

A NEW RESPIRATION CALORIMETER AND EXPERI-  
MENTS ON THE CONSERVATION OF ENERGY  
IN THE HUMAN BODY, II.

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III. TESTS OF THE APPARATUS AS A CALORIMETER.

TWO series of test experiments were instituted to ascertain whether the calorimeter would accurately measure a given quantity of heat generated within the respiration chamber. In the first series an electric current of measured strength flowing through a known resistance generated in a given time a quantity of heat which could be readily calculated. As there was no circulation of air and no water vapor produced in the apparatus, it was used at the best advantage simply as a calorimeter. In the second series alcohol was burned within the chamber, a current of air circulating through it supplying the necessary oxygen and carrying away the products of combustion. Here the complications arising from a ventilating current of air and the production of a large amount of moisture were introduced. Evidently, if the calorimeter will accurately measure a known quantity of heat generated in these two ways, it may be employed with confidence to measure the heat generated by a living subject within the chamber. In the latter case, however, we can not expect as high a degree of accuracy as in the former, for the rate of evolution of heat is more variable and the movement of the person or animal about the respiration chamber introduces disturbances which will prevent the highest degree of accuracy in the measurements; and furthermore the errors due to physiological causes may be considerable.

ELECTRICAL TEST EXPERIMENTS.

The arrangement of the apparatus in the electrical tests is shown in Fig. 13. The current from the 220-volt mains passes into the

respiration chamber through a variable resistance,  $RS$ , a Weston ammeter,  $Am$ , and two copper voltmeters,  $Vm$ , where it passes through  $PQ$ , a coil of German-silver wire No. 30, having a resistance of about 100 ohms. A Kelvin balance in series with a known resistance,  $R_1$ , in oil, and a Weston voltmeter in parallel with them are connected to the points  $a$ ,  $b$ , and indicate the fall of potential through the resistance,  $PQ$ . Usually an assistant keeps the current constant by adjusting the resistance,  $RS$ . The current is given with considerable accuracy by the Weston ammeter, which in the first test experiment was used alone. But when the copper voltmeters were employed the values for the current obtained with them were used.

Two test experiments were made on March 20 and 25, 1897, which gave very satisfactory results. A third on March 26th gave slightly more concordant results than either of the others and will be here given in some detail, in order to illustrate the operation of the calorimeter as well as to show its accuracy.

A sample page from the record of the test of March 26th, is given below. It gives the observations of one hour.

In the first column the time is recorded. In the second column are the deflections in the scale divisions in the thermo-electric circuit (No. 1) of the walls of the respiration chamber. Numbers at the left side of the column indicate deflections to the left and show that the inner chamber is a little cooler than air space  $B$ . At 5.10, the air in  $B$  having been cooled slightly, the deflection is zero. Then it becomes positive for a few minutes and the air in  $B$  requires slight warming. The deflections during the hour are on the average less than one division and indicate an average difference of temperature of about  $0.004^\circ$  C. But this difference is part of the time positive and part of the time negative, so that the algebraic average is only one-fourth of one division to the right, indicating that the inner chamber was on the average for the hour  $0.0018^\circ$  C. warmer than the surrounding space. By carrying these differences along from page to page the adjustments are made so that the differences cancel each other, and there is no correction to apply for flow of heat through the walls for the whole experiment.

One division deflection corresponds, as already stated, to  $0.007^\circ$

TABLE I.

Sample page from record of calorimetric observations of experiment of March 26, 1897.

Time, P. m.	Inner wall.		Water circuit.			Inside temp. No. 5.	Remarks.
	No. 1.	Parts.	$T_1, T_2.$	$T_2 - T_1.$	Bridge No. 6.		
<i>h. m.</i>			$^{\circ}\text{C.}$	$^{\circ}\text{C.}$	$^{\circ}\text{C.}$	$^{\circ}\text{C.}$	
5 00	$-3\frac{1}{2}$	$\frac{1}{2}$			12.80	22.61	
02	0	$\left\{ \begin{array}{c} +2 \\ +1 \\ 0 \\ -1\frac{1}{2} \end{array} \right\}$			12.80	22.61	
04	0				12.79	22.61	1st 10 kilos at 5.04.00.
06	0				12.80	22.62	Av. bridge read, 12.73.
08	1				12.87	22.62	$12.73 - .27 = 12.46^{\circ}$ .
10	0				12.85	22.62	$12.46^{\circ} \times 10 = 124.6$
12	$1\frac{1}{2}$		15.97		12.84	22.61	calories.
14	$1\frac{1}{2}$		3.42	12.55	12.78	22.62	
16	$1\frac{1}{2}$				12.72	22.62	
18	$1\frac{1}{2}$				12.80 $\frac{1}{2}$	22.62	
20	1				12.81	22.62	
22	$\frac{1}{2}$	$\left\{ \begin{array}{c} +1 \\ +1\frac{1}{2} \\ -1 \\ 0 \end{array} \right\}$			12.84 $\frac{1}{2}$	22.62	
24	0				12.83 $\frac{1}{2}$	22.62	
26	0				12.86	22.62	
28	0		15.93		12.76	22.63	
30	$\frac{1}{2}$		3.44		12.77	22.63	
32	0				12.87 $\frac{1}{2}$	22.63	
34	$\frac{1}{2}$			12.49	12.77	22.64	
36	1				12.80 $\frac{1}{2}$	22.64	
38	0				12.81	22.64	
40	1				12.81	22.64	
42	$\frac{1}{2}$		15.94		12.81	22.64	
44	$\frac{1}{2}$		3.43	12.51	12.77	22.64	
46	0	$\left\{ \begin{array}{c} 0 \\ -\frac{1}{2} \\ 0 \\ -\frac{1}{2} \end{array} \right\}$			12.78	22.65	2d 10 kilos at 5.47.45.
48	1				12.79	22.65	Av. bridge read, 12.81.
50	$\frac{1}{2}$				12.86	22.65	$12.81 - .27 = 12.54^{\circ}$ .
52	0				12.83	22.65	$12.54^{\circ} \times 10 = 125.4$
54	$\frac{1}{2}$				12.79	22.65	calories.
56	0		16.04		12.81	22.64	
58	0		3.47	12.57	12.85	22.64	
	7	$+11\frac{1}{2}$					

C. difference of temperature, and with this difference of temperature 4 small calories per minute, or 0.24 of a large calorie per hour, flow through the walls of the chamber. This was determined in the following manner: A current of 0.17 ampères was passed through a resistance within the calorimeter for four hours. The fall of potential was 43 volts, giving 7.3 watts or about 104 small

calories per minute. The temperature of the chamber rose a little at first, but was constant during the latter part of the experiment, showing that all of the heat was escaping through the walls. The deflection produced by the thermo-electric elements of circuit No. 1 was about 25 divisions, remaining substantially constant for some time before the end of the experiment. This gives 4 small calories per minute per scale division as the amount of heat flowing through the walls of the calorimeter. This may be called the radiation constant.

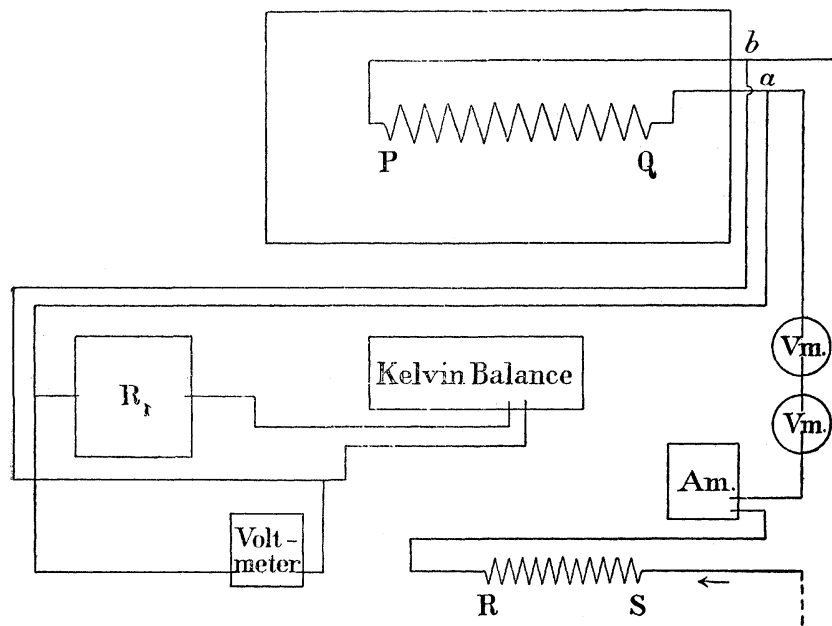


Fig. 13.—Arrangement of the electric apparatus for generating heat in the test experiments.

For an average deflection of one-fourth of one division the rate at which heat would be escaping from the interior of the calorimeter would be 0.06 calorie per hour. The amount of heat generated and carried away from the calorimeter was, in this experiment, 74 calories per hour. Thus the amount of heat passing through the walls is only  $0.060 \div 74 = 0.0008$  of the total, or one-twelfth of 1 per cent., and would not be an appreciable error if

uncorrected. It is, however, subsequently recovered by keeping the deflection slightly negative, as already explained.

In the third column are recorded the deflections observed when parts of the thermo-electric circuits are separately joined to the galvanometer, the four numbers being for the top, upper, lower and bottom sections, respectively. These deflections are all small and make more certain the balance indicated by zero deflection of the entire system in series.

In the fourth column are recorded the readings of the two mercury thermometers, *G* and *H* (Fig. 6), and the fifth column shows their difference ( $T_2 - T_1$ ), which is the gain in temperature of the water flowing through the absorbing pipes. The sixth column shows the readings of bridge No. 6 for the same difference of temperature.

The bridge does not give the exact difference of temperature of the two coils, which are immersed in the water, its readings being always too high. However, it correctly indicates the variations of temperature between the thermometer readings, and thus interpolations between the observed thermometer readings can be made. In actual practice the average of the bridge readings is reduced by the average difference between thermometer and bridge. For example 10 kilograms ran out during the period of forty-four minutes from 5.04 to 5.48 p. m. The average of the bridge readings for the forty-four minutes, during which the 10 kilograms of water were passing through the absorbers, was 12.81. The correction to be subtracted to reduce the bridge readings to degrees centigrade is 0.27. This gives an average difference of  $12.54^\circ$ , and hence 125.4 calories of heat were brought away in these forty-four minutes. In the same way the difference of temperature for each 10 kilograms is determined. A tabular statement of the heat measured during the entire experiment from 4.20 p. m. to 11.37 p. m. is given in the table on next page.

