

JOURNAL
OF THE
FRANKLIN INSTITUTE
OF THE STATE OF PENNSYLVANIA,
FOR THE PROMOTION OF THE MECHANIC ARTS.

VOL. CVI.

DECEMBER, 1878.

No. 6.

THE Franklin Institute is not responsible, as a body, for the statements and opinions advanced by contributors to the JOURNAL.

THE CHEMICAL COMPOSITION AND PHYSICAL PROPERTIES OF STEEL RAILS.¹

By C. B. DUDLEY, Ph. D., Chemist, Penna. R. R. Co.

In the spring of 1877, the Pennsylvania Railroad Company became so dissatisfied with the average life and wear of the steel rails it was then able to procure, that it determined to make an investigation into the chemical composition and physical properties of steel rails, with a view, first, to answering the question why one steel rail has to be removed from the track after, perhaps, 8 months' service, while another lasts 10 years; and, secondly, if this investigation succeeded in throwing light on this important subject, to use this information in securing better rails in the future. The results of that investigation are contained in the following report. In presenting this report to the Institute of Mining Engineers, which I am permitted to do by the kindness of the officers of the Pennsylvania Railroad Company, it has been thought best to retain the form and style in which the report

¹ A paper read before the October (1878), meeting of the American Institute of Mining Engineers.

was written. For although the report was originally written for the officers of the Pennsylvania Railroad Company, and, consequently, the discussion of details made a little more full than if it had been written as a scientific paper, yet this very fullness of detail may not be amiss in a field where knowledge is so urgently needed.

REPORT.

THEO. N. ELY, ESQ., *Supt. Motive Power, Penna. R. R. Co.*

Dear Sir:—I have finished the examination of the subject of steel rails in connection with their chemical constitution, physical properties, and wear, which has occupied my attention and study, more or less constantly, for six months past, and beg leave to present thereon the following report:

The question which led to, and has followed in all its details, the investigation embraced in this report, is: How shall the Pennsylvania Railroad Company obtain steel rails which shall give a satisfactory wear and be uniform in quality?

In order to understand the attempt which has been made to answer this question, it will be necessary to state a few preliminary principles. It seems to be agreed among metallurgists, that the quality of a piece of steel depends upon two sets of circumstances: 1st, upon its chemical constitution, and 2d, upon the treatment which the metal receives either during or after its manufacture. In other words, a piece of steel of certain chemical constitution and treatment will have certain physical qualities of strength, elasticity, ductility, power to resist wear, etc.; or again, a different chemical constitution and treatment will give a piece of steel which will differ in one or more of these respects from the first; the former being possibly more valuable for rails, the latter for cutting-tools.

Now it is to be confessed at the outset, that our knowledge of these two sets of circumstances, viz., the chemical constitution and treatment necessary to secure such a piece of steel as is desired, is far from being all that could be wished for. Nevertheless, some things are known, and the work which is described below is an attempt to add to our knowledge in this respect, with regard to steel rails.

Now inasmuch as all our steel rails are made at present by the Bessemer or Pneumatic process, and inasmuch as the conditions of successful working of this process are pretty well understood, it is assumed that the *treatment* which the steel receives during manufacture is constant or always alike. That this is an actual fact in prac-

tice, is probably not true. The carelessness of workmen, and the want of proper appliances, may at times cause more or less variation in the treatment which the successive "blows" or heats in the Bessemer converter receive. These variations are, however, undoubtedly small, and where care is taken, and the Bessemer process given its full chance, the want of uniformity of product, so far as that uniformity depends upon treatment or method of manufacture, should be very small. I would not be understood as saying, however, that I think the Bessemer process has reached its full development, or is incapable of further improvement. The difficulty of obtaining solid ingots, whether it is better to use the bottom or top cast, whether the slag is all separated before casting, at what temperature the rail should go through the rolls, and especially the last pass, and how to get this temperature, are questions still awaiting solution, and I think it undoubted, that to one or more, or possibly all combined, of these uncertainties are due some of the anomalies which are often met with in steel.

Nevertheless, assuming, as has already been stated, that the Bessemer process, as at present understood and worked, is capable, in careful hands, of turning out a moderately uniform product, so far as that uniformity depends upon *treatment* or method of manufacture—which is undoubtedly the case—the question how to obtain a good rail becomes one as to the chemical composition of the steel, and this is the part of the problem to which I have devoted some labor and study. We are fortunately, however, not entirely dependent for uniformity of product, so far as that uniformity depends upon treatment or method of manufacture, upon the uniformity with which the rail manufacturers work the Bessemer process. Just here comes in the sphere for appropriate physical tests and inspection. For example, it seems clear to me that if a "blow" or heat in the Bessemer converter is badly treated at any point during the manufacture, so that the steel is spoiled, appropriate physical tests and inspection will reveal this fact, and thus enable us to protect ourselves by rejecting that "blow." So that the question with which we started, viz., How shall the Pennsylvania Railroad Company obtain steel rails which shall give satisfactory wear and be uniform in quality? seems to be resolved into two others, viz., (1) With the present known metallurgical methods in the Bessemer process, what chemical composition shall the Pennsylvania Railroad Company prescribe for its rails? and (2) What physical tests and inspection shall it apply to

secure uniformity of product? What follows is an attempt to answer these questions.

I.—AS TO CHEMICAL COMPOSITION.

It is well known that there are six impurities which exist in nearly all iron and steel in greater or less amount, which are known to have important influences upon its quality, even in small quantities. These are carbon, phosphorus, silicon, manganese, sulphur and copper, and when we speak of the chemical composition of steel, we mean the amount of these various impurities which the steel contains. Steel, and especially pig iron contain other impurities, such as titanium, cobalt, nickel, arsenic, etc., but these are commonly disregarded in analysis because their amount is usually very small, and some of them are not known to have any influence upon the quality of the metal. A discussion as to the influence of these various impurities upon the quality of steel, will follow later. It is sufficient here to say, that almost the only effect that sulphur and copper are known to have on steel, is to render it what is technically known as "red short," that is, if a steel rail has too much sulphur and copper in it, it crushes in the rolls or flies to pieces, during manufacture. I am unable to find, anywhere, that sulphur and copper are said to have a deleterious effect on the wear or durability of a rail, and indeed, some metallurgists claim that they are advantageous in this respect. I have, therefore, not determined the sulphur or copper in the analyses given below, and would not recommend to prescribe any specifications in regard to them. We can safely trust the rail manufacturers not to give us rails containing too much sulphur and copper.

As to the other four impurities, the question now arises, how much of these various substances ought a good steel rail to contain? In order to answer this question, twenty-five pieces of steel rail have been carefully analyzed for carbon, phosphorus, silicon and manganese. The borings for analysis were taken out of the physical test pieces described below. The chemical work was all done in duplicate. The carbon was determined by combustion, working upon 7 grams, dissolving out the carbon with solution of the double chloride of copper and ammonium, and burning with chromate of lead. The phosphorus was determined by the molybdate of ammonium method, working upon 3 grams, and dissolving the steel in aqua regia. The manganese was determined by the bromine method, separating the iron as basic

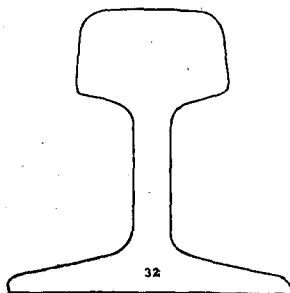
acetate, and using acetate of soda as the precipitant. The silicon was determined in the usual way, working upon 10 grams, and dissolving in hydrochloric acid. The twenty-five samples of steel rail which were analyzed, have all been in actual service; some of them have broken in service, some have crushed in service, some have worn badly with short service, and some have endured long and hard service. The brands of steel represented in the series, are: Penn. steel, Cambria steel, Lackawanna Iron and Coal Co.'s steel, Cammel steel, Mersey steel, Ebbw Vale steel, and John Brown steel. It was thought that the series would represent, as fairly as a series of twenty-five samples could do, the actual results of good and bad service of rails on the Penna. R. R. Moreover, the samples were taken from all parts of the road, thereby rendering inoperative the influence of local causes upon the life and wear of the rails. If now the chemical composition of the good rails should show uniformity within narrow limits, while the chemical composition of the bad rails should likewise show uniformity; and if these uniformities of chemical composition in the good rails and bad rails should differ from each other, it would seem to be fair to conclude that the composition of the bad rails should be avoided, while that of the good rails should be adopted. That the good rails show a moderate uniformity of chemical composition, different from that of the bad rails, will be evident, I think, from an inspection of the analyses which follow.

