A BICYCLE ERGOMETER
WITH AN
ELECTRIC BRAKE

BY

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PART I.

INTRODUCTION.

A practical application of thermodynamic principles that has interested economists and physiologists has been the problem of determining the mechanical efficiency of the human body as a machine. Not only were the earlier writers handicapped by an inability to determine accurately the intake of energy by the body in food and drink—a handicap that has since been admirably overcome by the use of the accurate calorimetric bomb—but they were likewise handicapped by an inadequate measurement of the mechanical output of the individual experimented upon. A study of this subject, therefore, must divide itself into two parts: first, the determination of the intake of energy, and second, the measurement and computation of the amount of work done. The present paper is concerned with the second of these two divisions.

Without going into an extended historical discussion relative to this subject, it may be said that the attempts to make computations of the intake and output of energy have been very numerous and for the most part extremely crude, those of the output of energy dealing usually with the work of either the arms or the legs. Among the various methods used for studying the amount of work done by the arm may be mentioned the lifting of weights, the filing of cast iron, pulling up weights by means of a rope, shoveling earth to a height of about 2 meters, pulling on an oar, pumping water, hammering, turning a crank or winch, and the more accurate method recently employed by Zuntz[1] of using a brake ergometer, and Johansson[2] of raising weights. In tests with the leg-motion, the muscular work has been for the most part confined to lifting the body to a definite height by ascending a ladder or stairs, carrying weights up stairs, wheeling a loaded wheelbarrow up an incline, walking on a treadmill, and, more especially, riding a bicycle or an apparatus similar in form.

In studying the muscular work in the leg-motion of bicycling, a special apparatus has been extensively employed. One of the earlier types of this machine was that described by Atwater and Benedict,[3] in which a pulley attached to the armature shaft of a small dynamo was pressed against the rear wheel of a bicycle; the current generated by this dynamo as it revolved by the movement of the pedals was then measured. By using the dynamo as a motor, the machine could also be calibrated.

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[1] Zuntz, Archiv für (Anat. und) Physiol., 1899, Suppl., p. 39.
[2] Johansson, Skand. Archiv für Physiologie, 1901, 11, p. 273.
[3] Atwater and Benedict, U.S. Dept. Agr., Office Expt. Stas. Bul. 136, 1899, p. 30.

Recently a brake ergometer employing bicycle pedals has been used with considerable success by Amar,[1] while in a private communication Dr. Krogh writes of a bicycle ergometer which he is using in collaboration with Dr. Lindhard, in which the principle of the electric brake plays an important rôle.

Numerous tests have also been made to compute the energy transformations of a bicyclist while traveling on the track against the resistance of air, wheels, tires, and chain. This was considered by Prof. R. C. Carpenter[2] in connection with the amount of energy consumed in a bicycle race, but was much more satisfactorily determined by Berg, duBois Reymond, and Zuntz[3] by means of a bicycle towed around the track by a motor cycle. In every instance thus far cited, it was necessary to convert the foot-pounds or kilogrammeters into calories, the accuracy in the measurement of foot-pounds or kilogrammeters being the criterion of the apparatus. In practically all instances, owing to the difficulty of determining these mechanical quantities exactly, the apparatus was by no means so accurate as the best physiological experimenting can to-day demand.

Certain muscular exercises, such as swimming or rowing with sliding seats, unquestionably bring into play more muscles than does the exercise of bicycle riding; on the other hand, the stationary position of the body, particularly of the head, makes the exercise of riding on a stationary bicycle distinctly advantageous for a study of the respiratory exchange, especially when the subject has to breathe through a mouthpiece or nosepiece, or through some other form of breathing appliance. Furthermore, as has been frequently demonstrated, most intense muscular exercise can be produced by means of the powerful leg muscles; hence, in any study of metabolism during muscular work, all of these advantages seem to point toward the desirability of utilizing some form of bicycle motion for the muscular work.

The great difficulty with the earlier types of bicycle ergometers, however, has been the uncertainty of the amount of work performed, for even with the apparatus of Atwater and Benedict there was considerable slip of the contact, and the determination of the work done was by no means satisfactory. With other forms of ergometers, in which there is the friction of a band, or belt, or weight, the uncertainty and variations in the resistance must always be reckoned with.

Mr. O. S. Blakeslee, formerly mechanician of Wesleyan University, made the ingenious suggestion that an electric brake be used for applying a constant source of resistance in a bicycle ergometer. This later form of apparatus consisted essentially of a bicycle, the rear wheel of which was replaced by a copper disk which rotated between the pole-faces of an electro-magnet. The usual form of pedal, sprocket-wheel, and sprocket-

[1] Amar, La Rendement de la Machine humaine, Paris, 1910.
[2] Atwater, Sherman, and Carpenter, U.S.Dept.Agr., Office Exp.Stas.Bul.98, 1901, p.57.
[3] Berg, duBois Reymond and Zuntz, Arch. f. Anat. u. Physiol., Physiol. Abt. 1904, p.20.

chain was used to convey the power from the foot to the disk. The first form of this instrument has been described in detail in a former publication by Benedict and Carpenter.[1] A second apparatus was constructed during the summer of 1911 by Mr. W. E. Collins, mechanician of the Nutrition Laboratory, and carefully tested. The original ergometer leaves little to be desired in the way of accuracy, constancy, and substantial construction, but as certain modifications have been made in constructing the second instrument, a detailed description of this ergometer seems desirable.

DETAILED DESCRIPTION OF THE BICYCLE ERGOMETER.

For the latest form of bicycle ergometer, which is shown in fig. 1, a high-grade bicycle frame, with sprockets and pedals, was purchased. Instead of the ordinary sprocket-chain, a special chain was used in which

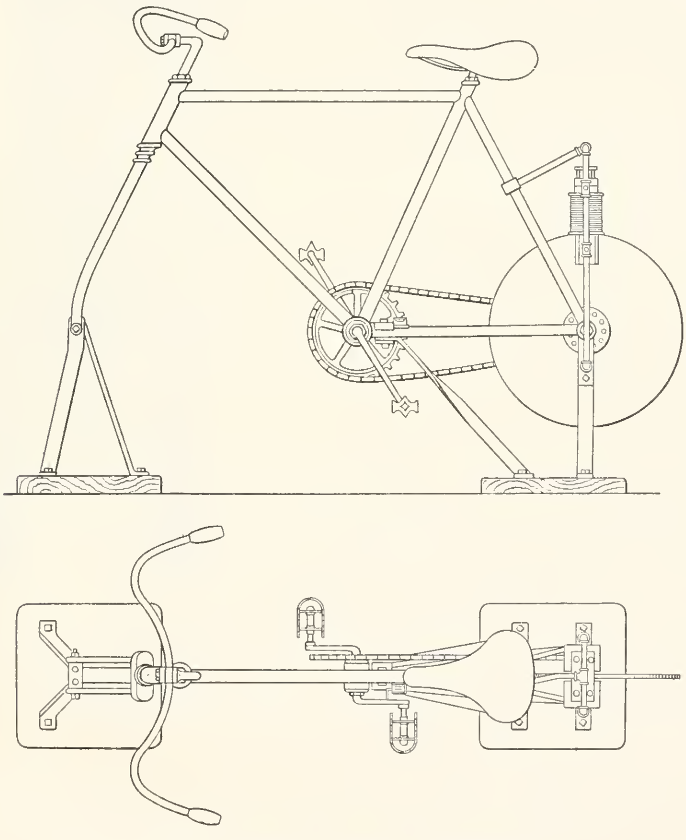

Fig. 1.—Side and top views of ergometer II.

the minimum resistance and maximum flexibility were secured by roller bearings in the links. The rear wheel was replaced by a hub of the type

[1] Benedict and Carpenter, U. S. Dept. Agr., Office Expt. Stas. Bul. 208, 1909, p. 11.

commonly used on motor cycles, which was fitted to a large copper disk, 40.5 cm. in diameter and approximately 6 mm. thick. A wooden split pulley (*W*, fig. 2) was also placed upon the hub for experiments in which the apparatus would be driven by an electric motor. This has been of especial value in some physiological tests on coasting in which the ergometer was driven by a motor, the feet of the man being on the pedals and revolving without doing any work.

The apparatus was substantially mounted upon a base-board by means of iron braces. A type of handle-bar was selected which could be comfortably adjusted for the various riders who were to use the ergometer, and the seat was also adjustable to any desired position. Provision was likewise made for recording the revolutions of the pedals by means of a mechanical counter attached near the pedal-wheel hub so as to be actuated by each pedal revolution.

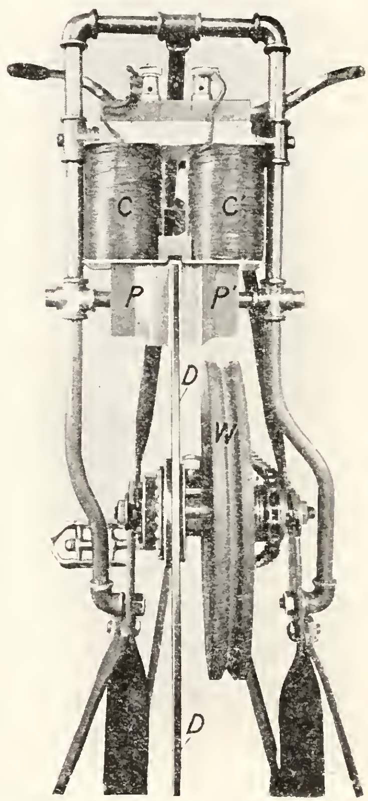

Fig. 2.—Electro-magnet and copper disk of ergometer II. The copper disk *D* rotates in a magnetic field between pole-faces *P* and *P′*. Currents of varying strength are passed through coils *C* and *C′*, thus varying the intensity of the magnetic field. The grooved wooden pulley *W* is used to drive the machine by a belt from a motor.

The electro-magnet used for the brake was made of a high-grade magnet iron, which subsequent tests showed to be especially satisfactory. The general construction and the method of mounting are shown in fig. 2. The length of the magnet, exclusive of the yoke, was 14.7 cm., and the dimensions of the pole-faces *P P′* were as follows: length, 6.4 cm.; width, 5.1 cm.; thickness, 2.8 cm. The magnet was wound with double cotton-covered magnet wire, substantially mounted on a framework made of standard ¼-inch brass piping, and attached to the iron braces supporting the bicycle. Four binding-posts at the top of the magnet provide for joining together the two magnet coils *C C′* and likewise permit the connection with the electric current used to magnetize the field and with the mil-ammeter which measures the current. When mounted on the brass support, the magnet was so adjusted that the disk *D* rotates in the gap between the pole-faces *P P′* with approximately 1 mm. air-space on each side. The upper edge of the pole-faces forms a line which is tangential to the circumference of the copper disk.

In constructing the magnet we were at a disadvantage in not knowing the exact dimensions of the magnet in the first ergometer, and since no records were available as to the size of the wire, we were obliged to make an approximate estimate. It was found subsequently that in order to secure a sufficiently strong magnetic field with a moderate current, it was necessary to rewind the magnet with a smaller size of wire (No. 19 B. & S. gauge), 0.91 mm. diameter, thus increasing the total resistance to 10 ohms.

With this winding of the magnet it was found that a current of 1.5 amperes through the coil produced substantially the same drag effect as did 1.25 amperes on the older machine. The new machine has a disadvantage in that it develops a larger amount of heat in the magnet coil itself than the first ergometer, thus making a somewhat larger correction to be deducted from the total heat measured if the apparatus is used inside a calorimeter. As a matter of fact, with a current of 1.5 amperes through the field, the heat development in the magnet itself is 17.8 to 17.9 calories per hour, while with the older form of apparatus with a current of 1.25 amperes through the field, the heat development was 10.9 calories per hour.

GENERAL CONSIDERATIONS REGARDING METHOD OF USE.

When the ergometer is in use, a variable resistance, which consists of German-silver or manganin wire, is placed in series with the magnet coil and the mil-ammeter. By altering the variable resistance, the current is kept constant throughout any experiment. At the beginning of an experiment the coil is cold, and if the adjustable resistance is set at a given point the current passing through the magnet gradually decreases as the field begins to warm up; it accordingly becomes necessary to adjust the resistance until the desired amount of current through the field is obtained. In approximately 20 minutes to half an hour constant temperature conditions are obtained and thereafter no material adjustment of the resistance is necessary. The larger sprocket has 26 teeth and the smaller sprocket 8, the ratio being 1 to 3.25. While one can compute from the number of revolutions the distance that theoretically would have been traversed had the subject been riding a bicycle with a standard wheel of 28 inches, this really has very little significance, as of course in riding a stationary bicycle there is no wind resistance and there is no energy expended on tires; consequently it is necessary to supply sufficient resistance to the copper disk to compensate for the absence of these factors.

With this ergometer it was possible within certain limits to vary the amount of work done per hour by varying the speed of revolution of the disk. But few riders care to ride for any length of time at less than 50 revolutions of the pedal per minute, and tests on a number of individuals have shown that the revolutions usually ranged from 55 to 80 per minute; with highly trained professional bicyclists, the rate of revolution may rise as high as 100 to 120, or indeed, for short periods, to 135 or 140. To increase the amount of work done it is necessary to alter not only the speed, but more particularly the magnetic drag upon the disk. This is done by increasing the current through the field. The lowest current that has been used with the new instrument, either in actual riding or in the calibration of the ergometer, has been 0.95 ampere, and the highest 1.5 amperes. With the earlier form of instrument, the current varied from 0.70 to 1.25 amperes.

