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SUPERHEATED STEAM IN LOCOMOTIVE SERVICE

(A REVIEW OF PUBLICATION NO. 127 OF THE CARNEGIE INSTITUTION OF WASHINGTON)

BY

W. F. M. GOSS

UNIVERSITY OF ILLINOIS
ENGINEERING EXPERIMENT STATION

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BY W. F. M. GOSS

DEAN OF THE COLLEGE OF ENGINEERING
DIRECTOR OF THE ENGINEERING EXPERIMENT STATION
DIRECTOR OF THE SCHOOL OF RAILWAY ENGINEERING AND ADMINISTRATION

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PREFACE

Publication No. 127, of the Carnegie Institution of Washington, entitled, "*Superheated Steam in Locomotive Service*", is a publication of 144 pages, dealing with a research which was carried on in the laboratory of Purdue University, during the writer's connection with that University. It presents, in tabulated and graphical form, the full record of observed and derived results.

In this Review, the text of the original publication has been freely quoted, and the conclusions and arguments by which they are sustained, appear as given in the orginal publication. This Review, therefore, takes the form of a resumé of the research and its results, the complete record of which is available elsewhere.

Acknowledgments are due Mr. F. W. Marquis for the editorial work incident to this Review.

W. F. M. Goss

April, 1912

SUPERHEATED STEAM IN LOCOMOTIVE SERVICE

I. INTRODUCTION

1. *A Summary of Conclusions.*—The results of the study concerning the value of superheated steam in locomotive service, the details of which are presented in the succeeding pages, may be summarized as follows:

1. Foreign practice has proved that superheated steam may be successfully used in locomotive service without involving mechanism which is unduly complicated or difficult to maintain.

2. There is ample evidence to prove that the various details in contact with the highly heated steam, such as the superheater, piping, valves, pistons, and rod packing, as employed in German practice, give practically no trouble in maintenance; they are ordinarily not the things most in need of attention when a locomotive is held for repairs.

3. The results of tests confirm, in general terms, the statements of German engineers to the effect that superheating materially reduces the consumption of water and fuel and increases the power capacity of the locomotive.

4. The combined boiler and superheater tested contains 943 sq. ft. of water-heating surface and 193 sq. ft. of superheating surface; it delivers steam which is superheated approximately 150°. The amount of superheat diminishes when the boiler-pressure is increased, and increases when the rate of evaporation is increased, the precise relation being

$$T = 123 - 0.265\,P + 7.28\,H$$

where T represents the superheat in degrees F., P the boiler-pressure by gauge, and H the equivalent evaporation per foot of water-heating surface per hour.

5. The evaporative efficiency of the combined boiler and superheater tested is

$$E = 11.706 - 0.214\,H$$

where E is the equivalent evaporation per pound of fuel and H is the equivalent evaporation per hour per foot of water-heating and superheating surface.

6. The addition of the superheater to a boiler originally designed for saturated steam involved some reduction in the total area of heat-transmitting surface, but the efficiency of the combination, when developing a given amount of power, was not lower than that of the original boiler.

7. The ratio of the heat absorbed per foot of superheating surface to that absorbed per foot of water-heating surface ranges from 0.34 to 0.53, the value increasing as the rate of evaporation is increased.

8. When the boiler and superheater are operated at normal maximum power, and when they are served with Pennsylvania or West Virginia coal of good quality, the available heat supplied is accounted for approximately as follows:

	Per cent
Absorbed by water	52
Absorbed by steam in superheater	5
Utilized	57
Lost in vaporizing moisture in coal	5
Lost in CO	1
Lost through high temperature of escaping gases	14
Lost in the form of sparks and cinders	12
Lost through grate	4
Lost through radiation, leakage, and unaccounted for	7

9. The water consumption under normal conditions of running has been established as follows:

Boiler-pressure	Corresponding Steam per i. h. p. hr.
lb.	lb.
120	23.8
160	22.3
200	21.6
240	22.6

The minimum steam consumption for the several pressures is materially below the values given. The least for any test was 20.29 lb.

10. The coal consumption under normal conditions of running has been established as follows:

Boiler-pressure	Coal Consumed per i. h. p. hr.
lb.	lb.
120	3.31
160	3.08
200	2.97
240	3.12

11. Neither the steam nor the coal consumption is materially affected by considerable changes in boiler-pressure, a fact which justifies the use of comparatively low pressures in connection with superheating.

12. Contrary to the usual conception, the conditions of cut-off attending maximum cylinder efficiency are substantially the same for steam superheated 150° as for saturated steam. With superheated steam, when the boiler-pressure is 120, the best cut-off is approximately 50 per cent stroke, but this value should be diminished as the pressure is raised, until at 240 lb., it becomes 20 per cent.

13. Tests under low steam pressures, for which the cut-off is later than half stroke, give evidence of superheat in the exhaust.

14. The saving in water consumption and in coal consumption per unit power developed, which was effected by the superheating locomotive, *Schenectady No. 3*, in comparison with the saturated-steam locomotive *Schenectady No. 2*, is as follows:

Saving in Water Consumption				Saving in Coal Consumption			
Boiler-pressure	Locomotive			Boiler-pressure	Locomotive		
	Saturated Steam	Super-heating	Gain		Saturated Steam	Super-heating	Gain
lb.	lb.	lb.	per cent	lb.	lb.	lb.	per cent
120	29.1	23.8	18	120	4.00	3.31	17
160	26.6	22.3	16	160	3.59	3.08	14
200	25.5	21.6	15	200	3.43	2.97	13
240	24.7	22.6	9	240	3.31	3.12	6

15. The power capacity of the superheating locomotive is greater than that of the saturated-steam locomotive.

II. Foreign Practice in the Use of Superheated Steam in Locomotive Service

2. The Use of Superheated Steam in Locomotive Service.—In the year 1898, the first superheating locomotives, two in number, were placed in service upon the Prussian State Railway. As might have been expected in machines of new design, a number of difficulties were encountered in their operation, but one by one these were overcome. Special forms of pistons, of piston-valves, and of rod packing, designed better to withstand exposure to steam of high temperature, were introduced. In 1899, the two original superheating locomotives were followed by two superheating express locomotives, and in 1900, by two superheating tank locomotives, the superheaters of all being of the same design. While these six trial engines were by no means perfect, they served to show that highly superheated steam might be generated and successfully employed in locomotive service. As a result of the experience thus gained, the Prussian State Railway has, since 1900, made large purchases of the new type of engine. So rapidly has their use increased that in April, 1907, there were 682 in service and 467 in the process of building, or covered by orders; while in the whole Empire of Germany there were 1320 locomotives of the new type running or on order. The locomotive builders of Germany draw their support from many different countries. While building superheating locomotives for the Empire, they have stimulated interest in and created a demand for the new type in other countries. Thus, Belgium, Russia, Austria, Sweden, Switzerland, Italy, France, Holland, England, Denmark, Spain, Greenland, Canada, and South America all have their German-designed and German-built superheaters, and at the time just quoted, April, 1907, the total number of superheating locomotives in service or on order for all countries approached closely to 2000. This rapid extension of a new practice expresses the degree of confidence which many engineers have in its value. In fact, the introduction of the superheater has become a world-wide movement, and as such it is entitled to the respect and the thoughtful attention of American engineers.[1]

3. *Types of Superheaters.*—The original Schmidt locomotive superheater was of the smoke-box type, and practically half of the superheating locomotives now (1907) in operation on the Prussian State Railway are of this design. The later introduction of the Schmidt fire-tube type of superheater has, however, proved so satisfactory that the manufacture of the earlier smoke-box type has in recent years been discontinued. All of the superheating locomotives of the Prussian State, now under construction, are to be equipped with this later type. Other forms of superheaters have been proposed and one of these has been used experimentally, but the practice of superheating in Europe as it exists to-day implies the use of the Schmidt fire-tube superheater. The introduction of this superheater (Fig. 1 and 2) requires that the

[1] Supplementing the statements of this paragraph, which were formulated in 1907, it may be stated that the number of superheating locomotives in Europe is now (1911) reported as 7000 and that the number in this country, in service or under order, is approximately 2000.