One or two things more ought to be mentioned. In order to measure the value of a rail as to whether good or bad, the approximate tonnage which has passed over each of these pieces of rail has been computed; it being of course evident to all that the burden which a rail has sustained, even though approximately determined, is a much more accurate measure of its value than time of service. Again, position in a track, whether on a curve or on a straight line, and also whether subject to high speed or not, obviously have an influence upon the durability of a rail, and attention has been given to these points in estimating the value of a rail. It will be noticed in the tables which follow that the principle of measuring the value of a rail by the tonnage which has passed over it has not been strictly followed. The rails have been divided in the tables into two classes on this principle, viz.: *Those which crushed or broke in service* and *those which did not crush or break in service*. The former are regarded as bad rails and the latter as good rails. This principle of division

brings among the bad rails four whose tonnage is higher than the lowest tonnage of any rail among the good ones. But in view of the liability to accident which a broken or crushed rail may occasion, I think no one will claim that a rail which has broken or crushed in service should be classed among good rails, even though its tonnage may entitle it to be so rated.

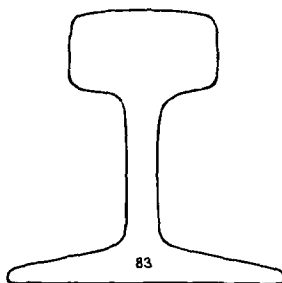
Finally, as a means of determining whether good rails differed from bad rails in physical qualities, such as tensile strength, ductility, etc., and if it was found that they did so differ, as a means of enabling us to specify what physical tests the steel for our rails ought to stand, careful physical tests have been made of every piece of steel analyzed except two, the samples sent for analysis of these two being so small as to prevent physical tests being made. The physical tests were made on Prof. Thurston's Torsional Testing Machine, as being the best means of determining the largest number of physical qualities at a single test. A copy of the diagrams obtained in making these tests accompanies this report, and will be referred to later.

The history of each piece of rail analyzed, together with an outline sketch of the piece (one-third size) as it appeared when removed from the track, the tonnage, chemical analysis, and results of physical tests are given in order below. Following these is a tabulated statement of these results, and the conclusion drawn from them.



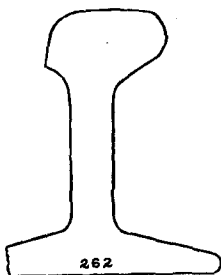
No. 32—Broken near *Edgar Thomsen Steel Works*, first time train passed over it.
Tonnage, 0,000,000 tons.

| CHEMICAL ANALYSIS. | PHYSICAL TESTS. |
|----------------------------|---|
| Carbon..... 0.359 | Angle of Torsion..... 111° |
| Phosphorus..... .156 | Moment of Torsion..... 333 |
| Manganese..... .505 | Tensile Strength at Rupture..... 78,255 |
| Silicon..... .035 | “ “ Elastic Limit..... 30,550 |
| Total Hardeners..... 1.055 | Percentage of Elongation..... 16.898 |
| “ in P. units..... 39.4 | Proportional Ultimate Resilience..... 29.80 |



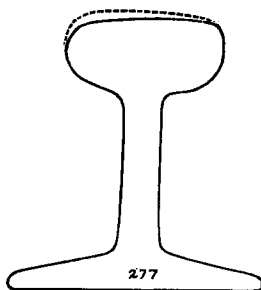
No. 83.—In service from June, 1875, to September, 1876; sixteen months. Was in south track on 9° curve, just east of Columbia Tunnel. Broke in service. Tonnage, 10,027,131 tons.

| CHEMICAL ANALYSIS. | | PHYSICAL TESTS. | |
|----------------------|-------|---------------------------------------|--------|
| Carbon..... | 0.323 | Angle of Torsion..... | 106° |
| Phosphorus.... | .135 | Moment of Torsion..... | 340 |
| Manganese..... | .522 | Tensile Strength at Rupture..... | 79,900 |
| Silicon..... | .035 | “ “ “ Elastic Limit..... | 33,135 |
| Total Hardeners..... | 1.015 | Percentage of Elongation..... | 15.509 |
| “ in P. units..... | 36.4 | Proportional Ultimate Resilience..... | 28.60 |



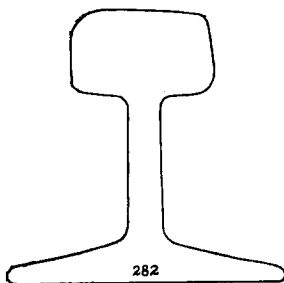
No. 262.—In service from October, 1868, to November, 1876; eight years, one month. Was in south track on 9° curve, just west of Valley Creek Bridge. Tonnage, 44,636,201 tons.

| CHEMICAL ANALYSIS. | | PHYSICAL TESTS. | |
|----------------------|-------|--|--|
| Carbon..... | 0.337 | No Physical Tests were made, because of smallness of piece of rail sent. | |
| Phosphorus..... | .056 | | |
| Manganese..... | .374 | | |
| Silicon..... | .056 | | |
| Total Hardeners..... | .823 | | |
| “ in P. units..... | 27.1 | | |



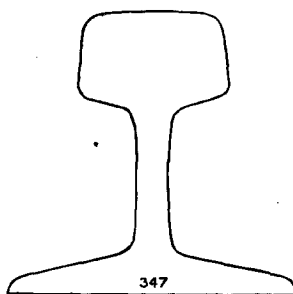
No. 277.—*In service from September, 1872, to December, 1876; four years, three months.*
Was in south track on tangent, about midway between South Elizabeth and Linden.
Broke in service. Tonnage, 16,600,728 tons.

| CHEMICAL ANALYSIS. | PHYSICAL TESTS. |
|----------------------------|---|
| Carbon..... 0.573 | Angle of Torsion..... 101° |
| Phosphorus..... .075 | Moment of Torsion..... 433 |
| Manganese..... .853 | Tensile Strength at Rupture..... 101,755 |
| Silicon..... .182 | “ “ “ Elastic Limit... 43,005 |
| Total Hardeners..... 1.688 | Percentage of Elongation..... 14.169 |
| “ in P. units... .52.9 | Proportional Ultimate Resilience... 36.81 |



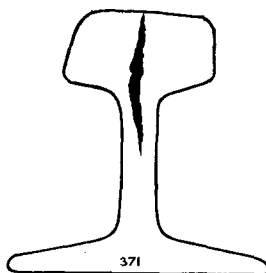
No. 282.—*In service from August, 1875, to January, 1877; one year, five months.*
Was in single track near Marr's Run Station, on N. C. R. W. Broke in service.
On tangent. Tonnage, 4,535,318 tons.

| CHEMICAL ANALYSIS. | PHYSICAL TESTS. |
|----------------------------|--|
| Carbon..... 0.354 | No Physical Tests were made, because of smallness of piece of rail sent. |
| Phosphorus..... .132 | |
| Manganese..... .552 | |
| Silicon..... .050 | |
| Total Hardeners..... 1.088 | |
| “ in P. units..... 38.5 | |



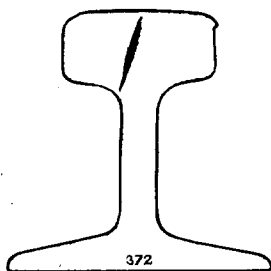
No. 347.—*Broke after five days' service on New York Division. Tonnage, 0,000,000 tons.*

| CHEMICAL ANALYSIS. | PHYSICAL TESTS. |
|----------------------------|--|
| Carbon..... 0.387 | Angle of Torsion..... 67° |
| Phosphorus056 | Moment of Torsion..... 306 |
| Manganese670 | Tensile Strength at Rupture..... 71,910 |
| Silicon..... .035 | “ “ “ Elastic Limit.... 30,550 |
| Total Hardeners..... 1.148 | Percentage of Elongation..... 6.467 |
| “ in P. units.....36.6 | Proportional Ultimate Resilience.... 16.65 |



