THERMAL STRESSES IN CHILLED IRON CAR WHEELS

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ABSTRACT

A method is described for testing car wheels in the laboratory under conditions approximating those encountered by heavy brake application in descending long, mountainous grades. The wheels were heated by passing an electric current through a band of iron encircling the wheel. The resulting stresses were calculated from strain-gage measurements after correcting for thermal expansion. Twenty-eight wheels of varying weights and design from three manufacturers were tested in this manner, of which sixteen failed by cracking in the plate. The maximum stresses developed are very close to the tensile strength of the cast iron and occur in a radial direction near the junction of the double plates in the M. C. B. or Washburn type of wheel. In the arch-plate type the maximum stress is somewhat nearer the hub. Data are also given regarding the properties of the wheels tested.

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I. INTRODUCTION

For over half a century most of the freight cars in use in this country have been equipped with chilled-iron car wheels. The process of manufacturing does not differ fundamentally from that of 50 years ago. Along with improvements in the process of manufacture there have been redistributions of the metal and changes

in design. Perhaps the chief factor toward enabling the chilled-iron wheel to meet operating conditions was the adoption of standard designs. As a result the percentage of failures when considering the number of wheels in service is less to-day than it was before the adoption of the standards and has been steadily growing less while operating conditions have been growing more severe.

Some slight variations exist in the making of wheels by different manufacturers. A brief description of the method of making a chilled-iron wheel follows. The materials charged into the cupola consist of scrap wheels, pig iron, and special alloys, in which the proportions are varied to produce a metal which will have satisfactory chilling qualities and sufficient strength to satisfy the service requirements. After tapping the iron from the cupola it is cast directly into wheels. The iron for the tread of the wheel is poured against iron chillers, while the remainder of the mold is made up of sand. This method of molding produces white or chilled iron, which is extremely hard and capable of resisting both wear and deformation in the tread, while the remainder of the wheel is composed of soft and easily machined gray cast iron. After casting, the wheels are left in the molds 15 to 60 minutes, depending on the weight of the wheel. The lighter wheels remain in the mold the minimum and the heavier ones for the maximum length of time. At the time of stripping the mold the interior parts of the wheel are at a temperature of approximately 925° C (1697° F) while the surface is about 700° C (1292° F) to 760° C (1400° F).

The method of molding, whereby a portion of the metal is poured against a chiller, results in the metal being solidified at different times at various positions within the wheel. For instance, the metal poured against the chiller sets very quickly after contact with the chiller, while the metal poured against the sand parts of the mold take a longer time to solidify. As a result the wheels cast in this way contain internal strains and stresses when taken from the mold. In order to reduce or eliminate the internal stress, the wheels after taken from the molds (at temperatures as indicated above) are placed in deep circular pits which will accommodate 10 to 20 wheels. After placing the wheels in the pits the pits are covered and sealed and the wheels left therein from two to five days. By this process, called "annealing" or "pitting," the inequalities in temperatures of the wheel are removed, as are also a

very considerable portion of the internal stresses. The temperature of the wheels upon removal from the pits is from 90 to 315° C (194 to 599° F). After being taken from the pits the wheels are placed in a room in close formation and allowed to cool slowly to room temperature. These rooms are generally inclosed to prevent undue air circulation. To illustrate the effect of annealing, it may be stated that a wheel if allowed to cool in air after removal from the mold will most certainly crack on account of internal stresses, whereas a wheel after being properly annealed will not crack from the internal stresses still present (if any), but its internal structure has been so modified that it will withstand the stresses produced through static load, flange pressure, brake application, impact, etc., as found in service. The operation of annealing is an important one and is a large factor in the manufacture of good wheels.

After the wheels are cooled to room temperature they are cleaned by sand blast and then inspected to see if they satisfy the specifications[1] of the buyer. After passing inspection the hubs are bored, the wheels then mounted on axles, and they are then ready to be placed in service.

Chilled-iron wheels have given general satisfaction, even under the present existing conditions of greater speeds and increased stresses due to the use of heavier wheel loads. With the advent of more severe operating conditions there are frequently cases of improper usage in which the car wheels are subjected to conditions much more severe than the service for which they are designed. Through such conditions it is found that occasional failures of chilled-iron wheels occur at the foot of long, steep grades as found in mountainous regions. This particular type of failure is caused by prolonged brake application at high speed and the absence of cooling stations. The effect of long-continued application of the brakes is to heat the tread of the wheel to high temperatures, while the central portion or hub of the wheel remains relatively cool. At points intermediate between the tread and hub the temperature decreases from that of the tread to that of the hub. The rate of decrease, in general, is not uniform and varies at different positions within a wheel. These variations in temperature as caused by brake application induce stress and strain of varying amount within the wheel.

[1] The specifications generally are those as determined by the American Railway Association (mechanical division).

The magnitude of these stresses and strains depends on the rate of heating the tread of the wheel, which in turn is dependent on the brake-shoe pressure, speed of train, kind of shoe, and time applied. When the difference in temperature between the tread and hub becomes sufficiently large, the wheels will crack and occasionally break in parts, with the possibility of derailing the car and wrecking the train. One of the large railroad systems found that in a period of seven months approximately one-fifth of their wheel failures were due to the effects of brake application. As stated above, this type of wheel failure usually occurs through improper usage, and investigation generally reveals either excessive speed with brake heavily applied when descending long grades, improperly maintained braking equipment, whereby one car does more than its share in retarding the train, or the absence of cooling stations, whereby the train may be stopped and the temperatures allowed to equalize. Although the number of failures of chilled-iron car wheels is relatively small, yet they are of sufficient importance to warrant investigating the strains and stresses that are developed under various operating conditions with a view toward improving the design and harmonizing operating conditions with design. For these reasons it was decided after consultation with representatives of the Association of Manufacturers of Chilled-Iron Car Wheels to conduct at the Bureau of Standards an investigation of the thermal stresses in chilled-iron car wheels.

Innumerable problems present themselves in connection with the subject of strain or stress due to brake application; as, for instance, the effect of speed and shoe pressure and length of brake application in producing thermal strain. Accordingly, this investigation has been restricted to the problem of determining the manner in which the thermal stresses build up in wheels and chiefly to determine the relative ability of the various weights of chilled-iron wheels to withstand the effects produced by temperature gradient within the wheel.

II. GENERAL PLAN OF INVESTIGATION

1. DISPOSITION OF WHEELS

Fifty wheels were used in this investigation, and in order to make the tests general the wheels were furnished by three different manufacturers, designated A, B, and C, instead of by name. Each manufacturer was requested to supply four wheels of each

weight or type which he wished to submit. One of these was used for drop and one for thermal tests (American Railway Association Specifications) at the works of the manufacturer and the remaining two wheels for special Bureau thermal stress tests. The drop and thermal tests made at the foundries were of the usual type required by current specifications for chilled-iron car wheels.[2] Manufacturer A cast wheels for the special Bureau of Standards tests only, but the other manufacturers provided wheels for all tests.

2. DESIGNS AND WEIGHTS OF WHEELS TESTED

Three types of wheels were tested in this investigation, namely, the Washburn, arch-plate, and single-plate types. A cross sectional drawing of the Washburn, commonly called the M. C. B. type, is shown in Fig. 1. In Figs. 2 and 12 are shown, respectively, the arch-plate and single-plate types. The M. C. B. was the standard shape adopted by the Master Car Builders' Association in 1909, and although many of this type are still in service it has been replaced by and all renewals are of the arch-plate type. The chief difference between the two types is in the cross section, as will be apparent from Figs. 1 and 2. The present M. C. B. standard wheels are of the arch-plate design and weigh 650, 700, 750, and 850 pounds for cars of 30, 40, 50, and 70 tons, respectively. The single-plate type (Fig. 12) is a special experimental design

[2] DROP TEST.—The wheels shall conform to the following drop-test requirements: The test wheel shall be so placed on the three supports, with flange turned downward, that the tup will strike centrally on the hub. When tested in accordance with the following conditions, the wheel shall stand the following specific number of blows:

Weight of wheel in pounds	Weight of tup in pounds	Height of drop in feet	Number of blows	Weight of wheel in pounds	Weight of tup in pounds	Height of drop in feet	Number of blows
625	200	9	10	725	200	12	12
700	200	10	12	850	200	15	12

DROP-TEST MACHINE.—The three supports shall not be more than 5 inches wide. The anvil shall be supported on rubble masonry at least 2 feet deep and shall weigh not less than 1700 pounds. The striking face of the tup shall be 8 inches in diameter and be flat.

THERMAL TEST.—Should the test wheel stand the given number of blows without breaking into two or more pieces, the inspector will then subject the other wheel to the following test:

(*a*) *Preparation.*—The wheel shall be laid with the flange downward in the sand and a channelway 1½ inches wide and 4 inches deep must be molded with green sand around the wheel. The clean tread of the wheel must form one side of the channelway, and the clean flange must form as much of the bottom as its width will cover.

(*b*) *Test.*—The above-described channel must be filled with molten cast iron, which shall be hot enough when poured so that the ring which is formed when the metal is cold shall be solid or free from wrinkles or layers. The time when pouring ceases must be noted, and two minutes later an examination of the wheel must be made. If the wheel is found broken in pieces, or if any cracks in the plate extend through or into the rim, all wheels of the same tape size as the wheel broken will be rejected.

and is not at present used by any railroad. For purposes of convenience the wheels were given serial numbers 1 to 50, inclusive. Wheels 1 to 28, inclusive, were tested at the Bureau of Standards and are described in Table 1, while wheels 29 to 50, inclusive, were tested at the place of manufacture. Wheels 29 to 39, inclusive, were subjected to drop test (Table 2), and 40 to 50, inclusive, were used for the ordinary thermal test (Table 3).

Manufacturer A furnished three types of wheel, B supplied four, and C furnished seven different types.

TABLE 1.—Description of Wheels Tested at Bureau of Standards

Type	Wheel number	Manufacturer	Weight	Tape size [a]	For drawing see Figure—
			Pounds		
M. C. B.[b]	1	A	625	.....	1
Do	2	A	625	.....	1
Do	3	A	700	.....	2
Do	4	A	700	.....	2
Do	5	A	725	.....	3
Do	6	A	725	.....	3
Arch plate	7	B	625	2	4
Do	8	B	625	2	4
Do	9	B	700	2	5
Do	10	B	700	2	5
Do	11	B	775	3	6
Do	12	B	775	3	6
Do	13	B	850	3	7
Do	14	B	850	3	7
M. C. B	15	C	625	2	8
Do	16	C	625	2	8
Arch plate	17	C	650	2	9
Do	18	C	650	3	9
M. C. B	19	C	700	3	10
Do	20	C	700	3	10
Do	21	C	725	4	11
Do	22	C	725	4	11
Single plate	23	C	750	4	12
Do	24	C	750	4	12
Arch plate	25	C	775	4	13
Do	26	C	775	4	13
Do	27	C	850	5	14
Do	28	C	850	4	14

[a] No tape-size measurements were furnished by foundry A.
[b] Present standard wheels adopted by Master Car Builders' Association are 650, 700, 750, and 850 pound weights of arch-plate type.