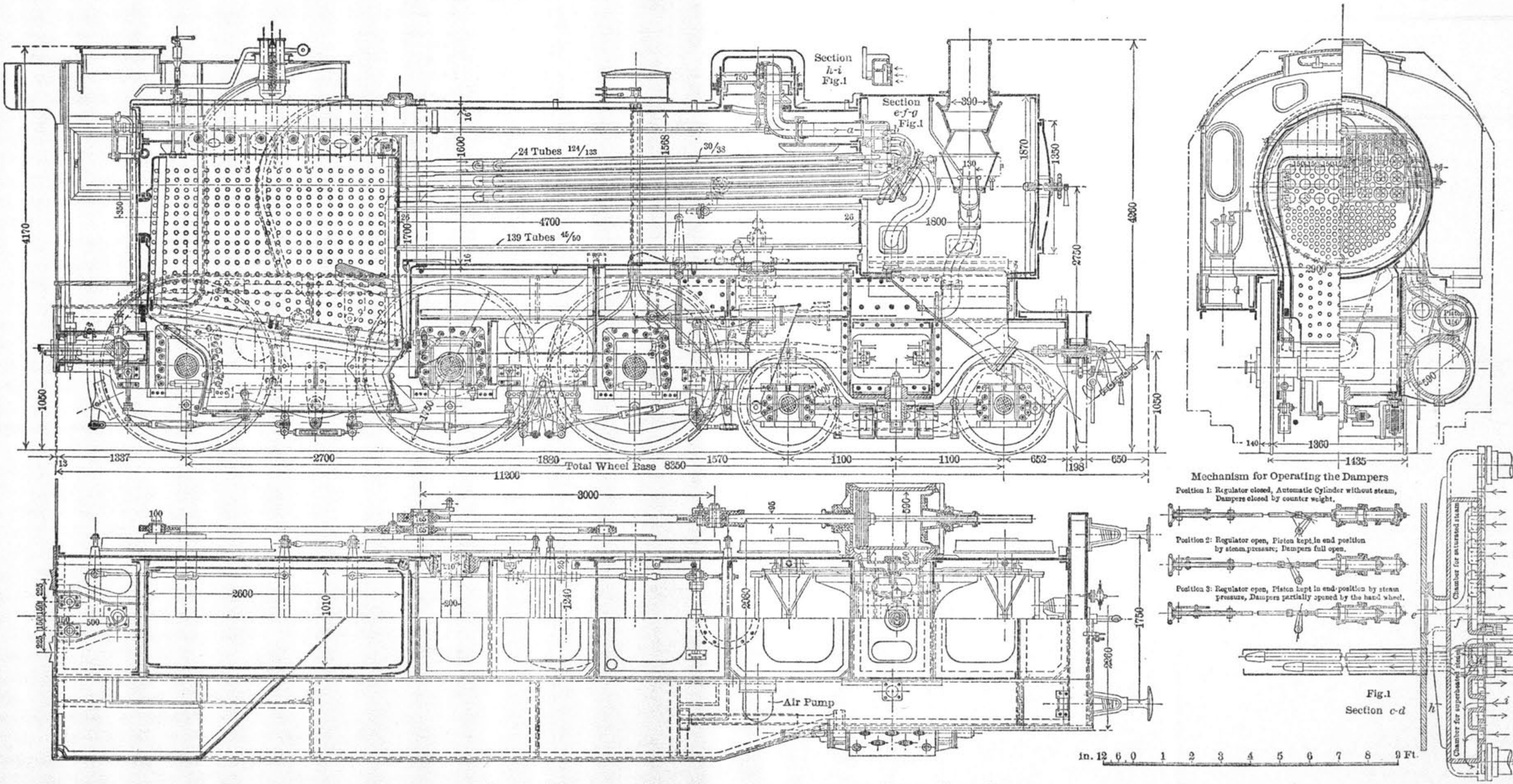

FIG. 1. A SUPERHEATED STEAM EXPRESS LOCOMOTIVE OF THE PRUSSIAN STATE RAILWAY

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upper part of the boiler be fitted with from two to four rows of large smoke-tubes which are expanded into the fire-box and front tube-sheet of the boiler, in a special manner. These tubes have an inside diameter ranging from 4 to 5.25 in., which diameter is reduced somewhat near the fire-box end. Inserted in each of these large tubes is a superheater element or section consisting of a set of pipes bent in the form of a double U and connected at the smoke-box end to a header, the whole arrangement being such as to form a continuous double-looped tube. Each particle of steam in passing from the boiler to the branch-pipes has to traverse some one of these elements, making four passes in the movement[1].

The ends of each element extend into the smoke-box, where they are bent slightly upward and are expanded into a common flange which is secured to a steam-collector by a single central bolt. Two slightly different methods are employed in arranging the pipe-ends in the smoke-box. By the first method, the pipes are bent upward only (Fig. 2), as already described, in which case the flange-joints are horizontal, and the flanges are fastened by vertical bolts, the heads of which are movable in slots in the bottom of the collector casting. By the second method (Fig. 1) the pipes are carried forward and are bent upward and backward in such a manner as to connect with vertical flanges secured by horizontal studs to the steam-collector. Both methods have been extensively used, the latter being the one which has been finally selected by the Prussian State Railway. The construction of the steam-collector and the manner in which connection is made with the steam-pipes and with the branch-pipes is best shown by the figures.

By the construction which was adopted, the gases of combustion are divided, one part passing through the ordinary boiler-tubes and the other through the larger tubes. In the larger tubes, a portion of the heat is given up to the water surrounding the tubes, and a portion to the steam contained in the superheating elements inclosed. The flow of heat through the large tubes is controlled by dampers hinged or pivoted below the steam-collector in the smoke-box. As long as the throttle of the locomotive is closed, these dampers are kept closed, either by a counterweight or by a spring, but, as soon as the throttle is opened, they are opened

[1] In the original arrangement, each element consisted of two separate single-loops, but it has been found that the double looping of the superheating pipes, by increasing the velocity at which the steam travels, results in the better protection of the tubes against overheating and in the more effective superheating of the steam.