Certain fundamental criticisms can be made as to the propriety of comparing the metabolism of a subject riding on a stationary bicycle with that of a man riding a bicycle in the open air or on the track. Under the latter condition there is a very rapid movement of air against the body of the subject, with increased respiration, and hence a temperature regulation due to the vaporization of water from the skin. There is also a certain stimulus due to the presence of spectators. The psychical conditions are unquestionably markedly different in ordinary bicycle riding from those obtained when riding a stationary bicycle in the confines of a laboratory, and especially in the confines of a respiration chamber. That this psychical stimulation unquestionably plays an important rôle in securing the greatest output of heat and mechanical work, particularly in momentary special exertion incidental to a spurt, no one can deny. On the other hand, experimental evidence thus far accumulated seems to indicate that the relations between the total energy output of the body and that actually transformed into heat by the ergometer remain for the most part essentially unaltered; furthermore, it appears that although under these conditions the psychical stimulation of actual riding may possibly be conducive to greater muscular effort at the time, yet this factor does not necessarily play any rôle with regard to the efficiency of the body as a machine. The subject may have the personal impression that the work done upon the bicycle ergometer in the confines of the laboratory or inside a respiration chamber is a greater strain and requires more physical exertion than ordinary bicycle riding; on the other hand, we have no evidence to indicate that experiments made upon this ergometer are in any way physiologically abnormal. Indeed, the absence of the necessity for balancing or steering the wheel might easily lead to a diminution of the extraneous muscular effort incidental to outdoor bicycle riding, and thus result in a larger proportional output of energy due to the leg muscles.

In using the bicycle ergometer the subject ordinarily rides for half to three-quarters of an hour before the actual experiment begins. This is more for the purpose of establishing a physiological equilibrium in the body of the man than to adjust the apparatus to any particular condition; during this period, also, there is a warming of the magnet coil to a constant temperature and likewise a heating of the copper disk until it reaches a point when the heat production is exactly equal to the heat lost through conduction and radiation, so that the temperature of the copper disk remains essentially constant.

This form of electric brake has proved particularly advantageous, inasmuch as it is at ordinary temperatures absolutely constant; for comparison experiments, in which the same individual uses the apparatus under differing conditions of diet, or in which different subjects use the same apparatus, the results are especially satisfactory, since a definitely known amount of muscular activity for all subjects is obtained. Nevertheless it is necessary at times to know not only the relative but also the absolute energy value of the work done upon the apparatus, and hence it was considered desirable to calibrate the instrument in order to find in absolute units the heat output per revolution of the pedals.

METHOD OF CALIBRATION.

The bicycle ergometer may be calibrated in a number of ways. Either a cradle dynanometer can be used or the rear wheel of the bicycle can be driven by means of a belt or sprocket chain, or, better still, by a gear or direct-friction drive; but these methods involve so many and so large corrections that the final value might be seriously in error. A method for calibrating this type of instrument suggested by the late Prof. W. O. Atwater has been in use for some time and has given admirable results. Professor Atwater's method involved placing the ergometer, exactly as it was to be used for an experiment, inside of a respiration calorimeter, and driving the apparatus from the outside by means of a shaft, magnetizing the field as desired. The number of revolutions of the pedal could then be counted and the heat directly given off by the instrument measured as in an ordinary calorimeter experiment.[1]

This method of calibration was extensively employed on the first apparatus and it has already been described.[2] The calorimeter then used was the original respiration calorimeter in the chemical laboratory of Wesleyan University in Middletown, Connecticut. This calorimeter was a universal apparatus, inasmuch as with it experiments could be made with men not only at rest but also undergoing severe muscular work. The apparatus was consequently of considerable size. While the earlier check-tests showed an agreement among themselves that was highly satisfactory, certain apparent abnormalities in the curve of calibration have been adversely criticized by European observers in private communications. The earlier calorimetric calibrations of the ergometer indicated, for example, that within the limits of speed used, namely, from 55 to 85 revolutions per minute, the heat per revolution was approximately constant, with the same degree of magnetization in the field. From elementary

[1] It is interesting to recall in this connection that Violle (Comptes rendus, 1870, **70**, p. 1283) many years ago made determinations of the mechanical equivalent of heat by expending a known amount of energy in rotating a disk of metal between the poles of an electro-magnet and then quickly plunging the disk into a water calorimeter.

[2] Benedict and Carpenter, loc. cit., p. 14.

theoretical considerations, as will be shown in the third section, this was not what would be expected; it appeared desirable, therefore, to repeat the calibrations with a more delicate respiration calorimeter subsequently constructed in the Nutrition Laboratory at Boston. Through the courtesy of Dr. C. F. Langworthy, of the U. S. Department of Agriculture, Washington, D. C., the original bicycle ergometer was sent to Boston and installed inside the respiration chamber, fitted with a crank-shaft, motor, belting, and shafting, and rotated at the varying rates of speed formerly used. The range of speed was then considerably altered so as to secure a rate of revolution of the pedals as low as 11 and as high as 120 per minute.

When the new bicycle ergometer, constructed in the mechanical department of the Nutrition Laboratory, had been completed, it was subjected to similar calibration tests, so that we now have an extensive series of calibration tests with two ergometers of this type, built some 10 or 12 years apart, having different electro-magnets and yet embodying the same fundamental principle. The next section of this report gives an account of these calibration tests, while in the third section a study is made of the magnetic reactions that take place when the disks of these instruments are in rotation.

PART II.

CALIBRATION TESTS.

The calorimeter used for the later calibration tests of the two bicycle ergometers was the so-called chair calorimeter, which has been described in detail by Benedict and Carpenter.[1] Since this description was published, it has been found desirable to change the location of the entrance from the top to the front of the apparatus. This permits the easy introduction of the ergometer and the carrying of the driving-shaft straight out from the front of the calorimeter.

The apparatus consists, in brief, of a series of chambers surrounded by alternate layers of air and insulating materials. The inner copper chamber is surrounded by a layer of air, in which is located the structural-steel framework of the calorimeter. A zinc wall incloses this air-space, and is in turn surrounded by a second air-space of approximately 8 cm., which is inclosed by an insulating outer layer of hair-felt, with a final covering of asbestos. Between the zinc and copper walls there is a series of thermo-electric junctions which indicate the temperature differences between the two. By arbitrarily heating or cooling the air between the hair-felt and the zinc wall, the temperature of the latter can be controlled at will and adjusted so that it will be equal to that of the copper wall, thus preventing any heat radiation and holding the calorimeter adiabatic. The heat given off by the subject is absorbed by a current of cold water passing through a system of brass pipes inside the chamber, the heat-absorbing surface of these pipes being greatly increased by a large number of copper disks, approximately 5 cm. in diameter, which are soldered to them. The rate of flow and the temperature of the water entering the chamber are arbitrarily adjusted so as to bring away the heat as rapidly as it is produced. The mean temperature of the air in the calorimeter is thus held constant, this being the criterion of the thermal equilibrium. As the current of water enters and leaves the chamber its temperature is accurately measured with mercurial thermometers; from the mass and rise in temperature of the water the amount of heat brought away can be readily computed. When the apparatus is used for calibrating the ergometer, in the final calculation of the total intake of heat, it is necessary to deduct the heat of magnetization, *i. e.*, the heat produced in the coils of the magnet. As previously stated, this is with the first ergometer 10.9 calories per hour when the magnetizing current is 1.25 amperes, and with the new ergometer 17.8 calories per hour when the magnetizing current is 1.5 amperes.

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[1] Benedict and Carpenter, Carnegie Institution of Washington Publication No. 123, 1910, p. 10.

When placed in the calorimeter, the ergometer was divested of the handle-bar and pedals, and usually of the front support. Furthermore, in order to secure it properly inside the calorimeter, it was necessary to place it on end. This position is shown in fig. 3. A somewhat diagrammatical representation of the electric motor and of the pulley systems used to reduce the speed is also shown in the lower part of the figure. In actual practice the motor, instead of being bolted to one of the calorimeter supports, was fastened to the laboratory floor. A separate support for the pulleys and shafting was likewise arranged so that the entire driving-mechanism was independent of the calorimeter, the only connection between the ergometer and the driving-mechanism being the long shaft passing out through a small hole in the front of the calorimeter. This shaft was so adjusted as to have free clearance at all points. The temperature of the calorimeter room was also carefully controlled, so that it would be equal to the temperature inside the calorimeter, thus preventing any interchange of heat along the metallic shaft.

By means of an adjustable resistance in the motor circuit, it was possible to regulate the speed of the motor so as to have the rotation of the pedals vary from 11 to 120 per minute. The particularly low speeds were used only in calibrating the new ergometer, being especially utilized for studying the magnetic conditions in the field during calibration.

THE TECHNIQUE OF A CALIBRATION EXPERIMENT.

In order to bring the ergometer and the calorimeter into temperature equilibrium, a preliminary period of approximately 1 hour was necessary, during which time the ergometer was rotated at the desired speed, the rate of flow of the water-current through the heat-absorbing coils inside the calorimeter adjusted, and the temperature of the calorimeter regulated so that the heat brought away was exactly equal to the heat developed by the ergometer. The current through the magnet was likewise adjusted to constancy. When complete temperature equilibrium had been established, the experiment proper began. An automatic counter recorded the number of revolutions of the shaft outside the chamber; at the exact moment of beginning the period, a reading of this counter was taken, the current of water to bring away the heat was deflected into a large can on a platform balance, so that the amount of water passing through the heat-absorbing coils could be accurately weighed, and the initial temperature of the air inside the calorimeter was carefully recorded, all of these records being continued for several successive series of 1-hour periods. Every 4 minutes the temperatures of water entering and leaving the chamber were recorded, and the temperature of the zinc wall was adjusted whenever necessary to bring it to the temperature of the copper wall, so as to maintain adiabatic conditions throughout the whole experiment. Usually each calibration test occupied five or six 1-hour periods. At the end of the experiment the calorimeter door was opened

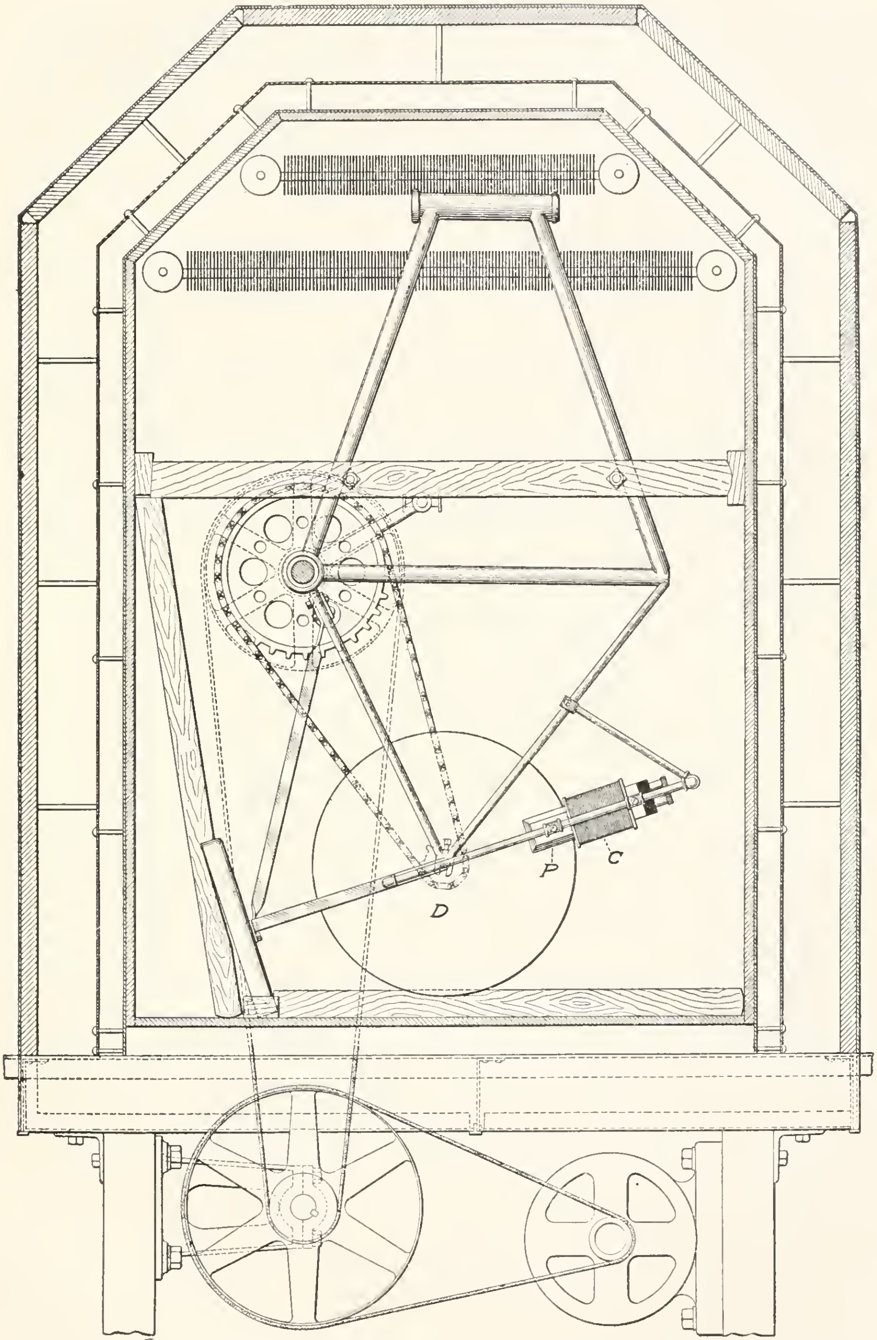

Fig. 3.—Scheme for calibration of the ergometer in a respiration calorimeter. The ergometer, divested of handle-bars and seat, is placed in a vertical position inside a respiration chamber. The copper disk *D* rotating between the pole-faces *P* of the electro-magnet *C* generates heat which is measured by the calorimeter. The electric motor and reduction pulleys are used to rotate the ergometer at different speeds for purposes of calibration.

quickly and the temperature of the copper disk recorded by placing a mercurial thermometer upon it, a rapid conduction of the heat being secured by covering the bulb of the thermometer first with a closely fitting piece of sheet lead and then with a large piece of cotton batting. As soon as the mercurial thermometer reached its maximum point the temperature was recorded. While possibly this method did not give the exact temperature of the inner part of the copper disk, nevertheless it was assumed that the record obtained could be considered as an index of the temperature of the copper in the different experiments. These readings of temperature were taken chiefly for comparison with the magnetic tests (see Part III).[1]

Occasionally it was possible on the same day to run two calibration tests, either at two different speeds or at two different intensities of field magnetization, in which case, immediately after taking the temperature of the copper disk, the calorimeter was again closed and the second preliminary period run. Under these conditions it was usually not necessary that the second preliminary period should be so long as the first and it was possible to begin the measurements on the second basis inside of half or three-quarters of an hour.