TABLE 2.—Results of Drop Tests Made by Manufacturers [a]

Type	Wheel number	Manufacturer	Weight	Tape size	Average depth of chill	Result of test
			Pounds		Inches	
Arch plate.....	29	B	625	2	1 3/16	Satisfactory; at the sixth blow a crack developed in the backplate; the front plate cracked at the twelfth blow; the wheel cracked in two pieces at the fourteenth blow.
Do.....	30	B	700	3	5/8–3/4	Satisfactory; a slight crack was apparent in backplate on twenty-eighth blow; the wheel cracked through the tread on the thirty-second blow, and the wheel broke into two pieces on the sixty-sixth blow.
Do.....	31	B	775	3	5/8–3/4	Satisfactory; at the sixteenth blow a slight crack developed in the backplate, and at the twenty-first blow the cracks extended to the tread; at the twenty-ninth blow the wheel broke in two pieces.
Do.....	32	B	850	3	5/8–3/4	Satisfactory; at the eighteenth blow the wheel cracked through the tread; it broke into three pieces at the forty-sixth blow.
M. C. B.....	33	C	625	x	1	Satisfactory; twenty-fifth blow, no break.
Arch plate.....	34	C	650	2	3/4	Do.
M. C. B.....	35	C	700	3	1/2	Do.
Do.....	36	C	725	4	3/8	Do.
Single plate.....	37	C	750	4	3/8	Satisfactory; broke at twenty-first blow.
Arch plate.....	38	C	775	4	1/2	Satisfactory; twenty-fifth blow, no break.
Do.....	39	C	850	4	9/16	Do.

[a] No drop tests were made of wheels furnished by manufacturer A.

TABLE 3.—Results of Thermal Tests Made by Manufacturers [a]

Type	Wheel number	Manufacturer	Weight	Tape size	Average depth of chill	Result of test
			Pounds		Inches	
Arch plate.....	40	B	625	3	1 3/16	Satisfactory; no break in 3½ minutes.
Do.....	41	B	700	3	5/8–3/4	Satisfactory; no break in 4 minutes.
Do.....	42	B	775	2	5/8–3/4	Do.
Do.....	43	B	850	4	5/8–3/4	Do.
M. C. B.....	44	C	625	2	1/2	Satisfactory; no break in 5 minutes.
Arch plate.....	45	C	650	x	9/16	Do.
M. C. B.....	46	C	700	3	1/2	Satisfactory; no crack.
Do.....	47	C	725	3	7/16	Do.
Single plate.....	48	C	750	3	1/2	Do.
Arch plate.....	49	C	775	4	3/8	Do.
Do.....	50	C	850	3	9/16	Do.

[a] No thermal tests were made of wheels furnished by manufacturer A.

III. TESTS AT PLACE OF MANUFACTURE

The tests at foundry B were made in the presence of a Bureau representative, while the tests at foundry C were made in the presence of the foundry engineer. No tests were made at foundry A, as stated previously.

1. DROP TESTS

The results of the drop tests, together with the tape size and depth of chill, are shown in Table 2. By comparison with the requirements of the drop test as given in the car-wheel specifica-

tions [3] it will be noted that all the wheels—namely, four wheels from manufacturer B and the seven wheels from foundry C—gave satisfactory results in the test. The weakest wheel of those tested was the 625-pound wheel furnished by manufacturer B. This maker stated that all 16 wheels furnished by him for this investigation were made from the same heat, with the object of giving comparative results by reducing the number of variables. He predicted before the tests were made that the light wheels would not be as satisfactory as the heavier ones, as it is his ordinary practice to make the lighter-weight wheels of slightly higher silicon content than the heavier wheels.

The drop tests at foundry B were carried to destruction; that is, until the wheel broke into two or more pieces. At foundry C, however, the tests were discontinued at the twenty-fifth blow.

2. THERMAL TESTS

Upon examination of the results of the thermal tests in Table 3 and by comparison with the specification it will be seen that all of the wheels satisfactorily met the requirements. As in the case of the drop tests, the 625-pound wheel from foundry B was the weakest wheel. The tape size and depth of chill of these wheels are also shown in Table 3.

IV. TESTS AT BUREAU OF STANDARDS

The 28 chilled-iron car wheels sent to the Bureau were subjected to a special thermal stress test approximating severe service conditions, yet so conducted as readily to permit the taking of the necessary strain and temperature measurements.

1. METHOD OF PROCEDURE FOR THERMAL STRESS TESTS

In the special thermal stress tests the wheel was mounted on a hollow water-cooled 6-inch axle. The axle in turn rested upon cast-iron and concrete supports, such that the bottom of the wheel was 2 feet 8 inches above the floor. A soft-steel resistor 3½ inches in width and one-fourth inch in thickness was placed on the tread of the wheel, but insulated from it by a thin sheet of perforated asbestos, and an alternating current of 1000 to 1500 amperes at 15 to 30 volts from a 30-kva transformer was passed through the resistor. As the wheel was in an upright position and remained stationary throughout the test, it was readily possible to take such observations as necessary. Fig. 15 shows the

[3] See footnote 2.

arrangement of this apparatus. It was found possible to bring the resistor itself to a red heat within 5 to 10 minutes. Undue radiation of heat into the air was prevented by the use of asbestos covering. The tread of the wheel attained a maximum temperature of approximately 380° C (716° F) in each experimental run.

In order to interpret the results of these tests, it was necessary to determine satisfactorily the distribution of temperature in the wheel from tread to hub. Copper-constantan thermocouples of No. 30 B. and S. gage wire were used—seven couples along a vertical radius at approximately 2-inch intervals and seven others similarly located along the horizontal radius. Readings were taken along both radii for the purpose of obtaining duplicate results. Two other thermocouples were inserted into the treads of the wheel. Thus, four couples, one at the gap in the resistor, were placed at equidistant points in the tread of the wheel and assurance given that uniformity of tread temperature was attained. The 16 copper-constantan thermocouples can be seen in Fig. 15, extending from the wheel to overhead supports and then down to the potentiometer on the transformer table.

A 2-inch Berry strain gage was used for measuring the deformation, six sets of readings being taken at 1-inch intervals on both the vertical and horizontal radii. It will be observed that these readings were taken over a considerable area, this being the only manner of satisfactorily determining the location of the point of maximum stress. A better understanding of the location of the points at which strain gage and thermocouple readings were taken can be obtained from Fig. 16.

It was only necessary to take a survey of the stresses on the plate side of the wheel (outside as mounted on axle), since preliminary measurements had shown that the stresses on the bracket side of the wheel were of a compressive nature and of relatively small magnitude.

Identical rates of power input were maintained for each test in order to obtain comparative results. It was necessary to increase the power input near the end of the test to attain the desired tread temperature in a comparatively short time.

The rate of heat input in these tests was considerably more severe than that found in normal operating service. Table 4 shows the schedule of power supplied to the resistor for all of the tests. It does not, however, indicate the exact amount of work performed on the wheel, as a portion of the heat input is lost through radiation.

TABLE 4.—Power and Energy Supplied to Resistor

Time from start (minutes)	Kilowatts	Total kilowatt-hours	Million foot-pounds	Time from start (minutes)	Kilowatts	Total kilowatt-hours	Million foot-pounds
10	8.7	1.45	3.85	70	16.8	17.05	45.27
20	15.0	3.95	10.49	80	17.4	19.95	52.97
30	15.0	6.45	17.12	90	18.0	22.95	60.93
40	15.0	8.95	23.76	100	18.0	25.95	68.90
50	15.6	11.55	30.67	110	18.0	28.95	76.86
60	16.2	14.25	37.83	120	18.0	31.95	84.83

From the above table it will be noted that the power input was not uniformly applied. The amount applied per minute during the different periods of the test was as follows:

	Foot-pounds
First half hour	570 000
Second half hour	690 000
Third half hour	770 000
Fourth half hour	797 000

Table No. 5 gives an approximate comparison between the work performed on the test wheels and the energy required to hold a train at a constant speed on descending grade. This table shows the brake work per wheel in millions of foot-pounds per mile for cars of various capacities and grades up to 4 per cent.

TABLE 5.[a]—Brake Work Per Wheel Per Mile (in million foot-pounds per mile[b]) for Constant Velocity on Various Grades for Various Car Capacities and Wheel Loads

Car capacity	60 000	80 000	100 000	120 000	140 000	160 000	180 000	200 000
Maximum wheel load (tons)	6	8	10	11.25	12.5	14.75	15	16.25
Grade (per cent):								
1	0.38	0.51	0.63	0.71	0.79	0.87	0.95	1.03
2	1.01	1.35	1.69	1.90	2.11	2.32	2.53	2.75
3	1.65	2.20	2.75	3.09	3.43	3.78	4.12	4.46
4	2.28	3.04	3.80	4.28	4.75	5.23	5.70	6.18

[a] This table is, in part, due to F. K. Vial, consulting engineer, Association of Manufacturers of Chilled Car Wheels.

[b] An allowance of 8 pounds per ton has been made for train resistance.

It is apparent from the above table that 630 000 foot-pounds of energy are destroyed per minute by the brake on each wheel of a 100 000-pound car in maintaining a constant velocity under the following operating conditions: Descending a 1 per cent grade at 1 mile per minute, or 60 miles per hour; 2 per cent grade at 1 mile per 2.68 minutes, or 22 miles per hour; 3 per cent grade at

1 mile per 4.37 minutes, or 13 miles per hour; 4 per cent grade at 1 mile per 6.03 minutes, or 10 miles per hour.

However, the actual test conditions were more severe than these figures indicate on account of the difference in the heat dissipation in the two cases. In these tests the resistor completely encircled the wheel and was thermally insulated to drive the heat into the wheel. Under these conditions a larger percentage of the energy supplied to the resistor entered the wheel than would be the case when the same wheel is subjected to brake application, as occurs in service, due to the fact that part of the energy destroyed by friction between the shoe and wheel goes to heating the brake shoe, and thence by radiation to the air, and, further, the shoe only bears on a small part of the circumference, thus allowing the heat in the uncovered part of the tread to radiate directly into the air instead of entering the wheel.

In the Bureau tests the treads of the lightest wheels reached a temperature of 380° C (716° F) in about 75 minutes, while it required from 100 to 105 minutes for the heaviest wheels to reach the same temperature. Readings were taken of the temperature, strain, and power input at regular intervals, a strain gage reading of the cold wheel being also taken before the test was started. When the desired tread temperature was reached, the power was shut off and the asbestos covering on the resistor was removed to permit more rapid dissipation of the heat. Temperature and strain gage readings were also taken during cooling and after the wheel was at room temperature.

The elongation as determined by the strain gage is attributable to two causes: (1) An elongation due to the thermal expansion of metal, and (2) elongation caused by the strain due to the temperature gradient from tread to hub of the wheel. By knowing the coefficient of expansion and the temperature rise it was possible to calculate the thermal expansion. By deducting the elongation due to this expansion from the total elongation the elongation due to stress alone was determined. The relation between stress and strain on samples actually taken from the wheels made it possible to convert the strain readings into stress values.

2. AUXILIARY TESTS

It was necessary to make a number of auxiliary tests to supplement and interpret the results of the special thermal tests made at the Bureau of Standards. These tests consisted of determina-

tion of the coefficient of expansion, stress-strain curves, cnemical analyses, and metallographic examination.

(*a*) LINEAR THERMAL EXPANSION.—The coefficient of expansion from the range 20 to 310° C was determined on specimens cut from one of the wheels furnished by each of the three manufacturers. The samples were 31 centimeters in length and 1 centimeter square.[4]

The iron from A showed a unit expansion represented by the equation $\frac{\Delta l}{l} = 10.47 \times 10^{-6}t + 7.51 \times 10^{-9}t^2$, where t is the temperature rise in degrees centigrade and will apply for temperatures between 0 and 300° C. For manufacturers B and C the equations are, respectively, $\frac{\Delta l}{l} = 10.76 \times 10^{-6}t + 6.86 \times 10^{-9}t^2$ and $\frac{\Delta l}{l} = 10.62 \times 10^{-6}t + 7.34 \times 10^{-9}t^2$. The above equations were obtained by the method of least squares, and by the same manner a composite equation was computed which would apply to all three products. The composite equation is $\frac{\Delta l}{l} = 10.60 \times 10^{-6}t + 7.30 \times 10^{-9}t^2$. Although the coefficients in these equations appear somewhat different, the table below shows that the unit expansion as calculated from the separate equations agrees well within the precision required, as shown later, and the use of the composite equation is justified.