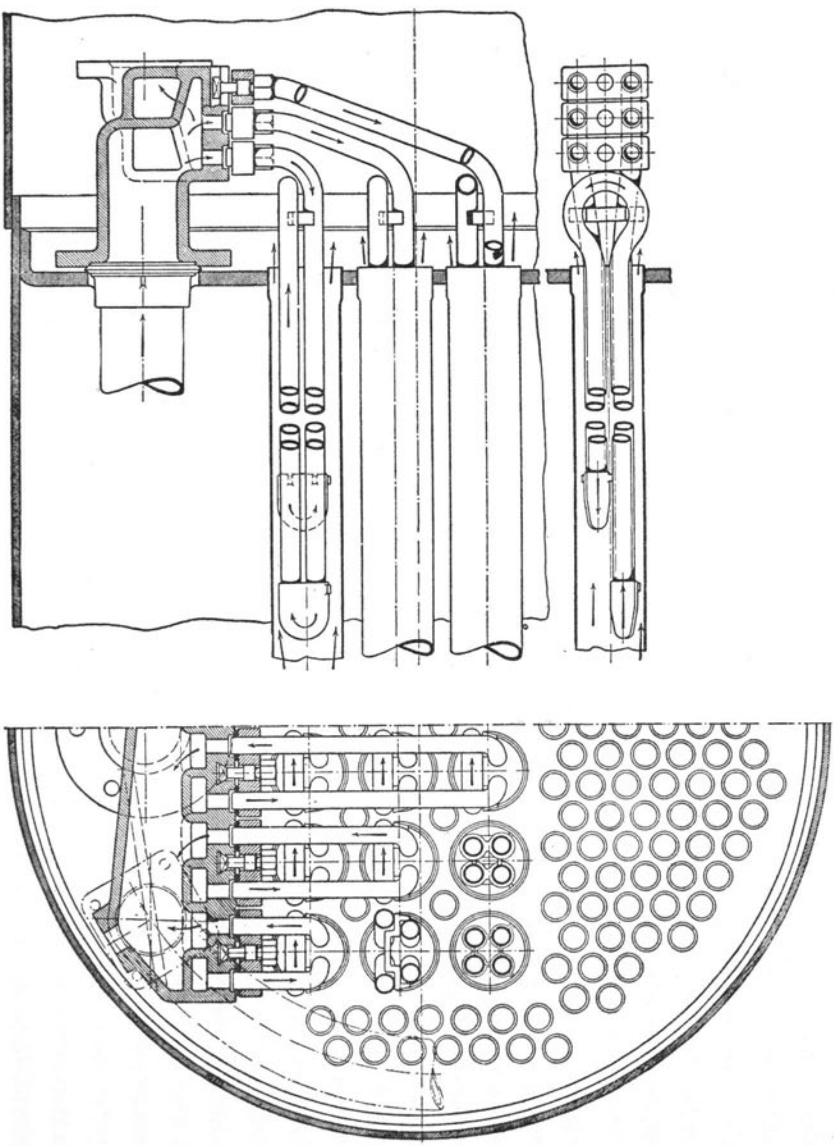


FIG. 2. SMOKE-TUBE SUPERHEATER, WILHELM SCHMIDT'S PATENT

simultaneously by means of a piston working in a small automatic steam-cylinder. Thus, while getting up steam or while standing at stations, under any conditions, in fact, for which no steam is passing the loops of the superheater to keep them cool, no gases of combustion can pass through the large smoke-tubes to heat them. This arrangement provides against the overheating of the superheating pipes. It is only when the throttle is open, and when, as a consequence, steam is passing through the superheating pipes, that the dampers which control the circulation of the heated gases open and permit them to have contact with the superheating elements.

The limited number of the superheating elements and their small diameter provide a comparatively small area through which the steam must pass from the boiler to the engine-cylinders. The degree of restriction constitutes one of the important elements in the design of the Schmidt superheater. It has been found that the superheating surface is made more effective as the flow of the circulating steam is made more rapid; the statement by a German authority being that for constant-temperature differences, the rate of heat transmission varies as the square root of the velocity of the steam. By maintaining high velocities through the superheating pipes, therefore, two important results are accomplished: first, a higher degree of superheat is obtained than would otherwise be possible; and, second, the protection of the superheating elements against overheating is made more complete. The degree of restriction employed in the Schmidt superheaters is such that when the engine is working at full power with the throttle wide open, the drop in pressure between the boiler and the valve-box is approximately 15 lb. It is stated that under these conditions the velocity through the superheating tubes varies from 325 to 400 ft. per sec.

The superheaters thus described have an abundant capacity. Locomotives fitted with them are provided with a dial thermometer showing the temperature of the steam in the valve-box. After starting, this temperature steadily rises until it exceeds 300° C. (572°F.), after which the dampers controlling the circulation of heat through the superheater-tubes are partially closed by means of mechanism which connects with a hand-wheel in the cab. This manipulation of the dampers is such as will check the rising temperature before the maximum safe limit of 350° C. (662° F.) is reached.

It is said that there is now no difficulty in designing, for any locomotive, a superheater which will give with certainty any desired degree of superheat within limits which are practicable. Rules governing all portions of the design have been formulated and are strictly adhered to by the Wilhelm Schmidt Company, Limited, in working out the details of their design. Such rules have not yet been published.

4. *The Maintenance of Superheating Locomotives.*—From such inspection in shops and roundhouses as could be had, and from the testimony of those concerned in the handling of locomotives at terminals, it appears reasonably certain that no special difficulty is experienced in the maintenance of those details which are peculiar to a superheating locomotive. This statement applies especially to the superheater itself. In a repair-shop, a boiler was inspected from which the superheater had been drawn bodily and laid upon blocking beyond the boiler. All of the ordinary small tubes of the boiler were being cut out in preparation for retubing. The superheater, meanwhile, had been judged to be in good condition, and it was to go directly back to its place without having any work done upon it. Even those German engineers who are not friendly to the superheating locomotive frankly say that there is no difficulty in maintaining the present type of fire-tube superheater.

With respect to the care bestowed in freeing the large flues containing the superheating tubes from deposits of fuel and ash, the superheating locomotive requires additional labor. The extent of this depends, however, upon the nature of the fuel used. The fact that solid matter entering the large tubes from the fire-box comes upon the ends of the loops of the superheater, as upon an obstacle set in their path, naturally leads to such a result. With some grades of fuel little or no difficulty arises, while with other fuels it is difficult to get a locomotive over its division. Roundhouses, therefore, which handle superheating engines, are equipped with long pipe-nozzles through which a blast of air is delivered for the purpose of clearing the large flues. Upon at least one division inspected, an equipment of these nozzles was carried upon locomotives. In certain roundhouses a set of small tools from 3 to 6 ft. long, with sharp cutting-edges, usually at right angles to the axis, which could be inserted from the fire-box, was in use for the purpose of cutting out the deposits in the tubes. A round of inspection gives abundant evidence that the stopping-up of flues is a serious matter. Engineers friendly to the use of superheating locomotives admitted that there are coals which are serviceable in other classes of locomotives which can not be used by the superheating locomotives.

In the matter of maintaining valves and valve-gears, much has already been said. There appears to be no difficulty in maintaining lubrication in the presence of superheated steam, and it is repeatedly asserted that the wear of piston-rings and of valve-parts in the superheating locomotive is of less consequence than the similar wear which occurs in compound and simple engines using saturated steam.

It will be remembered that in Germany the natural competitor of the superheating locomotive is the compound, and that in passenger service the compound is of the four-cylinder type. This fact is often mentioned as important from a roundhouse point of view, since it is easier to wipe the superheating locomotives after a run than the compounds, a statement which, of course, grows out of the fact that there are fewer parts to receive attention. Whether the superheating passenger engines are on the whole easier to maintain than the balanced compounds is a matter concerning which little definite information can be obtained. It is admitted everywhere that the absence of balance for reciprocating parts in the superheating engines tends to increase the cost of maintenance, and it is not unlikely that the newness of the type also operates to its disadvantage. The compounds, on the other hand, with their duplication of parts and their higher boiler-pressures, demand attentions which are peculiar to their type. In Berlin, where superheating is in the ascendancy, it is generally agreed that the problems of maintaining the superheating engine are far more simple than those of maintaining the compound, while in Hanover, which is the home of the balanced compound, opinions are likely to be the reverse of this.

