all conditions of work so far examined, and if peradventure a worker shows a fall in the ordinate one may be certain that a temporary remission of work has occurred just before observation.

In the present examples the hourly rise has been particularly well marked with piece-work, as shown in diagram, where the starred hours have been piece-work and the unstarred hours time-work. It is still more marked, though with less apparent regularity, in cold storage labour, which is less regular, but while it lasts, more exacting.

The cold storage workman, on duty from 1 A.M. to 7 P.M., is "standing by" through the night hours upon an hourly time wage that we may call basal.

As goods come in he is told off in gangs for piece-work, which brings him supplementary pay as his surplus. He wants to earn this surplus, and each workman does so under the automatic supervision of his mates in the gang, who are earning money in common ; therefore he is working at full pressure, and the expired air collected from him at the end of each hour affords a fair sample of the level of CO_2 expenditure at which he is working. This expenditure is the important fact to ascertain ; the result in cubic centimetres per second can afterwards be translated into calories per hour, and in this translation there is perhaps room for difference of opinion among different physiologists. I am accustomed for the mental arithmetic of the conversion to think of 1 c.c. per second CO_2 as representing 20 cals. per hour ; but in case any other observer should be of a different opinion, and prefer to reckon from another respiratory quotient, I have given in the last column of Table VII Kalories per hour that correspond with different respiratory quotients. The further conversion of calories per hour per individual into calories per hour per square metre is, of course, readily accomplished by taking out from Tables (*e.g.*, that of Du Bois*) the surface values corresponding to the weight and height of the individual in question. Thus, *e.g.*, in the cases of Labourers No. 1 and No. 2 :—

Labourer.	——	Net CO_2 per sec.	Net Kals per hour.	Surface in sq. metres.	Net Kals per hour per sq. metre.
No. 1	Time-work	12·4	248	1·95	127·2
No. 2	Time-work	12·3	246	2·00	123·0
	Piece-work	21·0	420		210·0

I do not like to estimate a day's work by taking the hourly estimate multiplied by hours of work. I think it preferable to plot the CO_2 ordinate of the whole day and to estimate the day's work from the area representing its net cost in cubic centimetres of CO_2 or in Kalories (*i.e.*, cubic centimetres of $CO_2 \times 20$). The hourly figures given above have been averaged from the three last hours of work, omitting the first reading as being possibly too low. Estimation of the area for the whole day includes, of course, the first reading and the hourly estimate obtained by dividing the day's value by the number of hours of work comes out lower than the hourly figures averaged from the last three hours. In the case of Labourer No. 2 the net cost of his six days' work calculated by area comes out as follows :—

* Du Bois and Du Bois, "Tenth Paper on Clinical Calorimetry," 'Archives of International Medicine,' vol. 15, Part II (May 15, 1915). (It is stated in this paper that Meet's formula 12·313 $W^{2}/_{3}$ is more correctly stated as 10·5 $W^{2}/_{3}$. This is the value I found by direct observation, 'Introduction to Human Physiology,' 1st edition.)

Labourer No. 2.	Net cost in Kalories.		Per hour, per sq. metre.
	Per day.	Per hour.	
Friday, December 13*	2431	324	167
Saturday " 14†	1792	299	149·5
Monday " 16*	2535	362	181
Tuesday " 17‡	1568	209	104·5
Wednesday " 18‡	1288	184	92
Thursday " 19†	1155	165	82·5

* Piecework (coaling). † Mixed work. ‡ Time-work.

From these figures I read as the hourly cost of piece-work 175 Kals per hour per square metre; of time-work 100 Kals per hour per square metre, or 1400 and 800 Kals per day of eight hours.

The man-value of this labourer is considerably above that of the "average man" as defined by the Committee (weight 89 kgrm., surface 2 square metres). The allowance of 1900 calories made by the Committee for an average man should therefore, be increased by, say, 22 per cent. (27 per cent. according to weight, 17 per cent. according to surface), raising the allowance from 1900 to 2318. The total food-requirements of this labourer are thus:—

Per day (8 hours) of heavy work (time) $2318+1600 = 3918$
Of heaviest work (piece) $2318+2800 = 5118$,

or in round figures, 4000 and 5000 Kalories.