TABLE 6.—Comparison of Expansion Equations

Temperature rise (° C)	Total expansion, in inches per inch calculated by equations, for iron from manufacturer—			
	A	B	C	Composite
50	0.00054	0.00056	0.00055	0.00055
100	.00112	.00115	.00114	.00113
150	.00174	.00177	.00176	.00175
200	.00239	.00243	.00242	.00241
250	.00309	.00312	.00311	.00311
300	.00382	.00385	.00385	.00384

(*b*) MECHANICAL PROPERTIES.[5]—The mechanical properties of the material were determined on specimens of 8-inch gage length taken from the plates of the wheels which had not cracked after the thermal stress tests had been completed. The samples were cut from a chord of the wheel or in a direction principally normal

[4] The method used for the determination of expansion is described in B. S. Sci. Papers, No. 352, p. 390. These determinations were made in the expansion laboratory under the direction of Dr. W. H. Souder.

[5] These tests were made in the engineering materials section under the direction of H. L. Whittemore.

to the radial stresses developed by the thermal tests. Preliminary runs on other wheels in which strain measurements were also taken circumferentially as well as radially had shown the circumferential stresses to be practically negligible, so that specimens taken from the wheel as above described can be considered as not having been previously strained, and the stress-strain data obtained in the tensile test would not be affected by heatings of the wheel. Preliminary data were also obtained on the tensile properties of cast iron at temperatures up to 350° C which gave results similar to those at room temperature.

Several specimens were taken from two wheels of each manufacturer in order to obtain a fair average of the wheels from each foundry. For the purpose of computing the stress values in the heated wheels the modulus of elasticity is required, but since cast iron has no such constant modulus when tested in tension the stress-strain curve was determined up to as near rupture as possible and then extrapolated to rupture by the data obtained for the elongation and ultimate strength. Such curves, each the mean of all tests on iron from a given manufacturer, are shown in Fig. 17. A 230 000-pound Emery testing machine and an Ewing extensometer were used in the tests.

TABLE 7.—Average Results of Tensile Tests

Manufacturer	Apparent elastic limit	Ultimate strength	Elongation in 8 inches	Reduction of area	Modulus of elasticity at "zero stress"
	Lbs./in.²	Lbs./in.²	Per cent	Per cent	Lbs./in.²
A	9 600	26 700	0.8	0.3	17 300 000
B	6 300	18 900	.8	.4	15 400 000
C	11 000	27 000	.8	.4	18 400 000

In Table 7 are shown the average results for the tensile tests. Here the modulus of elasticity for "zero stress" is given, this value being the slope of the stress-strain curve at the origin. The "apparent elastic limit" [6] was also determined rather than the proportional limit. The iron from the wheels of manufacturer C showed the highest apparent elastic limit, ultimate strength, and modulus of elasticity, while that from manufacturer A was next, and the B iron gave values considerably lower.

[6] "The apparent elastic limit is the point on the stress-strain diagram of any material in any kind of test at which the rate of deformation is 50 per cent greater than it is at the origin"—Materials of construction, Johnson, 1st ed., p. 19.

(*c*) CHEMICAL COMPOSITION.—The chemical composition of the 28 wheels tested at the Bureau of Standards was determined.[7] The samples were obtained by drilling completely through the plate of the wheel about midway between hub and tread. The results of the analyses are shown in Table 8.

TABLE 8.—Chemical Composition of Wheels Tested at Bureau of Standards

Wheel number	Manufacturer	Carbon			Manganese	Phosphorus	Sulphur	Silicon
		Total	Graphitic	Combined				
		Per cent	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent
1	A	3.33	2.79	0.54	0.61	0.40	0.144	0.59
2	A	3.40	2.75	.65	.57	.41	.137	.58
3	A	3.39	2.82	.57	.57	.39	.140	.62
4	A	3.37	2.73	.64	.57	.40	.141	.62
5	A	3.25	2.81	.44	.55	.38	.138	.61
6	A	3.41	2.64	.77	.52	.40	.140	.59
Average	A	3.36	2.76	.60	.57	.40	.140	.60
Maximum	A	3.41	2.82	.77	.61	.41	.144	.62
Minimum	A	3.25	2.64	.44	.52	.38	.137	.58
7	B	3.36	2.85	.51	.77	.33	.126	.56
8	B	3.69	3.00	.69	.74	.32	.113	.60
9	B	3.66	3.01	.65	.74	.33	.125	.57
10	B	3.57	3.01	.56	.73	.33	.110	.55
11	B	3.59	2.94	.65	.73	.33	.109	.54
12	B	3.70	3.01	.69	.75	.35	.114	.65
13	B	3.46	3.06	.40	.75	.33	.116	.59
14	B	3.41	3.10	.31	.72	.34	.118	.58
Average	B	3.56	3.00	.56	.74	.33	.116	.58
Maximum	B	3.70	3.06	.69	.77	.34	.126	.65
Minimum	B	3.36	2.85	.31	.72	.32	.109	.54
15	C	3.27	2.56	.71	.65	.31	.176	.62
16	C	3.26	2.56	.70	.64	.30	.172	.80
17	C	3.25	2.56	.69	.60	.31	.185	.60
18	C	3.14	2.63	.51	.63	.31	.181	.56
19	C	3.20	2.70	.50	.80	.30	.158	.57
20	C	3.18	2.56	.62	.79	.29	.160	.64
21	C	3.26	2.60	.66	.77	.30	.167	.60
22	C	3.29	2.62	.67	.74	.29	.172	.87
23	C	3.23	2.79	.44	.71	.28	.164	.67
24	C	3.29	2.62	.67	.67	.28	.166	.80
25	C	3.19	2.60	.59	.64	.28	.169	.67
26	C	3.27	2.80	.47	.65	.28	.172	.70
27	C	3.22	2.49	.73	.68	.28	.185	.80
28	C	3.14	2.54	.60	.76	.28	.173	.65
Average	C	3.23	2.62	.61	.70	.29	.172	.68
Maximum	C	3.29	2.80	.73	.80	.31	.185	.87
Minimum	C	3.14	2.49	.44	.60	.28	.158	.56

The ranges of the various elements in the 28 test wheels are as follows:

	Per cent
Total carbon	3.14 –3.70
Graphitic carbon	2.49 –3.06
Combined carbon	0.31 –0.77
Manganese	0.52 –0.77
Silicon	0.54 –0.87
Phosphorus	0.28 –0.41
Sulfur	0.109–0.185

[7] These analyses were made under the direction of H. A. Bright.

Since the wheels which were tested at the place of manufacture were supposed to be representative of the wheels tested at the Bureau of Standards, and since the former passed the requirements of the American Railway Association specifications, it seems safe to say that apparently satisfactory wheels may be made in which the composition covers the ranges given. It may be stated, further, that by proper control of manufacturing conditions, such as molding, pouring, annealing, etc., the ranges given above can no doubt be enlarged upon.

These statements, however, should not be construed to mean that it is necessary to confine the various elements within the above ranges, because chemical composition is only one of the factors that assist in the production of good wheels. Although the chemical composition of the wheels is of interest, it is thought to be undesirable to attempt to correlate so few compositions in terms of the behavior of the wheels in view of the great chemical complexity of car-wheel mixture and on account of varying mechanical properties from apparently similar composition. It would be highly desirable to later secure additional and adequate information on the questions of composition and foundry mixtures particularly with respect to the manganese-sulphur ratio, combined carbon, and phosphorus.

(*d*) METALLOGRAPHIC EXAMINATION.[8]—The three specimens used for micrographic examination were cut from the ends of the bars taken from the wheels for tensile tests, one from each manufacturer. The material was examined as follows: First, the polished but unetched specimen, to show the distribution of graphitic plates and the size and distribution of the inclusions; second, the polished and heat-tinted specimen, to show the distribution and relative amount of phosphide eutectic and also to identify the sulphide inclusions; and, thirdly, the etched specimens, to show the nature of the matrix, which comprises the body of the iron. The micrographs, nine in number, are shown in Figs. 18 to 20, inclusive. A careful examination of these micrographs will show differences in the structure. For instance, the iron from foundry B seems to contain long, thin, intermingling graphite flakes, while the iron from the other two manufacturers contains shorter and thicker flakes. Differences in the amount of sulphides and phosphides from the different foundries are also apparent. For reasons similar to those given under chemical composition no

[8] This examination was made by S. Epstein.

attempt is made to correlate these micrographs with the test results on the wheels.

3. ACCURACY OF STRESS MEASUREMENT

The measured elongation is due to two effects—thermal expansion and stress—and may be represented by the equation $e = \Delta l + \Delta s$. Δl is represented approximately by the formula $\frac{\Delta l}{l} = 10.6t \times 10^{-6}$, where t is the temperature rise. The coefficient of t may have a possible error of one-half per cent, and the temperature measurements are good to 5° C. For a temperature rise of 100° C, then

$$\frac{\Delta l}{l} = \left\{10.6\ (1 \pm 0.005)\right\}\left\{100(1 \pm 0.05)\right\} \times 10^{-6}$$
$$= 1060\ (1 \pm 0.005 \pm 0.05) \times 10^{-6}$$
$$= 0.0011 \pm 0.0001 \text{ inch per inch.}$$

A 2-inch Berry strain gage when rigidly fastened to a test bar will admit of estimations being made to 0.00001 of an inch; but in this work, where the strain gage was held in the hand and constantly changed from various gage marks, it was impossible to estimate as closely as above, and the readings of e may be considered as having a possible error of ± 0.0001 of an inch. Then $(e \pm 0.0001) = (\Delta l \pm 0.0001) + \Delta s$ or Δs will have a probable error ± 0.0002 inch per inch.

By comparison with Fig. 17 it will be seen that this error in strain corresponds to an error in stress of ± 4000 pounds per square inch for low values of stress, but for higher values would be considerably less, or about 400 pounds per square inch. The error in determining the stress-strain curves for the tensile specimens is negligible for small strains in comparison with the strain measurements on the wheels. In the upper region of the curves, however, the error is of about the same magnitude as the wheel-strain error, such that it is a fair assumption that the probable error throughout the major range of the stress measurements is ± 3000 pounds per square inch.

4. RESULTS OF THERMAL STRESS TESTS

(*a*) STRESSES.—It was found in the tests that an unexpectedly large number of the wheels developed cracks in the plates. These cracks were circumferential in nature and were all approximately at the same distance from the center of the wheel, namely, 9

inches. Of the 28 wheels 16, or 57 per cent, developed cracks in the plates. Some of the cracks were barely perceptible to the unaided eye even at the time that the maximum temperature gradient between tread and hub existed and were of very short length, while others developed comparatively early in the test and almost completely encircled the wheel. These larger cracks opened up to about one-sixteenth of an inch and were, of course, readily apparent. In Figs. 21 to 23, inclusive, are given typical examples of the cracked wheels. The cracks themselves were marked with white chalk in order to make their location easily visible in the photographs.

For the 28 wheels which were used for thermal stress tests at the Bureau computations were made which showed the stresses existing in the wheels at each of the strain-gage positions at intervals of 10 minutes on heating and for longer intervals of time during cooling of the wheel. The magnitude of these stresses is shown in Figs. 1 to 14, where they are plotted against their relative positions along the radius of the wheel. These curves indicate the stresses existing in the wheel at the time of failure of the wheel by cracking or in the event the wheel did not crack at the time the maximum temperature gradient existed between tread and hub. The temperature distribution at the same time is also shown in a similar manner. As all the wheels were tested in duplicate, both curves of each design of wheel were plotted together. Thus, in Fig. 1, the stress distribution curves of wheels 1 and 2 are given. The arrows on the drawing show the approximate location of the cracks, if any occurred.