If a calorie be defined as the amount of heat required to raise 1 kilogram of water  $1^\circ$  C., at  $15^\circ$  C. it will be equivalent to a definite number of ergs, which must be determined by experiment. The value given by E. H. Griffiths,<sup>1</sup> as the result of his elaborate work

<sup>1</sup>Phil. Trans. Royal Society, A, 1893. Proc. Roy. Soc., vol. 55.

TABLE II.

Summary of heat measurements, March 26, 1897.

Time.	(a) Duration of period.	Calorimetric measurements.				Electrical measurements.				Temper- ature of the inside by the copper therm- ometer. No. 5.
		(b) Water.	(c) Differ- ence in temper- ature by bridge No. 6.	(d) Cor- rected differ- ence in temper- ature, $c - 0.27$ .	(e) Amount of heat, $b \times d$ .	<i>E</i> Voltage on coil.	<i>I</i> Cur- rent through coil.	<i>W</i> Watts, $E \times I$	(k) Calories, $W \times a$ $\times .2378$ .	
<i>h. m. s.</i>	<i>Secs.</i>	<i>Kilos.</i>	$^{\circ}\text{C.}$	$^{\circ}\text{C.}$	<i>Cals.</i>		<i>Amps.</i>			$^{\circ}\text{C.}$
4 20 20										22.63
5 04 00	2,620	10	12.73	12.46	124.60	147.8	1.363	201.5	125.54	22.61
5 47 45	2,625	10	12.81	12.54	125.40	147.8	1.363	201.5	125.78	22.65
6 31 45	2,640	10	12.92	12.65	126.50	147.8	1.363	201.5	126.50	22.67
7 15 27	2,622	10	12.77	12.50	125.00	146.0	1.350	197.1	122.89	22.57
7 59 10	2,623	10	12.80	12.53	125.30	147.8	1.363	201.5	125.68	22.59
8 42 40	2,610	10	12.79	12.52	125.20	147.8	1.363	201.5	125.06	22.60
9 26 15	2,615	10	12.78	12.51	125.10	147.8	1.363	201.5	125.30	22.60
10 09 50	2,615	10	12.68	12.41	124.10	147.8	1.363	201.5	125.30	22.64
10 53 30	2,620	10	12.82	12.55	125.50	147.8	1.363	201.5	125.54	22.62
11 37 10	2,620	10	12.81	12.54	125.40	147.8	1.363	201.5	125.54	22.61
					1,252.10	Heat generated by				
Capacity correction for $0.02^{\circ}$ ..... =					-1.2	electric current.... = 1,253.13				
Heat measured by calorimeter. .... =					1,250.9					

on the determination of the relation between the electric units and those of heat is,

$$J = 4.1982 \times 10^7 \text{ ergs, at } 15^{\circ} \text{ C.}$$

The average temperature of the water in the absorbers in our experiments was in every case between  $8^{\circ}$  and  $10^{\circ}$  C. The specific heat of water<sup>1</sup> at  $10^{\circ}$  C. is 1.0019<sup>2</sup> times its value at  $15^{\circ}$  C., and hence it requires 1.0019 times as much heat to raise 1 kilogram one degree at  $10^{\circ}$  C. as at  $15^{\circ}$  C., so that

$$J = 4.2062 \times 10^7 \text{ ergs, at } 10^{\circ} \text{ C.}$$

This value is practically the same as that given by Professor Rowland<sup>3</sup> for the mechanical equivalent of heat at  $8^{\circ}$  C., and so appears to be the most nearly correct for our use.

<sup>1</sup> Bartoli and Stracciati, Boll. mens. dell'Acc. Gioenia, 18, Apr. 26, 1891. Preston's Theory of Heat, p. 265.

<sup>2</sup> As estimated from the figures of the table on p. 231—*i. e.*,  $1.0029 \div 1.0010 = 1.0019$ .

<sup>3</sup> Proc. Am. Acad. Sci., 15 (1879), p. 75.

A recent recalculation of Rowland's value of the mechanical equivalent of heat<sup>1</sup> gives  $4.200 \times 10^7$ , at  $8^\circ$  C., and it has been suggested that the difference between this value and Griffith's is accounted for by the uncertainty in the value of the ampère, but as we use the same ampère as Griffith did we should use his value of  $J$ .

The energy of the electric current expressed in ergs being

$$CEt \times 10^7,$$

when expressed in calories becomes

$$\frac{CEt \times 10^7}{4.2062 \times 10^7} = CEt \times 0.23775.$$

Referring to the above table, it will be seen that the total amount of heat generated by the current is 1253.13 calories. The amount measured is 1252.10 calories, less than that produced by the electric current by 1.03 calories. During the experiment the temperature of the chamber fell from  $22^\circ.63$  to  $22^\circ.61$ . The capacity for heat of the apparatus is equivalent to that of 60 kilograms of water—that is, it requires 60 calories to raise the temperature  $1^\circ$ . This was determined in the following manner:

The calorimeter was held at a constant temperature ( $23^\circ.8$ ) for several hours. A current of 1.77 ampères, at 33 volts, was then passed through it for two hours. The temperature slowly rose and, keeping the deflection of the No. 1 thermo-electric circuit zero, no heat was allowed to pass through the walls. At the end of this time the current was stopped and the calorimeter came to a constant temperature at  $25^\circ.4$ . This rise in temperature was thus  $1^\circ.6$ . The amount of heat generated by the electric current was 98.2 calories, or 61.5 calories per degree. Other determinations gave similar results, and the round number 60 was taken as a sufficiently exact value of the thermal capacity of the apparatus.

In the above case, where the temperature fell 0.02, there will be  $.02 \times 60 = 1.2$  calories which are absorbed and measured in addition to the heat from the current. Applying this correction, we have for the measured amount of heat produced by the current  $1252.10 - 1.2 = 1250.9$  calories, which is 2.2 calories, or 0.18 per cent. less than indicated by the electrical determination.

<sup>1</sup> Phil. Mag., 44 1897, p. 169.

The current in the above experiment was maintained constant, and the voltage measured by the Kelvin balance. About 7 p. m. the voltage on the mains was lower than usual for some minutes, and the variable portion of the resistance was insufficient to maintain the voltage on the coil. Consequently the balance was set at a lower point and the current kept constant at this smaller value until it could be restored to its former value. This makes the average voltage and current for the fourth period smaller than the others. The totals show that the amount measured was 2.2 calories, or 0.18 per cent. too small. This, however, assumes that the measurements of temperature at the beginning and the end are accurate and that the temperature of the whole apparatus is the same as that of the air. An error of a few hundredths of a degree might throw the difference in the opposite direction. Since this change is so slight, and as all the measurements of the temperature are presumably equally reliable, it would be more accurate if the average of all was used in obtaining the capacity correction. This can be done by taking different portions of the experiment and applying the capacity correction to each portion; the average of the errors from the different portions will give a more probable value of the error of the experiment. The above experiment is thus discussed in Table III.

TABLE III.  
Discussion of experiment of March 26, 1897.

Periods.	(e) Heat as measured.	Temperature No. 5.			(i) Capacity correction, $h \times 60$ .	(j) Corrected heat, $e + i$ .	(k) Heat put in by the electric current.	Error in heat measurement, $j - k$ .
		(f) At the beginning.	(g) At the end.	(h) Change, $g - f$ .				
1-6.....	Cals. 752.0	o 22.63	o 22.60	o -0.03	Cals. -1.8	Cals. 750.2	Cals. 751.5	Cals. -1.3
2-7.....	752.5	22.61	22.60	-0.01	-0.6	751.9	751.1	+0.8
3-8.....	751.2	22.65	22.64	-0.01	-0.6	750.6	750.6	0.0
4-9.....	750.2	22.67	22.62	-0.05	-3.0	747.2	749.6	-2.4
5-10.....	750.6	22.57	22.61	+0.04	+2.4	753.0	752.2	+0.8
					Sum . . . . .	3,752.9	3,755.0	-2.1
					Avg. . . . .	750.6	751.0	-0.4
	0.4 750.6 = 0.053 per cent.							

In the first column is indicated the number of periods corresponding to the section of the experiment taken for discussion. In the



second, (*e*) is the heat measured during the same period—*i. e.*, the sum of the values in column (*e*), Table II. The next three columns show the change in temperature of the apparatus, and the necessary correction is given in the sixth column. Applying these corrections to the values in the second column gives the corrected heat in (*j*). The values of the heat generated, (*k*), are obtained by adding those in column (*k*), Table II. The last column gives the differences between the heat generated and that measured, and the average of these shows the error of the apparatus. In this experiment the error is about 0.05 per cent., which is as close as the electrical energy could be measured.

Another test of a somewhat different nature was made April 30th. A small incandescent electric lamp, rated at 4 candle power, but burned low, taking 4.21 watts, or 1 small calorie per second, was placed within the chamber and the heat given off was measured. The heat being so small it was necessary to have the water enter at a temperature nearly as high as the air inside, and to flow in a very slow stream. The results of six hours' run are given in Table IV.

TABLE IV.

Experiments with 4-candle power electric lamp—Summary of heat measurements, April 30, 1897.

Time.	Calorimetric measurements.					Electrical measurements.				Temperature of the inside by the copper thermometer No. 5.
	(a) Duration of period.	(b) Water.	(c) Difference in temperature by bridge No. 6.	(d) Corrected difference in temperature. $c - 0.09^\circ$ .	(e) Amount of heat, $b \times d$ .	<i>E</i> Voltage on lamp.	<i>I</i> Current through lamp.	<i>W</i> Watts, $E \times I$ .	( <i>k</i> ) Calories, $W \times a \times .2378$ .	
<i>h. m. s.</i>	<i>Secs.</i>	<i>Kilos.</i>	$^\circ C.$	$^\circ C.$	<i>Cals.</i>		<i>Amp.</i>			$^\circ C.$
9 56 00	.....	.....	.....	.....	.....	.....	.....	.....	.....	19.72
10 11 45	945	1	1.82	1.73	1.72	5.61	0.75	4.21	0.95	19.70
10 40 35	1,730	2	1.35	1.26	2.52	5.61	.75	4.21	1.73	19.65
10 54 55	860	1	1.28	1.19	1.19	5.61	.75	4.21	.86	19.63
11 38 45	2,630	3	1.15	1.06	3.18	5.61	.75	4.21	2.63	19.62
1 55 00	8,175	9	.97	.88	7.92	5.61	.75	4.21	8.17	19.63
2 22 30	1,650	2	.41	.32	.64	5.61	.75	4.21	1.65	19.66
3 08 00	2,730	2.6	.61	.52	1.35	5.61	.75	4.21	2.73	19.72
3 54 00	2,760	3.3	.95	.86	2.84	5.61	.75	4.21	2.76	19.73
Heat measured..... = 21.37					Heat generated..... = 21.48					

It will be seen that the measurement is very close. There is apparently a small capacity correction, which if applied, makes the error in the opposite direction. It is so small, however, that it is impossible to say with certainty how much the correction should be.