5. *The Economy Resulting from the Use of Superheating Locomotives*.—The degree of economy attending the operation of the superheating locomotive is probably not definitely understood in Germany. There are as yet no locomotive-testing plants in the Empire, and while the results of many road tests are reported, they are upon a comparative rather than upon an absolute basis. As the superheating locomotives are all of recent design, there are no simple locomotives using saturated steam whose performance can fairly be compared with them. Partisan advocates of the superheating locomotive not infrequently claim for it a sav-

ing in water of from 30 to 40 per cent and in coal from 25 to 35 per cent when compared with the simple locomotive, and some data are presented in support of such claims. It is also claimed that the superheating locomotives consume 25 per cent less water and 10 per cent less coal than the four-cylinder balanced compounds. Such statements, of course, reflect partisan opinions. One who is a close student of these matters and whose position is such as to make him quite independent in opinion believes that the saving in water could be taken at from 20 to 25 per cent and in coal at from 15 to 20 per cent, as compared with the consumption of simple locomotives.

When comparisons are made between the performance of a superheating locomotive and that of the compound, partisan advocates of the superheating claim an advantage for their type of machine. Conservative experts give the opinion that the performance of the superheating locomotives is without question equal to that of the compound. Others, whose opinions are perhaps entitled to equal attention, affirm that it is better, but how much better they are not willing to say. The performance sheet of a division operating balanced compounds and also superheating locomotives in the same service shows that the coal used per 1,000 kilometers run by superheating locomotives varied from 12.1 tons to 14.4 tons and for the balanced compounds from 8.9 to 14.2 tons. Upon the basis of these statements, it would appear safe for the American engineer to assume that the superheating locomotives are as economical in their use of water and fuel as are the highest types of compounds. This applies to a practice which involves locomotives using a high degree of superheat on the one hand, and a well-perfected type of compound on the other.

6. *Concerning the Trend of Foreign Practice with Reference to Superheating in Locomotive Service.*—In the development of this chapter, attention has been given thus far to the single type of locomotive which may properly be referred to as the Garbe type. Taking now a more general view of the tendency manifested in Europe with reference to superheating, mention may be made of several significant facts. First, it should be noted that while it is the opinion of the officials of the Prussian State Railway that success in superheating depends in large measure upon the adoption of those details in the design of machine parts which are peculiar to their special type, this view is not shared by the locomotive builders of Germany or by engineers not connected with

railway service. While, therefore, the high character of the details of the Garbe engine from the designer's point of view is unquestioned, it is probably true that the superheater may enter as a detail into the design of any well-considered locomotive without disturbing other details.

Among certain foreign engineers, the plan of combining the superheater with the compound engine has been favored, and a considerable number of locomotives have been constructed on this plan. In favor of such an arrangement, it is urged that the presence of the superheater will serve to reduce the coal consumption of the compound to the extent of approximately 7 per cent. Against it are urged the objections that the two systems are in the main antagonistic; that the compound, to work effectively, must be supplied with steam at high pressure, whereas it is counted as one of the advantages of the superheating locomotive that without sacrifice of its efficiency, it may employ much more moderate pressures. The American engineer is likely to concur in the opinion that the saving which can result from the combination is too small to justify the complication incident to the presence of both systems.

It is an interesting fact that in France, the birthplace of the balanced compound, there is to-day an extremely active interest in the practice of superheating as developed in Germany. A commission representing the leading railways of France has, after a careful investigation, made a report most favorable to the new practice. While it is not likely that superheating locomotives will, in France, be allowed to take the place of the highly developed types of balanced compound common in that country, and while it is not likely that superheating will be employed to any considerable extent in connection with the compounds, there are still in the freight and switching service of France many simple engines, and the hope is expressed that the superheater may be the means of improving them. Meantime, in Belgium, where the advantage of the balanced locomotive is well understood, and the objections of combining the superheater with the balanced compound engine are appreciated, practice is involving a four-cylinder balanced simple engine with the superheater, an arrangement which gives promise of very great success.

7. *Arguments Favoring the Adoption of Superheating.*—These, as based upon results derived from German experience, may be set forth as follows:

1. The advantages of superheated steam may be had in practice without involving undue complication in mechanism and without involving a degree of attention in maintenance in excess of that demanded by a simple engine.

2. The superheating locomotive will perform its service efficiently while employing a comparatively low steam-pressure, a condition which tends to reduce cost in maintenance. The presence of the superheater does not necessitate any qualification of this statement.

3. Superheating will materially reduce the consumption of water, which in bad-water districts constitutes a matter of importance.

4. The superheating locomotive will reduce the fuel consumption probably to that required by a first-class compound engine.

5. As to power and capacity, the superheating locomotive is tc be compared with the compound rather than with the simple engine. It may be forced to limits of power far beyond those possible with simple engines.

6. In operation the degree of superheat increases with increased rate of power, which tends to conserve the steam supply as the demand for power is increased.

III. Tests to Determine the Value of Superheating in Locomotive Service

8. *Conditions Suggesting Tests.*—The fact that the efficiency of a steam engine may be improved by superheating the steam supplied it, is a matter which has long been understood and appreciated and the effect of such highly heated steam upon the process of heat interchange, which goes on in the engine cylinder, has been so carefully traced that the precise manner in which the improvement is brought about has been made a part of the common knowledge of the engineer. But the process of producing superheated steam is one which consumes heat and involves apparatus which has been expensive in first cost and difficult to maintain. Against the thermodynamic gain, therefore, which may be secured by the use of superheated steam is to be set the cost of fuel necessary to produce the superheating and the interest and maintenance charges arising from the presence of the superheater. Costs resulting from these accounts are in large measure functions of the design of the superheater and of the materials which enter into its con-

struction, so that the wisdom of adopting the superheater in any branch of steam-engine practice is a matter which involves very much more than the fundamental thermodynamic theory—a fact which greatly complicates the task of the present-day student in this particular field of research. In recent years, the problem of superheater design has received generous attention, and materials possessing qualities hitherto unobtainable have been made available to the designer, so that a practice which a quarter of a century ago was generally regarded as of doubtful expediency has gradually been advanced to a position of great promise.

Attention has been called to the extensive use of superheated steam in the locomotive practice of Germany and to the influence of this practice upon that of other European countries and of America. In America, especially, there are evidences of a strong professional interest which is doing much to secure for our country a more general introduction of superheating locomotives. Under the stimulus of these developing conditions, it was natural that the energies of the locomotive-testing laboratory of Purdue University should have been turned in the direction of superheated steam. The University's locomotive, designed originally for work under high steam pressure, was converted into a superheating locomotive, and with the aid of many friendly influences has since been subjected to an elaborate series of tests, the results of which define the performance which is to be expected from such a machine. This performance, when compared with that of a normal locomotive using saturated steam, should aid in making up an estimate of the gain to be secured by the use of the superheater in locomotive service.

9. *The Means Employed.*—The locomotive laboratory of Purdue University, established in 1891 for the instruction of students and for research, has been many times described[1]. The locomotive, which for a number of years had been operated upon this plant, is of the single-expansion American type, having a boiler designed to carry working pressures as high as 250 lb. per sq. in[2]. In preparation for a new program of tests, this locomotive was fitted with a Cole superheater, the boiler and other parts being rebuilt, so far as was necessary, to make the reconstructed machine a normal superheating locomotive which, from the time of reconstruction, has been known as *Schenectady No. 3.*

[1] "The Purdue University Locomotive Testing Plant;" also Locomotive Testing Plants" (A. S. M. E.).

[2] "For complete description with drawings of this locomotive, see High-Steam Pressures in Locomotive Service, Publication No. 66, Carnegie Institution of Washington.