Figs. 1 to 3, inclusive, show the curves of the 6 wheels submitted by manufacturer A. Wheels 3 and 4 developed slight cracks, while the remaining 4 wheels showed no evidence of failure.

Figs. 4 to 7, inclusive, show the curves of the 8 wheels submitted by manufacturer B, numbers 7 to 14, inclusive. The maximum stresses in the wheels submitted by this manufacturer are considerably lower than those in the wheels submitted by either manufacturer A or C. Three of the 8 wheels, numbers 7, 8, and 10, developed cracks in the tests.

The stress curves of wheels 15 to 28, inclusive, furnished by manufacturer C, are shown in Figs. 8 to 14, inclusive. With the exception of Fig. 12, the stress distribution is of the same general character as in the other wheels tested. In the single-plate wheel, as shown in Fig. 12, the stress distribution is decidedly

different than it is in the other types. The single-plate type of wheel is a special experimental design and is not used by any railroad. It was thought that this type of wheel might show greater ability to withstand operating conditions. It is apparent from Fig. 12 that the metal is in compression near the rim on the outside of the wheel. In order to have the stresses in equilibrium, there must necessarily be tensile stresses near the rim on the opposite or inside of the wheel. No measurements were made to determine the stresses on the inside. It will be noticed further from the same figure that the maximum tensile stress occurs on the large radius on the outer face near the hub of the wheel. Although this wheel showed higher strains and hence stresses for a given heat input than the M. C. B. and arch-plate types, yet the distribution is such that when subjected to additional stress-producing factors, such as mounting, static load, and flange pressure, it seems probable that the strain or stress under those conditions would be less than in either the M. C. B. or arch-plate designs. For instance, the compression found near the rim on the outer face through heat application may be increased slightly when the static load is added, but the addition of the flange pressure or side thrust would more than offset this addition, so that the net effect would be a reduction in the strains or stresses found. The tension unquestionably present on the inner face near the rim would similarly be reduced. Further, the magnitude of the tensile strains or stresses found in the hub region would be counteracted by compression resulting from mounting the wheel onto its axle. Both of the wheels of this type withstood the thermal and drop tests as required by the M. C. B. specifications. In view of these facts the results indicate that the single-plate design, although it does not withstand the special thermal test made by the Bureau as well as the M. C. B. and arch-plate types, yet it may possibly be better adapted to service conditions.

The highest maximum stress measured was 28 400 pounds per square inch, while the lowest stress at which failure occurred was 14 000 pounds per square inch. It is possible that the latter wheel, No. 18, had an internal flaw which accelerated the failure. The maximum stresses observed are in nearly all cases very close to the ultimate strength of the cast iron of which the wheel is composed. Thus, for manufacturer C the stresses are in the neighborhood of 26 000 pounds per square inch, and this material

was shown to have a tensile strength of 27 000 pounds per square inch. The wheels from foundry B usually showed stresses around 17 000 pounds per square inch, while the tensile strength was about 19 000 pounds per square inch.

(*b*) TEMPERATURES.—The curves for temperature distribution are all of the same general character, showing the highest temperature at the tread and gradually falling off toward the center. The data from which these curves are plotted are given in Table 9, which gives the temperatures along the vertical axis, as indicated by the thermocouples 1 to 7, inclusive, at the time of failure or maximum temperatures in the event that the wheel did not fail.

TABLE 9.—Temperature Distribution in Wheels Due to Heating Tread

Wheel number	Foundry	Cracked or not	Temperature at failure or maximum for seven radial positions						
			1	2	3	4	5	6	7
			°C	°C	°C	°C	°C	°C	°C
1	A	No	355	310	241	189	155	130	107
2	A	No	348	319	240	189	171	132	104
3	A	Yes	308	242	194	158	136	108	92
4	A	Yes	334	299	247	193	147	135	89
5	A	No	358	314	245	191	153	126	98
6	A	No	355	311	245	193	169	145	117
7	B	Yes	314	297	225	171	155	128	87
8	B	Yes	225	208	164	130	114	85	71
9	B	No	352	323	259	206	173	135	104
10	B	Yes	323	312	251	192	167	134	110
11	B	No	360	325	258	210	183	153	135
12	B	No	352	319	263	227	189	175	145
13	B	No	361	328	263	227	206	185	153
14	B	No	343	319	270	221	179	143	119
15	C	Yes	260	237	176	130	102	77	17
16	C	Yes	215	179	139	107	75	58	44
17	C	Yes	243	207	151	108	79	64	52
18	C	Yes	174	138	95	67	53	42	31
19	C	Yes	250	216	174	165	132	92	69
20	C	Yes	303	.....	211	147	111	85	70
21	C	Yes	310	285	223	175	159	111	96
22	C	Yes	285	242	189	165	129	94	79
23	C	No	386	349	299	228	185	132	121
24	C	Yes	358	337	279	210	171	112	116
25	C	No	356	317	254	208	169	157	128
26	C	Yes	303	268	212	172	161	118	101
27	C	Yes	311	286	221	190	150	128	86
28	C	No	349	302	247	187	159	147	109

A typical curve showing the manner in which the temperatures build up with time at different positions in the wheel is given in Fig. 24 for the 700-pound arch-plate wheel No. 3. Couple No. 1, which was nearest the tread, attained a maximum temperature of 344° C (651° F) after 95 minutes, and couple No. 7, which was nearest the hub, indicated a temperature of 147° C (297° F). This wheel, however, cracked 65 minutes after the start of the test, at which time the temperatures were 279° C (554° F) and

91° C (196° F) for couples Nos. 1 and 7, respectively. It is evident that these temperature gradients were sufficient to develop stresses in the plate of the wheel reaching the ultimate strength of the iron.

TABLE 10.—Condition of Wheels at End of Heating Period or at Time of Cracking

Type of wheel	Wheel number	Approximate circumferential length of crack in degrees	Length of test in minutes	Total energy to resistor in millions of foot-pounds	Temperature of couple No. 1 (nearest tread)		Temperature difference between couples Nos. 1 and 7		Maximum stress in pounds per square inch	
					°C	°F	°C	°F	Estimated amount	In gage line
625-pound M. C. B.	1	None	83	55.0	355	671	248	478	27 600	D
	2	None	86	57.6	348	658	244	471	23 300	I
	15	145	50	30.7	260	500	243	469	25 900	I
	16	340	42	24.9	215	419	171	340	24 700	E
625-pound arch plate	7	190	64	40.8	314	597	227	441	20 200	J
	8	220	49	29.8	225	437	154	309	19 900	D
650-pound arch plate	17	120	43	25.6	243	469	191	376	26 700	J
	18	350	33	19.0	174	345	143	289	14 000	E
700-pound arch plate	3	35	65	41.3	308	586	216	421	23 300	D
	4	75	75	49.0	334	633	245	473	24 500	E
	9	None	95	64.5	352	666	248	478	17 400	D
	10	15	80	53.0	323	613	213	415	17 100	E
	19	130	53	32.9	250	482	181	358	26 000	J
	20	130	68	43.7	303	577	263	505	26 500	E
725-pound M. C. B.	5	None	85	56.7	358	676	260	500	24 800	H
	6	None	87	58.2	355	671	238	460	23 800	C
	21	120	75	49.0	310	590	214	417	26 400	D
	22	210	60	37.8	285	545	206	403	26 900	I
750-pound single plate	23	None	90	60.9	386	727	265	509	26 900	J
	24	10	80	53.0	358	676	242	468	28 400	J
775-pound arch plate	11	None	97	66.1	360	680	225	437	16 800	I
	12	None	104	71.5	352	666	207	405	17 100	J
	25	None	79	52.0	356	673	228	442	23 500	.....
	26	40	79	52.0	303	577	202	396	24 800	I
850-pound arch plate	13	None	112	78.5	361	682	208	406	17 700	I
	14	None	94	63.7	343	649	224	435	18 300	E
	27	10	82	54.4	311	592	225	437	23 400	D
	28	None	97	66.1	349	660	240	464	24 800	D

Table 10 classifies the wheels in the order of the temperature of the tread at the time of failure or at the maximum temperature in case cracking did not occur. There is also given the circular length of the crack in degrees, the time at which this crack occurred, energy supplied to the wheel by the electric heater, and the maximum stress resulting from this energy. It will be noticed that those wheels which failed comparatively early with low values of applied energy had very long cracks, sometimes nearly encircling

the wheel; also, as would be expected, the lighter-weight wheels fail with smaller application of energy than the heavier wheels.

In Table 11 is given the average temperature rise in one hour in the parts of the wheels indicated.

TABLE 11.—Temperature Distribution in Wheels Due to Heating Tread

Wheel weight (pounds)	Temperature gradient at the end of one hour in degrees centigrade for thermocouple positions—							Temperature differences between 1–7
	1	2	3	4	5	6	7	
625	283	254	198	149	125	99	75	208
700	278	244	196	156	126	102	79	199
775	263	232	181	146	119	99	81	182
850	252	225	178	142	112	90	73	179

It would appear from Table 11 that for a given heat input the rate at which the wheel becomes heated is slightly retarded as the weight of the wheel increases. The difference in temperature indicated above decreases at an average rate of 10 degrees for each additional 75 pounds of metal. This shows that the heavier wheels have lesser gradients at the end of a given heating period and suggest also lesser strains and stresses.

(*c*) Relation of Weight to Strain.—To show the relative ability of different weights of the arch-plate type wheel to withstand the effects of temperature gradients, Table 12 was made.

In it are given the unit strains due to internal stress 40 minutes after the start of the tests. The unit strains at that time were averaged as shown for each of the types tested. Then, by using the average unit strain as found in the 625-pound M. C. B. type of wheel as a basis for comparison, the relative average strains at the end of 40 minutes of heating are given in the table. It is evident that the 850-pound M. C. B. (arch plate) was best able, while the 750-pound single plate was least able to withstand the special Bureau thermal test. In the case of the single-plate wheel this does not necessarily indicate that this type would be least satisfactory in service, as was indicated above. By plotting the average unit strain against the weight of wheel (Fig. 26) for the arch-plate pattern the effect of the additional weight becomes apparent. Since only two 625-pound and two 650-pound arch-plate wheels were tested and each of these types were furnished by different foundries, the averages given for them should be given less weight than the remaining three weights, namely, 700,

TABLE 12.—Maximum Strains (in Inches) Recorded After 40 Minutes of Heating

Type of wheel	Wheel numbers	Gage lines	Strains in wheels submitted by manufacturers— A	B	C	Average maximum strain	Relative average strain
625-pound M. C. B.	1, 2, 15, 16	Vertical	0.0030		0.0032	0.0030	100
			.0018		.0038		
		Horizontal	.0021		.0040		
					.0033		
625-pound arch plate	7, 8	Vertical		.0027		.0030	100
				.0029			
		Horizontal		.0035			
				.0031			
650-pound arch plate	17, 18	Vertical			.0028	.0034	113
		Horizontal			.0041		
700-pound arch plate	3, 4, 9, 10, 19, 20	Vertical	.0021	.0024	.0017	.0024	80
			.0025	.0020	.0042		
		Horizontal	.0016	.0023	.0026		
					.0030		
725-pound M. C. B.	5, 6, 21, 22	Vertical	.0023		.0026	.0027	90
			.0018		.0034		
		Horizontal	.0025		.0029		
			.0025		.0034		
750-pound single plate	23, 24	Vertical			.0030	.0035	117
					.0035		
		Horizontal			.0034		
					.0040		
775-pound arch plate	11, 12, 25, 26	Vertical		.0014	.0022	.0020	67
				.0015	.0022		
		Horizontal		.0018	.0026		
				.0018	.0025		
850-pound arch plate	13, 14, 27, 28	Vertical		.0017	.0016	.0018	60
				.0020	.0019		
		Horizontal		.0018			
				.0017	.0020		

775, and 850 pounds. It is felt that the curve as shown gives a fair approximation of the effect of additional metal in withstanding the effect of thermal gradients. Taken from the curve their relative strains are as follows:

Arch plate type	Relative strain
625-pound	100
650-pound	86
700-pound	69
775-pound	57
850-pound	51

The curve indicates further that a certain amount of metal does more good when added to the lighter weight than it does when added to the heavier weight wheels. In addition, it will be noticed that at 850 pounds the curve is rapidly approaching the horizontal. This indicates that if the weight were still further in-

creased a weight would be reached at which additional metal would have little effect toward enabling the wheel to withstand brake application.