As this amount of heat is only about 1 per cent. of the maximum which the apparatus will measure and about 3 per cent. of the heat usually measured, it is evident that there can be no appreciable loss or gain of heat by radiation or otherwise. We therefore believe that this calorimeter, with proper manipulation, will measure heat as accurately as it is possible to measure it by any other form of calorimeter.

#### ALCOHOL TEST EXPERIMENTS.

The electrical tests above described demonstrate the accuracy of the apparatus as a calorimeter when the evolution of heat inside the chamber is reasonably uniform, and there is no current of air passing through and no vaporization of water within the chamber. In experiments with men, however, the development of heat is less uniform; furthermore, a current of air is passing through the chamber, water and carbon dioxide are produced, and water is vaporized within it. In these experiments the principal measurements made with the aid of the apparatus are the amounts of water and carbon dioxide produced by the man and the heat given off from his body. In experiments where the external muscular work has been considerable the latter has been transformed into electrical energy, measured, and transformed into heat. This heat has been measured with that given off directly by the body. The crucial test of the accuracy of the determinations of carbon dioxide, water and heat must be made in test experiments under circumstances closely similar to those of the actual experiments with men. When ethyl alcohol is burned in air carbon dioxide, water and heat are produced. If known quantities of alcohol be burned inside the chamber while a current of air is passing through, the conditions will approach very closely those of an experiment with man. To make these experiments accurate, the amount of alcohol burned must be exactly known and the combustion must be complete.

Several series of experiments were made in which alcohol was

burned inside the chamber. The rate of flow of the ventilating current, the method of analysis of the incoming and outgoing air, and the method of measurement of heat were the same as if a man were inside the chamber.

#### I. COMPOSITION OF ALCOHOL USED—SPECIFIC GRAVITY.

In some of the tests here described we have used pure ethyl alcohol kindly furnished by Dr. Edward R. Squibb, but for the larger part of our work, including the alcohol tests with the respiration calorimeter, a high grade of commercial alcohol was used instead of the so-called absolute alcohol, because it can be more easily stored, weighed, and measured without change of water content. The specific gravity of this alcohol was determined at the time of each experiment. The variations in the different samples were small, the proportion of alcohol being not far from 90.5 per cent. by weight. From the percentage of alcohol present the amount of carbon dioxide and water that would be formed by complete oxidation is readily calculated as follows: Taking the atomic weight of hydrogen as 1, that of oxygen<sup>1</sup> is here taken as 15.88, and carbon 11.91. With these atomic weights the molecular weight of alcohol,  $C_2H_6O$ , is 45.70, of  $H_2O$  is 17.88 and of  $CO_2$  is 43.67. The reaction in the combustion of alcohol is  $C_2H_6O + O_6 = 2CO_2 + 3H_2O$ . By molecular weights,  $45.70 + 95.28 = 87.34 + 53.64$ , or 1 gm. alcohol + 2.0848 gm. oxygen = 1.9110 gms.  $CO_2$  + 1.1737  $H_2O$ . Hence one gram of ethyl alcohol ( $C_2H_6O$ ) will yield on oxidation 1.9110 grams of carbon dioxide and 1.1737 grams of water. One gram of a mixture of alcohol and water containing 90.77 per cent. absolute alcohol (the strength of that used in the first three tests) will give  $1.9110 \times 0.9077$ , or 1.7346 grams of carbon dioxide, and  $1.1737 \times 0.9077$ , or 1.0654 grams of water from the combustion of the ethyl alcohol in addition to the 0.0923 grams of water present in the mixture, making a total of 1.1577 grams of water from 1 gram of the alcohol mixture used. The estimates of the quantity of heat produced by the oxidation of a gram of each of the different specimens of alcohol are made by use of the factor

<sup>1</sup>F. W. Clarke, *Journal of Am. Chem. Soc.*, March, 1898. Richards, *Am. Chem. Journal*, p. 534, July, 1898

7.067 calories for the heat of the combustion of 1 gram pure ethyl alcohol as explained beyond.

## 2. HEAT OF COMBUSTION OF ALCOHOL—DETERMINATION WITH THE BOMB CALORIMETER.

The heat of combustion of the alcohol used in the tests was determined by the bomb calorimeter. This well known instrument<sup>1</sup> which has been used in determining the heats of combustion of the food and excreta in the experiments with a human subject, is illustrated in section in Fig. 14. The so-called bomb is a steel cylinder, about 12 cm. deep and 6 cm. average interior diameter, the wall being about 0.6 cm. thick. A groove in the cover contains a lead gasket, and when the outer ring or collar is screwed down with a heavy spanner, the bomb is closed perfectly tight, even for pressures of 30 to 40 atmospheres. The cover is provided with a neck *D*. The valve screw *F* passes through a second screw *E*, and at the bottom of *E* is a lead packing *L*. The pressure of *E* upon *L* makes a perfectly tight joint about the bottom of *F*. Oxygen is admitted to the bomb through a narrow passage extending from *G* to the bottom of *F*, and then directly downward to the interior of the cylinder. This passage is closed when *F* is screwed down. The bomb is fitted with a platinum cup, spun from a single piece of platinum, which serves as lining, and the cover is also lined with platinum. This effectually prevents any oxidation of the bomb itself by the compressed oxygen during the combustion. Two platinum rods *H*, *I*, serve to hold a platinum capsule *O*, containing the substance to be burned, and also to conduct an electric current which, flowing through the fine iron wire over the capsule, fuses the wire and so ignites the substance to be burned.

The bomb is placed in a cylinder of brittania metal, 12 cm. in diameter and 22 cm. high, and about 1700 c.c. of water added, the whole being surrounded by two concentric cylinders of "indurated fiber," in the manner shown in the figure. A stirrer *SS*, is driven at a uniform speed by a small electric motor. The thermometer is

<sup>1</sup> See description by W. O. Atwater in Bulletin 21 of the Office of Experiment Stations of the U. S. Department of Agriculture and by W. O. Atwater and O. S. Blakeslee in report of Storrs (Conn.) Agricultural Experiment Station for 1897.

graduated to one-hundredth of a degree, and read with a magnifying glass to thousandths. Those here used were made by Fuess of Berlin and calibrated at the Physikalisch-technische Reichsan-

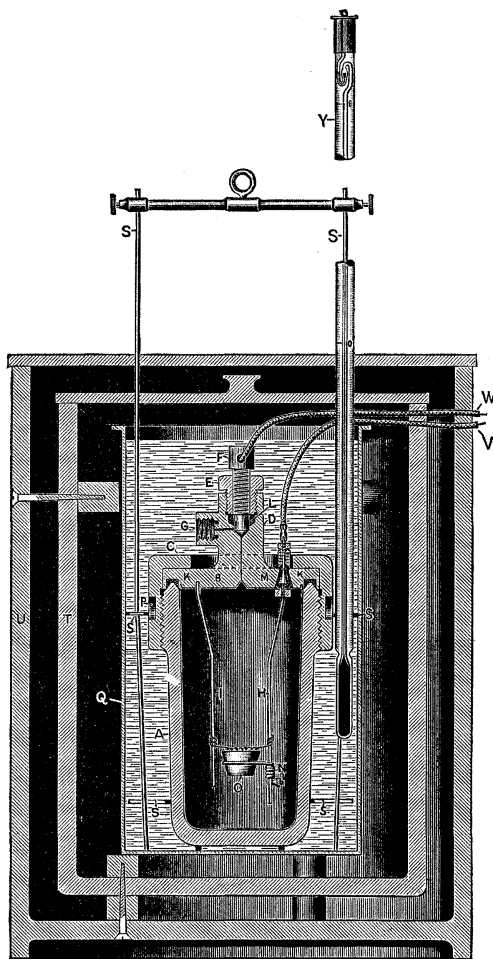


Fig. 14.

Bomb calorimeter; apparatus as used for actual determination of heats of combustion.

stalt. Oxygen is supplied by the S. S. White Dental Mfg. Co., New York in cylinders about 125 cms. long and 18 cm. in diameter, at a pressure of 200 atmospheres. It is admitted to the bomb until

the gauge indicates a pressure of 20 atmospheres. One cylinder full of oxygen will thus suffice for hundreds of combustions.

In the combustions of alcohol two methods were used. In one the alcohol was poured upon cellulose filter blocks. The weighing was made with due precautions to prevent, if possible, any loss by evaporation. The alcohol and filter block were burned in the calorimeter, a correction being applied for the heat of combustion of the filter block used. Eight determinations were made by this method with commercial alcohol of high grade and of different strengths.

The use of filter blocks is objectionable because of the difficulty of avoiding evaporation of alcohol during the process of weighing and transferring to the bomb, and because of the considerable and not absolutely certain correction to be applied for the heat of combustion of the filter blocks used. The first difficulty was avoided entirely and the other partially by the second method employed. In this the alcohol was inclosed in small gelatin capsules by which the evaporation is prevented. The weight of gelatin is also small and the correction for its heat of combustion is less than with the filter blocks. Eight determinations were made with Squibb's alcohol and nine with commercial alcohol, such as was used in the tests in the respiration calorimeter. The results obtained by both methods are shown in Table V.

The heat of combustion when determined by the first method ranged from 7,030 to 7,090, and averaged 7,069 small calories per gram of absolute alcohol.

The results obtained by the second method with Squibb's alcohol ranged from 7,044 to 7,090 small calories, and averaging 7,061 small calories per gram, absolute alcohol. The results of similar determinations with the commercial alcohol ranged from 7,045 to 7,103 small calories, and averaging 7,070 small calories per gram, absolute alcohol. The average of these 17 determinations with alcohol in gelatin capsules gives 7,066 small calories, practically the same result as was obtained by the use of the filter blocks. Considering the range of variation in these different determinations, we would hardly be justified in assuming that the figure 7,067 represents to a very high degree of accuracy the heat of combustion of

TABLE V.