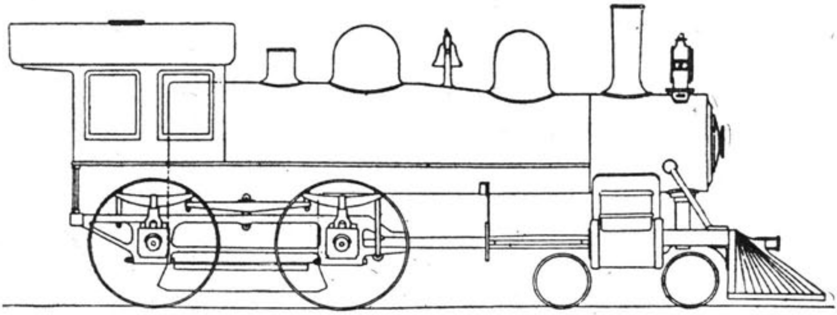


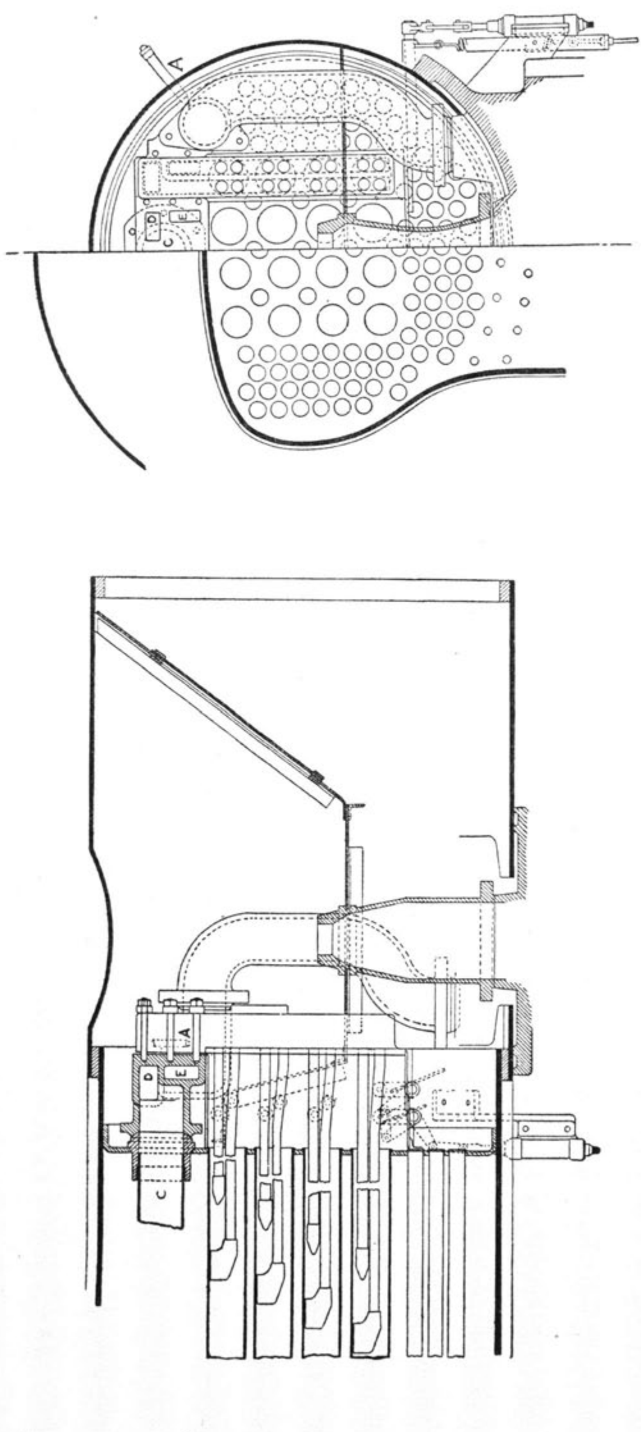
FIG. 3. OUTLINE ELEVATION OF LOCOMOTIVE

10. *The Principal Characteristics of Locomotive Schenectady No. 3* are as follows:

Type	4-4-0
Total weight (pounds)	109,000
Weight on four drivers (pounds)	61,000
Valves (type, Richardson balance):	
Maximum travel (inches)	6
Outside lap (inches)	$1\frac{1}{8}$
Inside lap (inches)	0
Ports:	
Length (inches)	12
Width of steam-port (inches)	$1\frac{1}{2}$
Width of exhaust-port (inches)	3
Total wheel-base (feet)	23
Rigid wheel-base (feet)	$8\frac{1}{2}$
Cylinders:	
Diameter (inches)	16
Stroke (inches)	34
Drivers, diameter outside of tire (inches)	$69\frac{1}{4}$
Boiler (type, extended wagon-top):	
Diameter of front-end (inches)	52
Length of fire-box (inches)	$72\frac{1}{16}$
Width of fire-box (inches)	$34\frac{1}{4}$
Depth of fire-box (inches)	79
Number of 2-inch tubes	111
Number of 5-inch tubes	16
Length of tubes (feet)	11.5
Heating-surface in fire-box (square feet)	126
Heating-surface in tubes, water side (square feet)	897
Heating-surface in tubes, fire side (square feet)	817
Total water-heating surface, including water side of tubes (square feet)	1,023
Total water-heating surface, including fire side of tubes (square feet)	943
Superheater; type, Cole return tube:	
Outside diameter of superheater tubes (inches)	$1\frac{1}{4}$
Number of loops	32
Average length of tube per loop (feet)	17.27
Total superheating surface based upon outside surface of tubes, surface of headers neglected (square feet)	193
Total water and superheating surface, including water side of boiler tubes (square feet)	1,216
Total water and superheating surface, including fire side of boiler-tubes (square feet)	1,136
Total water and superheating surface, accepted for use in all computations (square feet)	1,216

Ratio of heating-surface based on water side to that based on fire side	1.074
Thickness of crown sheet (inch)	$\frac{7}{16}$
Thickness of tube-sheet (inch)	$\frac{9}{16}$
Thickness of side and back sheet (inch)	1
Diameter of radial stays (inches)	1⅛
Driving-axle journals:	
Diameter (inches)	7½
Length (inches)	8⅛

11. *The Cole Superheater*, as applied to the locomotive, is well shown in Fig. 4. It consists chiefly of a series of return-tubes extending inside of certain of the flues which make up a portion of the water-heating surface. To make room for the superheater, the upper central portion of the usual flue-space is taken by sixteen 5-inch flues, which are reduced to a diameter of 4 in. for 7 in. of their length at the fire-box end and increased to a diameter of 5 $\frac{1}{16}$ in. at the front tube-sheet. They have a length between flue sheets of 138 in. In each of these sixteen flues, there is an upper and a lower line of superheating tubes. Each line extends from a steam-pipe header in the smoke-box back into its flue to a point near the back tube-sheet, where it meets and is screwed into a return-pipe fitting of special design. From the second of the two openings in this fitting, a similar pipe extends forward through the flue and into the smoke-box to a second header, from which branch-pipes lead to the cylinders. All together, there are 32 of these loops. In 13 of the flues, the lower loops are 116 $\frac{3}{8}$ in. long, extending into the flue within 2 ft. 5 in. of the back of the tube-sheet. In the other 3 flues the loops are, respectively, 3 ft., 2 ft., and 1 ft. shorter than the normal. The upper loop in each flue is, in all cases, approximately 9 in. shorter than the lower loop. The headers to which the pipes of the superheater connect at the smoke-box end are of cast steel. They have walls three-eighths of an inch thick and are cored in such a manner that all steam passing the throttle-valve must traverse some one of the several loops. In its passage from the boiler, the steam leaves the dry-pipe *C*, Fig. 4, and passes into the headers through the openings *D* in the top part of the tee-head. It then flows downward through the passage in one side of this header and passes back toward the fire-box through the 8 tubes which are joined to it. At the castings which form the return bends, its direction is reversed and it passes back through the return tubes to the passage in the other side of the header. It then passes upward into the lower half of the tee-head *E*, and from there into the branch steam-pipes.