V. SUMMARY AND CONCLUSION

A method has been described for electrically heating car wheels in the laboratory which produce effects similar to that encountered through long application of the brakes on heavy grades. Observations have been made of the strains resulting from such heating on wheels of various design and weight from three different manufacturers. The rate of heating was severe enough to crack many of the wheels, and the internal stresses in all cases approximated the ultimate tensile strength as shown by test specimens. The total number of wheels tested is too small to draw any definite conclusions, but the results seem to point to the following generalities, which should be confirmed by a greater number of tests:

1. The method used was such that the heat input to the wheel was much greater than that which would enter a wheel doing its proportionate part in taking any car down any grade found on trunk-line railroads at a reasonable speed.

2. The rate of heating in the special thermal test as conducted by the Bureau were more severe than actual service conditions, so that wheels which stand up under the foregoing tests will not fail under the extreme conditions of a long and heavy application of the brakes. These special thermal tests, however, are not as severe as the thermal test required by the M. C. B. specifications, in which for rejection a wheel must crack through the rim in two minutes. In the tests here reported no wheels cracked through the rims, although a large number developed cracks in the plates.

3. The maximum stresses developed are very close to the tensile strength of the cast iron and are some function of the strength of the iron.

4. Preliminary tests (not recorded herein) show that the stress in a tangential direction on the outer face and also the stress in both the radial and tangential direction on the bracket side of the wheel are relatively small when compared to those in a radial direction on the outer face of the wheel.

5. The maximum tensile stresses occur in a radial direction near the junction of the double plates in the M. C. B. or Washburn type of wheel. In the arch-plate type the maximum stress is somewhat nearer the hub. This seems a desirable condition in

that it then lies in the region where it is counteracted by the strains due to forcing the wheel onto its axle.

6. The tests also lead one to believe that the operating conditions to which wheels are subjected may be as important a factor in the safety of the wheel as are the problems arising in their manufacture.

7. By proper distribution of metal in the single-plate type of wheel there would appear to be a possibility of securing a wheel more capable of meeting service requirements.

8. With identical rates of heat input the heavier-weight wheels withstand the effect of tread heating with less strain than the lighter wheels. It seems conceivable, however, that a wheel may be made where increased weight will not aid the wheel to withstand brake application. Such weight, however, is beyond the weights in use to-day.

It is expected to publish shortly the results of similar tests on typical steel wheels, and it is considered desirable to continue work on chilled-iron wheels to answer some of the outstanding questions as to their behavior as related to design, composition, and manufacture.

The authors desire to acknowledge the assistance given by several members of the Bureau throughout the investigation. The method used was largely suggested by Dr. P. D. Merica, who had immediate charge of the investigation at its inception. He was succeeded by C. H. Strand, under whose direction many of the data were obtained. A. S. McCabe, A. L. Hamilton, and E. Q. Martin assisted in making the necessary measurements on the wheels; G. W. Quick and S. J. Rosenberg aided in the calculations. We are also glad to record the cooperation of those manufacturers who so generously furnished the wheels and otherwise gave assistance, and especially F. K. Vial, consulting engineer of the Association of Manufacturers of Chilled Car Wheels.

WASHINGTON, February 21, 1921.

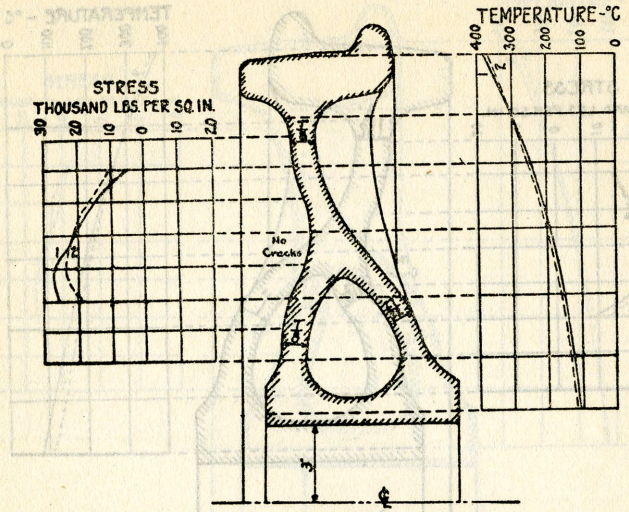

FIG. 1.—*Cross section and stress and temperature gradients for wheels 1 and 2—625-pound M. C. B. type*

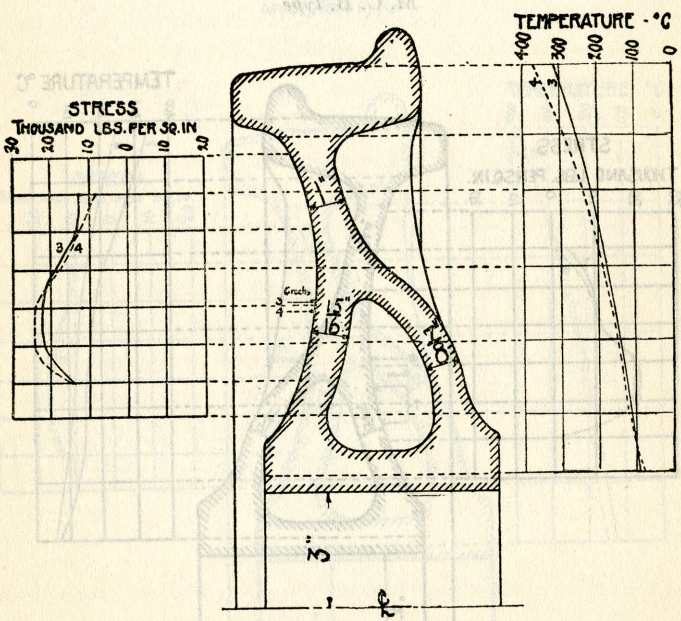

FIG. 2.—*Cross section and stress and temperature gradients for wheels 3 and 4—700-pound arch-plate type*

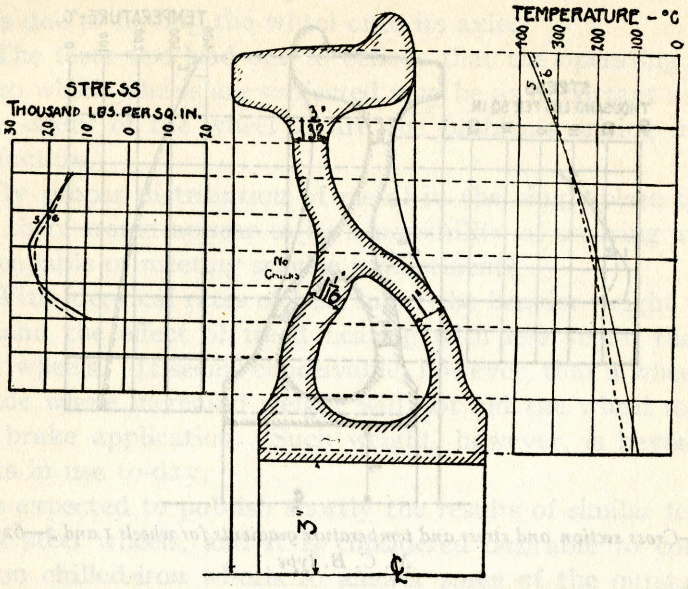

FIG. 3.—*Cross section and stress and temperature gradients for wheels 5 and 6—725-pound M. C. B. type*

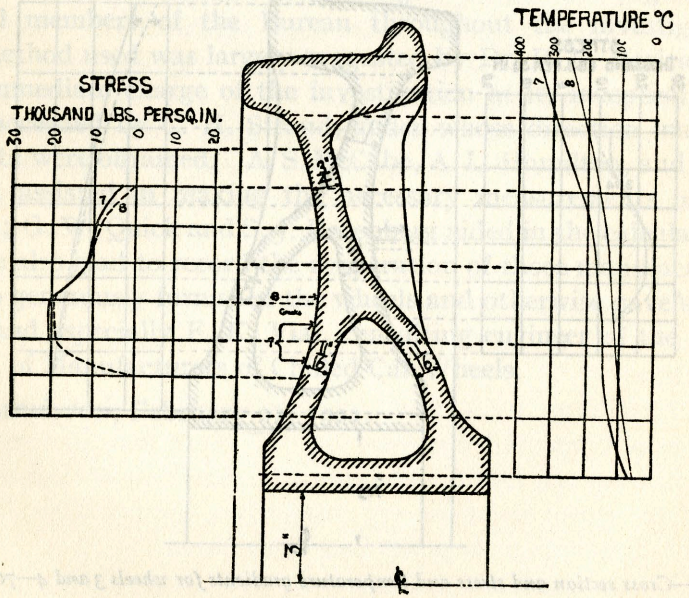

FIG. 4.—*Cross section and stress and temperature gradients for wheels 7 and 8—625-pound arch-plate type*

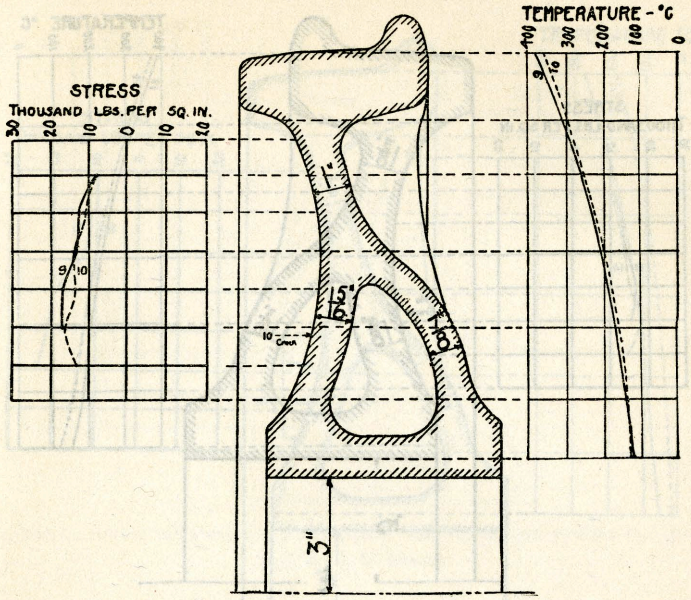

FIG. 5.—*Cross section and stress and temperature gradients for wheels 9 and 10—700-pound arch-plate type*

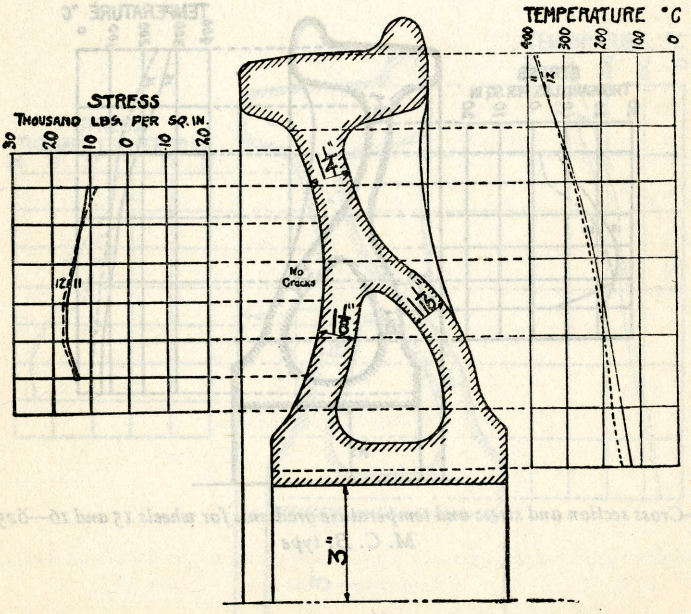

FIG. 6.—*Cross section and stress and temperature gradients for wheels 11 and 12—775-pound arch-plate type*