CALIBRATION TESTS OF ERGOMETER I.

EARLIER CALIBRATION TESTS.

The original ergometer (which we will designate as ergometer I) was calibrated frequently in the large respiration-chamber at Middletown, Connecticut, in 1903, 1904, and 1905. These calibrations were published by Benedict and Carpenter in an earlier publication,[2] but they are reproduced here in table 1 with some slight correction and rearrangement, so that they may be readily compared with the results of the later calibration tests. The shortest experiment recorded was 2 hours and 21 minutes in length and the longest 7 hours and 10 minutes, the strength of current through the ergometer magnet varying from 0.70 ampere to 1.25 amperes. Of particular significance are the data given in the last two columns of the table, showing the number of revolutions per minute and the heat per revolution. It will be observed that in these experiments the lowest number of revolutions studied was 71 per minute and the highest 102, those for 1904 and 1905 ranging almost exclusively between 71 and 83 revolutions per minute. The heat per revolution ranged from 0.0124 to 0.0236. A comparison of the data regarding the heat per revolution with the strength of current used in the various tests shows that in general the higher the magnetizing current the higher the heat per revolution.

[1] The influence of the temperature of surroundings on the constancy of the ergometer is discussed in Part III.

[2] Benedict and Carpenter, U. S. Department of Agriculture, Office of Expt. Stas. Bul. No. 208, 1909, p. 16.

TABLE 1.—*Results of earlier calibration tests of ergometer I.*

[Experiments made in the respiration calorimeter at Wesleyan University, Middletown, Connecticut.]

Date.	Duration of experiment.			Current.	Heat measured.	Corr. for change of cal. temp.	Corr. for heat of magnetization.	Heat produced.	Total no. of revolutions of pedals.	No. of revolutions per min.	Heat per revolution.
1903.	*h.*	*m.*	*s.*	*amp.*	*cals.*	*cals.*	*cals.*	*cals.*			*cals.*
Oct. 5	6	17	6	1.25	774.8	−3.6	−68.7	702.5	29,967	79	0.0234
6	4	52	46	1.25	743.4	−9.0	−53.4	681.0	30,006	102	.0227
9	6	50	34	1.25	855.8	−2.4	−74.7	778.7	33,554	82	.0232
12	4	49	30	1.25	533.4	....	−52.9	480.5	20,837	72	.0231
12	4	20	30	1.25	637.8	....	−47.4	590.4	25,833	99	.0229
1904.											
Oct. 26	7	10	50	1.25	874.5	....	−78.6	795.9	34,158	79	.0233
Nov. 18	5	39	30	1.25	644.3	+3.0	−62.0	585.3	25,214	74	.0232
18	5	14	27	1.25	666.8	+2.4	−57.2	612.0	25,964	83	.0236
1905.											
May 13	6	30	0	.80	481.2	+3.0	−27.6	456.6	27,769	71	.0164
15	6	0	0	.70	359.1	+ .6	−19.4	340.3	27,361	76	.0124
16	6	0	0	.90	503.6	+ .6	−32.5	471.7	26,713	74	.0176
17	6	0	0	1.25	726.1	+ .6	−65.7	661.0	29,157	81	.0227
18	6	0	0	.70	381.3	....	−19.4	361.9	27,290	76	.0133
19	6	0	0	.80	440.2	− .6	−25.5	414.1	26,532	74	.0156
20	6	0	0	1.25	746.3	+ .6	−65.6	681.3	29,958	83	.0227
22	2	21	0	.90	200.5	−7.2	−12.7	180.6	10,654	76	.0170
23	7	0	0	.80	521.0	+2.4	−29.7	493.7	31,586	75	.0156
24	7	0	0	.90	614.3	....	−37.8	576.5	32,950	78	.0175
26	4	0	0	.70	252.5	....	−13.0	239.5	19,227	80	.0125
27	7	0	0	1.25	837.4	−4.2	−76.6	756.6	32,945	78	.0230
29	6	0	0	.70	394.8	+ .6	−19.4	376.0	28,899	80	.0130
29	6	0	0	1.10	671.3	− .6	−50.5	620.2	30,035	83	.0207

CALIBRATION TESTS OF 1911.

An extensive series of calibration tests of ergometer I was carried out at the Nutrition Laboratory in June and July of 1911. The details of a single day's experiment, that of July 7, 1911, will serve to show the method used in these tests. While the results of the experiments are usually expressed in totals for 3 to 6 hours, the particular experiment selected was run in a series of six 1-hour periods, and the individual hourly determinations are given in table 2. Even when experimental periods are longer than 1 hour, computations made on the hourly basis are frequently of much value in indicating abnormalities in the course of an experiment; usually these periods agree very satisfactorily with each other.

The weight of water passing through the heat-absorbing system during the experimental period and the rate of flow per minute are first recorded, then the average temperature difference between the water entering and that leaving the chamber, with a slight correction suggested as necessary by Armsby[1] for the pressure of water upon the glass bulbs of the thermometers, the final corrected temperature difference being also given. Multiplying the weight of water by this corrected temperature difference gives the heat measured in terms of *large calories*. A further correction

[1] Armsby, U.S. Dept. Agr., Bureau of Animal Industry Bul. 51, 1903, p. 34; Atwater and Benedict, Carnegie Institution of Washington Publication No. 42, 1905, p. 134.

is necessary for the changes in temperature of the calorimeter. Since an increase or decrease in temperature indicates a storage or loss of heat, it is necessary to add or subtract the heat thus stored or lost to find the amount of heat actually produced during the experimental period. The heat produced by the current passing through the magnet amounted to 10.9 calories per hour, the third and fourth periods in the table being respectively 1 minute shorter and 1 minute longer than the hour, thus accounting for the slight variations from the average. The total heat produced, then, is the heat measured, corrected for the changes in temperature of the calorimeter and for the heat produced by the magnetizing current. The records of the total number of revolutions per hour as obtained from the revolution counter are given, together with the number of revolutions per minute. The final column indicates the number of calories of heat produced per revolution of the pedals.

TABLE 2.—*Results of calibration test of ergometer I, July 7, 1911.*
[Current in ergometer magnet, 1.25 amperes.]

Duration of period.	Weight of water.	Avg. rate per min.	Avg. temp. diff.	Corr. for pressure on bulbs.	Corr. temp. diff.
	kilos.	*c. c.*	°*C.*	°*C.*	°*C.*
10h22m a.m. to 11h22m a.m.	35.09	585	3.03	+0.02	3.05
11 22 a.m. to 12 22 p.m.	34.81	580	3.11	+ .01	3.12
12 22 p.m. to 1 22 p.m.	34.58	576	3.04	+ .01	3.05
1 22 p.m. to 2 21 p.m.[1]	33.91	575	3.12	+ .01	3.13
2 21 p.m. to 3 22 p.m.[2]	34.72	569	3.16	+ .01	3.17
3 22 p.m. to 4 22 p.m.	34.07	568	3.13	+ .01	3.14
10 22 a.m to 4 22 p.m.	207.18	575	3.10	+.01	3.11

Duration of period.	Heat measured.	Corr. for change of cal. temp.	Corr. for heat of magnetization.	Heat produced.	No. of revolutions of pedals.	No. of revolutions per min.	Heat per revolution.
	cals.	*cals.*	*cals.*	*cals.*			*cal.*
10h22m a.m. to 11h22m a.m.	107.0	+0.6	−10.9	96.7	4,306	72	0.0225
11 22 a.m. to 12 22 p.m.	108.6	− .6	−10.9	97.1	4,264	71	.0228
12 22 p.m. to 1 22 p.m.	105.5	+1.5	−10.9	96.1	4,278	71	.0225
1 22 p.m. to 2 21 p.m.[1]	106.1	+ .2	−10.7	95.6	4,196	71	.0228
2 21 p.m. to 3 22 p.m.[2]	110.1	−1.8	−11.1	97.2	4,300	70	.0226
3 22 p.m. to 4 22 p.m.	107.0	....	−10.9	96.1	4,246	71	.0226
10 22 a.m. to 4 22 p.m.	644.3	....	−65.6	578.7	25,590	71	.0226

[1] 59 minutes long. [2] 61 minutes long.

During the experiment of July 7, 1911, the heat per revolution of the pedals ranged only from 0.0225 to 0.0228 calorie per revolution, the average for the whole experiment being 0.0226 calorie per revolution. The average number of revolutions during the test was 71.1 per minute. With this ergometer, therefore, with a current of 1.25 amperes through the magnet, it can be stated that at this speed each revolution results in the development of 0.0226 calorie.

TABLE 3.—*Results of later calibration tests of ergometer I.*

[Experiments made in the chair calorimeter at the Nutrition Laboratory, Boston, Massachusetts.]

Date.	Duration of experiment.			Current.	Heat measured.	Corr. for change of cal. temp.	Corr. for heat of magnetization.	Heat produced.	No. of revolutions of pedals.	No. of revolutions per minute	Heat per revolution.
1911.	*h.*	*m.*	*s.*	*amp.*	*cals.*	*cals.*	*cals.*	*cals.*			*cal.*
June 7	5	0	0	1.25	592.9	—0.2	—54.7	538.0	23,245	77	0.0231
8	3	0	0	1.25	253.6	— .6	—32.8	220.2	10,071	56	.0219
9	4	57	53	1.25	275.1	— .2	—54.3	220.6	11,600	39	.0190
12	4	0	0	1.10	426.7	....	—33.9	392.8	18,383	77	.0214
15	4	0	0	1.10	187.2	— .4	—33.9	152.9	8,824	37	.0173
16	3	0	0	1.10	250.1	— .2	—25.4	224.5	10,861	60	.0207
26	4	0	0	.90	359.1	....	—22.7	336.4	19,962	83	.0169
27	6	0	0	.90	397.7	— .8	—34.0	362.9	20,680	57	.0175
28	4	0	0	.90	422.9	— .2	—22.7	400.0	26,135	109	.0153
30	3	0	0	1.10	424.9	+ .2	—25.4	399.7	21,739	121	.0184
July 3	3	0	0	1.25	429.4	+ .4	—32.8	397.0	18,006	100	.0220
6	3	0	0	1.25	483.9	— .2	—32.8	450.9	21,494	119	.0210
7	6	0	0	1.25	644.3	....	—65.6	578.7	25,590	71	.0226
8	3	0	0	.80	279.2	....	—13.4	265.8	21,982	122	.0121
10	3	0	0	.90	340.0	+ .2	—17.0	323.2	21,928	122	.0147
11	3	0	0	.90	325.9	— .4	—17.0	308.5	20,729	115	.0149
12	3	0	0	.90	169.1	....	—17.0	152.1	8,941	50	.0170
13	5	0	0	.70	297.8	— .2	—17.1	280.5	22,461	75	.0125
14	3	0	0	.80	222.5	— .8	—13.4	208.3	13,272	74	.0157
15	3	0	0	.70	182.4	— .2	—10.3	171.9	13,964	78	.0123
18	3	0	0	.90	124.5	+ .6	—17.0	108.1	7,108	39	.0152
20	2	59	25	.90	356.6	— .4	—16.9	339.3	27,463	153	.0124

The results of all of the later tests of ergometer I, made with the chair calorimeter at the Nutrition Laboratory, Boston, Massachusetts, are given in table 3, the averages alone being recorded. Special attention is again directed to the column indicating the number of revolutions of the pedals per minute and the heat per revolution. While it will be remembered that in the earlier tests the rate of revolution of the pedals varied only between narrow limits, *i.e.*, from 70 to 90, here we find values as low as 37 revolutions per minute and as high as 153.

While no bicyclist could be expected to ride at the enormous speed of 153 revolutions of the pedals per minute, it may be interesting to note that a professional bicycle rider, who has been recently experimented upon in this laboratory, has repeatedly maintained speeds of 130 to 140 revolutions per minute for 2 minutes at a time during a spurt; in fact, in experiments with men, much difficulty has been experienced in securing a low rate of speed. The tests with abnormal rates of speed are, however, included more for the purpose of studying the peculiar relationship recently noted between the revolutions per minute and the heat produced per revolution. An examination of the results in table 3 again shows that, in general, as would be expected, the greater the heat produced by the magnetizing current the greater the heat per revolution.

For an adequate study of the relationship between the number of revolutions per minute and the heat per revolution, it was advisable to express the calibrations for the different strengths of current through the field in the form of curves. Accordingly, in fig. 4 we have all of the experiments made with ergometer I with a current through the armature of 0.70 and 0.80 ampere. On this diagram the points indicated by circles are those obtained with the earlier calibrations with this ergometer, of which the results are given in table 1. The values indicated by small crosses are those obtained in the tests during June and July of 1911 (see table 3).