G. 4. Cole Superheater

12. *A Comparison of the Dimensions* of the boiler as set forth above with those of *Schenectady No. 2*, follows. The exhibit shows the extent of the change brought about by the installation of the Cole superheater.

Number of 2-in. flues displaced by sixteen 5-inch flues, necessary to give place to the superheater	89
Reduction in water-heating surface (square feet)	299
Reduction in water-heating surface (per cent)	22.6
Heating-surface replaced by the installation of the superheater (square feet)	193
Heating-surface replaced by the installation of the superheater (per cent of surface removed)	64.5
Reduction in total transmitting-surface (water and superheating) (square feet)	106
Reduction in total transmitting-surface (water and superheating) (per cent)	8

13. *The Tests* were begun in November, 1906, and were completed, so far as the series at present under consideration is concerned, in July, 1907. During this period of 8 months, the experimental locomotive ran 1,417,995 revolutions, which is equivalent to 4,851 miles.

The tests were run at pressures of 240, 200, 160, and 120 lb., respectively, the number of tests under each pressure being sufficient to disclose the performance when running at several different speeds and cut-offs. The exhibit is especially full for a pressure of 160 lb., a pressure which is a close approach to that commonly used in connection with superheating locomotives. Altogether, 38 tests were run. A concise statement of the pressure, speed, and cut-off represented is set forth by Fig. 5 to 8, in which each

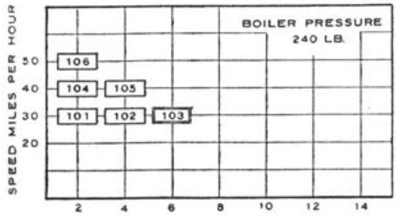


FIG. 5. TESTS AT 240-LB. PRESSURE

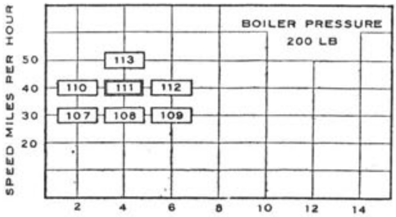


FIG. 6. TESTS AT 200-LB. PRESSURE

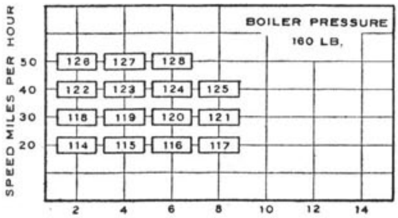


FIG. 7. TESTS AT 160-LB. PRESSURE

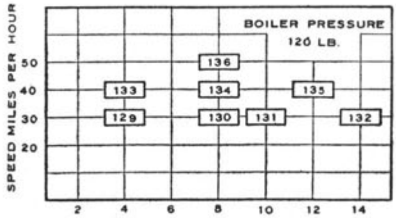


FIG. 8. TESTS AT 120-LB. PRESSURE

rectangle represents the general conditions of one test. Concentric rectangles represent conditions for which duplicate tests were run; the enclosed numeral is the serial number of the tests.

All results presented are directly comparable with corresponding results obtained when using saturated steam, which are set forth in the published account of a previous research.[1]

IV. Performance of Boiler and Superheater

14. Attention should early be called to the fact that because of threatened interruptions in the running of the tests, it was thought expedient to use two grades of coal and to rely upon the results disclosed by the heat-balance of the several tests as a basis for final comparisons. Of the two fuels used, the Youghiogheny coal has been accepted as standard, and where results obtained from the Pocahontas coal have been needed in formulating conclusions, they have been reduced to equivalent results which would have been obtained had the standard coal been used throughout the work. One man served as fireman for all tests.

In the paragraphs which follow, an attempt will be made to state briefly some of the more significant facts which may be developed from the data; in some cases graphic methods are employed to emphasize their importance.

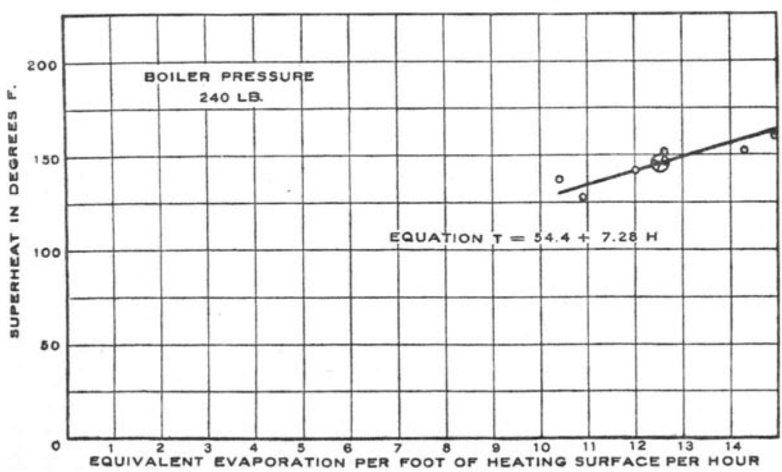


Fig. 9. Superheating as Affected by Rate of Evaporation, Boiler Pressure 240 lb.

1 *High Steam-Pressures in Locomotive Service*, by W. F. M. Goss, Publication No. 66, Carnegie Institution of Washington, reviewed and presented as Bulletin No. 26, *High Steam-Pressures in Locomotive Service*, Engineering Experiment Station, University of Illinois.

15. *Superheating.*—The observed temperature of the steam delivered from the superheater was measured by a high-grade mercurial thermometer placed in the header at a point near its opening into the left-hand branch-pipe, point *A*, Fig. 4. Fig. 9 to 12 present the extent of the superheating effect for the different rates of power to which the boiler was worked, (equivalent