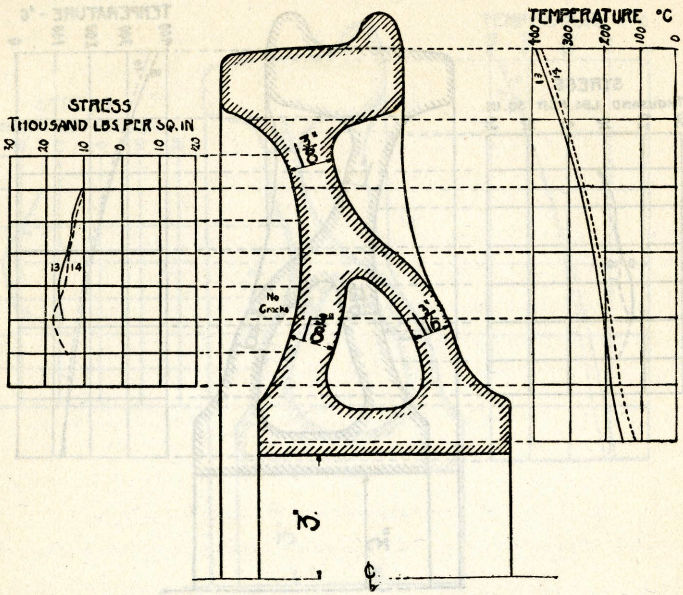

FIG. 7.—*Cross section and stress and temperature gradients for wheels 13 and 14—850-pound arch-plate type*

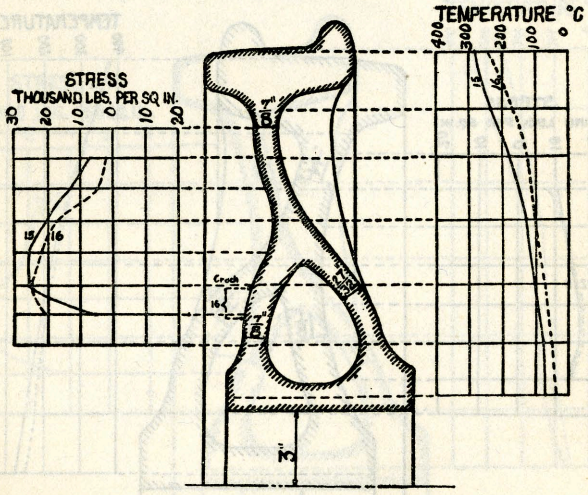

FIG. 8.—*Cross section and stress and temperature gradients for wheels 15 and 16—625-pound M. C. B. type*

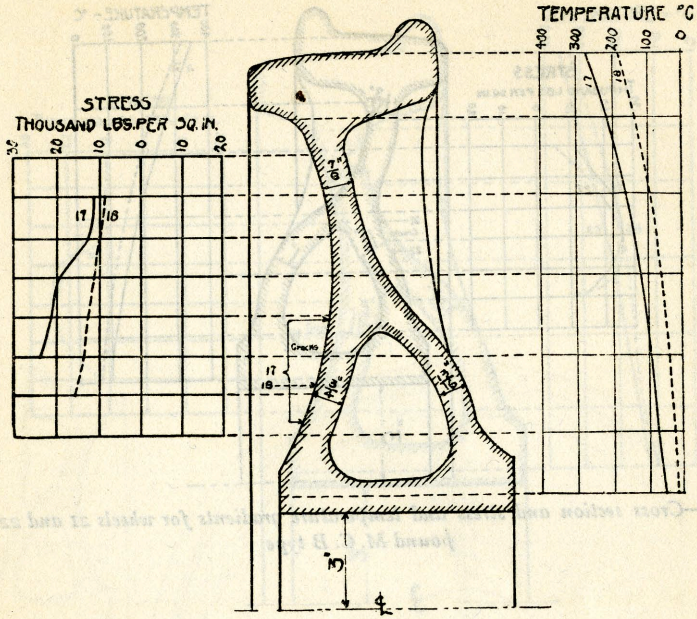

FIG. 9.—*Cross section and stress and temperature gradients for wheels 17 and 18—650-pound arch-plate type*

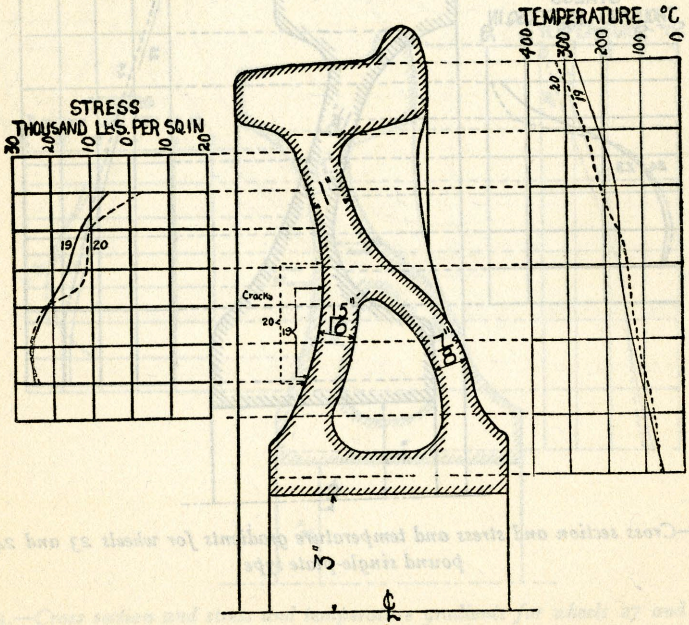

FIG. 10.—*Cross section and stress and temperature gradients for wheels 19 and 20—700-pound arch-plate type.*

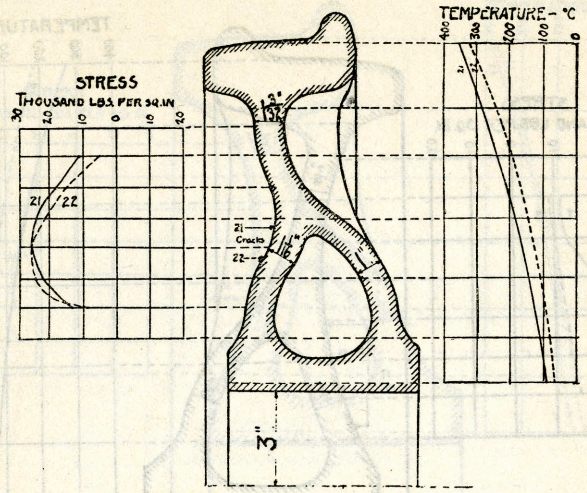

FIG. 11.—*Cross section and stress and temperature gradients for wheels 21 and 22—725-pound M. C. B type*

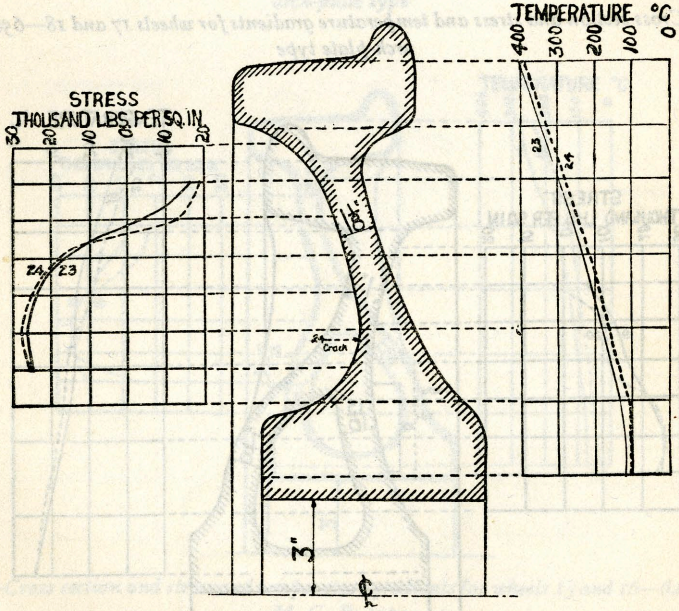

FIG. 12.—*Cross section and stress and temperature gradients for wheels 23 and 24—750-pound single-plate type*

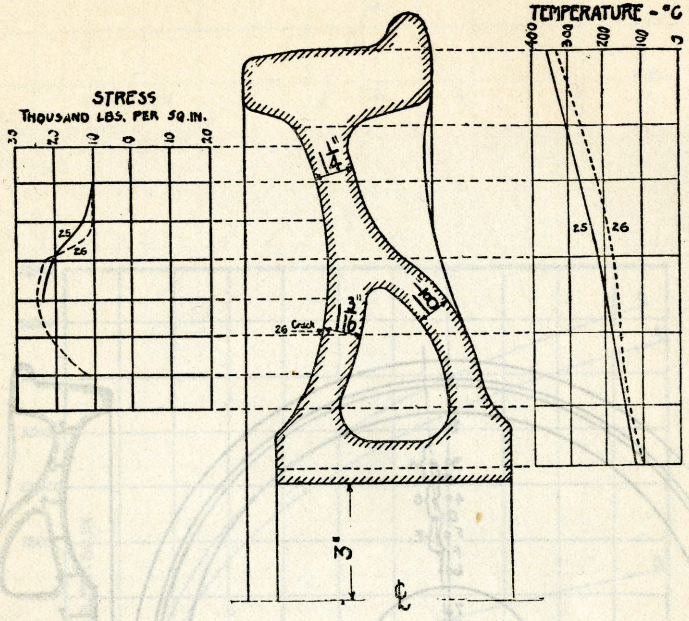

FIG. 13.—*Cross section and stress and temperature gradients for wheels 25 and 26—775-pound arch-plate type*

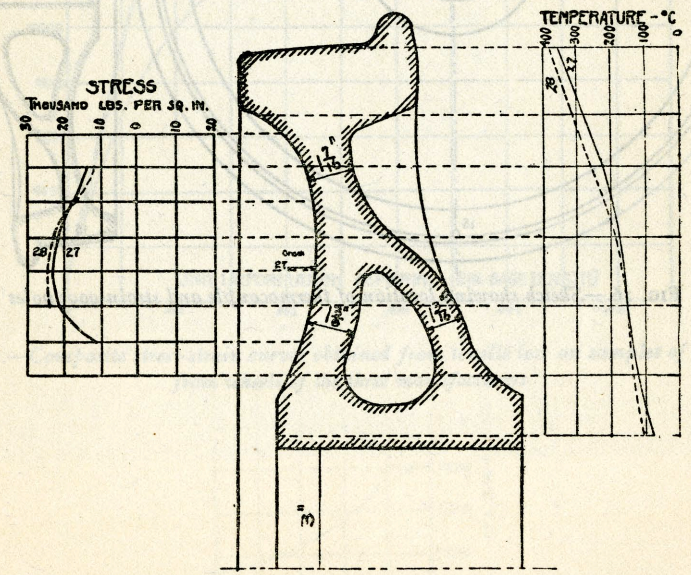

FIG. 14.—*Cross section and stress and temperature gradients for wheels 27 and 28—850-pound arch-plate type*