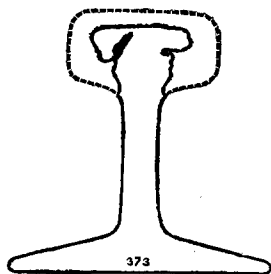
No. 371.—*In service from July, 1876, to March, 1877; eight months. Was in single track, on Tyrone and Clearfield Division, south of Mount Pleasant. On curve 16°. Tonnage, 2,741,056 tons.*

| CHEMICAL ANALYSIS. | PHYSICAL TESTS. |
|---------------------------|--|
| Carbon..... 0.386 | Angle of Torsion..... 85° |
| Phosphorus127 | Moment of Torsion..... 342 |
| Manganese380 | Tensile Strength at Rupture..... 80,370 |
| Silicon..... .053 | “ “ “ Elastic Limit.... 47,000 |
| Total Hardeners..... .946 | Percentage of Elongation..... 10.223 |
| “ in P. units.....35.8 | Proportional Ultimate Resilience.... 24.68 |



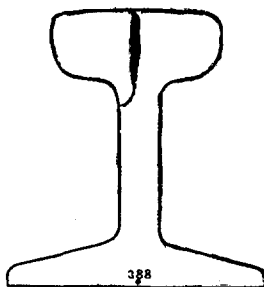
No. 372.—*In service from July, 1876, to March, 1877; eight months. Was in single track on 17° curve, Tyrone and Clearfield Division, south of Mount Pleasant. Tonnage, 2,741,056 tons.*

| CHEMICAL ANALYSIS. | | PHYSICAL TESTS. | |
|----------------------|-------|---------------------------------------|--------|
| Carbon | 0.416 | Angle of Torsion..... | 102° |
| Phosphorus | .155 | Moment of Torsion..... | 346 |
| Manganese | .460 | Tensile Strength at Rupture..... | 81,310 |
| Silicon | .034 | “ “ “ Elastic Limit..... | 30,550 |
| Total Hardeners..... | 1.065 | Percentage of Elongation..... | 14.433 |
| “ in P. units..... | 40.3 | Proportional Ultimate Resilience..... | 29.26 |



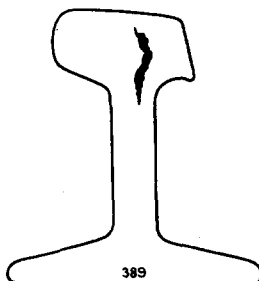
No. 373.—*In service from July, 1876, to March, 1877; eight months. Was in single track on 20° curve, Tyrone and Clearfield Division, south of Mount Pleasant. Tonnage, 2,741,056 tons.*

| CHEMICAL ANALYSIS. | | PHYSICAL TESTS. | |
|----------------------|-------|---------------------------------------|--------|
| Carbon | 0.300 | Angle of Torsion..... | 102° |
| Phosphorus... .. | .138 | Moment of Torsion | 281 |
| Manganese..... | .412 | Tensile Strength at Rupture..... | 66,035 |
| Silicon | .024 | “ “ “ Elastic Limit..... | 25,850 |
| Total Hardeners..... | .874 | Percentage of Elongation..... | 14.433 |
| “ in P. units..... | 33.2 | Proportional Ultimate Resilience..... | 23.06 |



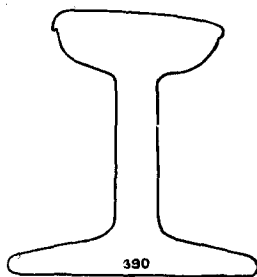
No. 388.—*In service from March, 1867, to March, 1877; ten years. Was in north track on a tangent near Ardmore Station. Tonnage, 37,005,142 tons.*

| CHEMICAL ANALYSIS. | | PHYSICAL TESTS. | |
|----------------------|-------|---------------------------------------|--------|
| Carbon..... | 0·303 | Angle of Torsion..... | 120° |
| Phosphorus..... | ·166 | Moment of Torsion..... | 322 |
| Manganese..... | ·316 | Tensile Strength at Rupture..... | 75,670 |
| Silicon..... | ·032 | “ “ “ Elastic Limit..... | 31,725 |
| Total Hardeners..... | ·817 | Percentage of Elongation..... | 19·514 |
| “ in P. units..... | 34·6 | Proportional Ultimate Resilience..... | 31·21 |



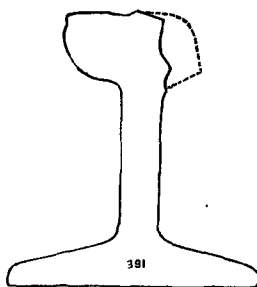
No. 389.—*In service from March, 1872, to April, 1877; five years, one month. Was on south track on a curve, one mile west of Huntingdon. Tonnage, 34,333,639 tons.*

| CHEMICAL ANALYSIS. | | PHYSICAL TESTS. | |
|----------------------|-------|---------------------------------------|--------|
| Carbon..... | 0·343 | Angle of Torsion..... | 121° |
| Phosphorus..... | ·127 | Moment of Torsion..... | 320 |
| Manganese..... | ·670 | Tensile Strength at Rupture.... | 75,200 |
| Silicon..... | ·036 | “ “ “ Elastic Limit.... | 30,550 |
| Total Hardeners..... | 1·176 | Percentage of Elongation..... | 19·813 |
| “ in P. units..... | 39·3 | Proportional Ultimate Resilience..... | 31·02 |



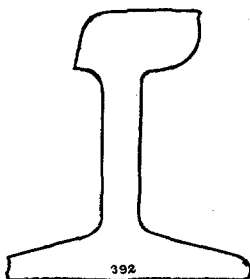
No. 390.—In service from March, 1868, to March, 1877; nine years. Was in south track on 2° curve, on eastern slope of mountain. Pittsburg Division. Tonnage, 47,832,411 tons.

| CHEMICAL ANALYSIS. | PHYSICAL TESTS. |
|----------------------|---------------------------------------|
| Carbon | Angle of Torsion..... |
| Phosphorus | Moment of Torsion..... |
| Manganese | Tensile Strength at Rupture..... |
| Silicon..... | “ “ “ Elastic Limit..... |
| Total Hardeners..... | Percentage of Elongation..... |
| “ in P. units..... | Proportional Ultimate Resilience..... |



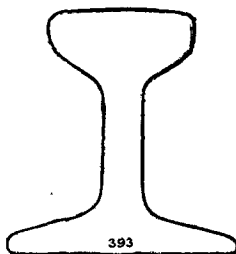
No. 391.—In service from June, 1871, to April, 1877; five years, ten months. Was in south track on 4½° curve, 1700 feet west of M. P., 84 from Pittsburg. Tonnage, 30,873,173 tons.

| CHEMICAL ANALYSIS. | PHYSICAL TESTS. |
|----------------------|---------------------------------------|
| Carbon..... | Angle of Torsion..... |
| Phosphorus | Moment of Torsion..... |
| Manganese..... | Tensile Strength at Rupture..... |
| Silicon..... | “ “ “ Elastic Limit..... |
| Total Hardeners..... | Percentage of Elongation..... |
| “ in P. units..... | Proportional Ultimate Resilience..... |



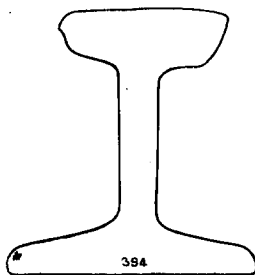
No. 392.—In service from April, 1871, to April, 1877; six years. Was in south track on 4° curve, 800 feet east of M. P., 106 from Pittsburg. Tonnage, 32,957,247 tons.

| CHEMICAL ANALYSIS. | | PHYSICAL TESTS. | |
|----------------------|--------|---------------------------------------|--------|
| Carbon..... | 0.231 | Angle of Torsion..... | 151° |
| Phosphorus..... | - .087 | Moment of Torsion..... | 294 |
| Manganese..... | .364 | Tensile Strength at Rupture..... | 69,090 |
| Silicon..... | .047 | “ “ “ Elastic Limit..... | 30,550 |
| Total Hardeners..... | .729 | Percentage of Elongation..... | 29.548 |
| “ in P. units..... | 26.0 | Proportional Ultimate Resilience..... | 37.24 |