*Determination of heats of combustion of alcohol in the bomb calorimeter.*

	Ethyl hydroxid by weight.	Heat of combustion per gram actually determined.	Calculated heat of combustion per gram of ethyl hydroxid.
Alcohol contained in filter blocks :	<i>Per cent.</i>	<i>Small cals.</i>	<i>Small cals.</i>
Specimen No. 1.....	89.9	6,348	7,062
Do.....	89.9	6,345	7,058
Do.....	89.9	6,377	7,093
Average of above 3.....	.....	.....	7,071
Specimen No. 2.....	81.3	5,744	7,063
Do.....	81.3	5,763	7,090
Average of above 2.....	.....	.....	7,076
Specimen No. 3.....	72.5	5,132	7,078
Do.....	72.5	5,094	7,030
Do.....	72.5	5,132	7,078
Average of above 3.....	.....	.....	7,062
Average of above 8.....	.....	.....	7,069
Alcohol contained in gelatin capsules :			
Specimen No. 4.....	88.0	6,205	7,050
Do.....	88.0	6,224	7,072
Do.....	88.0	6,209	7,055
Do.....	88.0	6,199	7,044
Do.....	88.0	6,204	7,050
Do.....	88.0	6,203	7,049
Do.....	88.0	6,227	7,076
Do.....	88.0	6,240	7,090
Average of above 8.....	.....	.....	7,061
Specimen No. 5.....	90.61	6,435	7,101
Do.....	90.61	6,384	7,046
Do.....	90.61	6,401	7,064
Do.....	90.61	6,383	7,045
Do.....	90.61	6,403	7,066
Do.....	90.61	6,397	7,060
Do.....	90.61	6,436	7,103
Do.....	90.61	6,433	7,099
Do.....	90.61	6,386	7,047
Average of above 9.....	.....	.....	7,070
Average of above 17.....	.....	.....	7,066
Average of above 25.....	.....	.....	7,067

ethyl hydroxid. There is reason to hope, however, that some of the sources of error in the determinations may yet be partially eliminated, and that thus more reliable results may be obtained. It is worthy of note that Berthelot and Matignon<sup>1</sup> obtained the figure 7,068 as the average of two determinations, which gave 7,067.3 and 7,068.5 small calories, respectively, at 13°. The average 7,068 corresponds to 7,079 at 20°, a value very close to those obtained here.

The heat of combustion of alcohol of any given dilution with water is found by multiplying the heat of combustion of 1 gram of absolute alcohol by the percentage present in the specimen. Thus in the specimen of alcohol used in the first three tests the heat of combustion was  $7,067 \times .9077$ , or 6,415 small calories per gram.

While the heat of combustion of 1 gram of absolute alcohol is thus 7,067 small calories per gram, this does not represent the amount of heat that is given off by the combustion of 1 gram of alcohol within the chamber of the respiration calorimeter. In the bomb calorimeter all the water vapor formed is condensed within the apparatus, and hence the heat that had been required to vaporize the water is given off again. In the respiration calorimeter, on the other hand, the water passes out as vapor in the ventilating air current. The heat required to vaporize it comes from the combustion of the alcohol, and is not measured by the calorimeter. In order to obtain the total amount of heat given off in the combustion, therefore, the heat actually measured must be added to the amount required to vaporize the excess of water in the outgoing over that in the incoming air current, which is the amount of water vaporized at the expense of the heat produced in the combustion of the alcohol.

### 3. THE CALORIE HERE USED AS THE UNIT OF MEASURE.

Although the specific heat of water is often taken as unity for all temperatures, it actually varies by an appreciable amount. Hence if the unit of heat be defined as the amount required to raise unit mass of water 1 degree, this unit will be a variable one. The theoretical large calorie, namely, the quantity of heat that will raise a kilogram of water from 0° to 1°, or from 4° to 5°, is a very incon-

<sup>1</sup> Ann. Chim. et Phys., 6 ser., 27 (1892), p. 312.



venient unit in practice. Moreover, the specific heat of water changes quite rapidly at these low temperatures, and hence a higher temperature is more favorable for the working unit. Many authorities take the specific heat of water at  $15^{\circ}$  C. as unity. Inasmuch, however, as we have used  $20^{\circ}$  C. as our standard temperature for the respiration calorimeter in experiments with human subjects, and inasmuch also as the specific heat of water has a minimum near to  $20^{\circ}$  and changes very slowly in that vicinity, we have found it desirable to take as our working unit of heat the calorie at  $20^{\circ}$ . In other words, the large calorie at  $20^{\circ}$ , which we designate in the tables as  $C_{20}$ , is the amount of heat required to raise the temperature of a kilogram of water 1 degree at  $20^{\circ}$  C. (that is, from half a degree below  $20^{\circ}$  to half a degree above). The large calorie at any other temperature is here designated by  $C_t$ , and is the amount of heat required to raise the temperature of a kilogram of water 1 degree at the temperature  $t$ .

Since the specific heat of water is nearly a minimum at  $20^{\circ}$  C., our standard calorie,  $C_{20}$ , is nearly always less than  $C_t$ . This difference is ordinarily neglected. But in the alcohol-test experiments and in the experiment with a human subject to be described later, this difference is, relatively speaking, not inconsiderable. In Table VI. the specific heat of water is given for different temperatures between  $0^{\circ}$  and  $31^{\circ}$ . The figures are based upon the experiments of Rowland,<sup>1</sup> Bartoli and Stracciati,<sup>1</sup> Griffiths,<sup>1</sup> and Ludin.<sup>2</sup> The differences in the results obtained by these investigators at temperatures below  $22^{\circ}$  are very small, and, in view of the care with which their experiments were made, we do not believe that the estimates of this table can be far enough from the truth materially to diminish their value for the present purpose.

It will be seen that at  $0^{\circ}$  the calorie ( $C_0$ ) is nearly 1 per cent. greater than  $C_{20}$ , and that  $C_{10}$  is about three parts in a thousand greater than  $C_{20}$ .

The results of all the combustions by the bomb calorimeter, as

<sup>1</sup> See p. 00 above.

<sup>2</sup> Inaug. Diss., Zurich, 1895; cited by Longuinine, Bestimmung der Verbrennungswärme, Berlin, 1897, p. 17. See discussion of results of experiments on the specific heat of water on pp. 12-20 of this valuable treatise.

TABLE VI.

*Specific heat of water at different temperatures referred to that at 20°C. as unity.*

Temp. °C.	Specific heat.	Temp. °C.	Specific heat.	Temp. °C.	Specific heat.	Temp. °C.	Specific heat.
0	1.0090	8	1.0039	16	1.0007	24	.9998
1	1.0083	9	1.0034	17	1.0004	25	.9998
2	1.0076	10	1.0029	18	1.0002	26	.9998
3	1.0069	11	1.0024	19	1.0001	27	.9999
4	1.0062	12	1.0020	20	1.0000	28	.9999
5	1.0056	13	1.0016	21	.9999	29	1.0000
6	1.0050	14	1.0013	22	.9998	30	1.0001
7	1.0044	15	1.0010	23	.9998	31	1.0002

well as the measurements by the respiration calorimeter, are to be expressed in terms of  $C_{20}$ . To do this it is necessary to know the mean specific heat of water for the range of temperature employed in any given experiment. For example, if water is warmed from 3° to 17° in passing through the absorbed pipes of the respiration calorimeter, the result will be in terms of  $C_{(3-17)}$ ; that is, in terms of the mean calorie from 3° to 17°. This is 1.0032 times as great as the standard calorie  $C_{20}$ , whereas  $C_{10}$ , the calorie for the mean temperature, is only 1.0029 times as great as  $C_{20}$ . In other words, the mean specific heat from 3° to 17° is 1.0032 times the specific heat at 20°, whereas the specific heat at 10°, the mean temperature, is 1.0029 times that at 20°. The difference between the mean specific heat for this range of temperature and the specific heat of the mean temperature is therefore appreciable; this is of course because the variation of the specific heat is not linear. We have accordingly calculated the mean specific heat of the water in every case for the range of temperatures employed, and expressed the heat measured in terms of  $C_{20}$ . In the tables this range of temperature is given in the fourth column, and the heat in terms of  $C_{20}$  in the fifth column.

#### 4. THE LATENT HEAT OF WATER VAPOR.

The value commonly used for the latent heat of vaporization of water at different temperatures is that given by Regnault<sup>1</sup> as the result of his classical investigations half a century ago. Reg-

<sup>1</sup>Mém. Acad. Roy. Sci. Inst. France, 21 (1847), pp. 635-728.

nault's formula, which expresses quite closely the results obtained from  $63^{\circ}$  to  $195^{\circ}$ , is  $H = 606.5 + .305t$ .  $H$  represents what Regnault called the "total heat" of steam or water vapor, at the temperature  $t$ ; that is, it is the number of small calories required to raise a gram of water from  $0^{\circ}$  C. to any temperature  $t$  and then completely vaporize it at that temperature. For  $t = 100^{\circ}$ , this gives  $H = 637$ . The "latent heat of vaporization" at any temperature, as distinguished from the "total heat" at the same temperature, is the number of units of heat required to evaporate the water after it has been brought to the temperature of evaporation. Hence at  $100^{\circ}$  C. the latent heat of vaporization is 537 calories. The formula for the latent heat at any temperature  $t$  is

$$\begin{aligned} L &= H - t \\ \therefore L &= 606.5 + .305t - t \\ \text{or } L &= 606.5 - .695t. \end{aligned}$$

Regnault's value for the latent heat of steam at  $100^{\circ}$  is abundantly confirmed by later researches.

At lower temperatures than  $63^{\circ}$ , however, the method employed was inapplicable because the change of state from water to steam at low pressure is irregular and explosive; hence a different method became necessary. The process was accordingly reversed, and water contained in a small reservoir inside a much smaller calorimeter than that previously used was evaporated at reduced pressure. The heat absorbed in the vaporization of the water (about 5 grams at each experiment) was then determined from the lowering of the temperature of the water which surrounded the vessel in which the evaporation took place. The results, as Regnault himself points out, were subject to comparatively large experimental errors, and were very discordant. The mean results over a range of temperature from  $0^{\circ}$  to  $16^{\circ}$  are, however, fairly well represented by the formula given above for higher temperatures.