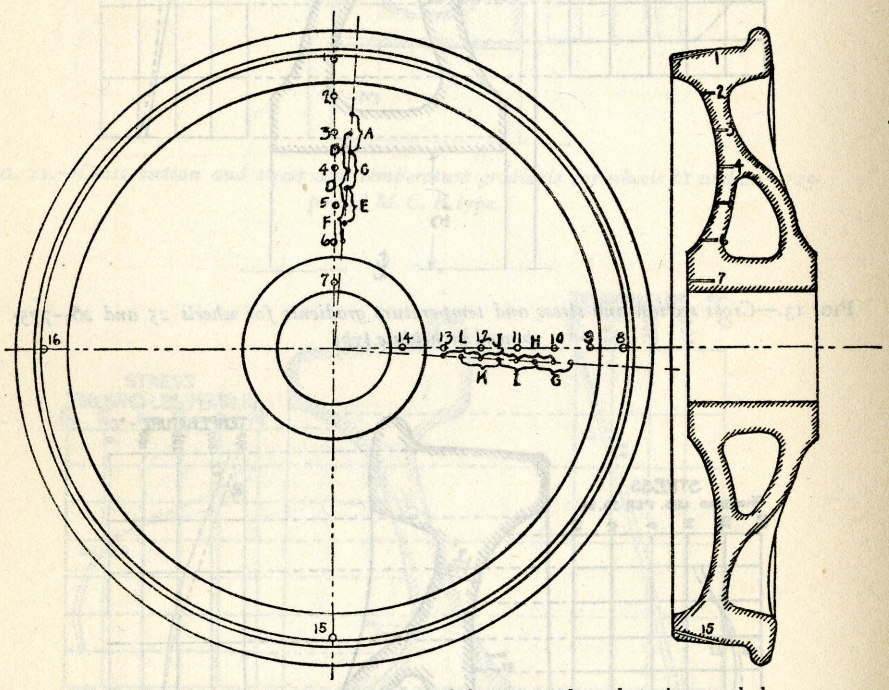

FIG. 16.—*Sketch showing location of thermocouple and strain-gage holes*

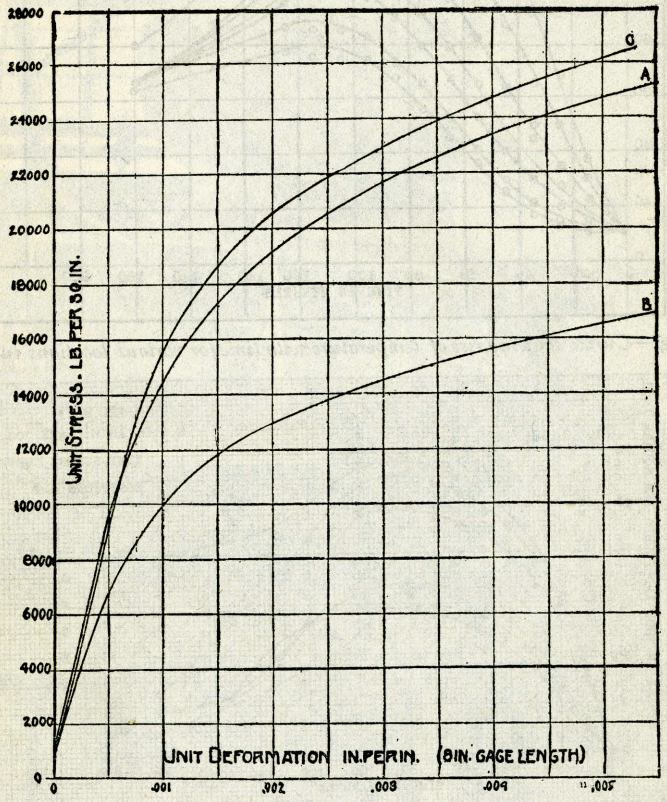

FIG. 17.—*Composite stress-strain curves obtained from tensile test on samples of cast iron from wheels of the three manufacturers*

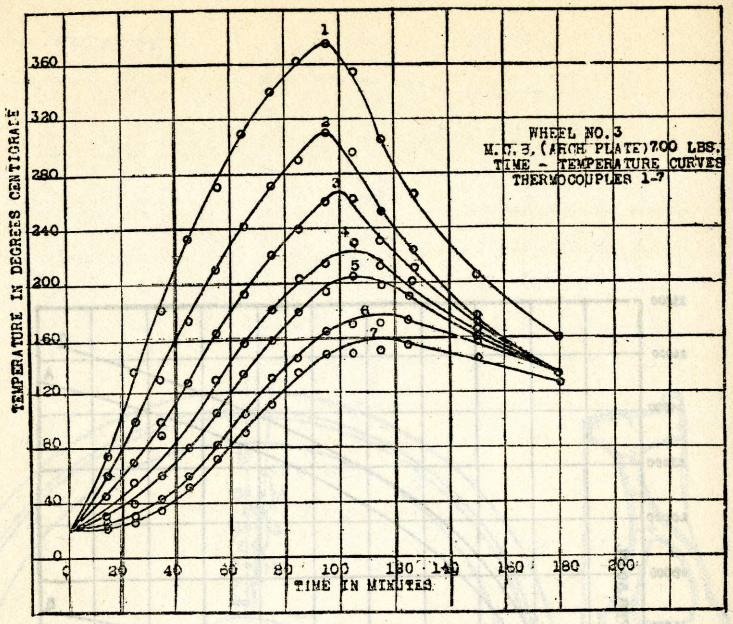

FIG. 24.—*Curves showing rise of temperature with time for various locations in wheel 3*

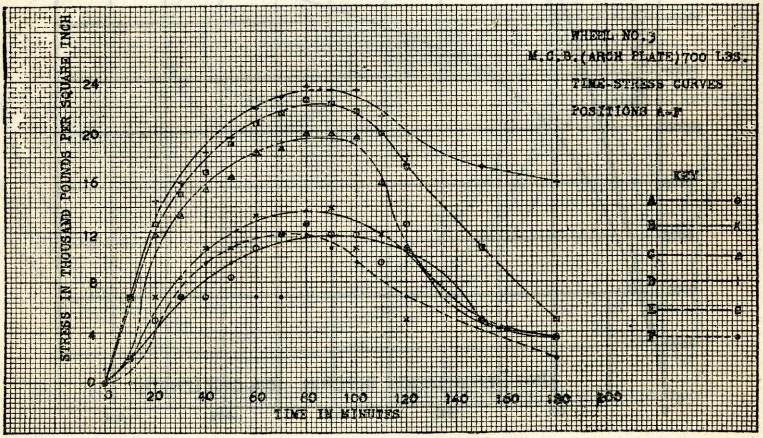

FIG. 25.—*Curves showing rise of stress with time for various locations in wheel 3*

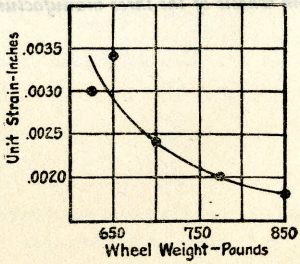

FIG. 26.—*Relation of strain to weight for arch-plate wheels of various weights*

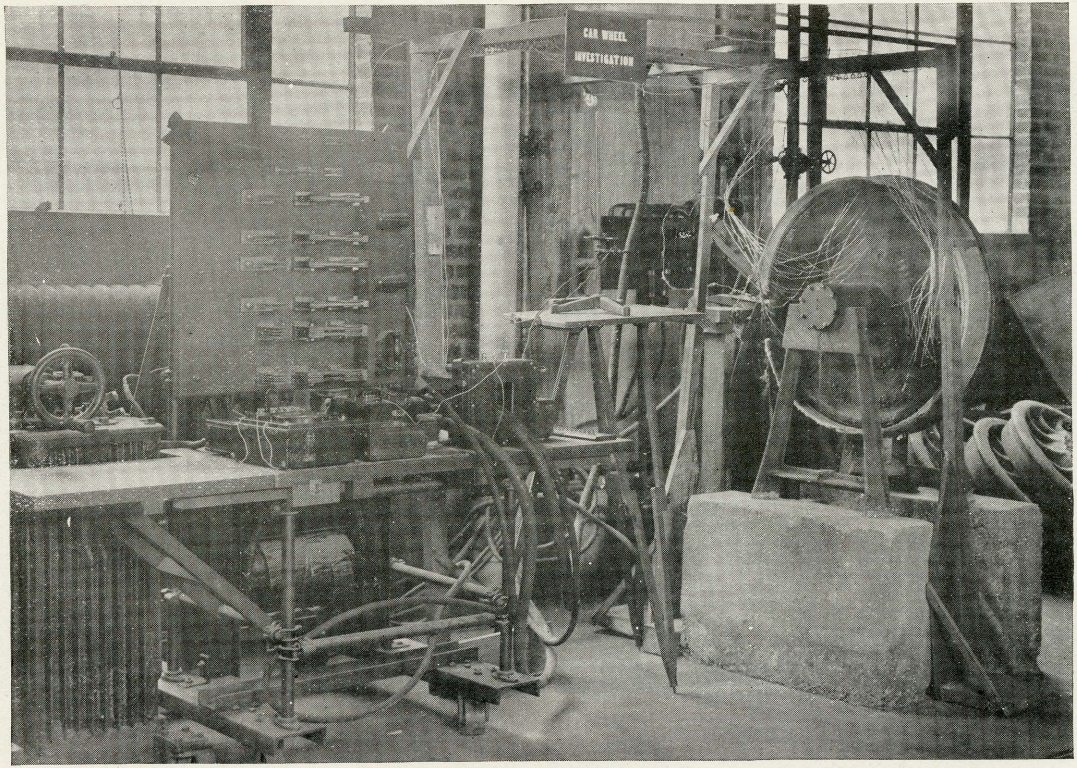

FIG. 15.—*Car wheel in test stand ready for special Bureau of Standards thermal test*

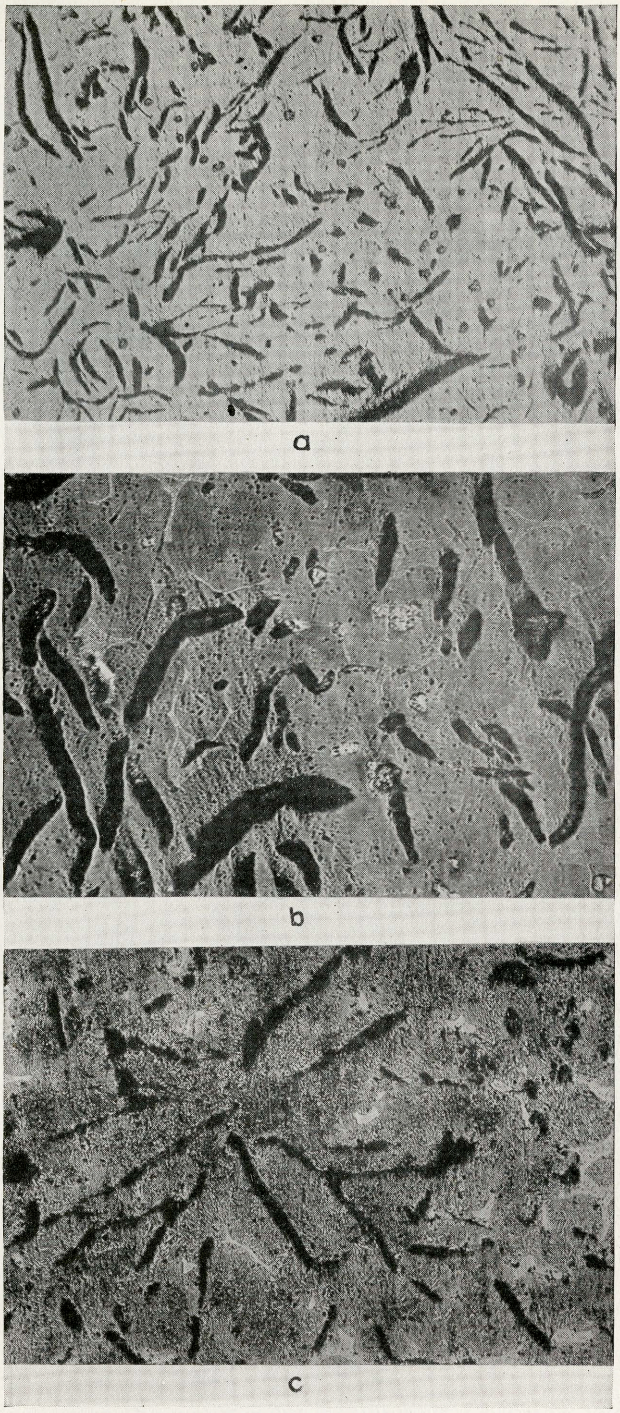

FIG. 18.—*Specimen from wheel 5, foundry "A"*

(*a*) Polished but unetched; × 50. Most of the small black specks represent inclusions principally of sulphide; the graphite flakes (wide black lines) are much larger than these
(*b*) Heat-tinted specimen; × 100. The light branching areas are the phosphide eutectic; the white spots are the sulphide
(*c*) Specimen etched in 5 per cent picric acid, × 100. The gray background is the pearlitic matrix of the iron; the light branching islands are the phosphide eutectic