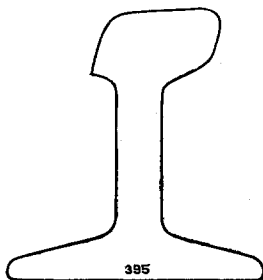
No. 393.—In service from July, 1867, to July, 1873, in north track at M. P., 115 from Philadelphia; then from July, 1873, to April, 1877, in No. 1, south siding, Mifflin Yard. Total service, nine years, ten months. Tonnage, 17,083,416 tons.

| CHEMICAL ANALYSIS. | | PHYSICAL TESTS. | |
|----------------------|-------|---------------------------------------|--------|
| Carbon..... | 0.219 | Angle of Torsion..... | 217° |
| Phosphorus..... | .065 | Moment of Torsion..... | 285 |
| Manganese..... | .272 | Tensile Strength at Rupture..... | 66,975 |
| Silicon..... | .028 | “ “ “ Elastic Limit..... | 28,200 |
| Total Hardeners..... | .584 | Percentage of Elongation..... | 54.944 |
| “ in P. units..... | 20.6 | Proportional Ultimate Resilience..... | 49.63 |



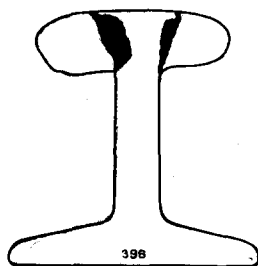
No. 394.—In service from April, 1871, to April, 1877; six years. Was in south track on 2° curve, 2600 feet west of M. P., 27 from Pittsburg. Tonnage, 25,043,350 tons.

| CHEMICAL ANALYSIS. | | PHYSICAL TESTS. | |
|----------------------|-------|---------------------------------------|--------|
| Carbon..... | 0.286 | Angle of Torsion..... | 149° |
| Phosphorus..... | .083 | Moment of Torsion..... | 322 |
| Manganese..... | .418 | Tensile Strength at Rupture..... | 75,670 |
| Silicon..... | .023 | “ “ “ Elastic Limit..... | 45,825 |
| Total Hardeners..... | .810 | Percentage of Elongation..... | 28.857 |
| “ in P. units..... | 27.3 | Proportional Ultimate Resilience..... | 41 65 |



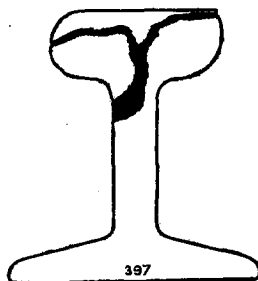
No. 395.—In service from September, 1872, to March, 1877; four years, seven months. Was in south track on 4° curve, 1200 feet west of M. P., 59 from Pittsburg. Tonnage, 24,606,889 tons.

| CHEMICAL ANALYSIS. | | PHYSICAL TESTS. | |
|----------------------|-------|---------------------------------------|--------|
| Carbon..... | 0.853 | Angle of Torsion..... | 134° |
| Phosphorus..... | .103 | Moment of Torsion..... | 338 |
| Manganese..... | .576 | Tensile Strength at Rupture..... | 79,430 |
| Silicon..... | .059 | “ “ “ Elastic Limit..... | 32,900 |
| Total Hardeners..... | 1.091 | Percentage of Elongation..... | 28.860 |
| “ in P. units..... | 36.5 | Proportional Ultimate Resilience..... | 37.49 |



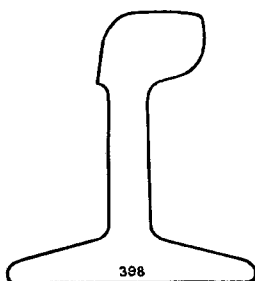
No. 396.—In service from January, 1874, to January, 1877; three years. Was in Subdivision 11, Pittsburg Division; the records of which were destroyed by the riots. Tonnage, 13,683,266 tons.

| CHEMICAL ANALYSIS. | | PHYSICAL TESTS. | |
|----------------------|-------|---------------------------------------|--------|
| Carbon | 0.350 | Angle of Torsion..... | 105° |
| Phosphorus | .134 | Moment of Torsion..... | 342 |
| Manganese | .626 | Tensile Strength at Rupture | 80,370 |
| Silicon..... | .058 | “ “ “ Elastic Limit..... | 36,425 |
| Total Hardeners.. .. | 1.168 | Percentage of Elongation..... | 15.237 |
| “ in P. units..... | 40 5 | Proportional Ultimate Resilience..... | 29.06 |



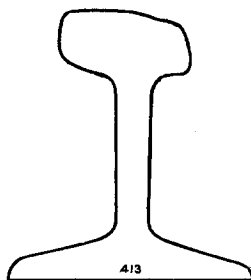
No. 397.—In service from July, 1872, to May, 1877; four years, seven months. Was in south track on tangent 650 feet west of M. P., 11 from Pittsburg. Tonnage, 21,935,613 tons.

| CHEMICAL ANALYSIS. | | PHYSICAL TESTS. | |
|----------------------|-------|---------------------------------------|--------|
| Carbon | 0.365 | Angle of Torsion..... | 82° |
| Phosphorus | .130 | Moment of Torsion..... | 260 |
| Manganese | .458 | Tensile Strength at Rupture..... | 61,100 |
| Silicon..... | .020 | “ “ “ Elastic Limit..... | 25,860 |
| Total Hardeners..... | .973 | Percentage of Elongation..... | 9.545 |
| “ in P. units..... | 35.3 | Proportional Ultimate Resilience..... | 16.86 |



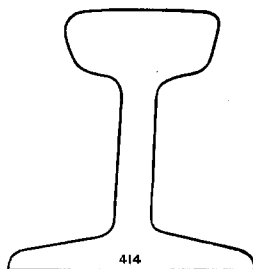
No. 398.—In service from January, 1871, to March, 1877; six years, two months. Was in north track on 4° curve, 120 feet west of M. P., 12 from Pittsburg. Tonnage, 27,296,043 tons.

| CHEMICAL ANALYSIS. | | PHYSICAL TESTS. | |
|----------------------|-------|---------------------------------------|--------|
| Carbon | 0.225 | Angle of Torsion..... | 180° |
| Phosphorus..... | .111 | Moment of Torsion..... | 282 |
| Manganese..... | .318 | Tensile Strength at Rupture..... | 66,270 |
| Silicon..... | .016 | “ “ “ Elastic Limit..... | 27,025 |
| Total Hardeners..... | .670 | Percentage of Elongation..... | 22.586 |
| “ in P. units..... | 25.8 | Proportional Ultimate Resilience..... | 28.93 |



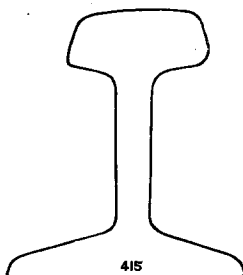
No. 413.—In service from June, 1867, to October, 1876; nine years, four months. Was in single track on 8° 40' curve, at west end of Schuylkill Bridge, Del. Ex. R. R. Tonnage, 36,901,508 tons.

| CHEMICAL ANALYSIS. | | PHYSICAL TESTS. | |
|----------------------|-------|---------------------------------------|--------|
| Carbon..... | 0.233 | Angle of Torsion..... | 175° |
| Phosphorus | .041 | Moment of Torsion..... | 280 |
| Manganese | .208 | Tensile Strength at Rupture..... | 65,800 |
| Silicon..... | .074 | “ “ “ Elastic Limit..... | 28,435 |
| Total Hardeners..... | .556 | Percentage of Elongation..... | 38.239 |
| “ in P. units..... | 19.7 | Proportional Ultimate Resilience..... | 39.49 |