Starkweather,<sup>1</sup> in a critical review of various determinations of the latent heat of water vapor, quotes the work of Dieterici,<sup>2</sup> Griffiths,<sup>3</sup>

<sup>1</sup> "Concerning Regnault's calorie and our knowledge of the specific volumes of steam." Amer. Jour. Sci., 7 (1899), p. 13.

<sup>2</sup> Ann. Phys. u. Chem. (Wiedemann), 38, 1889.

<sup>3</sup> Phil. Trans. Roy. Soc. (London), A, 1895.

and Svensson,<sup>1</sup> as the best that has been done at low pressure and temperatures. Dieterici and Svensson determined with an ice calorimeter the latent heat of water vapor at 0° C. Dieterici's work is very carefully done, and his result is  $L = 598.9$  at 0° C., in terms of the quantity of heat required to raise 1 gram of water from 15° to 16° as the unit of heat. Svensson's result agrees very closely with this, being 599.9. Griffiths measured the latent heats of water vapor between 25° and 50° C., and succeeds in representing them by the formula  $L = 596.73 - .601t$ . Extrapolating to 0° and 100°, this agrees quite well with Dieterici at 0° and Regnault and others at 100°, being 596.73 at 0° and 536.6 at 100°. None of these experiments, however, have been carried out at the temperature commonly used in the respiration calorimeter—*i. e.*, 20° C. Hence we are obliged to deduce the latent heat of vaporization at 20° from formulas given by experiments at other temperatures.

Using Regnault's original formula, from which  $L = 606.5 - .695 t$  we get  $L = 592.6$  at 20° C. Using Starkweather's modification of this formula, which agrees with Regnault's results at temperatures between 63° and 100° better than Regnault's, *viz.*,  $L = 598.9 - .558 t - .00064t^2$ ,  $L$  becomes 587.5 at 20° C. Using Griffith's formula above as quoted  $L = 584.5$  at 20° C.

Some preliminary experiments have been made with the respiration calorimeter, with a view of determining this quantity  $L$ , *i. e.*, the latent heat of vaporization of water at 20°, under the circumstances of the respiration experiment. The results so far have not, however, given a satisfactory value for this quantity. We have therefore taken 592 as a provisional value for the calculation of the experiments reported in this article, and it would appear that this is probably within 1 per cent. of the truth, although it is possibly more than one per cent. too great. Further investigations at 20° are necessary in order to fix the value more precisely.

##### 5. DESCRIPTION OF THE TEST EXPERIMENTS.

Various substances have been used by experimenters with different forms of respiration apparatus for burning within the chamber

<sup>1</sup> Beiblätter, Ann. Phys. u. Chem. (Wiedemann), 20, p. 356.

in order to deliver known quantities of carbon dioxide and water for the purpose of testing the accuracy of the apparatus and methods.

The chief difficulty is to find substances which can be so burned as to insure complete oxidation of the carbon and hydrogen. The first attempts in this laboratory with the combustion of alcohol were unsatisfactory because the oxidation of the alcohol was incomplete, and a considerable amount of experimenting was necessary in order to learn the conditions under which complete combustion could be secured. As the result a small lamp, such as is ordinarily used with kerosene for illuminating purposes, has been employed. By proper arrangement of wick and chimney the alcohol is burned so completely that no traces of volatilized alcohol, acetone, aldehyde, carbon monoxide, or other substances capable of yielding carbon dioxide upon heating with oxygen could be found among the products of combustion.

A considerable number of alcohol test experiments were made. The individual experiments included from one to seven periods or "runs" of approximately six hours each.

The lamps used in these tests contain approximately 380 grams of alcohol. By adjusting the wick the rate of burning was so regulated as to give off carbon dioxide and water in the desired amounts.

In Table VII. are summarized the principal results of all the alcohol check tests which were made up to the ninth, except the preliminary tests, in which the methods of manipulation were being worked out, and two tests the completion of which was prevented by accident. These individual experiments continued from 5 to 78 hours each, the total time being 317 hours. The rate of burning of the alcohol ranged from 10 to 27 grams per hour, and the strength of the alcohol from 90.26 to 90.77 per cent. Most of the tests were made in alternation with experiments with men, the object being to test the accuracy of the apparatus before and after each of the latter experiments.

It will be noticed that in No. 4 the determination of carbon dioxide was unsatisfactory, though we were unable to decide whether the error was due to imperfect sampling or other cause. The result is not included in the average of Table VII. The measurement of the

TABLE VII.

Summary of nine alcohol test experiments

No.	Date.	Duration.	Alcohol burned.	Carbon dioxide.			Water.			Heat.		
				Required.	Found.	Ratio of amount found to amount required.	Required.	Found.	Ratio of amount found to amount required.	Required.	Found.	Ratio of amount found to amount required.
		<i>h.</i> <i>m.</i>	<i>Grams.</i>	<i>Grams.</i>	<i>Grams.</i>	<i>Per cent.</i>	<i>Grams.</i>	<i>Grams.</i>	<i>Per cent.</i>	<i>Calories.</i>	<i>Calories.</i>	<i>Per cent.</i>
1	1897. April 27-29	52 31	955.4	1,657.2	1,657.6	100.0	1,106.1	1,109.7	100.3	6,129.0	6,077.1	99.15
2	May 10-11	29 56	798.8	1,385.6	1,384.4	99.9	924.8	925.0	100.0	5,124.2	5,167.1	100.84
3	May 26-27	33 50	505.4	876.7	887.8	101.3	585.1	627.9	[107.3]	3,242.1	3,217.7	99.25
4	October 27-28	34 33	797.7	1,384.8	1,335.7	[96.5]	925.7	1,007.9	[108.8]	5,120.5	5,141.5	100.41
5	November 2-3	35 09	788.2	1,365.1	1,376.7	100.8	912.3	920.8	100.9	5,048.4	5,050.0	100.03
6	December 2	11 39	245.3	423.1	417.6	98.6	283.7	287.5	101.3	1,564.8	1,556.8	99.48
7	1898. January 6	5 50	112.2	193.5	193.5	100.0	129.8	131.3	101.2	715.7	731.1	102.15
8	January 24-27	77 57	1,607.8	2,784.4	2,769.7	99.5	1,860.8	1,881.6	101.1	10,294.7	10,268.5	99.74
9	May 9	35 55	699.7	1,206.9	1,198.9	99.4	809.3	807.9	99.8	4,463.4	4,466.0	100.05
	Total <sup>1</sup>	317 20		9,892.5	9,886.2	99.9	6,026.8	6,063.8	100.6	41,702.8	41,675.8	99.93

<sup>1</sup>Omitting the carbon dioxide and water in test No. 4 and the water in test No. 3.

heat was, however, very close to the theoretical value. Almost immediately after the close of this test another was made, in which all the results were very closely in accord with the theoretical values. If the determinations of carbon dioxide in test No. 4 are omitted, the maximum variation of the amounts determined from the theoretical amounts given off by the combustion of the alcohol was 1.4 per cent. and the average variation only 0.1 per cent., or 1 part in 1,000 from the theoretical.

In tests Nos. 3 and 4 the determinations of water were unsatisfactory. We are inclined to attribute the errors to variations in the amounts of water condensed upon the absorbers. These results, like that for carbon dioxide in No. 4, are omitted from the averages. Omitting the determinations of water in tests Nos. 3 and 4, the maximum variation, as actually determined from the theoretical amount, was 1.2 per cent. and the average variation only 0.6 per cent. In test No. 7 the proportion of heat measured was larger than usual. It will be observed, however, that this test continued only through one period of six hours. Some time is required to get the apparatus in temperature equilibrium, and the heat measurements of the first experimental period are frequently incorrect on this account. The omission of this experiment would not materially affect the total averages. Omitting this experiment, the maximum variation of the heat actually measured from the theoretical amount was 0.8 per cent. and the average variation only 0.1 per cent.

#### 6. SUMMARY OF TEST EXPERIMENTS.

The accuracy of the methods for the determination of carbon dioxide, water and heat was tested by heat generated in the chamber by passing an electric current through a resistance coil and by burning ethyl alcohol within the chamber. In the electrical tests the measurements of heat generated and found were practically identical, the differences between the theoretical and actual results averaging about 0.1 per cent.—that is, about 1 part in 1,000. In the alcohol tests the average amounts found by actual experiment were: For carbon, 99.9 per cent.; hydrogen, 100.6 per cent.; and heat, 99.9 per cent., respectively, of the theoretical amounts.

The determinations of carbon dioxide and water made by burning

large quantities of alcohol in the respiration chamber agree reasonably well with each other and with the theoretical amounts. The variations, indeed, are not greater than are found in ordinary laboratory experience when alcohol is burned in the combustion furnace by the usual methods of organic analysis.

The agreement thus shown to exist between the results given by the respiration calorimeter and the bomb calorimeter for the heat of combustion of alcohol, is also very satisfactory when the great difference in the circumstances of the experiments is taken into consideration. In the bomb calorimeter a fraction of a gram of alcohol is absorbed in a small block of cellulose or inclosed in a gelatin capsule and placed in a steel cylinder of perhaps half a liter capacity, which is filled with oxygen at a pressure of 20 atmospheres. An electric current passes through a fine iron wire, melts the latter, and ignites the alcohol, which is completely oxidized in an instant. The increase of temperature of the bomb and the water in which it is immersed gives the quantity of heat evolved, and from that the heat of combustion of a gram of alcohol is computed. In the respiration calorimeter, on the other hand, the alcohol contained in a small lamp burns quietly for many hours in a chamber ten thousand times as large as the bomb. Oxygen is supplied by a continuous current of air pumped through the apparatus, and a considerable portion of the heat of combustion is carried away in the latent heat of the water vapor produced. The sum of the heat measured by the calorimeter and the latent heat of the water vapor collected gives the total heat produced by the burning alcohol. That the average of a series of nine experiments should vary less than 0.1 per cent. from the average of the determinations with the bomb calorimeter seems a gratifying result. Taken in connection with the electrical tests and the determinations of carbon dioxide and water already given, the results show that the respiration calorimeter is an instrument of precision and abundantly capable of doing the work for which it was designed.