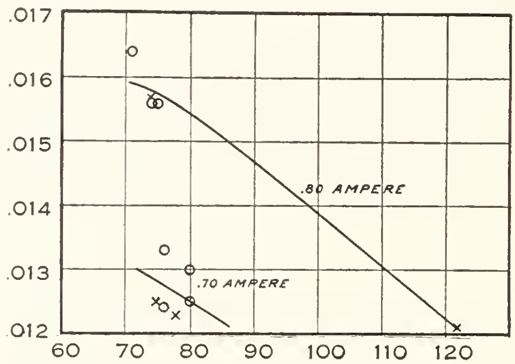

FIG. 4.—Heat per revolution of ergometer I for currents of 0.7 and 0.8 ampere through field. Ordinates represent heat per revolution expressed in large calories. Abscissæ represent revolutions per minute.

In practically all of the experiments made with a current of 0.70 ampere, it will be seen that the average speed ranged between 75 and 82 revolutions per minute, and that the variations in heat per revolution are not very great. Four of the five experiments made with 0.80 ampere through the field were between the limits of 71 and 75 revolutions per minute, and hence these values were all clustered around one point. Of particular interest is the fact that the fifth experiment was made with 122 revolutions per minute, and in this experiment we find that the heat per revolution was considerably less than when the speed was 71 to 75 revolutions.

In the earlier tests of this ergometer, practically all of the experimental evidence was accumulated at a speed which was found to be the most practicable and comfortable for the subject, namely, from 65 to 80 revolutions per minute. On the basis of these calibrations it was believed that the evidence showed that the heat per revolution was constant, irrespective of speed; accordingly it is of interest to note that all of the experiments with a current of 0.70 ampere, and four of the five experiments with 0.80 ampere, show essentially this feature, namely, that within narrow limits the results are grouped around a certain value which is practically independent of the speed. On the other hand, we find that in the experiment with a very high speed and a current of 0.80 ampere there is a greatly decreased heat per revolution.

In fig. 5 are shown the values obtained with a current of 0.90 ampere. With this current the experiments are much more numerous and include, as before, both the earlier calibrations with this ergometer and those of 1911. The speed varied from 39 to 153 revolutions, the circles indicating, as before, the earlier observations, and the small crosses those that have recently been made. The plotting of these points shows a sharply defined curve with a striking dissimilarity between the rate of revolution and the heat production per revolution. This distinctly contradicts the statement previously made that the heat per revolution was independent of the rate of speed. With a low rate of speed, the heat per revolution is likewise low, rises to a maximum when the speed is not far from 60

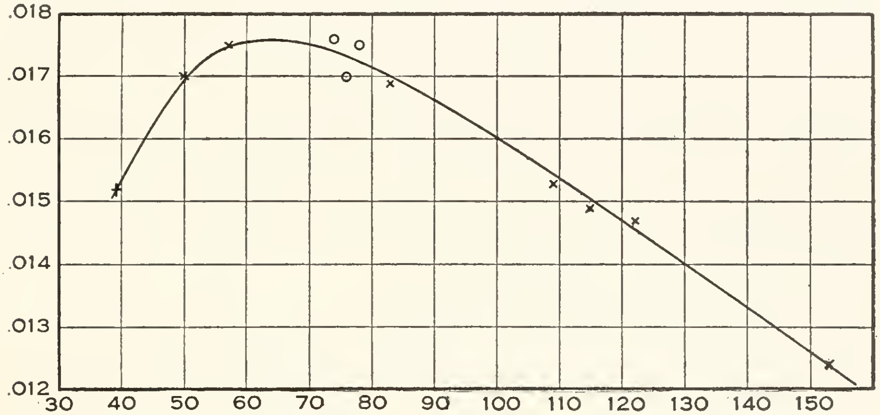

FIG. 5.—Calibration curve of ergometer I for magnetizing current of 0.9 ampere.

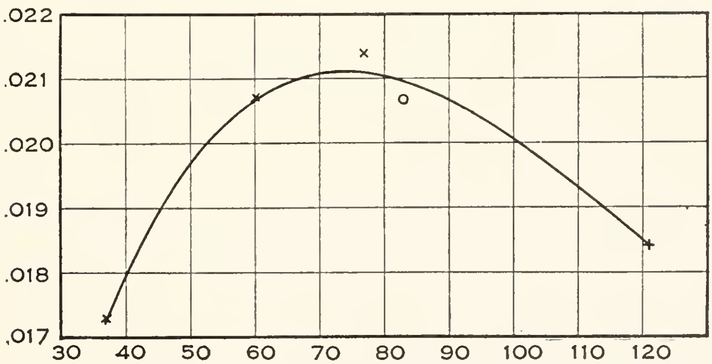

FIG. 6.—Calibration curve of ergometer I for magnetizing current of 1.1 amperes.

to 80 revolutions per minute, and gradually falls off with increasing speed until, with a speed of 153 revolutions per minute, it is even lower than at the very low rate of 39 revolutions per minute. It is of especial importance to note that the top of the curve is obtained when the speed is from 55 to 80 revolutions per minute.

Since it was highly improbable that all subjects would wish to ride the bicycle ergometer with exactly the same degree of resistance, the calibrations were made so extensive as to cover practically all of the different variations in resistance that could be experienced. The values obtained in five tests with a current having a strength of 1.1 amperes are presented in fig. 6, only one of these observations being made in the earlier calibration tests. The general trend of this curve has a striking similarity to that observed with a strength of current of 0.90 ampere.

By far the greater number of the work experiments performed with ergometer I and published in the earlier report were made with a current through the field of 1.25 amperes, and hence in the later calibration tests of this instrument, especial care was taken to secure values at different rates of speed with this strength of current. On fig. 7 are plotted the points for the earlier observations ranging between the speeds of 72 and 102; these are more or less grouped about the high point of the curve, which is somewhat flat, and therefore again gives justification for the assertion that the heat per revolution is constant irrespective of speed between 70 and 100 revolutions per minute. The points determined in the later calibrations, with the speed varying from 39 to 119 revolutions, indicate the same general form of curve, with a maximum between 70 to 90 revolutions per minute.

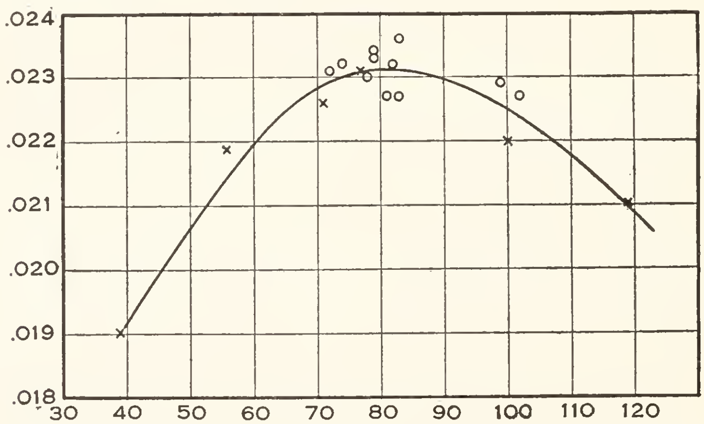

Fig. 7.—Calibration curve of ergometer I for magnetizing current of 1.25 amperes.

It is a matter of some interest that all of the more recently determined points are slightly lower than those determined in the earlier observations. While this is not strikingly shown in the preceding curves, it is possibly due to the fact that the apparatus may have been a little better lubricated during the last test, since it had been put in thorough working condition after several years of use and a smaller and more accurate calorimeter was used. Furthermore, certain of the earlier friction tests appear to show that the apparatus was distinctly not so free from friction as it should have been, since the later friction tests indicated a very much smaller value than that originally found. It should be stated, however, that the two friction tests made and reported in the earlier publication were by no means sufficient in number or extent to justify definite conclusions.

The general trend of these curves can best be compared by plotting them all in one diagram, and in fig. 8 this has been done. The marked uniformity in the general trend of the curves is obvious, showing that with a speed between 65 and 90 revolutions the heat per revolution is nearly constant. Below 60 and above 90 the heat per revolution is considerably less. Since in the series of calibrations previously published the speed ranged only between 60 and 90 or 100, these extreme variations in the heat per revolution were not observed, and not until these later tests were made did they appear. They naturally provoke discussion and awaken much interest.

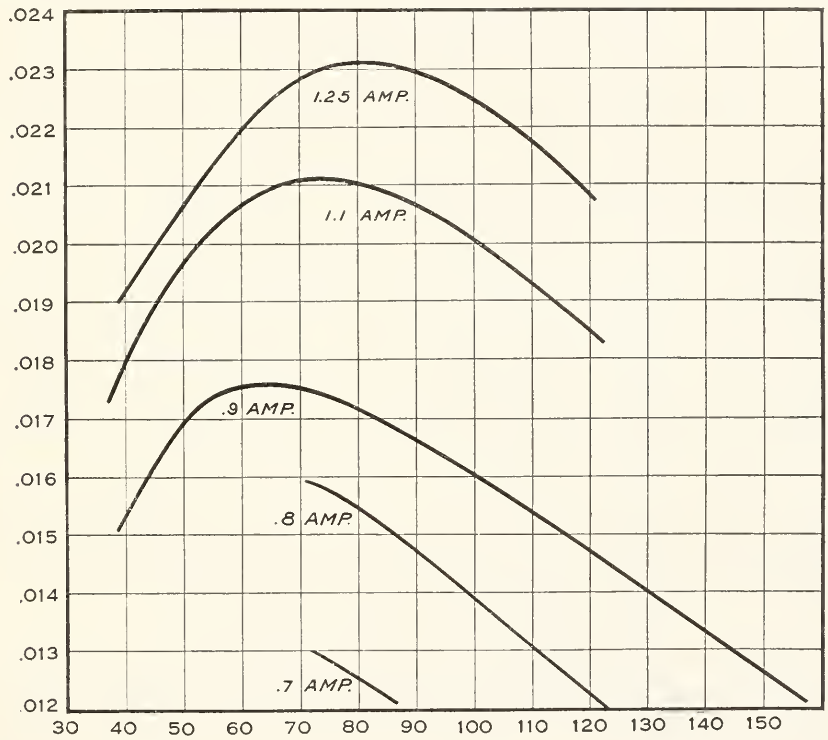

FIG. 8.—Calibration curves of ergometer 1 for magnetizing current of 0.7 to 1.25 amperes.

FRICTION TESTS WITH ERGOMETER I.

Since in certain experiments when a man is riding the machine the work of "coasting" is to be measured, a determination of the internal friction of the machine is desirable. The determination is made by rotating the shaft at the desired speed but without exciting the magnet.

A great fault in the earlier tests with this instrument lay in the fact that the friction tests were made under extremely adverse conditions. To measure a heat production of approximately 2 calories per hour with an apparatus designed to measure not less than 50 calories and as high as 625 calories per hour, naturally introduced an enormous percentage error. The value reported by Benedict and Carpenter,[1] as found in the one experiment made, was 0.001547 calorie per revolution. This represents about 8 per cent of the total heat per revolution with a current of 1.25 amperes. Unwarranted use of this figure was made by the authors in their discussion of the problems involved in experiments on men, but the best data then available were used. That this value was always too high seems obvious, and at the earliest opportunity a measurement of the heat of friction given off by this machine was made in the chair calorimeter at the Nutrition Laboratory. The results of two experiments in June 1911 are given in table 4.

TABLE 4.—*Results of friction tests of ergometer I.*

[Magnet not excited.]

Date and length of experiment.	Heat measured.	Corr. for change of cal. temp.	Heat produced.	No. of revolutions of pedals.	No. of revolutions per min.	Heat per revolution.
	cals.	*cals.*	*cals.*			*cal.*
1911, June 13, 11^h00^ma.m. to 1^h00^mp.m.	3.8	+0.4	4.2	15,308	128	0.000274
June 14, 12 12 p.m. to 5 12 p.m.	7.4	−1.4	6.0	38,100	127	.000157

These values, while by no means as concordant as could be desired, are but approximately one-fifth to one-tenth of that found in the single test made in Middletown, Connecticut. Subsequent tests made with ergometer II (see p. 29) indicate that these values are probably not far from correct, though it should be stated that a calorimeter designed to measure the heat production of a man is not best adapted to measuring so small an amount as 1 or 2 calories per hour.

Exactly what use of this value is justified in an experiment with a man it is not the province of this paper to discuss. These tests are given primarily to show that the earlier value was entirely wrong and hence all calculations made with it should be regarded as worthless.

CALIBRATION TESTS OF ERGOMETER II.

The second ergometer was constructed during the summer of 1911 and, after preliminary tests as to the winding of the magnets, the apparatus was substantially installed in the chair calorimeter for a series of tests. These tests covered wide ranges of speed and magnetizing current. A further variant was introduced in that in some of the experiments the relative position of the disk and pole-faces was changed so that the disk rotated much nearer one pole-face than the other. Subsequently, the entire magnet was moved towards the hub in a straight line, so that in a few experiments the pole-faces were nearer the hub by about 20 mm. In this new position the disk was at times in the center of the space between the pole-faces and at other times it was as near as possible to one of the pole-faces without actual contact with it. These tests with varying positions of the magnet were all incidental to a study

[1] Benedict and Carpenter, loc. cit., p. 15.

of the peculiar behavior of the magnetic field when the copper disk was rotated at different speeds. The results of the several calibration tests are reported in abstract in table 5.