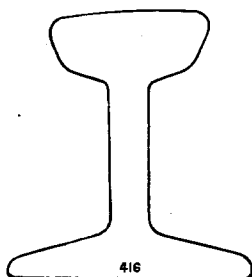
No. 414.—*In service from May 1867, to November, 1876; nine years, six months. Was in west bound freight track on tangent, east of 35th Street Bridge, West Philadelphia. Tonnage, 34,839,538 tons.*

| CHEMICAL ANALYSIS. | PHYSICAL TESTS. |
|---------------------------|---|
| Carbon..... 0.309 | Angle of Torsion..... 148° |
| Phosphorus..... .058 | Moment of Torsion..... 292 |
| Manganese..... .326 | Tensile Strength at Rupture..... 68,620 |
| Silicon..... .030 | “ “ “ Elastic Limit..... 27,730 |
| Total Hardeners..... .723 | Percentage of Elongation..... 28.514 |
| “ in P. units..... 24.1 | Proportional Ultimate Resilience..... 35.86 |



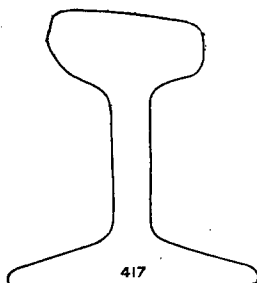
No. 415.—*In service from April, 1867, to July, 1876; nine years, three months. Was in south track, four years on 2° curve, and five years on tangent, near Marysville, Middle Division. Tonnage, 48,037,879 tons.*

| CHEMICAL ANALYSIS. | PHYSICAL TESTS. |
|---------------------------|---|
| Carbon..... 0.336 | Angle of Torsion..... 137° |
| Phosphorus..... .079 | Moment of Torsion..... 321 |
| Manganese..... .458 | Tensile Strength at Rupture..... 75,485 |
| Silicon..... .061 | “ “ “ Elastic Limit..... 31,725 |
| Total Hardeners..... .934 | Percentage of Elongation..... 24.833 |
| “ in P. units..... 31.3 | Proportional Ultimate Resilience..... 36.76 |



No. 416.—*In service from June, 1868, to September, 1876; eight years, three months. Was in south track on tangent opposite Harrisburg Freight Warehouse. Tonnage, 47,354,754 tons.*

| CHEMICAL ANALYSIS. | | PHYSICAL TESTS. | |
|----------------------|-------|--------------------------------------|--------|
| Carbon | 0.283 | Angle of Torsion..... | 127° |
| Phosphorus | .114 | Moment of Torsion..... | 289 |
| Manganese..... | .334 | Tensile Strength at Rupture..... | 67,915 |
| Silicon..... | .030 | “ “ “ Elastic Limit.... | 28,200 |
| Total Hardeners..... | .761 | Percentage of Elongation..... | 21.647 |
| “ in P. units..... | 29.0 | Proportional Ultimate Resilience.... | 29.87 |



No. 417.—*In service from December, 1867, to July, 1876; nine years, six months. Was in north track on 4½° curve, at Jackstown Water Station, Middle Division. Tonnage, 34,108,667 tons.*

| CHEMICAL ANALYSIS. | | PHYSICAL TESTS. | |
|----------------------|-------|--------------------------------------|--------|
| Carbon | 0.345 | Angle of Torsion..... | 124° |
| Phosphorus | .075 | Moment of Torsion..... | 312 |
| Manganese..... | .426 | Tensile Strength at Rupture..... | 73,320 |
| Silicon..... | .041 | “ “ “ Elastic Limit.... | 30,080 |
| Total Hardeners..... | .887 | Percentage of Elongation..... | 20.722 |
| “ in P. units..... | 29.6 | Proportional Ultimate Resilience.... | 31.77 |

TABLE I.

*Showing Tonnage, Location and Results of Chemical Analysis of
Twenty-five Samples of Steel Rail.*

| RAIL No. | TONNAGE. | LOCATION. | C. | PHOS. | MAN. | SI. | TOTAL. | TOT. IN PHOS. UNITS. |
|-------------|------------------|-------------------|-------|-------|-------|-------|--------|----------------------------|
| 415 | 48,037,879. | 2° C. and Tangent | 0.336 | 0.079 | 0.458 | 0.061 | 0.934 | 31.3 |
| 416 | 47,354,754 | Tangent. | 0.283 | 0.114 | 0.334 | 0.030 | 0.761 | 29.0 |
| 390 | 47,332,411 | 2° Curve. | 0.291 | 0.057 | 0.354 | 0.068 | 0.770 | 25.9 |
| 262 | 44,636,201 | 9° “ | 0.337 | 0.056 | 0.374 | 0.056 | 0.823 | 27.1 |
| 413 | 36,901,508 | 8½° “ | 0.233 | 0.041 | 0.208 | 0.074 | 0.556 | 19.7 |
| 414 | 34,839,538 | Tangent. | 0.309 | 0.058 | 0.326 | 0.030 | 0.723 | 24.1 |
| 417 | 34,108,667 | 4½° Curve. | 0.345 | 0.075 | 0.426 | 0.041 | 0.887 | 29.6 |
| 392 | 32,957,247 | 4° Curve. | 0.231 | 0.087 | 0.364 | 0.047 | 0.729 | 26.0 |
| 398 | 27,296,043 | 4° “ | 0.225 | 0.111 | 0.318 | 0.016 | 0.670 | 25.8 |
| 394 | 25,043,350 | 2° “ | 0.286 | 0.083 | 0.418 | 0.023 | 0.810 | 27.3 |
| 395 | 24,606,889 | 4° “ | 0.353 | 0.103 | 0.576 | 0.059 | 1.091 | 36.5 |
| 393 | 17,083,416 | Tangent. | 0.219 | 0.065 | 0.272 | 0.028 | 0.584 | 20.6 |
| 388 | 37,005,142 | Tangent. | 0.303 | 0.166 | 0.316 | 0.032 | 0.817 | 34.6 |
| 389 | 34,333,639 | Curve. | 0.343 | 0.127 | 0.670 | 0.036 | 1.176 | 39.3 |
| 391 | 30,873,173 | 4½° Curve. | 0.294 | 0.181 | 0.354 | 0.020 | 0.849 | 36.0 |
| 397 | 21,935,613 | Tangent. | 0.365 | 0.130 | 0.458 | 0.020 | 0.973 | 35.3 |
| 277 | 16,600,728 | “ | 0.573 | 0.075 | 0.853 | 0.182 | 1.688 | 52.9 |
| 396 | 13,683,266 | Unknown. | 0.350 | 0.134 | 0.626 | 0.058 | 1.168 | 40.5 |
| 83 | 10,027,131 | 9° Curve. | 0.323 | 0.135 | 0.522 | 0.035 | 1.015 | 36.4 |
| 282 | 4,535,318 | Tangent. | 0.354 | 0.132 | 0.552 | 0.050 | 1.088 | 38.5 |
| 371 | 2,741,056 | 16° Curve. | 0.386 | 0.127 | 0.380 | 0.053 | 0.946 | 35.8 |
| 372 | 2,741,056 | 17° “ | 0.416 | 0.155 | 0.460 | 0.034 | 1.065 | 40.3 |
| 373 | 2,741,056 | 20° “ | 0.300 | 0.138 | 0.412 | 0.024 | 0.874 | 33.2 |
| 347 | 5 Days' Service. | Unknown. | 0.387 | 0.056 | 0.670 | 0.035 | 1.148 | 33.6 |
| 32 | Broke 1st Train. | “ | 0.359 | 0.156 | 0.505 | 0.035 | 1.055 | 39.4 |

TABLE II.