## IV.

## EXPERIMENTS WITH MAN.

The apparatus previously described was designed exclusively for experiments with human subjects. There were several reasons for beginning with men rather than with domestic animals. The study of human nutrition is very important. In the earlier development of the work, when many difficulties were to be overcome, it was very desirable to have inside the apparatus an intelligent person who could make and record important observations during the experiment, rather than an animal whose movements, even, could not be controlled. Indeed, the most advantageous way to develop methods and apparatus for experiments with animals is through such preliminary experience with men. The results of the experience thus far gained are now being utilized both here and elsewhere in planning apparatus and methods to be used not only with small animals, as rabbits, sheep and dogs, but also with larger animals, as horses, oxen and cows.

## PLAN OF EXPERIMENTS.

The diet chosen for any given experiment is followed for eight days, of which the last four constitute the period of the experiment proper. In the first or preliminary period, extending through four days, the analyses of feces and urine are made, the data thus sufficing for a digestion and nitrogen metabolism experiment. On the evening of the fourth day the subject enters the respiration chamber, though the actual respiration calorimeter experiment does not begin until 7 o'clock on the morning of the fifth day. The night sojourn in the apparatus suffices to get the temperature of the apparatus and its content of carbonic acid and water into equilibrium, so that accurate measurements may begin with the morning of the fifth day and continue until 7 o'clock on the morning of the ninth day, thus making the duration of this experiment exactly four days. As in the test experiments already reported the determinations of carbon dioxide, water vapor and heat are made in six-hour periods, so that the complete data for an experiment show the total amounts of these compounds given off from the body during the periods ending

at 1 p. m., 7 p. m., 1 a. m. and 7 a. m. of each day of the experiment. The urine is also collected and the nitrogen determined for corresponding periods.

The accompanying schedule shows the daily routine followed in the experiment here reported, which was carried out in January, 1898.

TABLE VIII.  
*Daily program of the experiment.*

7.00 a. m.	Rise. Pass urine. Weigh self, stripped. Weigh absorbers. Collect drip.	1.15 p. m. 4.00 p. m. 6.30 p. m. 7.00 p. m.	Dinner. Drink 200 grams water. Supper. Pass urine. Collect drip.
7.45 a. m.	Breakfast.		Weigh absorbers.
10.30 a. m.	Drink 200 grams water.	10.00 p. m.	Drink 200 grams water.
1.00 p. m.	Pass urine. Collect drip. Weigh absorbers.		Weigh self, stripped. Retire. Pass urine.
		1.00 a. m.	

In this experiment the subject was as quiet as practicable. In the four days of the preliminary period he moved about but little and engaged in no considerable amount of either muscular or mental labor. During the four days passed in the chamber he was likewise quiet. The only muscular work done was that involved in dressing, putting up and taking down the folding chair, table, and bed, weighing himself and the absorbers, taking his meals, and caring for the excreta. He passed a large part of the time in reading and sleeping.

The heats of combustion of the food, feces, and urine were determined in the usual manner by means of the bomb calorimeter.

The determinations of carbon and hydrogen were made in the usual manner. The partially dried samples of food, feces and urine were burned with cupric oxid with the aid of a current of oxygen, and the water absorbed by sulphuric acid, the carbon dioxid by potassium hydroxid.

The percentage composition and heats of combustion of the food used in the experiment here described, and of the feces for the same experiment is shown in Table IX.

TABLE IX.

*Composition of food materials, etc.*

Food materials, etc.	Nitro- gen.	Car- bon.	Hydro- gen.	Water.	Protein (N × 6.25).	Fat.	Carbo- hyd'tes	Ash.	Heats of combustion per gram.
	<i>P. ct.</i>	<i>P. ct.</i>	<i>P. ct.</i>	<i>F. ct.</i>	<i>P. ct.</i>	<i>P. ct.</i>	<i>P. ct.</i>	<i>P. ct.</i>	<i>Cals.</i>
Beef, cooked.	4.10	16.35	2.25	67.3	25.6	5.4		1.56	1.928
Butter.	.19	62.68	10.27	10.2	1.2	84.8		3.80	7.761
Milk, skimmed.	.52	4.04	.57	90.7	3.3	.1	5.2	.78	.393
Bread.	1.34	24.53	3.54	44.7	8.4	.2	44.3	2.44	2.400
Breakf.food, wheat.	1.58	41.32	5.78	7.5	9.9	1.6	77.7	3.26	4.071
Ginger snaps.	.96	44.45	6.48	5.2	6.0	9.5	75.6	3.70	4.358
Breakf.food, maize.	1.78	44.34	6.45	5.6	11.1	8.7	71.1	3.46	4.444
Sugar.		42.10	6.48				100.0		3.960
Feces.	1.19	12.60	1.74	72.9	7.4	3.9	11.4	4.40	1.343

## EXPLANATION OF THE TABLES.

The results obtained in this experiment are shown in the following tables. Only such of the data are given here as it is believed will be sufficient for a clear understanding of the experiments.

The daily menu was as follows :

TABLE X.

*Daily menu.*

Breakfast.	Grams.	Dinner.	Grams.	Supper.	Grams.
Cooked beef.	100	Cooked beef.	150	Butter.	15
Butter.	15	Butter.	20	Skimmed milk.	390
Skimmed milk.	160	Skimmed milk.	210	Bread.	25
Bread.	25	Bread.	50	Breakfast food,	
Breakfast food,		Breakfast food,		wheat.	75
maize.	50	wheat.	50	Ginger snaps.	60
Sugar.	25	Sugar.	25	Sugar.	30
Coffee, about.	300	Coffee, about.	300	Coffee, about.	300

Table XI. shows the amount of carbon dioxide eliminated. The table shows the number of liters of air in the ventilating air current and the milligrams per liter of carbon dioxide in the incoming and in the outgoing air during each six-hour period of the experiment. From these data the total excess of carbon dioxide in the outgoing over that from the incoming air is calculated. The analysis of the

residual air in the apparatus at the close of each period gives data for the calculation of the increase or decrease of the carbon dioxide in the chamber at the end as compared with the beginning of each period. Applying this correction the actual elimination of carbon dioxide by the subject is obtained for each six-hour period. From this is calculated the total weight of carbon exhaled.

TABLE XI.

*Record of carbon dioxide.*

Day.	Period.	Ventilation: number of liters of air.	Carbon dioxide per liter.			Total excess in out- going air.	Cor- rection for car- bon dioxid in appa- ratus.	Cor- rected weight carbon dioxid exhaled by sub- ject.	Total weight carbon exhaled in carbon dioxid.
			In in- coming air.	In out- going air.	Excess in out- going air.				
1	7 a.m. to 1 p.m.	Liters. 25,712	Mg. 0.580	Mgs. 9.556	Mgs. 8.976	Grams. 230.8	Grams. + 3.1	Grams. 233.9	Grams. 63.8
	1 p.m. to 7 p.m.	25,987	.563	9.686	9.123	237.1	+14.9	252.0	68.7
	7 p.m. to 1 a.m.	26,785	.622	8.997	8.375	224.3	-14.7	209.6	57.2
	1 a.m. to 7 a.m.	26,065	.593	5.891	5.298	138.1	- 2.5	135.6	37.0
	Total.....	104,549	.....	.....	.....	830.3	+ .8	831.1	226.7
2	7 a.m. to 1 p.m.	27,057	.571	8.750	8.179	221.3	+11.3	232.6	63.4
	1 p.m. to 7 p.m.	25,878	.560	9.109	8.549	221.3	+ 5.3	226.6	61.8
	7 p.m. to 1 a.m.	26,652	.612	9.556	8.944	238.4	-12.6	225.8	61.6
	1 a.m. to 7 a.m.	26,011	.629	5.765	5.136	133.6	- 5.2	128.4	35.0
	Total.....	105,598	.....	.....	.....	814.6	- 1.2	813.4	221.8
3	7 a.m. to 1 p.m.	26,342	.624	9.139	8.515	224.3	+19.2	243.5	66.4
	1 p.m. to 7 p.m.	26,492	.721	9.349	8.628	228.6	+ .3	228.9	62.4
	7 p.m. to 1 a.m.	26,147	.722	9.326	8.604	225.0	-10.6	214.4	58.5
	1 a.m. to 7 a.m.	25,163	.727	5.917	5.190	130.6	- 8.1	122.5	33.4
	Total.....	104,144	.....	.....	.....	808.5	+ .8	809.3	220.7
4	7 a.m. to 1 p.m.	26,427	.710	8.973	8.263	218.4	+21.2	239.6	65.3
	1 p.m. to 7 p.m.	25,731	.735	9.525	8.790	226.2	+ .3	226.5	61.8
	7 p.m. to 1 a.m.	26,046	.636	10.021	9.385	244.5	-14.0	230.5	62.9
	1 a.m. to 7 a.m.	26,338	.612	5.870	5.258	138.5	- 9.1	129.4	35.3
	Total.....	104,542	.....	.....	.....	827.6	- 1.6	826.0	225.3
Total, 4 days...		418,833	.....	.....	.....	.....	.....	3,279.8	894.5
Av. per day...		104,708	.....	.....	.....	.....	.....	819.9	223.6

Table XII. shows the amount of water exhaled. It indicates the number of liters of air in the ventilating air current and the milligrams per liter of water vapor in the incoming air and in the

outgoing air after passing the freezers, which latter condense the major portion of the water vapor in the outgoing air current. From these data, together with the amount of water condensed in the freezers, the amount condensed in the chamber as "drip," and the determinations of residual water vapor in the chamber, is computed the total water exhaled by the subject.

TABLE XII.