TABLE 5.—*Results of calibration tests of ergometer II.*

Date.	Duration of period.		Current.	Heat measured.	Corr. for change of calorimeter temp.	Corr. for heat of magnetization.	Heat produced.	No. of revolutions of pedals.	No. of revolutions per min.	Heat per revolution.
1911.	*h.*	*m.*	*amp.*	*cals.*	*cals.*	*cals.*	*cals.*			*cal.*
Oct. 28	5	0	1.25	636.6	−0.2	— 60.8	575.6	36,148	120	0.0159
30	6	0	1.25	621.1	+ .2	— 72.7	548.6	29,072	81	.0189
31	6	0	1.35	705.5	− .2	— 85.8	619.5	29,228	81	.0212
Nov. 1	6	0	1.50	761.6	+2.1	—107.3	656.4	29,947	83	.0219
2	6	0	1.50	563.3	+ .4	—106.9	456.8	21,100	59	.0216
3	5	0	1.50	716.2	+2.1	— 89.1	629.2	30,228	101	.0208
4	6	0	1.50	937.1	− .8	—106.9	829.4	42,438	118	.0195
6	6	0	1.35	490.7	+1.8	— 85.4	407.1	20,834	58	.0195
7	6	0	1.35	752.5	+ .4	— 85.4	667.5	36,376	101	.0184
8	6	0	1.35	834.4	+ .2	— 85.1	749.5	42,870	119	.0175
9	6	0	1.25	455.9	− .6	— 72.4	382.9	20,858	58	.0184
10	3	0	1.25	356.5	+ .2	— 36.2	320.5	18,471	103	.0174
10	3	0	1.25	345.1	− .4	— 36.2	308.5	17,119	95	.0180
11	6	0	1.10	629.5	....	— 55.2	574.3	43,832	122	.0131
13	6	0	1.10	581.6	+1.8	— 55.2	528.2	36,573	102	.0144
14	6	0	1.10	489.9	−1.0	— 55.2	433.7	27,638	77	.0157
15	6	0	1.10	417.2	....	— 55.5	361.7	21,853	61	.0166
16	6	0	1.35	655.2	+ .4	— 85.4	570.2	28,840	80	.0198
17	6	0	1.35	767.8	+1.6	— 85.0	684.4	37,052	103	.0185
20	4	0	1.50	377.4	+0.2	— 70.9	306.7	14,300	60	.0214
21	6	0	1.50	588.8	−1.4	—106.4	481.0	21,888	61	.0220
22	5	0	.95	251.8	+ .6	— 34.0	218.4	15,932	53	.0137
23	6	0	.95	293.7	+ .4	— 40.8	253.3	18,739	52	.0135
24	4	0	1.50	195.3	+1.4	— 71.2	125.5	7,821	33	.0160
25	6	0	1.50	381.3	+2.9	—106.8	277.4	15,186	42	.0183
Dec. 1	6	0	1.35	362.7	− .2	— 85.4	277.1	15,162	42	.0183
2	6	0	1.25	329.8	+2.3	— 72.0	260.1	14,945	42	.0174
4	6	0	.95	441.9	....	— 40.8	401.1	27,502	76	.0146
5	6	0	.95	519.3	+1.0	— 40.9	479.4	36,311	101	.0132
6	6	0	.95	548.8	− .2	— 40.8	507.8	44,232	123	.0115
7	6	0	1.10	587.9	+ .6	— 55.7	532.8	30,389	84	.0175
8	6	0	1.10	638.7	+ .6	— 55.7	583.6	37,880	105	.0154
9	6	0	1.10	476.4	+ .8	— 55.6	421.6	24,020	67	.0176
11	6	0	1.25	492.5	+ .2	— 72.4	420.3	22,554	63	.0186
12	5	0	1.25	507.1	− .2	— 60.3	446.6	23,577	79	.0189
12	3	0	1.25	180.2	− .4	— 36.2	143.6	8,173	45	.0176
13	6	0	1.25	725.9	+ .8	— 72.4	654.3	39,910	111	.0164
1912.										
Jan. 1	4	0	1.25	284.8	−1.4	— 48.5	234.9	11,987	50	.0196
1	4	0	1.25	451.0	+6.2	— 48.5	408.7	21,630	90	.0189
1	4	0	1.25	496.2	+3.9	— 48.5	451.6	26,482	110	.0170
6	5	0	1.25	341.8	+1.4	— 60.6	282.6	14,880	50	.0190
9	5	0	1.25	340.7	−3.3	— 60.6	276.8	13,970	47	.0198
11	5	0	1.25	317.9	+2.5	— 60.6	259.8	13,753	46	.0189
15	5	0	1.25	443.9	+ .8	— 60.6	384.1	18,232	61	.0211
17	5	0	1.25	636.5	+2.0	— 60.6	577.9	32,937	110	.0175
18	5	0	1.25	473.6	− .4	— 60.3	412.9	21,791	73	.0189
19	5	0	1.25	508.4	−1.8	— 60.6	446.0	22,335	74	.0200
19	5	0	1.25	294.9	−4.1	— 60.6	230.2	12,682	42	.0182
20	4	0	1.25	414.1	+2.5	— 48.0	368.6	19,124	80	.0193
20	5	0	1.25	471.4	− .2	— 60.3	410.9	21,039	70	.0195
21	3	46	1.25	456.4	+1.2	— 45.4	412.2	22,909	101	.0180
21	5	0	1.25	610.0	+ .4	— 60.3	550.1	30,283	101	.0182
22	5	0	.95	465.5	− .4	— 34.0	431.1	36,949	123	.0117
22	5	0	.95	462.2	− .8	— 34.0	429.0	37,482	125	.0114

With ergometer I the magnetizing current ranged from 0.70 ampere to 1.25 amperes, but inasmuch as the winding of the magnet in ergometer II was somewhat different, the current ranged from 0.95 ampere to 1.50 amperes in the calibration tests of this ergometer. It was planned to secure calibrations of the ergometer at each current with variations in speed ranging from approximately 50 to 120 revolutions of the pedals per minute. For a given speed, the highest values of heat per revolution were obviously found with the largest magnetizing current, namely, 1.50 amperes. As a matter of fact, however, the experiments of November 4 and 6 show that with less current (1.35 amperes) through the field-coils but with a low speed, the heat per revolution was exactly the same as with a current of 1.50 amperes and with twice the number of revolutions, namely, 118 revolutions per minute. It is impossible, however, to analyze satisfactorily the varying conditions without recourse to a series of curves plotted for each intensity of magnetizing current.

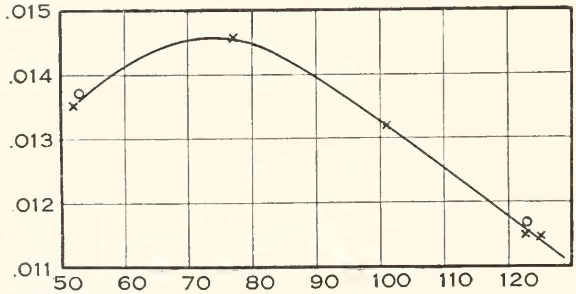

FIG. 9.—Calibration curve of ergometer II for magnetizing current of 0.95 ampere.

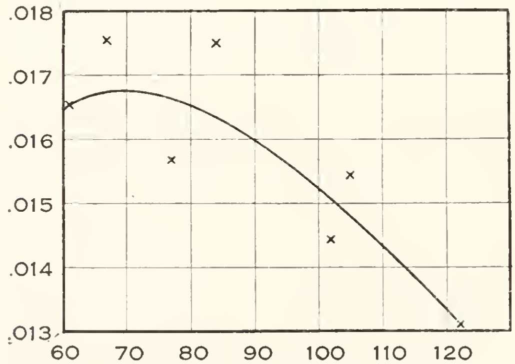

FIG. 10.—Calibration curve of ergometer II for magnetizing current of 1.10 amperes.

Beginning with the lowest current, namely, 0.95 ampere, we find that the values all lie fairly close to the curve (see fig. 9). Two of the observations shown on this curve were made when the disk was rotating very close to the rear pole, leaving a wide air-gap on the other side. These two values, which are indicated by small circles, lie approximately on the curve, and from these observations it would appear as if the rotation of the disk somewhat out of the center of the air-gap caused a very slightly larger amount of heat per revolution. The general form of the curve shows again a tendency toward a maximum heat per revolution with a speed of approximately 60 to 80 revolutions, and a tendency to fall off when the ergometer is running at a high speed.

With a magnetizing current of 1.10 amperes, we have two series of observations that are by no means concordant (fig. 10), and yet both indicate a noticeable falling off in the heat per revolution at high speed. We are unable at this time to account for the marked discrepancy between these two sets of observations, but since this current is not used at present in actual experimentation with man and since the curve agrees with the others in its general form, it is deemed inadvisable at this time to repeat the calibration test.

The calibrations made with a current of 1.35 amperes lie for the most part on a very definite curve (fig. 11). In one single observation at 80 revolutions per minute, it is approximately 5 per cent too high. The general form of curve noted for the other calibrations is here markedly shown, namely, a low heat per revolution with a low speed, a fairly constant heat per revolution between 60 and 80 revolutions per minute, and then a falling off in the heat per revolution as the speed is increased.

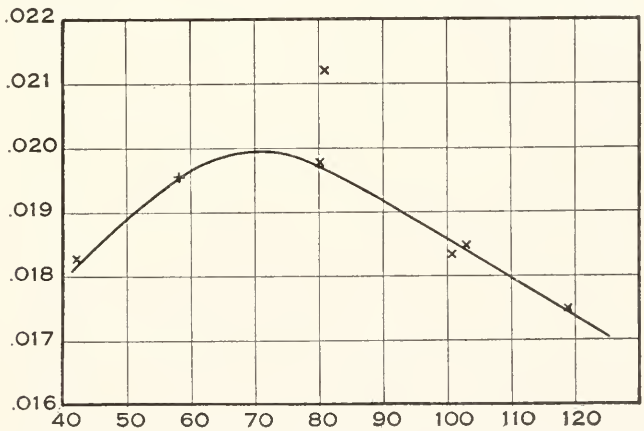

Fig. 11.—Calibration curve of ergometer II for magnetizing current of 1.35 amperes.

The observations with the strongest current through the field, namely, 1.50 amperes, are shown in fig. 12. One observation, characterized by a circle, was made when the disk was rotating near the rear pole, *i.e.*, out of center of the air-gap, but the variation from the normal is so slight as to make it almost imperceptible. In this curve we again find a low heat per revolution with low speed, a fairly constant heat per revolution between 60 and 80 revolutions per minute, and a decrease in the heat per revolution as the speed is further increased.

By far the largest number of tests were made with a current of 1.25 amperes, which was selected for the study of the magnetic field described in Part III of the report. In order to make this study it was necessary to move the disk as far as possible toward the rear pole-face and thus provide space in the air-gap between the front pole-face and the disk for a flat bismuth spiral. It was deemed advisable, therefore, to test the machine under these conditions in order to find if there was any marked difference in the calibration test when the circular disk was somewhat off center. The points obtained in this way are surrounded by circles in the curve shown in fig. 13. It will be seen that they lie somewhat above the curve, as was also the case with figs. 9 and 12. The reason doubtless is that the magnetic field, at least near the edges of the poles, is so non-uniform that the lines of induction intercepted by the disk are somewhat denser when the latter is brought close to one pole-face.

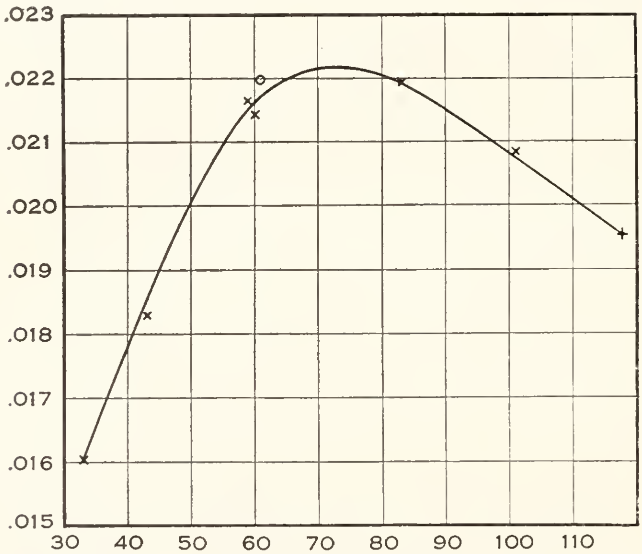

Fig. 12.—Calibration curve of ergometer II for magnetizing current of 1.50 amperes.

Tests were also made with the magnet covering more of the copper disk, *i.e.*, pushed in about 2 cm. toward the hub. Accordingly, in fig. 13 we find a large number of points which may be classified under several groupings. In the series of observations in which the magnet was pushed farther over the copper disk, one might expect a somewhat smaller brake-effect upon the copper disk; as a matter of fact, it was found that the curve was shifted somewhat to the left, showing abnormally high values of heat per revolution at low speeds. These points are indicated by squares (*cf.* Part III). Since the chief use of the instrument, however, is for a regular magnetizing current of 1.25 amperes, with the disk exactly in the center of the air-gap and the periphery of the disk tangential to the upper edge of the pole-face of the magnet, it seemed undesirable to make further calibrations of this instrument under these peculiar conditions, which were necessitated only by the study of the magnetic field. We have, therefore, chiefly to consider the observations made with the disk in the regular position. The heavy line[1] plotted curve represents all observations with the disk and magnet in their original positions. Here again we find with low speeds the low heat per revolution a fairly constant heat per revolution with a speed between 60 to 90, and a fall in heat per revolution as the speed increases beyond this.