Showing Tonnage, Location and Results of Physical Tests of Twenty-five Samples of Steel Rail.

| RAIL No. | TONNAGE. | LOCATION. | ANGLE OF TORSION. | MOMENT OF TORSION. | TENSILE STRENGTH. | TENSILE STRENGTH AT ELASTIC LIMIT. | ELONGATION. | ULTIMATE RESILIENCE. |
|----------|------------------|-------------------|-------------------|--------------------|-------------------|------------------------------------|-------------|----------------------|
| 415 | 48,037,879 | 2° C. and Tangent | 137° | 321 | 75,435 | 31,725 | 0.248 | 36.75 |
| 416 | 47,354,754 | Tangent. | 127° | 289 | 67,915 | 28,200 | 0.216 | 29.87 |
| 390 | 47,332,411 | 2° Curve. | 126° | 302 | 70,970 | 32,900 | 0.213 | 31.95 |
| 262 | 44,636,201 | 9° “ | No | tests | made | of this | rail. | |
| 413 | 36,901,508 | 8½° “ | 175° | 280 | 65,800 | 28,435 | 0.382 | 39.49 |
| 414 | 34,839,538 | Tangent. | 148° | 292 | 68,620 | 27,730 | 0.285 | 35.86 |
| 417 | 34,108,667 | 4½° Curve. | 124° | 312 | 73,320 | 30,080 | 0.207 | 31.77 |
| 392 | 32,957,247 | 4° “ | 151° | 294 | 69,090 | 30,550 | 0.295 | 37.24 |
| 398 | 27,296,043 | 4° “ | 130° | 282 | 66,270 | 27,025 | 0.226 | 28.93 |
| 394 | 25,043,350 | 2° “ | 149° | 322 | 75,670 | 45,825 | 0.288 | 41.65 |
| 395 | 24,606,889 | 4° “ | 134° | 338 | 79,430 | 32,900 | 0.239 | 37.49 |
| 398 | 17,083,416 | Tangent. | 217° | 285 | 66,975 | 28,200 | 0.549 | 49.63 |
| 388 | 37,005,142 | “ | 120° | 322 | 75,670 | 31,725 | 0.195 | 31.21 |
| 389 | 34,333,639 | Curve. | 121° | 320 | 75,200 | 30,550 | 0.198 | 31.02 |
| 391 | 30,873,173 | 4½° Curve. | 136° | 333 | 78,255 | 33,605 | 0.186 | 32.42 |
| 397 | 21,935,613 | Tangent. | 82° | 260 | 61,100 | 25,850 | 0.095 | 16.86 |
| 277 | 16,600,728 | “ | 101° | 433 | 101,755 | 43,005 | 0.142 | 36.81 |
| 396 | 13,683,266 | Unknown. | 105° | 342 | 80,370 | 36,425 | 0.152 | 29.06 |
| 83 | 10,027,131 | 9° Curve. | 106° | 340 | 79,900 | 33,135 | 0.155 | 28.60 |
| 282 | 4,535,318 | Tangent. | No | tests | made | of this | rail. | |
| 371 | 2,741,056 | 16° Curve. | 85° | 342 | 80,370 | 47,000 | 0.102 | 24.68 |
| 372 | 2,741,056 | 17° “ | 102° | 346 | 81,310 | 30,550 | 0.144 | 29.26 |
| 273 | 2,741,056 | 20° “ | 102° | 281 | 66,035 | 25,850 | 0.144 | 23.06 |
| 347 | 5 Days' Service. | Unknown. | 67° | 306 | 71,910 | 30,550 | 0.065 | 16.65 |
| 32 | Broke 1st Train. | “ | 111° | 333 | 78,255 | 30,550 | 0.169 | 29.80 |

TABLE III.

Showing Tonnage, Location, Results of Chemical Analysis, and Physical Tests of Twenty-five Samples of Steel Rail.

| RAIL NO. | TONNAGE. Million Tons. | LOCATION. | C. | PHOS. | MAN. | SI. | TOTAL IN PHOS. UNITS. | TENSILE STRENGTH. 1000 lbs. | ELASTIC LIMIT. 1000 lbs. | PERCENT. OF ELONGATION. | ULTIMATE RESILIENCE. | |
|----------|------------------------|--------------------|------|-------|------|------|-----------------------|-----------------------------|--------------------------|-------------------------|----------------------|------------------------------------|
| 415 | 48 | 2° C. and Tangent. | ·336 | ·079 | ·458 | ·061 | 31·3 | 75 | 32 | 25 | 37 | Did not Break or Crush in Service. |
| 416 | 47 | Tangent. | ·283 | ·114 | ·334 | ·030 | 29·0 | 68 | 28 | 22 | 30 | |
| 390 | 47 | 2° Curve. | ·291 | ·057 | ·354 | ·068 | 25·9 | 71 | 33 | 21 | 32 | |
| 262 | 45 | 9° “ | ·337 | ·056 | ·374 | ·056 | 27·1 | No | tests | made | | |
| 413 | 37 | 8½° “ | ·233 | ·041 | ·208 | ·074 | 19·7 | 66 | 28 | 38 | 39 | |
| 414 | 35 | Tangent. | ·309 | ·058 | ·326 | ·030 | 24·1 | 69 | 28 | 28 | 36 | |
| 417 | 34 | 4½° Curve. | ·345 | ·075 | ·426 | ·041 | 29·6 | 73 | 30 | 21 | 32 | |
| 392 | 33 | 4° “ | ·231 | ·087 | ·364 | ·047 | 26·0 | 69 | 30 | 29 | 37 | |
| 398 | 27 | 4° “ | ·225 | ·111 | ·318 | ·016 | 25·8 | 66 | 27 | 23 | 29 | |
| 394 | 25 | 2° “ | ·286 | ·083 | ·418 | ·023 | 27·3 | 75 | 46 | 29 | 42 | |
| 395 | 25 | 4° “ | ·353 | ·103 | ·576 | ·059 | 36·5 | 79 | 33 | 24 | 37 | Broke or Crushed in Service. |
| 393 | 17 | Tangent. | ·219 | ·065 | ·272 | ·028 | 20·6 | 67 | 28 | 55 | 50 | |
| 388 | 37 | Tangent. | ·303 | ·166 | ·316 | ·032 | 34·6 | 76 | 32 | 19 | 31 | |
| 389 | 34 | Curve. | ·343 | ·127 | ·670 | ·036 | 39·3 | 75 | 30 | 20 | 31 | |
| 391 | 31 | 4½° Curve. | ·294 | ·181 | ·354 | ·020 | 36·0 | 78 | 34 | 19 | 32 | |
| 397 | 22 | Tangent. | ·365 | ·130 | ·458 | ·020 | 35·3 | 61 | 26 | 9 | 17 | |
| 277 | 17 | “ | ·573 | ·075 | ·853 | ·182 | 52·9 | 101 | 43 | 14 | 37 | |
| 396 | 14 | Unknown. | ·350 | ·134 | ·626 | ·058 | 40·5 | 80 | 36 | 15 | 29 | |
| 83 | 10 | 9° Curve. | ·323 | ·135 | ·522 | ·035 | 36·4 | 80 | 33 | 15 | 29 | |
| 282 | 5 | Tangent. | ·354 | ·132 | ·552 | ·050 | 38·5 | No | tests | made | | |
| 371 | 3 | 16° Curve. | ·386 | ·127 | ·380 | ·053 | 35·8 | 80 | 47 | 10 | 25 | |
| 372 | 3 | 17° “ | ·416 | ·155 | ·460 | ·034 | 40·3 | 81 | 30 | 14 | 29 | |
| 373 | 3 | 20° “ | ·300 | ·138 | ·412 | ·024 | 33·2 | 66 | 26 | 14 | 23 | |
| 347 | 0 | Unknown. | ·387 | ·056 | ·670 | ·035 | 33·6 | 72 | 30 | 6 | 17 | |
| 32 | 0 | “ | ·359 | ·156 | ·505 | ·035 | 39·4 | 78 | 30 | 17 | 30 | |

Table III contains a condensed statement of the results of Chemical Analysis and Physical Tests, together with the tonnage and location of the 25 samples of rails analyzed. As has been previously mentioned, the rails analyzed have been divided into two groups. Those which *did not break or crush in service* have been placed first in Table III, and in the other tables of this report, and embrace the first 12 samples, down to and including No. 393. The remaining 13 rails either *crushed or broke in service*. To a study of this statement, attention is now directed.

But first a brief discussion as to the influence of the various substances affecting the quality of steel, viz., carbon, phosphorus, silicon and manganese, upon the metal, will perhaps be in order. And here, at the start, I should like to frankly confess that our knowledge of the influence of these substances upon each other, and upon steel, is far from being as complete as we could wish. How thoroughly this lack of knowledge is recognized, may be inferred from the fact that one of the important duties with which the U. S. Test Commission, organized some two years ago, was charged, was this very point of the influence of the various impurities which exist in iron and steel upon the metal and upon each other in the metal. In view of this lack of knowledge, we can only, as it seems to me, apply what is already known, and, at the same time, study the results which we ourselves have obtained, with a view of deriving from them, as far as possible, the information they are calculated to teach. What, then, is the influence, so far as we know, of phosphorus, silicon, carbon, and manganese, upon steel for rails? Phosphorus, even in very small quantities, hardens steel and makes it brittle, and, at the same time, seems to render it especially liable to fracture from percussion or blows. Silicon hardens steel and renders it brittle, but in less degree than phosphorus. Carbon hardens steel and makes it brittle, and, at the same time, up to certain limits, adds to its strength, but seems to diminish its ductility or percentage of elongation, almost directly in proportion to the increase in carbon and strength. Manganese hardens steel and renders it brittle, and adds to its strength, much like carbon, but in less degree, while, at the same time, it does not seem as rapidly as carbon to diminish the ductility, or percentage of elongation, proportional to the increase of manganese and strength.