The mechanical value of the (eight-hour) day's work, costing 2800 and 1600 Kals, could be estimated if we knew the "physiological efficiency" of the worker. This was not measured for Labourer No. 2, but assuming that his efficiency was substantially the same as that measured for Labourer No. 1, viz., 25 per cent., the calculation is as follows:—

Net cost.	Work done.	Rate of work.
2800 Kals	700 Kals (= 297,500 kg.-ms.)	0·138 H.P.
1600 "	400 " (= 170,000 ")	0·079 "

It will be instructive to compare these (high) figures with the lower figures arrived at by direct experiment on four O.T.C. cadets on staircase work (as given in a previous memorandum to the Committee on the Expression of Man-Power in terms of Horse-Power, September 30th, 1918). The pertinent figures given in this memorandum are as follows:—

1st Test: 25 Ascents of 20-metre Staircase in one hour.

Cadet.	Weight.	Total work done.	Kg. M. per sec.	H.P.
No. 1	63	31,500 kg. ms.	8·75	0·115
No. 2	57	28,500 „	7·92	0·109
No. 3	66	33,000 „	9·17	0·121
No. 4	56	28,000 „	7·77	0·102
		Average	8·20	0·112

2nd Test: 80 Ascents (1600 metres) in four hours.

Cadet.	Weight.	Total work done.	Kg. M. per sec.	H.P.
No. 1	—	101,520 kg. ms.	7·05	0·093
No. 2	—	92,720 „	6·43	0·084
No. 3	—	106,400 „	7·38	0·097
No. 4	—	·88,060 „	6·11	0·083

All four cadets were obviously distressed during the last half hour, *i.e.*, the work was excessive.

3rd Test: 80 Ascents (1600 metres) in eight hours with $\frac{1}{4}$ hour rest at each hour and one hour for lunch at end of 40 ascents.

Cadet.	Weight.	Total work done.	Kg. M. per sec.	H.P.
No. 1	—	110,880 kg. ms.	3·85	0·051
No. 5	—	110,880 „	3·85	0·051

Neither cadet felt tired; both were quite willing to go on.

The conclusion drawn from these tests was that an average healthy young man, fit for military service, can do at least 100,000 kgrm.-metres per day, and that a mechanical task of 200,000 kgrm.-metres per day is beyond his power. I much regret that I did not then possess the simple apparatus necessary for keeping the CO_2 ordinate during these tests, and should be very glad if any "healthy young man" would volunteer to repeat the tests with control of his CO_2.

Conclusion.

The Food (War) Committee, in its 'Report on the Food Requirements of Man,' March, 1919, has proposed the adoption of the following classification of manual workers, in conformity with the excess of energy expended during eight hours' work over that expended during eight hours of sleep, as follows (p. 5):—

	Calories.
Sedentary	Less than 400
Light work	400 to 700
Moderate work	700 to 1100
Heavy work	1100 to 2000
(Requirements apart from work)	(1900)

These are "net" values, applicable to the daily sustenance of an "average man," defined in the Report as "an adult man of 66 kgrm. (unclothed), 171 centimetres in height,"* performing eight hours' average work in a climate such as that of France or England.

We have to examine how far the results observed on these two dock labourers, working under normal conditions, conform to the recommendation of the Food (War) Committee, and to collate them with the results of other observers associated in the inquiry. To make this comparison it will be necessary to reduce all results to a common denomination, preferably to the expression "calories per square metre per hour."

Averaged from the last three hours of forenoon and afternoon work (the first hour of work being omitted from calculation in order not to include readings taken before a steady *régime* has been established), the results in Kalories per square metre per hour come out as 127 and 123 for time-work, and 210 for piece-work. But estimates based on the last three hours to the exclusion of the first are probably too high, and it is preferable (*vide infra*) to estimate from the entire period of work inclusive of the first hour. The results on this basis are approximately 100 Kalories per hour for time-work and 160 for piece-work. With the exception of the last value, which represents a maximal value for the very heavy work accomplished in piece-work against time, the ordinary output for the heavy work done by these two labourers falls within the limits (78 to 142) contemplated for "heavy work" by the Food (War) Committee of the Royal Society,

These results should also be compared with those reported to the Committee by Rosenheim and by Greenwood.