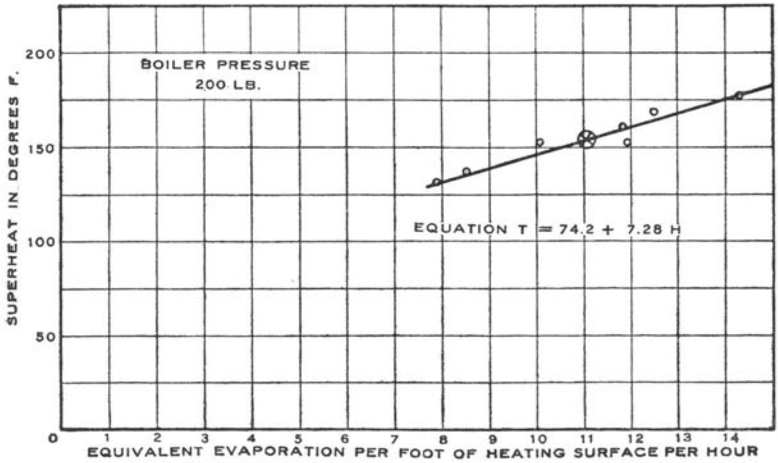


FIG. 10. SUPERHEATING AS AFFECTED BY RATE OF EVAPORATION
BOILER PRESSURE 200 POUNDS

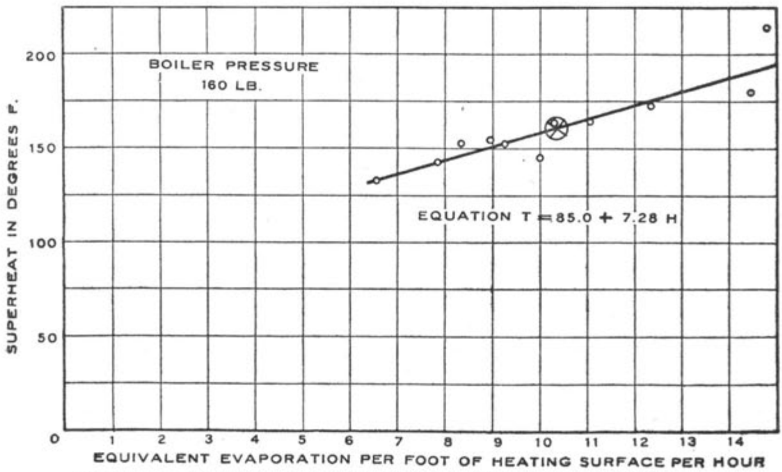


FIG. 11. SUPERHEATING AS AFFECTED BY RATE OF EVAPORATION,
BOILER-PRESSURE 160 POUNDS

evaporation per square foot of water-heating surface per hour), each diagram representing some one of the several pressures under which the boiler was operated. The ordinates and the abscissas of all points in each diagram have been averaged, and from values thus obtained, an average point, designated as a cross in a circle, has been located. Through this a straight line has been drawn which represents, with a fair degree of accuracy, all of the experimental points involved. It happens that the slope of these lines is the same for all of the diagrams under consideration. They define the change in the degree of superheat attending changes in the rate of evaporation when the boiler-pressure has the value stated.

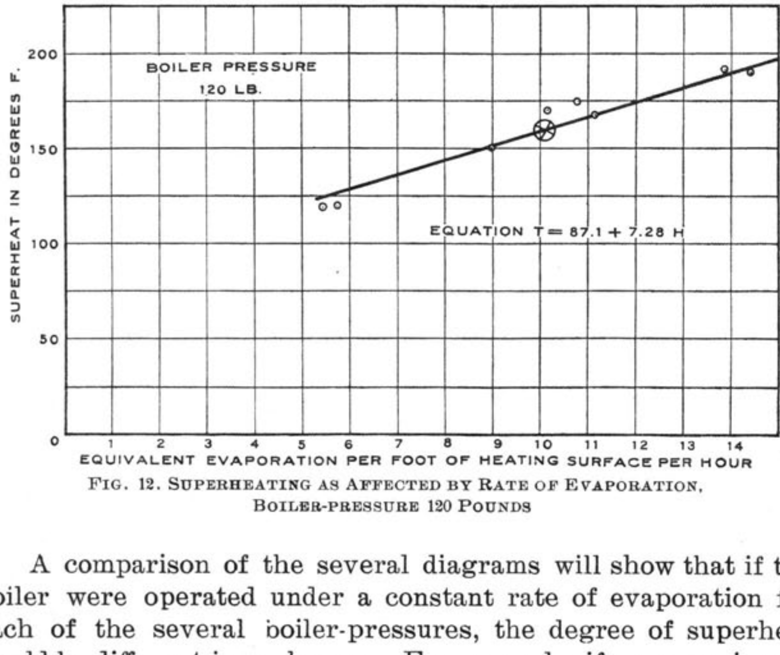


FIG. 12. SUPERHEATING AS AFFECTED BY RATE OF EVAPORATION, BOILER-PRESSURE 120 POUNDS

A comparison of the several diagrams will show that if the boiler were operated under a constant rate of evaporation for each of the several boiler-pressures, the degree of superheat would be different in each case. For example, if a comparison is based upon a rate of evaporation of 11 lb. of water per sq. foot of water-heating surface per hour, the degree of superheat will be:

170° when the boiler pressure is 120 lb.
165° " " " " " 160 "
154° " " " " " 200 "
135° " " " " " 240 "

These values are shown graphically in Fig. 13. Referring to this figure, it will be noticed that the superheat varies more rapidly for a given increment at the higher pressures than at the lower pressures, and that the line connecting the experimental points is a curve. A straight line may, however, be drawn which will represent all the experimental points with an error which in no case will be greater than 2 per cent. In the same manner, a series of straight lines may be determined, each showing the relation between boiler pressure and superheat at a different rate of evaporation. This series of straight lines may be represented by an equation, which defines the performance of the superheater for any pressure between 120 and 240 lb. gauge, with a maximum error of less than 2 per cent. The equation thus determined is

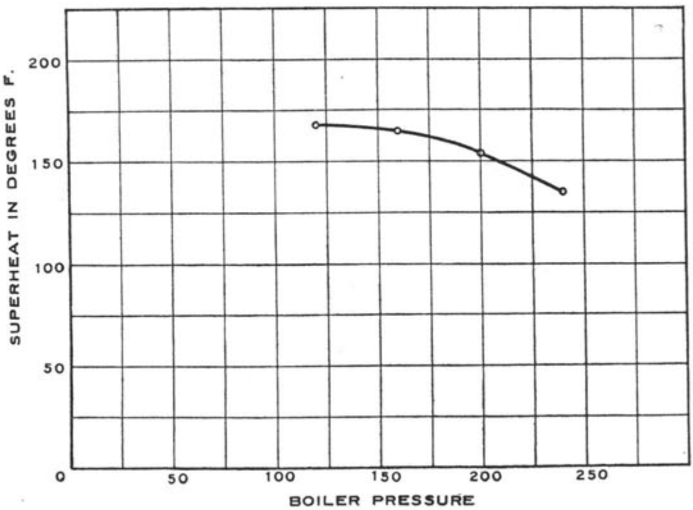


FIG. 13. DEGREES OF SUPERHEAT UNDER ALL CONDITIONS OF PRESSURE WHEN RATE OF EVAPORATION IS 11 POUNDS PER SQUARE FOOT OF HEATING-SURFACE PER HOUR

$$T = 123 - 0.265\,P + 7.28\,H$$

where T equals the number of degrees superheat; P the boiler-pressure by gauge, and H the equivalent evaporation per square foot of water-heating surface in the boiler.

16. *Draft.*—The draft produced in the front-end of the locomotive was measured at a point directly in front of the diaphragm. The rate of increase in draft values with increased rates of evaporation is well shown by Fig. 14. This figure gives the results

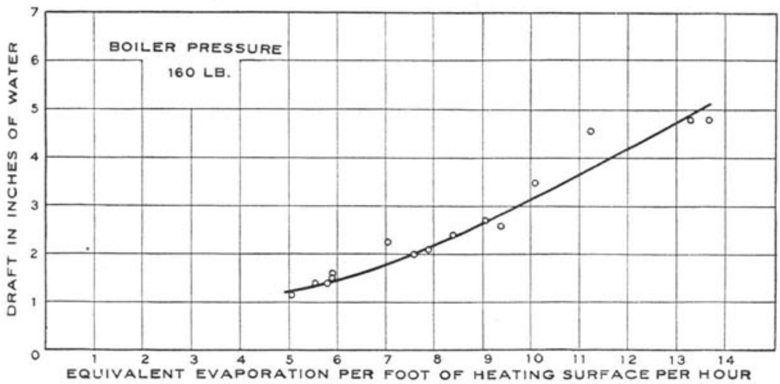


FIG. 14. DRAFT IN FRONT OF DIAPHGRAM

of tests at 160 lb. only. Curves representing points obtained at other pressures are practically identical with those shown, the fact being that changes in boiler-pressure, within the limits of the experiments, have practically no influence upon draft values. As would be expected, these depend entirely upon the rate of evaporation required.