Now it will be noticed that it is said of each of these four substances, phosphorus, silicon, carbon, and manganese, that they harden

steel and render it brittle. Phosphorus and silicon seem to harden steel without adding any other desirable qualities, except, perhaps, wear; while carbon and manganese seem likewise to have important influences upon the strength and ductility of the metal.

Leaving this point now for a moment, let us examine what qualities a steel rail needs to possess. A steel rail, as it seems to me, like every other piece of metal which is subject on the one hand to *strain*, and on the other, to *abrasion* or *wear*, has two things to avoid. On the one hand, it must not be so hard and brittle as to break under the strain or blows to which it is to be subjected; while on the other, it must not be so soft as to yield too rapidly to the abrasive action which it is to be called upon to withstand. If, now, this reasoning be correct, and if the influence which we have ascribed to the carbon, phosphorus, manganese, etc., be such as they actually possess, it would seem that we ought to find, by a study of the results of the chemical analyses—since the series analyzed embraces rails which have been broken or crushed in service, as well as those which have endured long and hard service—I say it would seem that we ought to find what amount of these hardeners or brittle-makers is so great that the rails have a tendency to break or crush in service; and this point being known, it is obvious that to get the most satisfactory wear, it is only necessary to have the rails as hard as they can be made with safety. In other words, if the limit of hardeners or brittle-makers is known, it is obviously good policy to make our rails approach this limit as closely as possible.¹

A word now as to method of studying the hardeners. If we take any single hardener and follow it through the series, regarding it alone as to its influence on the steel, we will usually find that the principal thing that we will learn will be, that if any one of these hardeners is very high the rail broke in actual service. We will also learn that in the 12 rails which did not break or crush in service, the average of the carbon is 0.287 per cent., while in those which did break or crush in service it is 0.366 per cent.; while in the 11 rails

¹ In connection with this paragraph, upon the relation between the hardness and wearing quality of steel, I would like to call attention to a more full discussion of this question in a paper in these proceedings under the title, "Does the Wearing Power of Steel Rails increase with the Hardness of the Steel?" As will be seen there, the reasoning given above does not seem to be fully sustained by the facts in the case. (Oct. 12th, 1878.) [This paper will appear in our next number.—Ed.]

which withstood the highest tonnage, the average carbon is 0.30 per cent. Also, that in the 12 rails which did not break or crush in service, the average of the phosphorus is 0.077 per cent.; while in those rails which did break or crush in service, the average of the phosphorus is 0.132 per cent. And just here I may be permitted to call attention to what seems to me a very significant fact, viz., that in every case in which the phosphorus is above 0.12 per cent. the rail either broke or crushed in service. We will also learn by inspecting the analyses as to single elements, that the average manganese in the rails which did not crush or break is 0.369 per cent.; while the average in those which did crush or break is 0.521 per cent., and that the average silicon in the unbroken rails is 0.044 per cent., while in the broken or crushed rails it is 0.047 per cent.

But it seems to me that the true way to study the influence of the carbon, phosphorus, etc., upon steel is not to regard each one separately, but since all are known to render steel hard and brittle, to consider them *all as hardeners or brittle makers*, and study them in connection with each other. There are two ways in which this may be done.

(1.) We may simply add together the percentages of carbon, phosphorus, silicon and manganese, as they are given in the analysis, the sum obtained being regarded, of course, as a comparative measure of the hardness of the steel. Doing this, and we find that the average sum of these constituents in those rails which did not break or crush in service, amounts to 0.778 per cent.; while in those rails which did crush or break it is 1.030 per cent. It would, therefore, almost seem fair to conclude that we cannot with safety have the total sum of the carbon, phosphorus, silicon and manganese in our rails as high as one per cent.

(2.) There is another way of looking at these results of analysis which seems to lead to even better results than are obtained by simply adding together the percentages of the hardeners. It is a question which has been somewhat discussed among metallurgists, how much carbon, for example, would have the same influence in rendering a steel hard and brittle as 0.01 per cent. of phosphorus. Or again, how much silicon or manganese would have the same influence in this respect as 0.01 per cent. of phosphorus. I am not aware that any definite relations have ever been discovered between these substances in this respect. But it is, of course, evident if we wish to express

numerically the hardness of steel as derived from its chemical composition, we must estimate the influence of each of the hardeners in the same unit. Now I have assumed 0.01 per cent. of phosphorus as the unit of measurement, and have called this 0.01 per cent. a phosphorus unit. I have likewise assumed that 0.02 per cent. of silicon, 0.03 per cent. of carbon, and 0.05 per cent. of manganese have each the same influence in rendering a steel hard and brittle as 0.01 per cent. of phosphorus. In any analysis of steel, therefore, the phosphorus units are found by adding together the phosphorus, $\frac{1}{2}$ the silicon, $\frac{1}{3}$ the carbon, and $\frac{1}{5}$ the manganese, expressed in hundredths per cent. Applying these data to the chemical analyses of the series and we find that the average sum of the hardeners—expressed in phosphorus units—in the rails which did not break or crush in service is 27, while the average sum of those which did break or crush is 38. Examining now Table III, a little in detail and we find that with one exception, No. 395, the total sum of the phosphorus units in the good rails in no case exceeds 31, while most of them are 29 or below; while, when we examine those rails which either crushed or broke in service, in no case is the total sum of the phosphorus units less than 33. It would almost seem fair to conclude, therefore, that, measured in phosphorus units, in the manner described, we cannot have rails whose total sum of hardeners in phosphorus units is over 31 or 32. Now, as has already been stated, I think no one will affirm that for successful wear the hardeners should be lower than is consistent with safety.¹ But in the rails which have not broken or crushed in service we find only one, No. 395, whose sum of hardeners is over 31. Therefore, measured in phosphorus units, it seems clear that the sum of the hardeners in rails for use on Pennsylvania Railroad should not vary far from 30. The "total hardeners" and "phosphorus units" given in the pages of this report, which contain the diagrams of the rails analyzed, are obtained in the manner described above.

And now, how shall the hardeners be distributed? It has already been mentioned that in every case where the phosphorus is above 0.12 per cent., the rail either crushed or broke in service. Examining the phosphorus in rails which did not crush or break in service, we find that in no case is it above $0.11\frac{1}{2}$ per cent., while in almost every case it is below 0.09 per cent. Remembering now that phos-

¹ See Note to page 383.

phorus makes steel brittle and especially liable to fracture from blows, and it would, perhaps, seem fair to place the limit of phosphorus at 0·10 per cent. As to silicon, the less in the rail the better. Nevertheless, as by the Bessemer process it is impossible to make rails entirely free from silicon, a small limit must be allowed for silicon. As the process is ordinarily worked, perhaps 0·04 per cent. will not be too high a limit.

The ability of rail-manufacturers to control the amount of carbon and manganese in the steel, requires a little broader limits for these two elements. If, now, we place the carbon at from 0·25 per cent. to 0·35 per cent., and the manganese at from 0·30 per cent. to 0·40 per cent., and are able to obtain rails on this formula, which are not injured or spoiled during the manufacture, I think we will get rails which will be entirely safe, and, at the same time, give satisfactory wear. The sum of the hardeners, measured in phosphorus units, for the limits of the formula, amounts to 26 for the lower limits of carbon and manganese, and to 32 for the higher. In view of the tendency to higher carbon which has seemed to prevail for a few years past in rail manufacture, it may appear that the carbon limits given above are low. But that this is correct will, I think, be evident from the considerations which follow. Of course if we could make a formula just as we would like, it would, perhaps, be entirely scientific to take the average of the carbon, phosphorus, manganese, etc., in the best rails as the standard for this formula. Doing this for the rails which did not crush or break in service and we have, carbon, 0·287 per cent.; phosphorus, 0·077 per cent.; manganese, 0·369 per cent.; silicon, 0·044 per cent.; and the same for the 11 rails which withstood the highest tonnage, and we have, carbon, 0·30 per cent.; phosphorus, 0·091 per cent.; manganese, 0·38 per cent.; silicon, 0·045 per cent. But in view of the difficulty of obtaining low phosphorus in this country, we have put it as high perhaps as it should be, viz.: 0·10 per cent. If, now, we make high carbon, we must diminish the manganese, or our total hardeners will be too high. That carbon should not be increased at the expense of manganese will, I think, be evident from an examination of the formula given just above, derived from the average composition of the best rails, as well as the separate analyses in Table III.