*Record of water.*

Day.	Period.	Ventilation; number of liters of air.	Water per liter.			Total excess in out- going air.	Con- densed in freez- ers.	Con- densed in cham- ber.	Correc- tion for water vapor in cham- ber.	Total water exhaled.
			In in- coming air.	In out- going air.	Excess in out- going air.					
		<i>Liters.</i>	<i>Mg.</i>	<i>Mgs.</i>	<i>Mg.</i>	<i>Grams.</i>	<i>Grams.</i>	<i>Grams.</i>	<i>Grams.</i>	<i>Grams.</i>
1	7 a.m. to 1 p.m.	25,712	0.895	1.301	0.406	10.4	207.5	14.0	-13.5	218.4
	1 p.m. to 7 p.m.	25,987	.816	1.258	.442	11.5	230.2	22.0	+15.3	279.0
	7 p.m. to 1 a.m.	26,785	.792	1.184	.392	10.5	238.1	-18.0	+ 3.1	233.7
	1 a.m. to 7 a.m.	26,065	.731	1.143	.412	10.7	223.0	.....	- 6.9	226.8
	Total.....	104,549	.....	.....	.....	43.1	898.8	18.0	- 2.0	957.9
2	7 a.m. to 1 p.m.	27,057	.737	1.187	.450	12.2	212.0	3.0	+ .5	227.7
	1 p.m. to 7 p.m.	25,878	.821	1.232	.411	10.6	213.7	- 1.0	+ 2.2	225.5
	7 p.m. to 1 a.m.	26,652	.749	1.221	.472	12.6	230.7	-21.0	+ 4.6	226.9
	1 a.m. to 7 a.m.	26,011	.723	1.219	.496	12.9	208.4	.....	- 9.7	211.6
	Total ....	105,598	....	.....	.....	48.3	864.8	-19.0	- 2.4	891.7
3	7 a.m. to 1 p.m.	26,342	.764	1.320	.556	14.6	202.1	13.1	+ 3.8	233.6
	1 p.m. to 7 p.m.	26,492	.772	1.206	.434	11.5	208.3	4.0	+ .5	224.3
	7 p.m. to 1 a.m.	26,147	.740	1.088	.348	9.1	230.6	- 8.0	+10.5	242.2
	1 a.m. to 7 a.m.	25,163	.799	1.271	.472	11.9	209.0	.....	-15.1	205.8
	Total.....	104,144	....	.....	.....	47.1	850.0	9.1	- .3	905.9
4	7 a.m. to 1 p.m.	26,427	.793	1.293	.500	13.2	209.2	41.8	+ 3.9	268.1
	1 p.m. to 7 p.m.	25,731	.726	1.273	.547	14.1	206.2	37.8	+ 2.3	260.4
	7 p.m. to 1 a.m.	26,046	.776	1.128	.352	9.2	235.5	- 6.7	+ 5.4	243.4
	1 a.m. to 7 a.m.	26,338	.715	1.109	.394	10.4	234.6	4.2	-11.6	237.6
	Total .....	104,542	.....	.....	.....	46.9	885.5	77.1	.....	1,009.5
Total, 4 days..		418,833	.....	.....	.....	185.4	3,499.1	85.2	- 4.7	3,765.0
Av. per day...		104,708	.....	.....	.....	.....	.....	.....	.....	941.3

The calorimetric results obtained in this experiment are shown in Table XIII. The details of the table and methods of computation are explained in Bulletin 63 of the Office of Experimental Stations, U. S. Dept. of Agriculture.

TABLE XIII.

Summary of calorimetric measurements

Day.	Period.	Heat measured.	Change of temperature of calorimeter.	Capacity correction.	Correction due to temperature of food and dishes.	Corrected heat.	Water vaporized.	Equivalent heat of water vaporized.	Total heat.
		<i>Cals.</i>	$^{\circ}$ C.	<i>Cals.</i>	<i>Cals.</i>	<i>Cals.</i>	<i>Grams.</i>	<i>Cals.</i>	<i>Cals.</i>
1	7 a.m. to 1 p.m.	547.9	+0.12	+ 7.2	- 22.2	532.9	217.9	129.0	661.9
	1 p.m. to 7 p.m.	556.6	- .12	- 7.2	- 37.5	511.9	241.7	143.1	655.0
	7 p.m. to 1 a.m.	472.7	- .05	- 3.0	0	469.7	248.6	147.1	616.8
	1 a.m. to 7 a.m.	277.3	- .03	- 1.8	0	275.5	233.7	138.4	413.9
	Total . . . .	1,854.5	.....	- 4.8	- 59.7	1,790.0	.....	557.6	2,347.6
2	7 a.m. to 1 p.m.	490.7	+ .04	+ 2.4	- 22.9	470.2	224.2	132.7	602.9
	1 p.m. to 7 p.m.	489.2	+ .08	+ 4.8	- 28.3	465.7	224.5	132.9	598.6
	7 p.m. to 1 a.m.	497.4	- .15	- 9.0	0	488.4	243.3	144.1	632.5
	1 a.m. to 7 a.m.	289.2	+ .15	+ 9.0	0	298.2	221.3	131.0	429.2
	Total . . . . .	1,766.5	.....	+ 7.2	- 51.2	1,722.5	.....	540.7	2,263.2
3	7 a.m. to 1 p.m.	524.6	+ .08	+ 4.8	- 21.2	508.2	216.7	128.3	636.5
	1 p.m. to 7 p.m.	512.1	+ .08	+ 4.8	- 31.8	485.1	219.8	130.1	615.2
	7 p.m. to 1 a.m.	486.6	- .18	-10.8	0	475.8	239.7	141.9	617.7
	1 a.m. to 7 a.m.	296.1	+ .10	+ 6.0	0	302.1	220.9	130.8	432.9
	Total . . . . .	1,819.4	.....	+ 4.8	- 53.0	1,771.2	.....	531.1	2,302.3
4	7 a.m. to 1 p.m.	503.3	- .05	- 3.0	- 21.3	479.0	222.4	131.7	610.7
	1 p.m. to 7 p.m.	536.4	+ .05	+ 3.0	- 29.2	510.2	220.3	130.4	640.6
	7 p.m. to 1 a.m.	497.5	- .10	- 6.0	0	491.5	244.7	144.9	636.4
	1 a.m. to 7 a.m.	290.7	+ .04	+ 2.4	0	293.1	245.0	145.0	438.1
	Total . . . . .	1,827.9	.....	- 3.6	- 50.5	1,773.8	.....	552.0	2,325.8
Total, four days . . . .		7,268.3	.....	+ 3.6	-214.4	7,057.5	.....	2,181.4	9,238.9
Av. per day		1,817.1	.....	+ .9	- 53.6	1,764.4	.....	545.3	2,309.7

As has been previously mentioned, the urine was collected in six-hour periods beginning at 7 a. m. (the hour of beginning and ending the experiment). The amount of nitrogen in the urine from 7 a. m. of one day to 7 a. m. next day is taken as a measure of the protein metabolized during this period. Of course this makes no allowance for the nitrogen lag, *i. e.*, the period between the metabolism of the nitrogen and its excretion, but it was considered that the error thus introduced might be ignored, since the subject had been living on the same diet and had had the same exercise from day to day for the experimental period of four days and the previous four days

of the preliminary experiment also. The amount of nitrogen in the urine for 12 to 24 hours after the close of the experiment was also determined in six-hour periods, although these values are not recorded here. In Table XIV. is summarized the amount of urine for each day of the experiment, together with the percentage and amounts of nitrogen and carbon, and the heat of combustion per gram and the total heat of combustion of the urine.

TABLE XIV.

*Amount and composition of urine.*

	Amount	Nitrogen.		Carbon.		Heat of combustion.	
		<i>Grams.</i>	<i>Per cent.</i>	<i>Grams.</i>	<i>Per cent.</i>	<i>Grams.</i>	<i>Per gm.</i>
First day.	1,855.3	1.01	18.75	0.69	12.80	0.082	152
Second day.	1,977.6	.95	18.75	.65	12.79	.081	160
Third day.	1,510.6	1.21	18.28	.83	12.50	.095	143
Fourth day.	1,358.9	1.32	17.89	.90	12.19	.102	139
Total, four days.	6,702.4	.....	73.68	.....	50.28	.....	594
Average per day.	1,675.6	.....	18.42	.....	12.57	.....	149

The data previously given serve for the calculation of Tables XV. and XVI., which show the gain or loss of nitrogen, carbon, protein and fat and the comparison of the estimated heat of the material oxidized in the body with the heat actually measured in this experiment. The calculations are partially explained by the letters and algebraic formulas at the tops of the columns. Thus column *d* indicates the gain or loss of nitrogen, and is computed by adding the amounts in the feces and urine, as shown in columns *b* and *c*, and subtracting this sum from the amount in the food as shown in column *a*. Protein contains, approximately, 16 per cent. of nitrogen, and hence by multiplying the nitrogen loss by 6.25 we get the quantity of protein of the body which must have been oxidized; this is given in column *e*.

The numbers in columns *f*, *g* and *h* are the results of direct chemical analysis of samples of food, feces and urine, the details of which are not here reported. The numbers in column *i* are taken from Table XI., and column *j* gives the net gain of carbon during each day of the experiment.

As protein contains, approximately, 53 per cent. of carbon, the amount of carbon yielded by the daily consumption of body protein is computed by multiplying the numbers of column *e* by .53; these results are given in column *k*. But there was a net gain to the body of carbon, which is explained by the inference that there was more carbon stored in fat accumulated than was lost in protein

TABLE XV.  
Income and outgo of nitrogen and carbon, with estimated gain or loss of protein and fat.

	Nitrogen.				Carbon.						<i>m.</i> Fat gain = $\frac{l}{l+o}$ 765.	
	<i>a.</i> In food.	<i>b.</i> In feces.	<i>c.</i> In urine.	<i>d.</i> Net loss = $\frac{a-c}{b+c}$ .	<i>e.</i> Pro- tein loss = $\frac{d}{6.25}$ .	<i>f.</i> In food.	<i>g.</i> In feces.	<i>h.</i> In urine.	<i>i.</i> In respi- ratory prod- ucts.	<i>j.</i> Net gain = $\frac{i}{(g+h)}$ .		<i>k.</i> Car- bon in protein lost = $e \times$ 0.53.
First day.	19.1	1.2	18.7	-0.8	5.0	261.5	13.3	12.8	226.7	+ 8.7	-2.7	+11.4
Second day.	19.1	1.3	18.8	-1.0	6.3	261.6	13.4	12.8	221.8	+13.6	-3.3	+16.9
Third day.	19.1	1.2	18.3	-.4	2.5	261.5	13.3	12.5	220.7	+15.0	-1.3	+16.3
Fourth day.	19.1	1.3	17.9	-.1	0.6	261.6	13.4	12.2	225.3	+10.7	-.3	+11.0
Total.	76.4	5.0	73.7	-2.3	-14.4	1,046.2	53.4	50.3	894.5	+48.0	-7.6	+55.6
Average per day.	19.1	1.2	18.4	-.6	3.6	261.5	13.3	12.6	223.6	+12.0	-1.9	+13.9



oxidized. We get the quantity of carbon stored in body fat by adding the numbers of columns *j* and *k*, and the sums are shown in column *l*. Finally, since fat contains about 76.5% of carbon, we obtain the quantities of fat daily stored in the body by dividing the numbers of column *l* by .765, and these quantities are shown in column *m*.