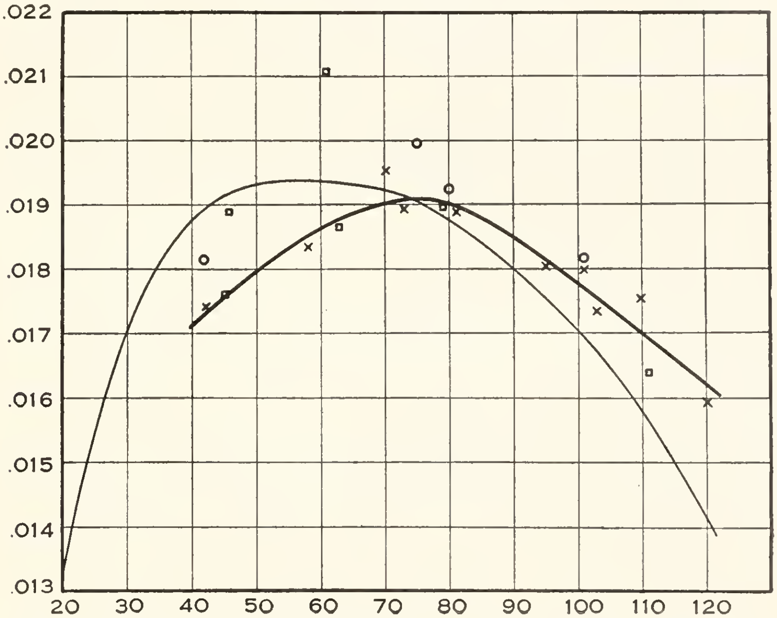

FIG. 13.—Calibration curves of ergometer II for magnetizing current of 1.25 amperes.
Black crosses: Disk in normal position between poles of magnet; curve in heavy line is based upon these.
Circles: Disk close to rear pole, air-gap on other side widened.
Squares: Poles moved 2 cm. in toward center of disk.
Curve in light line represents values of $\omega\phi^2$ (see p. 37).

To show their similarity the curves corresponding to the five magnetizing currents, 0.95, 1.10, 1.25, 1.35, and 1.50 amperes have been replotted on one diagram (see fig. 14). This series of curves is strikingly similar to those found with ergometer I when calibrated in June and July of 1911, and indicates that the instruments are essentially alike in their mechanical and electrical features. The special feature to be noted here is that the curves show uniformly a low heat per revolution with a low speed, nearly constant heat per revolution between approximately 60 to 90 revolutions per minute, and a rapidly falling heat per revolution at high speeds. Since practically all experiments are made with bicycle riders at speeds between 60 to 80, it may be stated again that, in general,

[1] The lighter lined curve is discussed in Part III, p. 37.

the heat per revolution is sufficiently constant between these limits, irrespective of speed, although reference should be made to the calibration curves if the speeds are below 60 or above 80. The abnormal appearance of these curves led to much speculation as to the cause. In Part III of this report it will be shown that a complete explanation of the observed effects is found in the magnetic reaction of the eddy currents induced in the copper disk.

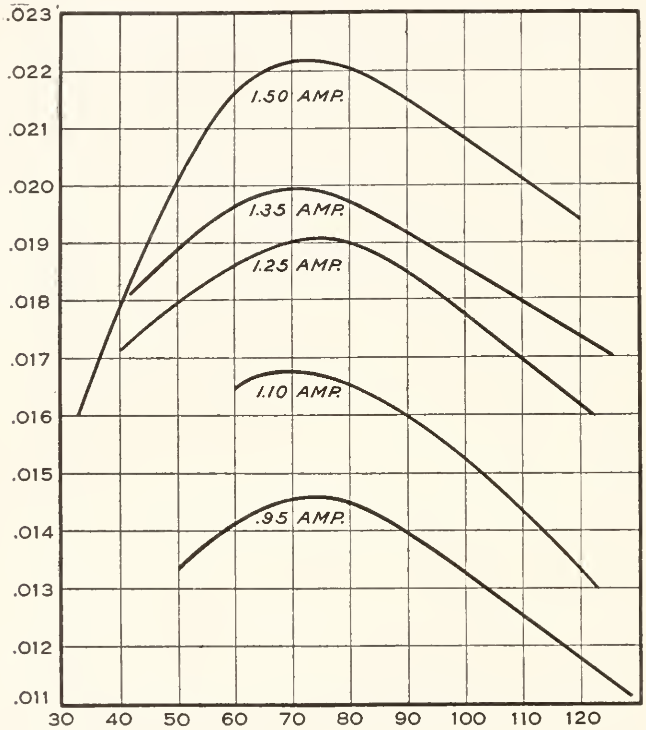

FIG. 14.—Calibration curves of ergometer II for magnetizing currents of 0.95 to 1.50 amperes.

For physiological experimenting, the apparatus is most satisfactory, since the constant brake-effect gives a constant heat production. Although unfortunately it is not everywhere possible to determine the absolute values by means of calibration tests inside a large calorimetric chamber, yet it may be that by driving the ergometer with an electric motor of known efficiency and measuring the input of electrical power, an approximate idea can be obtained of the actual power required to rotate the pedals. We have made some rough tests of this sort. The chief difficulty lies in running the disk at a sufficiently low speed without the various losses becoming disproportionately large.

In connection with these observations it is of especial interest to note that ergometer I remained essentially constant in its electrical and mechanical properties over a period of some 8 years, thus showing a remarkable constancy in the apparatus. We feel justified, therefore, in heartily recommending its use when a constant amount of work is to be done and uniformity in muscular work is essential. Furthermore, the amounts of energy computed from the speed of the magnetizing current are accurate to within about 2 per cent.

FRICTION TESTS WITH ERGOMETER II.

Although it was doubtful if a knowledge of the heat per revolution due to friction would be of any particular value, it seemed desirable to make measurements of the friction of this apparatus if only for comparison with those made with ergometer I, and for checking the recent experiments with the latter. Three friction tests were accordingly made with ergometer II on December 18, 20, and 22, 1911, the results being reported in table 6. As in the friction tests with ergometer I, the amounts of heat measured were so very small that but little reliance can be placed upon the results for individual periods; and it is not surprising that we find variations of 50 per cent between the heat per revolution found on December 18 and December 22 when compared with that in the test on December 20. When we consider, for example, that through a whole experiment lasting from $10^h\ 14^m$ a. m. to $2^h\ 15^m$ p. m. only a sum total of 7 calories was measured, the numerical values found are certainly not of great significance. The important thing is that these results show an average of heat per revolution not far from 0.0025 calorie, which is in reasonably close agreement with those found with ergometer I in the calibrations inside of this identical calorimeter. In general, the frictional heat per revolution is not far, therefore, from 1 to 2 per cent of the total heat produced when the apparatus is used with the field magnetized at 1.5 amperes.

TABLE 6.—*Friction test, ergometer II.*

Time.	Heat measured.	Corr. for change of cal. temp.	Heat produced.	No. of revolutions of pedals.	Rate per minute.	Heat per revolution.
	cals.	*cals.*	*cals.*			*cal.*
1911 Dec. 18, 2^h02^mp.m. to 5^h02^mp.m.	12.4	−4.5	7.9	22,276	124	0.000355
Dec. 20, 10 14 a.m. to 2 15 p.m.	7.08	−1.6	5.48	30,121	125	.000182
Dec. 22, 10 46 a.m. to 4 46 p.m.	14.89	+1.0	15.89	45,235	126	.000351

PART III.

THE MAGNETIC REACTIONS PRODUCED BY A COPPER DISK ROTATING BETWEEN THE POLES OF A MAGNET.

That a rotating disk exerts not merely a tangential drag, but also a repulsive force, on a magnet pole placed near it, has been known since the days of Arago.[1] Nobili [2] first discovered that the loops of induced current are displaced in the direction of rotation of the disk, though he did not understand the part played by self-induction in causing this. Indeed, as far as we are aware, no attempt has been made up to the present time to make a quantitative determination of the electric and magnetic effects.

Mathematically, the problem of the currents induced in bodies rotating in a magnetic field has been attacked by Felici, Jochmann, Maxwell, Himstedt, Niven, Larmor, Gans, and especially by Hertz.[3] The chief results of Hertz's work that have a bearing on the present paper may be summarized as follows: When a conducting mass is rotated in a magnetic field, the induced currents, owing to self-induction, are distorted in the direction of rotation to an extent independent of the intensity of the magnetic field but increasing with the angular velocity. At the surface of the conductor the currents are less distorted than in the interior. At infinite angular velocity the surface of the conductor would act toward magnetic forces like a conducting surface in an electric field, screening the interior entirely from all magnetic action.

These mathematical investigations were all made on the assumption of certain ideal conditions, which in general it would be hard to realize experimentally. In order to apply theoretical principles at all to the present case it is necessary to make some simple assumptions and to be content with qualitative relations. The problem would be comparatively simple if the disk were so thin that it could be regarded as a current sheet, if the magnetic induction B were uniform in the space between the poles, and if the self-induction of the disk could be neglected. Calling ω the angular velocity of the disk,[4] we would then have for the induced electromotive force

$$e = \text{constant} \times \omega B$$

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[1] Arago, Pogg. Ann., 1826, **7**, p. 590; Pohl, Pogg. Ann., 1826, 8, p. 369.

[2] Nobili, Pogg. Ann., 1833, **27**, p. 401. A very full account of the classical experiments on rotating disks is given in Wiedemann's "Galvanismus und Elektromagnetismus," Braunschweig, 1874.

[3] Felici, Annali di sci. mat. e fis., 1853, p. 173; Jochmann, Pogg. Ann., 1864, **122**, p. 214; Maxwell, "Electricity and Magnetism," **2**, p. 300; Himstedt, Wied. Ann., 1880, **11**, p. 812; Niven, Proc. Roy. Soc. 30, 1880, p. 113; Larmor, Phil. Mag. (5), 1884, **17**, p. 1; Gans, Zschr. f. Math. u. Phys., 1902, **48**, p. 1; Hertz, Inaugural Dissertation, also "Gesammelte Werke," **1**, 1895, p. 37.

[4] In Parts I and II speeds were expressed in revolutions per minute of the pedals, because in using the bicycle ergometer this is the important quantity. Since in Part III attention is centered chiefly on the disk, we shall, in what follows, in general refer to the angular velocity or number of revolutions per minute of the disk, obtained by multiplying all pedal speeds by 3.25, the ratio of the two sprocket-wheels.

Hence the currents in the disk would be proportional to

$$\frac{\omega B}{\sigma}$$

where σ is the specific resistance of the disk. The rate of production of heat would then be proportional to

$$\frac{\omega^2 B^2}{\sigma}$$

and the heat per revolution proportional to

$$\frac{\omega B^2}{\sigma}$$

Hence if these most elementary assumptions were sufficient, as might easily be supposed to be the case, the heat per revolution would be a linear function of the speed instead of reaching a maximum and then decreasing.

In the actual case the disk is of finite thickness and the current paths possess a self-inductance depending on the form of the paths and on the magnetic constants of the iron pole-pieces. Hence the current density is not uniform through the thickness of the disk, and the magnetic field is distorted and modified by the reaction of the eddy currents and by the changes in permeability, to an extent that it is not easy to predict.

Nevertheless, by making the following three fundamental assumptions, it is possible to establish relations between speed, resultant magnetic induction, and rate of production of heat, which are capable of experimental verification. These three assumptions are obviously valid only at low speeds; still, our observations were not extensive enough to furnish more than a rough test for the theory.

Owing to self-induction the currents are not symmetrically situated with respect to the magnet poles, but are advanced in the direction of rotation of the disk through a certain angle which we will call θ. In accordance with Hertz's results we may assume that for moderate speeds

$$\theta = k_1 \omega \tag{1}$$

where ω is the angular velocity of the disk and k_1 a constant independent of the strength of the magnetic field. This condition is shown in fig. 16, page 40, in which the disk is supposed to rotate counter-clockwise, and the magnetic induction to be directed from the observer into the disk. It is evident that the system of current loops whose magnetic field is opposed to the field of the electro-magnet is now brought more nearly between the magnet poles. If there were no such displacement of the loops, the magnetic induction would be weakened on the side where the current paths enter the air-gap, and strengthened on the other side. This would result in a crowding of the lines away from the "leading" edge of the pole, toward the "trailing" edge. The resulting decrease in permeability on the trailing half would be expected of itself to diminish the total magnetic flux somewhat. But owing to the self-inductance, the field must be weakened on one side much more than it is strengthened on the other.

The total original flux ϕ_0 across the disk will thus be diminished by a certain amount which we will call ϕ', the "counter flux" due to the eddy currents. This diminution in flux may be assumed for moderate speeds to be proportional to the intensity i of the eddy currents and to the angle θ, or

$$\phi' = k_2 \theta i \tag{2}$$

Thirdly, in accordance with the fundamental principle of electromagnetic induction, we have

$$i = k_3 \frac{\omega\phi}{\sigma} \tag{3}$$

where the actual resultant magnetic induction through the disk is

$$\phi = \phi_0 - \phi'$$

From these assumptions (1), (2), and (3), the following equations may be derived, in which the product $k_1 k_2 k_3$ is replaced by a single constant k:

$$\omega^2 \frac{\phi}{\phi'} = \frac{\sigma}{k} \tag{4}$$

$$\frac{i^2 \sigma}{\omega} = \frac{k^2{}_3 \omega \phi^2}{\sigma} \tag{5}$$

As will be seen, these assumptions do not take into account all of the variables; nevertheless, it will be shown on p. 37 that equation (4) is roughly verified. The significance of equation (5), which represents the heat per revolution of the disk, will be discussed in a later paragraph.

MEASUREMENT OF MAGNETIC FIELD BY MEANS OF A BISMUTH SPIRAL.

It seemed desirable to measure not simply the total magnetic flux at different speeds, but the induction at a number of points in and near the air-gap as well. Among the various practicable methods, that of the bismuth spiral seemed best adapted for our purpose. Most of the observations described below were made with a Hartmann and Braun spiral, kindly loaned us by the Worcester Polytechnic Institute. The fine bismuth wire of this spiral, coiled into a flat disk about 17 mm. in diameter, had a resistance under normal conditions of about 20 ohms. A small portion of the work was done with a second spiral, similar to the first, and the results obtained with the two instruments agreed very well. Unfortunately we did not have at our disposal a spiral of smaller diameter.