Both the formulas given above show the carbon to be lower than the manganese, and both are within the limits which we have given for

carbon and manganese, viz.: 0.25 per cent. to 0.35 per cent. for carbon and 0.30 per cent. to 0.40 per cent. for manganese. Again, in the separate analyses of the rails which did not crush or break in service, in only one case, No. 413, is the carbon higher than the manganese. Moreover, if the influence which we have ascribed to manganese, viz., that it increases strength and hardness of steel without diminishing elongation as much as carbon would do, be correct, the rails which we get on a formula in which manganese is higher than carbon, will be less liable to break or crush in service, and at the same time will, perhaps, give as satisfactory wear as if the carbon had been increased and the manganese diminished.

II.—PHYSICAL TESTS AND INSPECTION.

The question now arises what physical tests and inspection shall the Pennsylvania Railroad Company prescribe to the rail manufacturers to enable it to secure rails uniform in quality?

The inspection which is at present employed seems to be amply sufficient to enable us to discard rails whose defects are evident to the eye. The question as to physical tests is not so easily answered. Nevertheless, three methods of applying physical tests suggest themselves.

(1.) The bending test now in use. It seems to me fatal to this test as at present conducted that the test bar, $\frac{3}{4}$ inch square by 12 inches long, is hammered out from a piece of the rail. It is conceded, I think, that in proper hands a piece of steel is changed by hammering. We are, therefore, not testing the steel in the rails, but a different quality of steel. If the present bending test is to be continued, I would suggest that the test bar be cut from the rail head, instead of hammered from it.

(2.) The Drop Test. This test was in use for some time on the road to determine the quality and uniformity of the rails purchased. With regard to this test it may be said that unless the foundations are very solid, much of the force of the blow is lost; so that a rail tested under a rickety drop might stand the prescribed test, which, under a firm one would yield. It would seem, therefore, that the drop test, without extreme care and inspection on the part of the railroad company to hold the rail manufacturers up to specifications, would give erroneous results. It is due to this reason, as I understand, that the drop test was abandoned.

(3.) Still another method of testing our rails suggests itself, and that is to ask the rail manufactures to provide themselves with and use the same kind of machine upon which the physical tests of the series of rails analyzed have been made, viz.: Thurston's Torsional Testing Machine. That this would be the most valuable method of securing uniformity in the rails furnished us, will be evident, it seems to me, from a study of the physical tests in Table III. It should be stated here that of all the data in regard to the physical qualities of metal furnished by this machine, which data are given in full for record, in connection with the analyses, in the preceding pages, and are tabulated in Table II; we have selected out two, viz.: Tensile Strength and Percentage of Elongation, as best expressing the value of the steel with our present knowledge of the subject. It should also be stated that the tensile strength given in this report is $\frac{94}{100}$ of that obtained by the formula for determining the tensile strength which accompanies the machine, this being found by comparative tensile and torsion tests to most nearly express the tensile strength of this grade of steel.

Turning now our attention to Table III to the rails which crushed or broke in service, and noting that in the case of No. 397 the test is not very reliable on account of inability to secure a full size test piece from the rail sent for analysis, and we find that in every case except two, No. 373 and 347, the tensile strength of these rails is 75,000 pounds or above per square inch, while the percentage of elongation is 20 per cent. or below. Turning, now, to the rails which did not break or crush in service and we find, with the single exception of No. 395, the tensile strength is between 65,000 pounds and 75,000 pounds per square inch, while the percentage of elongation is 21 per cent., or above. If, therefore, we had had specifications that our rails should have a tensile strength above 65,000 pounds per square inch, and a percentage of elongation above 20 per cent., as determined by the machine referred to, a simple inspection of Table III. shows absolutely that we would have been able to reject every rail in this series which has crushed or broken in service. The same facts, and especially the defective elongation of the rails which broke or crushed in service is made evident to the eye by an inspection of the accompanying diagrams of tests of the rails analyzed and described in this report, and from which the physical tests given in this report were computed.

In view of the discussion and considerations given above, it seems fair to conclude:—

(1.) That with our present metallurgical methods high phosphorus in rails is inconsistent with safety.

(2.) That silicon should be as low as is consistent with the successful working of the Bessemer process.

(3.) That the best range for carbon is from 0.25 per cent. to 0.35 per cent.

(4.) That the best range for manganese, all things considered, is from 0.30 per cent. to 0.40 per cent.

(5.) That the total sum of the hardeners, expressed in phosphorus units in the manner described, should not be above 31 or 32, nor below 25.

(6.) That the tensile strength of rails for use on the Pennsylvania Railroad, determined in the manner described in this report, should be above 65,000 pounds per square inch, and that the percentage of elongation determined in the same manner should be above 20 per cent.

I would, therefore, respectfully recommend that the following formula be prescribed for the chemical composition of rails for the use of the Pennsylvania Railroad, viz.:

| | |
|--|--------------------|
| Phosphorus, not above | 0.10 per cent. |
| Silicon, " " | 0.04 " |
| Carbon, between 0.25 and 0.35 per cent., with an aim at | 0.30 " |
| Manganese, between 0.30 and 0.40 per cent. with an aim at | 0.35 " |
| Sulphur and Copper, | No specifications. |
| All other impurities, not more than traces. | |

Also, that the rail manufacturers be requested to procure one of Prof. R. H. Thurston's Torsional Testing Machines, and to furnish test pieces from each "blow," ready for testing, to our Rail Inspector, or other person authorized to attend to that work, who shall test the same on this machine, and that we shall be at liberty to reject all "blows" which do not conform to the physical tests, shown to be essential in the body of this report.

And I would also recommend that the rail manufacturers be informed that we feel ourselves at liberty, at any time, to make chem-

ical analyses of the rails furnished us, and if at any time the rails are found to differ from the above specifications, it will be regarded as a breach of contract and a proper subject for adjudication.

Very truly yours,

CHAS. B. DUDLEY,

ALTOONA, Nov. 13th, 1877.

Chemist Penna. R. R. Co.

EFFECT OF THE MOTION OF THE AIR WITHIN AN AUDITORIUM UPON ITS ACOUSTIC QUALITIES.

By W. W. JACQUES,

Fellow in Physics of the Johns Hopkins University.

It is the purpose of this paper to give an account of some experiments made for the purpose of determining the effects of the currents of air within an auditorium, upon its acoustic qualities. These experiments are in three series. The first being a laboratory investigation into the effects of currents of air upon a ray of sound. The second and third, studies, by different methods, of the effects of the currents of air in a lecture hall and a theatre, upon the waves of sound.

Since the air of a hall is the medium by which sound is conveyed from the speaker or singer to the hearer, it would certainly seem of fundamental importance that this air should be in the condition best suited to the propagation of sound. Experiments made by the author, in a considerable number of halls, show that the atmosphere is almost invariably disturbed by currents of air of varying density crossing the room in all directions. These currents have been traced out with thistle balls and their velocity measured with the anemometer. The estimates of density have been made from the velocity of motion. Now the experiments of Prof. Tyndall have shown that currents of air of varying density form one of the chief obstacles to the propagation of sound-waves. The author, in repeating these experiments in a somewhat modified form, found that such currents of air not only decrease the intensity of a sound-wave, as Prof. Tyndall has shown, but that they actually modify its form, and so give rise to great indistinctness. The experiments were made as follows: At *A* was placed a source of sound,

A + — + — + — + — + *E*,