In Table XVI. the values given in columns *n*, *o* and *p* are actual heats of combustion as determined by the bomb calorimeter. The values in columns *q* and *r* are obtained by the use of the factors 5.5 and 9.4 representing the average heat of combustion of 1 gram of protein and fat, respectively. The values in column *t* are obtained from Table XIII.

TABLE XVI.

*Income and outgo of energy.*

	Energy (heats of combustion).						<i>t</i> . Heat actually measured.	Ratio of heat measured to that of material actually oxidized. <i>t</i> ÷ <i>s</i> .
	Actually determined.			Estimated.				
	<i>n</i> . Of food.	<i>o</i> . Of feces.	<i>p</i> . Of urine	<i>q</i> . Of protein lost = <i>e</i> × 5.5	<i>r</i> . Of fat gained = <i>m</i> × 9.4	<i>s</i> . Of material actually oxidized in body = <i>n</i> - ( <i>o</i> + <i>p</i> + <i>q</i> + <i>r</i> ).		
<i>Calories.</i>	<i>Calories.</i>	<i>Calories.</i>	<i>Calories.</i>	<i>Calories.</i>	<i>Calories.</i>	<i>Calories.</i>	<i>Per Cent.</i>	
First day.	2,717	142	152	-27	+140	2,310	2,348	
Second day.	2,717	142	160	-35	+208	2,242	2,263	
Third day.	2,717	142	143	-14	+200	2,246	2,302	
Fourth day.	2,717	142	139	-3	+135	2,304	2,326	
Total.	10,868	568	594	-79	+683	9,102	9,239	.....
Av. per day.	2,717	142	149	-20	+171	2,275	2,310	101.5

## RESULTS OF THE EXPERIMENT WITH A HUMAN SUBJECT,

Table XV. shows that the subject under experiment eliminated daily on an average 19.7g. of nitrogen while he received only 19.1g. of nitrogen in his food. This daily loss of nitrogen is taken to indicate a daily metabolism of protein, the heat of combustion of which is given in column *q* of table XVI. The energy of the material actually oxidized in the body, as given in column *s*, is obtained as follows: Taking the first day as an example, we subtract the heat equivalent of feces

and urine, 294 calories, from the total heat value of the food, 2,717. This leaves 2,423 calories. But 140 was stored in the body as fat while 27 was realized by combustion of body protein. Hence 113 calories was stored over and above that derived from body protein, and subtracting 113 from 2,423 we have 2,310 calories as the net amount of energy that should have appeared as heat when all mechanical work of the body, internal and external, has been converted into heat. The average for the four days was 2,275, while the average quantity of heat measured by the calorimeter, including the latent heat of water vapor carried away in the air current, as shown in Table XIII., was 2,310 calories. This is a difference of 35 calories, or 1.5 %.

In later experiments, about to be reported, the differences between income and outgo of energy average somewhat nearer to the theoretical ; in other words, in these more accurate experiments not far from 99 per cent. of the potential energy of the material metabolized and oxidized in the body is accounted for in the kinetic energy given off in the forms of heat and external muscular work.

In how far this fairly close agreement is due to a counterbalancing of errors it is impossible to say. But in view of the physiological difficulties in the way of absolutely accurate results, and the evident possibility of minor errors in the purely chemical and physical determinations, and likewise in the factors used for computation, this agreement seems to us very satisfactory. We believe that it marks a stage in the development of the apparatus and methods sufficient to warrant extended series of experiments upon various questions connected with the laws of nutrition, and such experiments have been begun. Efforts are being made at the same time to eliminate part at least of the experimental errors. At present these efforts are chiefly in the direction of improvement of methods of sampling and analyzing the food materials and excretory products, and finding of minor sources of error in the determination of carbon, hydrogen and heat given off in the respiration chamber, and the direct determination of the oxygen of income and outgo. Minor alterations are also being made in the apparatus and the methods of its manipulation by which it is hoped that somewhat greater accuracy may be secured.

## MECHANICAL EFFICIENCY OF A MAN.

In May, 1897, an experiment was carried out in which the subject under investigation performed a considerable amount of muscular work. This was converted into heat by means of a small dynamo belted to a stationary bicycle. The current generated in the dynamo passed through an incandescent lamp, and all the heat produced, either by friction or by the electric current, was measured by the calorimeter along with that given off by the body directly. This experiment was less accurate than the one reported above for two principal reasons: first, because the methods of sampling the food were then less accurate than in the later experiments, and second, because the large amount of heat evolved during working hours, and the sudden changes of rate from work to rest, made it impossible to measure the heat as accurately as in the "rest" experiment. The average number of calories measured daily was 3,726, the number which corresponds to the total material oxidized was 3,830; thus the difference was 2.7 per cent. of the latter amount. The amount of work done by the subject on the bicycle-dynamo was separately determined. This was done by adding to the energy of the current, as measured by a voltmeter and an ammeter, the energy required to overcome the friction of the bicycle-dynamo. The latter was determined by driving the apparatus by the dynamo used as a motor, and measuring the energy required.

The average work done was the equivalent of 256 large calories per day. This is about 40 watts for nearly eight hours, or 109,000 kilogrammeters, or 788,000 foot-pounds, or 394 foot-tons. The total energy actually yielded by the body, including that derived from the food and the body fat oxidized was 3,726 large calories daily. Dividing the work done by the total energy yielded by the body we have .07 or 7 per cent. as the mechanical efficiency.

But inasmuch as the energy received by the body is largely expended in the internal physiological work and in maintaining the temperature of the body, we should charge against the work done only the excess of energy absorbed in the work experiment over that required in a rest experiment. The average amount of energy used in several rest experiments with the same man has been about 2,500 calories. This subtracted from 3,726 leaves 1,226

as the excess of the work experiment.  $256 \div 1,226 = .21$  Hence we have 21 per cent. as the efficiency of conversion of potential energy of food into mechanical energy.

The smaller value of the efficiency, namely 7 per cent. is greater than that of small steam engines, while the larger value, 21 per cent. equals or exceeds that of the best compound condensing engines with the highest efficiency boilers. A large part of the excess of heat in the work experiment is carried away in the latent heat of water vapor of perspiration. This may be likened to the latent heat of the expanded steam escaping from the cylinder of a steam engine. It is probable that other experiments may give a still larger value for the efficiency of man as a machine for converting the potential energy of food into mechanical energy. For man in this experiment was unused to the bicycle, and the work done by him was less than his maximum capacity, and was certainly very much less than the maximum capacity of an experienced bicyclist. As to the obscure but very interesting question of how this conversion is effected, whether it is a conversion of chemical potential energy directly into mechanical energy, or whether the material of food or muscle upon oxidation first yields heat which is subsequently converted into work by a process equivalent to that of a heat engine, or whether it is some other process, these experiments give no information.

#### GENERAL SUMMARY.

The attempt has been made in the preceding pages to describe (1) a new form of respiration calorimeter and the methods of its use, and (2) several experiments in which the apparatus and methods have been employed.

The experiments here described had a two-fold purpose: To test the accuracy of the apparatus and methods, and to determine the balance of income and outgo of matter and energy in the body. They are preliminary to more extended research upon some of the fundamental problems of nutrition.

The name here used for the apparatus, "respiration calorimeter," is suggested by the fact that it is essentially a respiration apparatus with appliances for calorimetric measurements. As a respiration apparatus it is similar in principle to that of Pettenkofer.

The accuracy of the apparatus and of the methods for the determinations of carbon dioxide, water and heat was tested by heat generated in the chamber by passing an electric current through a resistance coil and also by burning ethyl alcohol within the chamber. In the electrical tests the measurements of heat generated and found were practically identical. In the alcohol tests the average amounts found by actual experiment were: For carbon, 99.9 per cent.; hydrogen, 100.6 per cent.; and heat, 99.9 per cent. of the theoretical amounts. It thus appears that this apparatus when used for the analysis of alcohol and the determination of its heat of combustion gives results nearly, if not quite, as accurate as are obtained by the ordinary laboratory methods which can be used only with small amounts.

The measurements of heat given off from the body of a man inside the chamber are so delicate that very slight bodily movements, such as rising from a chair or turning over in bed, are immediately noticed by the observer, who is constantly watching the galvanometer and thermometers.

The experiments with men, one of the earlier of which is here reported, were undertaken for the study of several problems. The question especially considered in this article is this: Is the energy given off from the body in the form of heat, or of heat and external muscular work, equal to the potential energy or heat of combustion of the material actually burned in the body? In other words, when the compounds of the food and the body—proteids, fats, and carbohydrates—are burned is their potential energy transformed into the equivalent kinetic energy and into forms which can be measured by the means here used? Or, to state the question more broadly, does the law of the conservation of energy obtain in the living organism?

In the experiment reported above the outgo apparently exceeds the income by about 35 calories per day. This quantity is really quite small. It would correspond to the potential energy of about 4 grams of body fat, or nearly the same weight of butter, or 9 grams of sugar, or 14 grams of bread.

The sources of error and uncertainty in these experiments can, it seems to us, be divided into two classes: those incident to the ex-

perimental work as such, and those due to uncertainty as to the physical, chemical and physiological constants used as factors in the computations.

So far as the sources of error are those of chemical and physical analyses and manipulation, the attempt is being made to reduce them to a minimum. In so far as they are of physiological origin and practically beyond control the attempt is made to eliminate them so far as practicable by long experimental periods and by duplication of the experiments.

Meanwhile it is safe to say that in view of the physiological uncertainties and sources of error and the probable incorrectness of some of the physical and chemical constants employed, the differences between the estimated income and measured outgo of energy in the experiments with men are not at all surprising.

In view of these defects and sources of error in methods and apparatus we would perhaps be unwarranted in assuming that the experiments thus far made completely demonstrate the application of the law of the conservation of energy in the human organism. They do, however, seem to us to be reasonably near to such demonstration.

It is certainly safe to assume that the principle followed in the experiments is correct, and that the apparatus and methods are accurate to the degree required for the experimental study of a large variety of the fundamental problems of biological chemistry and physics. Among these are the metabolism of energy and the production of heat by the body in the performance of its ordinary functions, as circulation, respiration and digestion; the relations of muscular and mental work to the metabolism of matter and energy; the demands of the body for nutriment under different conditions of work and rest, and under different conditions of health and disease; the duties performed by the different nutrients of food in supplying the needs of the body; and finally, the nutritive values of food materials and the amount and proportions best adapted to the needs of people of different classes, with different occupations, and in different conditions of life.