In order to make it possible to introduce the bismuth spiral into the narrow gap between pole-face and disk, it was necessary to shift the electromagnet slightly, bringing one of its faces almost into contact with the disk, while the gap on the other side was correspondingly widened. The effect of this change on the heat per revolution was considered in Part II. Even with this increased air-space on one side of the disk, it was not easy to bring the spiral into the center of the field without its being chafed by the disk. Hence but few observations were made in the center of the field, and no reliable ones were obtained there when the disk was rotating. During the magnetic observations the ergometer was mounted inside the calorimeter, but the front of the calorimeter was open and no attempt was made to allow the thermal conditions to reach a steady state; each speed was generally maintained for only a minute or less. Hence in general the temperature of the disk was somewhat lower than during the calibration tests.

The bismuth spiral was clamped securely in a holder that was capable of being moved parallel to itself in various directions. In nearly all cases the exciting current in the electro-magnet was 1.25 amperes and in the few remaining cases the results have been corrected to this value. Resistances were measured with a Wolff Wheatstone bridge and sensitive galvanometer.

The spiral received heat by radiation from the copper, and by conduction from the strong current of air when the disk was in motion. As this made a direct determination of its temperature impossible, it was decided to estimate the temperature from the resistance of the bismuth when the magnetic field was off. This resistance was measured at frequent intervals and the temperature computed with the aid of the resistance temperature coefficient of bismuth. Thus, in a typical group of observations at each position of the spiral, the following resistances were observed: (1) magnetic field off, disk stationary; (2) magnetic field on, disk stationary; (3) field on, disk running at two or more speeds in succession, in many cases repeating in reverse order; (4) field still on, disk stationary; (5) field off, disk stationary.

Allowance was made whenever necessary for the drift in temperature between observations (1) and (5). In general, the mean of (1) and (5) gave w_0, the resistance of the spiral in a magnetic field of intensity (practically) zero. The remaining observations gave values of w_f, the resistance with field on, at various speeds. In most cases the speeds were 0, 11, 60, and 112 revolutions per minute of the pedals, or 0, 36, 195, and 364 revolutions per minute of the disk. For each speed the value of $w_f - w_0$ was corrected for temperature, and from this the induction in gausses was obtained from the calibration curve furnished with the spiral. At the conclusion of each set of observations the spiral was advanced a millimeter or so and the observations repeated.

Most of the magnetic distortion was to be looked for along lines parallel to the direction in which the portion of the disk between the poles was moving, *i.e.*, along the line *AB* in fig. 16. Nearly all of the observations were accordingly made along this line and they will be considered first. The results are shown in fig. 15, in which the abscissæ represent distances in millimeters measured from the center of the field along the line *AB* of fig. 16. Positive values lie in the direction in which the disk is supposed to be rotating. The heavy vertical lines *G G′* in fig. 15 indicate the position of the edges of the magnet pole; thus G' is the "trailing tip." The curves in heavy lines show the observed induction in gausses at different angular velocities. The number of revolutions per minute of the disk is indicated on each curve. To avoid confusion, the individual observations are omitted, except in the case of one curve. The points for

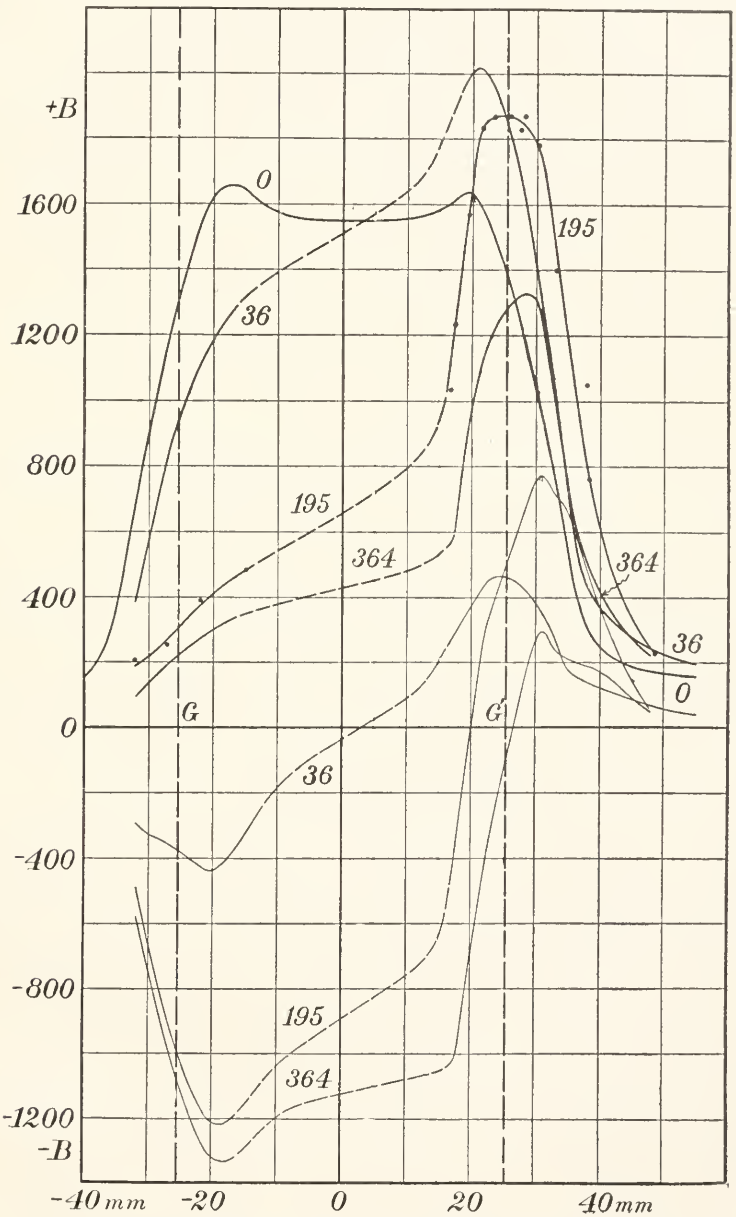

FIG. 15.—Magnetic induction across air-gap. Direction of motion of disk is to right. G, G' indicate position of edges of magnet poles.

the other curves agree among themselves to about the same degree of closeness as these. Owing to the unsatisfactory character of the observations in the middle of the field when the disk was in motion, but little weight was placed on these data, and the curves are accordingly shown as broken lines in this region.

Since the bismuth wire was coiled in a spiral about 17 mm. in diameter, it is clear that these curves can not show accurately the precise form of the magnetic field. A simple consideration shows that if the curves could be drawn with precision they would slope more steeply than the curves here drawn; they would then cross the lines $G\ G'$ at points higher up, and the maxima would all be higher. Still, crude as they are, they show clearly the reaction of the eddy currents in the disk.

The curve obtained with the disk stationary (speed 0), is quite symmetrical, showing slight maxima close to the edges of the poles. As the speed increases, the distortion of the magnetic field and the marked decrease in flux at high speeds are very evident. From the curve for speed 364, it might be inferred that here the induced current is confined entirely to a narrow path close to the trailing edge of the pole-face. That this is the case will be shown later.

Since the ordinates of the curves for speeds 36, 195, and 364 represent the resultant induction through the disk, it is evident that the algebraic difference between these ordinates and those for speed 0 must be a measure of the magnetic field that would be produced by the induced currents alone. These differences are plotted in fine lines. Negative ordinates signify a component opposing the flux from the electro-magnet. The most striking feature of these curves is the very pronounced demagnetizing field produced in the disk at high speeds. The points where the curves cross the axis of abscissæ show that the displacement of the currents in the direction of rotation increases with the speed (eq. (1)), though at a lower rate. It is presumably near these points that the induced currents attain their maximum values.

A few observations were made with the bismuth spiral in other positions. The induction was found to be practically uniform when the spiral was moved in a radial direction, except close to the outermost edge of the magnetic field near the circumference of the disk, for example at the point P in fig. 16. Here the flux density was found to increase with increasing speed, as would be expected, for the demagnetizing effect of the currents must lead partly to a diminution in the total flux around the magnetic circuit, and partly to increased leakage around the outer edge of the disk. Indeed, the currents along the edge of the disk on the side approaching the magnet flow in such a direction as to bend the lines of magnetic induction outward around the edge of the disk.

When the spiral was laid flat against the side of the magnet pole, with its plane perpendicular to the disk, it showed a decrease of about 30 per cent in magnetic induction on the "leading" side, while on the "trailing" side the induction was about doubled when the disk was running at 364 revolutions per minute.

COMPARISON OF RESULTS WITH THEORY.

Although, for the reasons given, the curves in fig. 15 do not represent the facts quite accurately, still it is worth while to inquire how well they satisfy the conditions expressed in equations (4) and (5). In these equations it is necessary to know the value of ϕ, the resultant flux at angular velocity ω, and ϕ', the "counter flux" at the same angular velocity. From the areas of the distorted curves in heavy lines ϕ is obtained, and ϕ' from the areas of the curves in fine lines (algebraic sum of negative and positive lobes). The areas were taken arbitrarily between —40 and +45 mm., since outside of these limits the ordinates are small. From the areas and the measured dimensions of the pole-faces, the values shown in columns 2 and 3 of table 7 were obtained.

TABLE 7.—*Magnetic fluxes at different speeds.*

ω	ϕ	ϕ'	$\omega^2\frac{\phi}{\phi'}\times 10^{-3}$	$\omega\phi^2\times 10^{-9}$
36	65,000	800	105	152
195	42,200	23,600	68	348
364	27,700	38,100	96	279

Since only relative values are required, ω is here given as the number of revolutions per minute of the disk.

The quantity $\omega^2\frac{\phi}{\phi'}$ in column 4 should, by equation (4), be equal to $\frac{\sigma}{k}$, a constant. This condition is satisfied as well as could be expected, considering that the increase in ω from the first to the third observation is ten-fold and the increase in ϕ' is nearly fifty-fold. It must also be remembered that as the speed increases, the distribution of the current paths and hence also the resistance of the paths may change to a marked degree. In other words, our assumptions considered only the total flux, although theoretically the distribution of magnetic induction and of the current loops in space ought to be considered. Moreover, since the magnetic lines pass between pole-pieces of limited extent, it is possible that our first assumption, equation (1), does not hold at the higher speeds. Changes of σ with temperature can hardly have affected the result materially; but, on the other hand, the lack of reliable observations in the central portions of the field lends an element of uncertainty.

In equation (5) we expressed the relation

$$\frac{i^2\sigma}{\omega}=\frac{k^2{}_3\,\omega\phi^2}{\sigma}$$

The left-hand member of this equation is proportional to the heat generated per revolution of the disk, since the numerator represents the rate of production of heat, while the denominator indicates the number of revolutions per minute. We are thus in a position to obtain relative values for the heat per revolution, based on magnetic data alone, which can be compared, for the same current in the electro-magnet (1.25 amperes), with the calibration curve of the ergometer (fig. 13). Since k_3 is a constant and the temperature of the disk changed but little during the magnetic tests, it is sufficient to compute the values of $\omega\phi^2$ at various speeds and to plot these values as functions of the speed. The values of $\omega\phi^2$ corresponding to the three observed values of ϕ are given in table 7.

In order to draw the entire curve, it was necessary first to find the relation between ϕ and ω. This relation, which can be derived from our fundamental assumptions, is

$$\phi = \frac{a}{\omega^2 + b}$$

where a and b are constants. The equation is roughly satisfied by our observed values of ϕ and ω, but we considered it better to obtain values of ϕ corresponding to various values of ω from a curve connecting these quantities. Since the curve was nearly a straight line over the observed range, the interpolation was simple. To facilitate the comparison with the ergometer calibration curve for 1.25 amperes, all of the values of $\omega\phi^2$ were multiplied by a constant numerical factor, so that the maximum of the calibration curve coincided with one point of the $\omega\phi^2$ curve. In fig. 13 the $\omega\phi^2$ curve is shown as a fine line. It has the same general form as the calibration curve, but its maximum comes at a lower speed. This is no doubt due in large measure to the sources of error already mentioned. But it may also be due partly to the fact that since no attempt was made in the magnetic tests to reach thermal equilibrium, the copper disk was, for the same speed, cooler during the magnetic tests than during the calibrations. At low speeds, where ϕ is nearly constant, the relatively small value of σ during the magnetic tests would make the heat per revolution relatively high. But at high speeds a smaller value of σ means a larger value of ϕ', hence a relatively small value of ϕ. Since equation (5) shows that the heat per revolution varies as the square of ϕ, the result will be a relatively small value of $\omega\phi^2$. A rough calculation shows that the correction from this cause would amount perhaps to 5 per cent, raising the ordinates to the right of the maximum of the $\omega\phi^2$ curve slightly, and reducing those to the left.

Nevertheless, aside from minor discrepancies, the similarity of the two curves is very striking, proving beyond a reasonable doubt that the peculiarity in the ergometer calibrations is due almost entirely to the demagnetizing effect of the eddy currents in the disk. The increased temperature of the disk at high speeds, by reducing the intensity of the currents, enhances this peculiarity, but only to a minor degree.

FURTHER EXPERIMENTS WITH THE EDDY CURRENTS.