I have found some difficulty in making this comparison in the case of Rosenheim's figures, which are for the most part given in terms of standard (basal) metabolism taken as 1.† To quote these figures as they stand would not afford any obvious comparison; I have therefore converted into Kalories

* For comparison with our observations which were made on clothed labourers, we have taken the average man as weighing 70 kgrm. clothed, with a body-surface of approximately 1·75 square metres.

† Rosenheim, "Prelim. Study of Energy Expenditure, etc., of Women Workers," 'Roy. Soc. Proc.,' B, vol. 91, p. 44 (1919).

per square metre per hour the averages of the principal data given on pp. 56 and 57 of his report, as follows:—

——	Increase of standard.	Kalories per square metre per hour.
Light work	37·4 × 0·708	26·48
Medium work	37·4 × 1·090	40·74
Hard work	37·4 × 1·814	67·84
Walking (2·7 to 3·1 m.p.h.)	37·4 × 2·740	102·50

These are relatively low values of energy output, which is stated as having been much lower for "hard work" than for walking at about three miles per hour.

Greenwood and his collaborators conclude their report by the following estimate, but the conditions of observation described in the text do not appear to have afforded any opportunity of securing normal work data.* According to the weight of work, the subjects of observation are arranged in four groups:—

	Calories per sq. metre per hour.
Group I needing approximately	100
„ II „ „	125
„ III „ „	160
„ IV „ „	180

These appear to be gross values, inclusive of the values of basal metabolism. As stated in the report, the work was remarkably slack. Nevertheless from them the four corresponding work quotas for a seven-hour day: 1120, 1400, 1782, 2016 calories, which, augmented by 1410 for travelling and household work, with a 10 per cent. allowance for digestion, give as the final figures for the requirements of "strenuously employed industrial women":—

2810, 3120, 3555, 3805 calories.

These are surprising figures in view of the slackness of work that prevailed during Greenwood's observations. According to his conclusion, a "strenuously

* Greenwood, Hodson, and Tebb, "Report on the Metabolism of Female Munition Workers," 'Roy. Soc. Proc.,' B, vol. 91, p. 62 (1919). It is stated in the Report that the experiments were carried out during November, December, January, February, and March, 1918–19, in a factory, manufacturing 6-inch shell cases, and that in consequence of the relaxation of effort caused by the Armistice, the individual output was reduced by at least 50 per cent. . . . .

"The value of observations in this department (Tool Setting) is reduced by the notorious idleness of the operatives after November 11th. Often the work under experimental study was all the work done in the hour." (p. 67.)

employed industrial woman," with a body surface of 1·6 square metres, requires nearly as much food-energy—3805 Kalories—as does our dock labourer during hard work, viz., 3918 Kalories.

The expression "work quota" might be understood to imply that the basal metabolism has been subtracted from the previous figures per metre, but, as stated on a previous page, the basal metabolism of the subjects was not measured. The gross values 100, 125, 160, 180 have, therefore, to be reduced by, say, 64 to give net results for comparison with our other data, viz., 34, 59, 96, 116.

With these modifications, which have been necessary for the purpose of reducing the figures to a common denomination, the various sets of values presented to the Committee may be briefly set out as follows:—

Net Kalories per square metre per hour.			
Food (War) Committee of the Royal Society.	Rosenheim.	Greenwood, Hodson, and Tebb.	Waller and de Decker.
Sedentary ... under 26	— —	— — (gross)	
Light work ... 26 to 50	Light work ... 23·6	Group 1 34 (100)	— —
Moderate work 50 to 78	Moderate work 36·4	„ 2 59 (125)	— —
Heavy work 78 to 142	Hard work ... 60·4	„ 3 96 (160)	— —
		„ 4 116 (180)	Heavy work ... 100
			Do. piecework 175

In presenting this interim Report, I desire to thank the Port of London Authority for the liberal way in which it has placed its organisation at my disposal and enabled the work to be carried out with, I hope, the least possible interference with the workman's job. Adequate laboratory space has been placed at my disposal, and the courtesy of the officials and labourers with whom I have been brought in contact has made my task most agreeable.

I wish also to acknowledge the zeal, tact, and efficiency with which my assistant, Miss G. de Decker, has carried out the observations; they could not have been made at all without such assistance, which has assumed more and more the character of an independent enquiry, conducted and reported on by herself alone. This acknowledgment applies in fullest measure to the observations (Part II) of day-work and night-work carried out by Miss de Decker upon cold storage labourers.