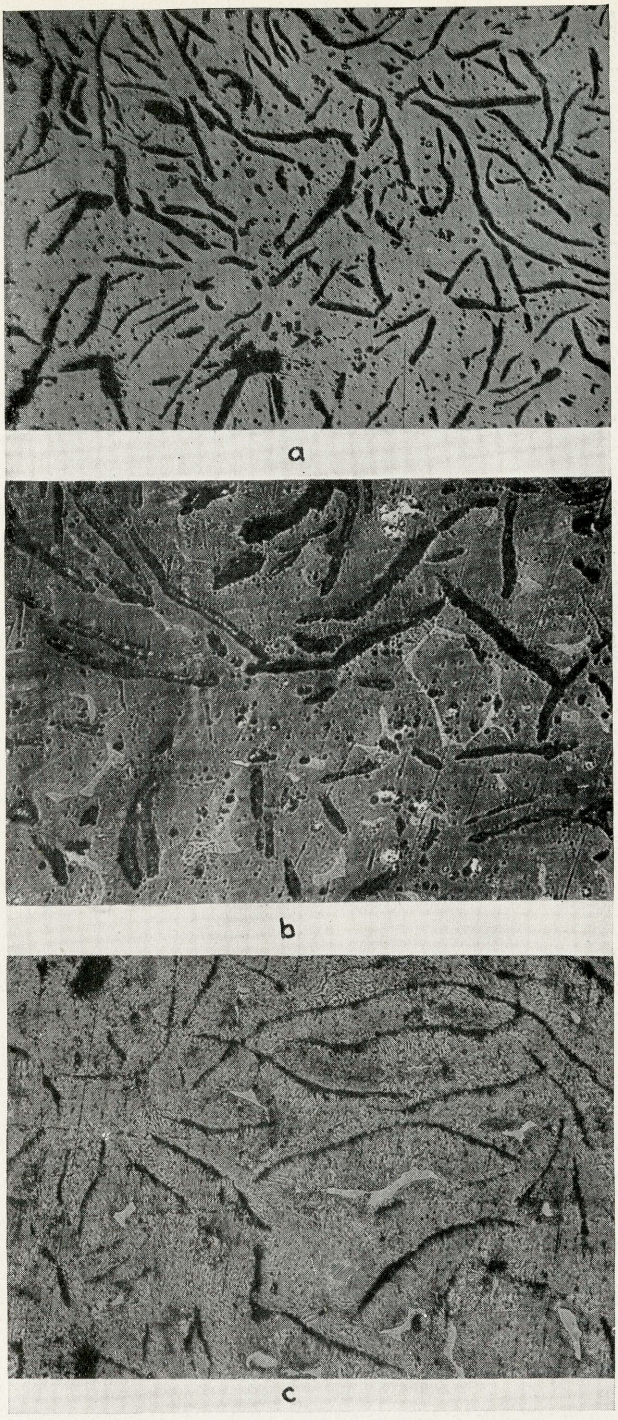

FIG. 19.—*Specimen from wheel 9, foundry "B"*

(*a*) Polished but unetched; × 50. Most of the small black specks represent inclusions principally of sulphide; the graphite flakes (wide black lines) are much larger than these

(*b*) Heat-tinted specimen; × 100. The light branching areas are the phosphide eutectic; the white spots are the sulphide

(*c*) Specimen etched in 5 per cent picric acid, × 100. The gray background is the pearlitic matrix of the iron; the light branching islands are the phosphide eutectic

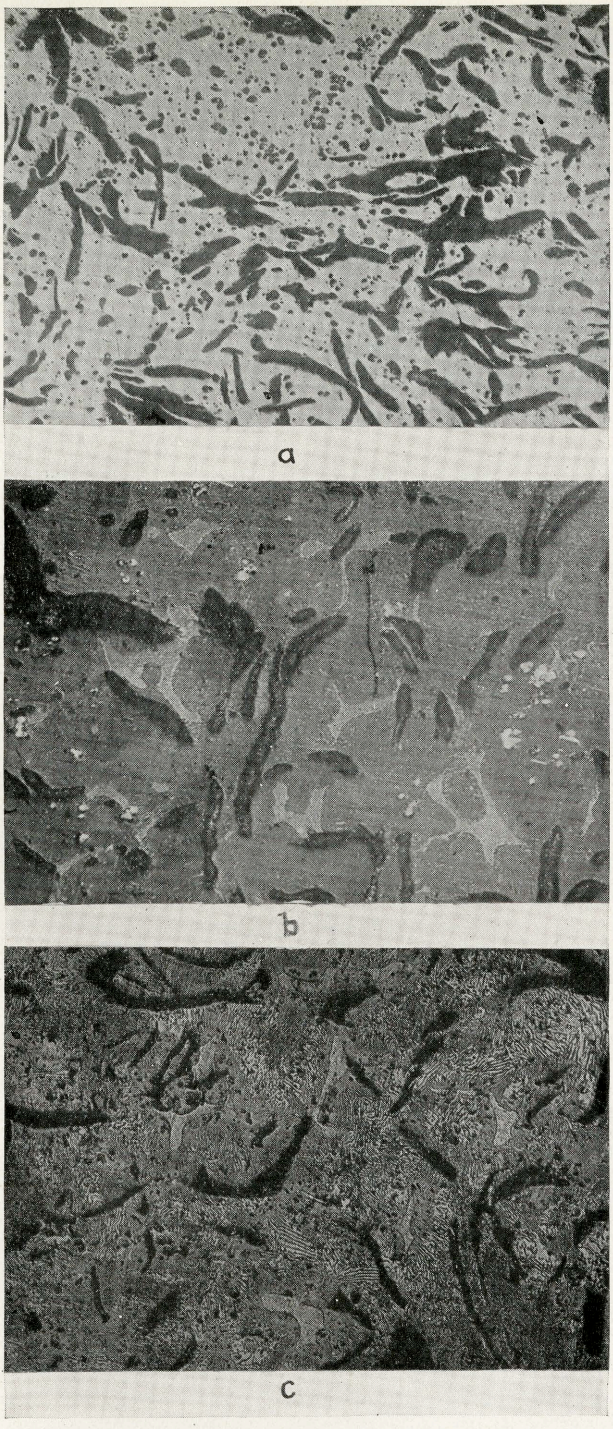

FIG. 20.—*Specimen from wheel 25, foundry "C"*

(*a*) Polished but unetched; × 50. Most of the small black specks represent inclusions principally of sulphide; the graphite flakes (wide black lines) are much larger than these

(*b*) Heat-tinted specimen; × 100. The light branching areas are the phosphide eutectic; the white spots are the sulphide

(*c*) Specimen etched in 5 per cent picric acid, × 100. The gray background is the pearlitic matrix of the iron; the light branching islands are the phosphide eutectic

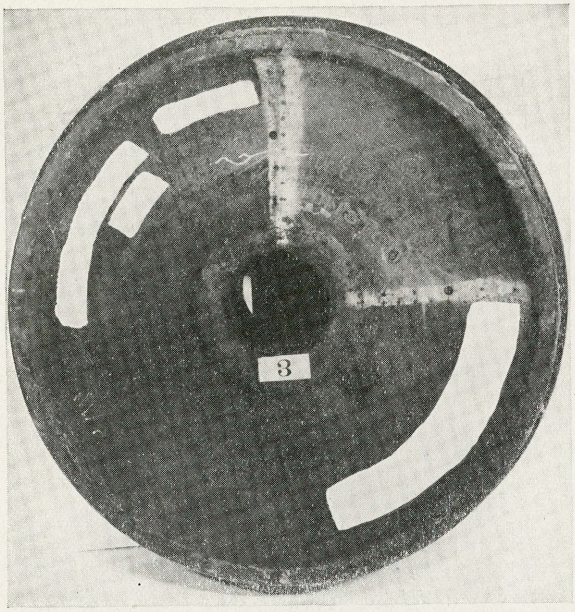

FIG. 21.—*Crack in wheel 3 after special thermal test*

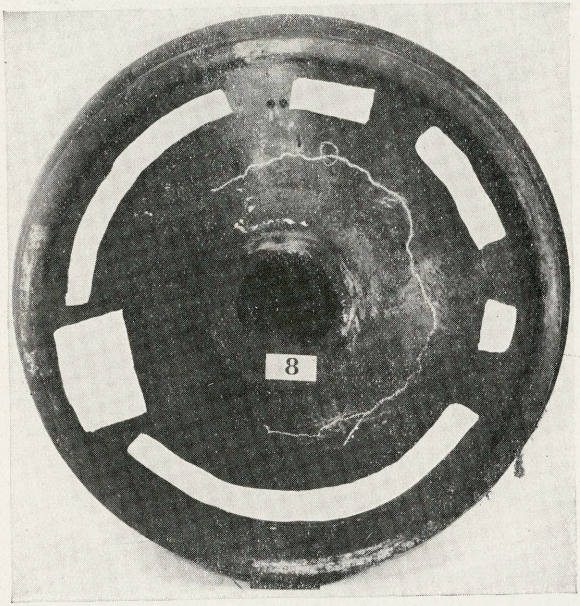

FIG. 22.—*Cracks in wheel 8 after special thermal test*

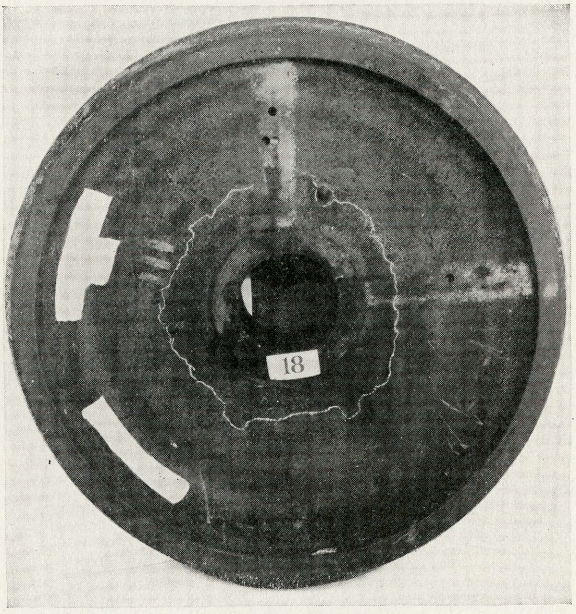

FIG. 23.—*Cracks in wheel 18 after special thermal test*