The great intensity of the currents in the disk was also made evident by the following quite elementary experiments:

(I) *Compass tests.*—A small pocket compass held near the disk showed the presence of a strong magnetic field due to the eddy currents, even at a considerable distance from the electro-magnet. One way of testing this was to trace out the magnetic lines parallel to the surface of the disk by the usual step-by-step method, holding the compass with its plane vertical like a dip needle, close to the disk near one pole of the magnet, and then advancing it by stages parallel to the disk and along the direction of the lines. In fig. 16 the heavy lines marked 0 were thus obtained with the disk stationary, showing the direction of the stray lines from the electro-magnet.[1] The dotted lines marked 390 were obtained when the disk rotated at 390 revolutions per minute. In this figure the north pole of the electro-magnet is on the side toward the observer and the disk rotates counter-clockwise. Observations at points on the other side of the magnet pole showed a corresponding change in the direction of the resultant magnetic field when the disk was in rotation. The point Q, just outside the disk, is a neutral point, where the field due to the eddy currents is equal and opposite to that due to the magnet.

(II) *Galvanometer tests.*—The copper leads from a sensitive galvanometer were touched to the surface of the disk at points from 1 to 5 mm. apart, the points being so oriented that the galvanometer showed no deflection. Care was taken to reduce the effect of thermo-electric forces to a minimum. This is the old method used by Faraday and Nobili for plotting the lines of current flow. Though it can not always be assumed that the current flows in a direction perpendicular to the line joining these "equipotential" points, still they furnish an approximate idea of the direction taken by the current paths. A few such pairs of points are indicated in fig. 16, and with their aid some of the current lines have been constructed, the arrow-heads indicating the direction of flow. These lines must not be confused with the magnetic lines described above. Tests made close to the magnet pole proved that at 390 revolutions per minute the inwardly directed current lines were confined to a narrow band about a centimeter wide, near the trailing edge of the pole, as shown. The demagnetizing effect of the currents is here very evident.

(III) *Intensity of the eddy currents.*—The galvanometer leads were touched to the disk, as described above, at a point near the magnet pole, but oriented in such a way as to produce a maximum deflection. From the distance between the points of contact and the resistance and sensitiveness of the galvanometer, the potential difference between the points was found, and from this and the specific resistance of copper

[1] At the time of these tests the magnetic poles were pushed in about 2 cm. from the outer edge of the disk. This can hardly have produced an appreciable change in any of the quantities observed (*cf.* fig. 13).

the current density was found to be of the order of 650 amp./cm². This was at about 300 revolutions per minute of the disk.

As a rough check on this, the electromotive force induced in the copper was computed from the observed flux and the speed of the disk. The potential gradient was found to be of the same order of magnitude as

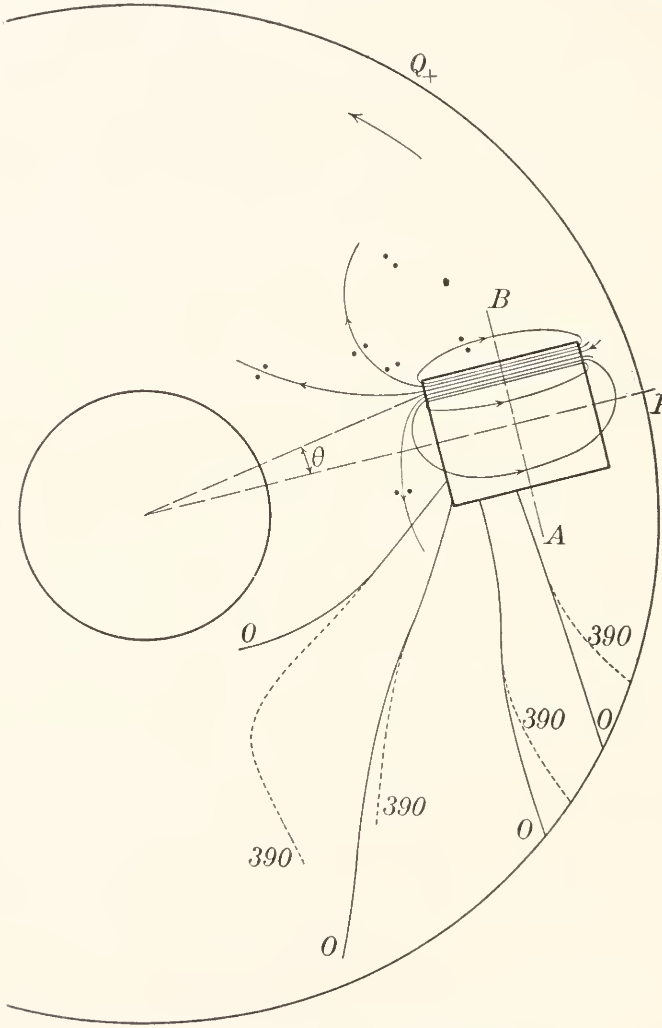

FIG. 16.—Magnetic lines and current loops on surface of rotating disk. Long arrow shows direction of rotation.

that derived from the galvanometer observations above, namely, about one-thousandth of a volt per centimeter. From these data we estimate the total current in the disk to have been not less than 2000 amperes.

(IV) *Effect of eddy currents on the flux through the magnet coils.*—In order to measure the diminution in total flux when the disk was running, a single turn of wire was wrapped around one of the magnet coils and connected to a ballistic galvanometer. The throw was measured when the field current was turned on, and again when the disk was suddenly set in rotation. The latter throw was always in the opposite direction to the former; its measured value was certainly somewhat too small, since it took an appreciable time for the disk to attain full speed. The results indicated a diminution of the total flux amounting to only about 4 per cent, when the disk rotated at 320 revolutions per minute. Even allowing for the gradual acceleration of the disk, it is apparent that the reaction of the eddy currents causes chiefly an increased magnetic leakage, without greatly diminishing the flux through the coils.

The diminution of the flux on starting the disk causes a slight momentary increase in the current through the electro-magnet, while suddenly stopping the disk diminishes the magnetizing current for an instant. This is analogous to the momentary changes produced in the current through a coil of wire when an iron core is moved in and out. Soret[1] seems to have observed this effect first. On the other hand, Jacobi[2] asserted that the magnetizing current was diminished when the angular velocity of his disk was increased. If we understand his paper aright, this must have been an error.

(V) *Effect of eddy currents on permanent magnets.*—It is of interest to consider briefly the effect of moving masses of metal on permanent magnets. If the pole of a bar magnet is held close to a rapidly revolving copper disk, its moment is permanently weakened. This method is sometimes made use of in the artificial seasoning of horseshoe magnets. In the design of at least one type of speedometer, this demagnetizing action is especially guarded against in an ingenious manner.

If one of the magnet systems of a Kelvin galvanometer employing astatic needles is inclosed in a copper damper, this system undergoes a slight demagnetizing action at every swing. Thus in time the astaticism of the systems must be perceptibly impaired, unless the needles are very well hardened.

The currents induced in masses of metal moving relatively to permanent magnets must, at the beginning and end of the motion, induce eddy currents in the magnet itself. If the acceleration is the same on starting and stopping, these currents can have little to do with the demagnetization of the magnet, for they flow in a direction tending to increase the magnetization when the motion begins, and tending to decrease it when the motion ceases. The case is analogous to moving the keeper of a horseshoe magnet rapidly up against the poles, which causes demagnetizing eddy currents to flow, while suddenly pulling off the keeper gives rise to currents in the opposite direction.

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[1] Soret, Comptes rendus, 1857, **45**, p. 301. [2] Jacobi, Comptes rendus, 1873, **74**, p. 237.

INFLUENCE OF TEMPERATURE ON THE CONSTANCY OF THE BICYCLE ERGOMETER.

From what has preceded, it is clear that the rate of heat production varies inversely as the resistance of the rotating disk, and hence that the heat per revolution varies in the same manner. Over the usual range of room temperatures, it may be assumed that the same expenditure of energy in the disk raises its temperature to the same extent above its surroundings. If the ergometer is used outside the calorimeter in a room at the same temperature as that inside the calorimeter during calibration, the results of the calibrations can be applied without correction, provided the circulation of air is approximately the same in the two cases. But if, for example, an accuracy of 2 per cent in the energy measured is desired, then, since the temperature coefficient of copper is approximately 0.004, a temperature correction will have to be applied if the temperature of the room differs by more than 5° C. from the mean temperature inside the calorimeter during calibration. In general, during the work that has been done thus far with the ergometer, no such correction has been necessary. The highest observed temperature of the disk (see Part II) was 43° C. at a pedal speed of 120 revolutions per minute, the room temperature being 20° C. It was to be expected that as the speed increased the maximum temperature would occur at a higher speed than the maximum value of the heat per revolution, since the maximum temperature depends on the heat per second, *i.e.*, it is proportional to the heat per revolution multiplied by the speed. In using the ergometer for accurate quantitative measurements, care should always be taken to maintain each speed long enough for the temperature of the copper disk to reach a sufficiently steady state. For practical purposes, this precaution is seldom necessary.

THE DESIGN OF ELECTRIC BRAKES.

In conclusion, we will summarize briefly the general principles that ought to be considered in the design of apparatus employing electromagnetic damping, particularly with reference to the demagnetizing effects of the eddy currents. We shall base our deductions in part on the equation

$$\phi' = \frac{k\omega^2\phi_0}{\sigma + k\omega^2} \qquad (6)$$

derived from our fundamental assumptions on p. 32. ϕ_0 is the impressed flux when the disk is stationary, ω the angular velocity, σ the specific resistance, and k a constant.

(*a*) *Material of disk.*—For the strongest effects soft iron or soft steel may be used. The resistance is of course comparatively high, but the magnetic induction will be very large, and the heating due to hysteresis will be added to that from the eddy currents. The magnetic reaction from an iron disk must be very large, as was indeed shown by Hertz in the paper already cited. Copper and aluminum are probably the most widely used metals on account of their low specific resistance. Aluminum has also a high specific heat to recommend it. If a weaker effect is desired, an alloy of high resistance may be used. Other things being equal, the demagnetizing effect of the eddy currents will be greatest for an iron disk, with copper and the other non-magnetic metals following in the order of their specific resistances. But for the same expenditure of power the demagnetizing effect will be practically independent of the material of the disk.

(*b*) *Thickness of disk.*—With the same magnetic flux, the intensity of the induced currents and also the heat will vary directly as the thickness. Since, according to Hertz, the currents in the interior of a thick disk lag more than those on the surface, it follows from equation (2) that the demagnetizing effect will increase at a more rapid rate than will the thickness of the disk.

In conjunction with the magnetic field and gear ratio employed, the particular thickness of disk used in these ergometers fortunately was just such as to produce a nearly constant heat per revolution over the range of speeds commonly used by riders.

(*c*) *Diameter of disk.*—This is probably of small consequence as long as the magnet pole covers only a small part of the surface of the disk. The essential factor is the linear velocity of the metal under the pole.

(*d*) *Linear velocity.*—The expenditure of power increases of course with increasing velocity. On the other hand, equation (6) shows that the counter-flux increases also, tending toward ϕ_0 as a limit. Hence in order to minimize the demagnetizing action for a given amount of power to be absorbed, it is best to use a large magnetic flux and a low speed.

(*e*) *Size and shape of pole-piece.*—The most important quantity is the width, measured in a direction tangential to the disk. The current paths may be regarded as consisting of two parts, one lying in a radial direction under the pole, in which the currents are induced, and the other consisting of the remainder of the disk, in which the circuits are completed. If the polar area is small in comparison with the area of the disk, it follows that the first portion mentioned will contain most of the ohmic resistance of the circuits, since the lines of flow are here very constricted. Hence the resistance may be assumed to be inversely proportional to the width of pole. If now the same total flux be spread out over a pole-face n times as wide, the total current will remain unchanged, while the production of heat and therefore the consumption of energy will be $\frac{1}{n}$ as great. On the other hand, if the magnetic induction remains constant, so that the total flux varies directly as the width of pole, the consumption of energy will also vary in the same manner.

The demagnetizing effect will probably be somewhat less with a broad pole, since the same angular lag will then not bring the demagnetizing system of current loops so directly under the pole. This is the case in the damping disk of watt-hour meters, which in addition to broad pole-faces employ thin disks and low speeds, thereby reducing the demagnetizing factor to a minimum.

Lengthening the pole-face in a radial direction will, by reasoning analogous to the preceding, cause a proportionate increase in the expenditure of energy if the flux density is kept constant, and a decrease in the same ratio if the total flux is constant.

(*f*) *Intensity of magnetic field.*—The consumption of energy varies as the square of the flux density. The percentage of demagnetization from the eddy currents is a constant for the same speed, independent of the field intensity. This explains why the maxima of the calibration curves in figs. 8 and 14 all occur at practically the same speed, whatever the current in the electro-magnet.

(*g*) *Reluctance of the magnetic circuit.*—To insure a "stiff" field, resisting the demagnetizing action of the eddy currents, it would be advantageous to use a magnetic circuit of relatively large reluctance and large magnetomotive force, with strongly saturated poles. Crowding of the flux in the neighborhood of the trailing edge of the pole could be reduced by widening the air-gap on that side of the magnet, or by using split pole-pieces, like those in the Lundell generators. By inserting a variable air-gap in the magnetic circuit, the maximum of the calibration curve could probably be shifted to the right or left.

(*h*) *Location of magnet poles.*—These should be far enough from the outer edge of the disk to minimize magnetic leakage around the edge. The entire magnet should be shaped in such a way as to reduce the leakage, especially in the neighborhood of the poles. This requirement is met, for example, in the permanent magnets of watt-hour meters. It is true that our calibration curves (fig. 13) do not show any less evidence of demagnetization when the poles are pushed 2 cm. nearer to the center of the disk, but this is because there was still considerable opportunity for magnetic leakage, owing to the construction of the magnet.

Thus on the whole it will be seen that, for maximum expenditure of energy, it is advantageous to use small magnet poles, while to minimize the magnetic reaction the poles should be broad. The best compromise between these opposing factors can only be reached by experiment. In any case, the magnetic field should be as intense as possible.

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