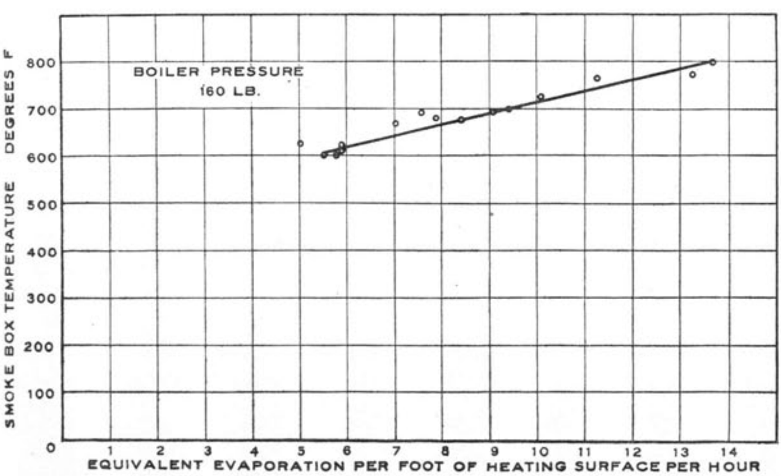


FIG. 15. SMOKE-BOX TEMPERATURE, BOILER-PRESSURE 160 POUNDS

17. *Smoke-Box Temperatures.*—The temperatures of the smoke-box gases were read by a mercurial thermometer placed midway between the diaphragm and the front tube-sheet. Fig. 15 shows the effect upon the smoke-box temperature of changes in the rate of power for a boiler pressure of 160 lb. It will be seen that the smoke-box temperature increases as the rate of evaporation is increased, an effect the significance of which is well understood. For example, when the rate of evaporation equals 6 lb. of water per sq. foot of heating-surface, the smoke-box temperature is approximately 600° F. When the rate of evaporation is increased to 12, the temperature of the smoke-box approaches 800° F. It is not far from the truth to say that a change of 1 lb. in the rate of evaporation produces a change of 20° in the temperature of the smoke-box. The smoke-box temperature shows a slight tendency to increase with increase of pressure, other things being the same, but the differences are too slight to be accepted as material.

18. *Evaporative Efficiency of the Combined Boiler and Superheater.*—The relation between the pounds of water evaporated

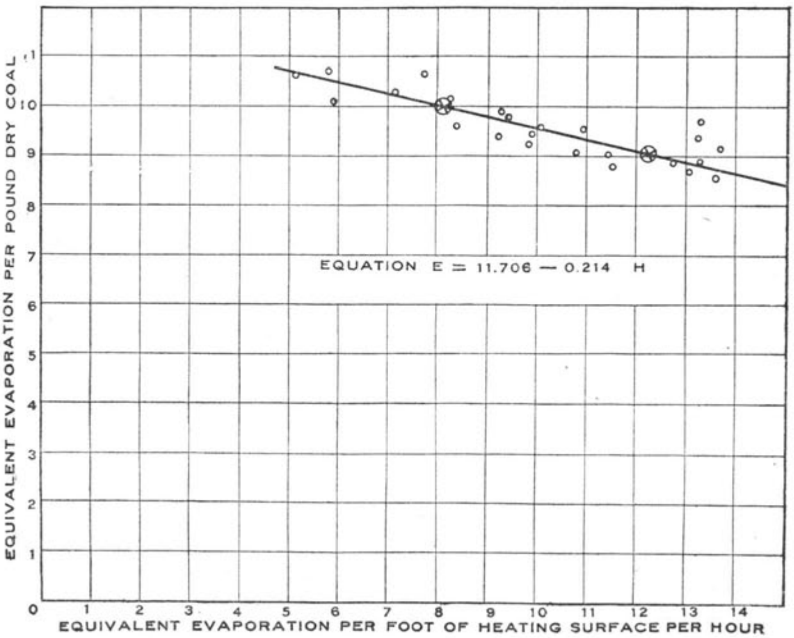


FIG. 16. EQUIVALENT EVAPORATION PER POUND OF COAL, UNDER ALL CONDITIONS OF PRESSURE; COMBINED BOILER AND SUPERHEATER

from and at 212°, equivalent to the weight of superheated steam delivered per pound of dry coal, and the equivalent evaporation per sq. ft. of surface in the boiler and superheater per hr., under all conditions of pressure, is given in Fig. 16. The data show that, if the discussion is allowed to concern itself with very small differences, the highest efficiency is obtained when the boiler pressure is lowest; conversely, the lowest efficiency results when the boiler pressure is highest. But, except in the case of tests at 120 lb., the results of which do not compare closely with those for other pressures, the differences are hardly more than measurable. In a larger sense, it seems to be true that changes in boiler pressure between the limits of 120 lb. and 240 lb., have practically no effect upon the evaporative efficiency of the boiler.

Proceeding on this basis, it is clear that a general expression for the evaporative efficiency of the combined boiler and superheater may be based upon the results of all tests, regardless of the pressure at which they were run. Such expression is represented by the line drawn through the plotted points of Fig. 16.

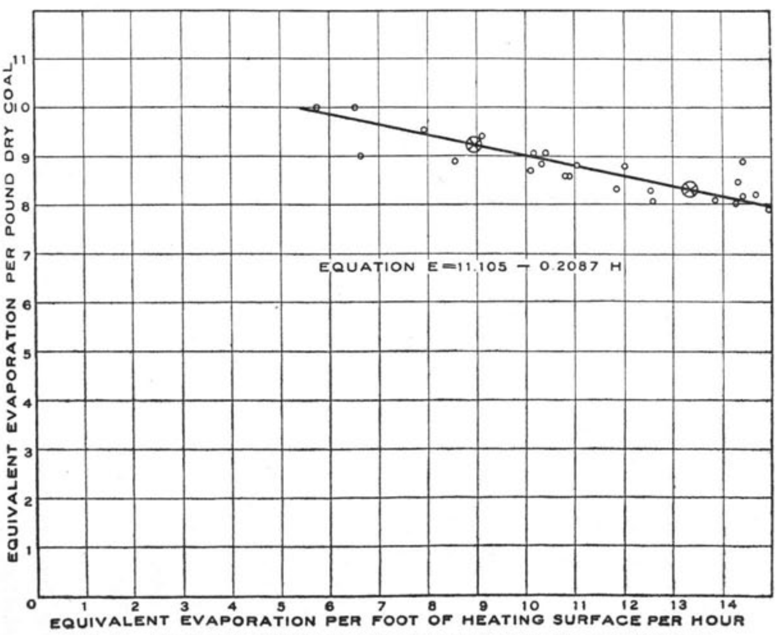


FIG. 17. EQUIVALENT EVAPORATION PER POUND OF COAL UNDER ALL CONDITIONS OF PRESSURE, EXCLUSIVE OF THE SUPERHEATER

The equation for this line, and consequently one which defines in general terms the performance of the combined boiler and superheater, is

$$E = 11.706 - 0.214\,H$$

where E is the equivalent evaporation from and at 212° F. per pound of dry coal, and H is the equivalent evaporation per square foot of water and superheating surface.

19. *Evaporative Efficiency of the Boiler, Exclusive of the Superheater.*—The equivalent evaporation of the boiler per pound of dry coal, in terms of the equivalent evaporation per square foot of waterheating surface in the boiler per hour is shown in Fig. 17. The equation for the mean line drawn through these points is:

$$E = 11.105 - 0.2087\,H$$

This curve is substantially of the same slope as that which represents the performance of the combined boiler and superheater (Fig. 16), but it represents values which are lower, a result due to the fact that the basis of the comparison practically assumed that the heat which is normally absorbed by the superheater is in this case lost.

20. *The Division of Work between Water and Superheating Surface.*—The ratio of the heat absorbed per square foot of superheating surface to that absorbed per square foot of water-heating surface may be accepted as an expression of the relative efficiency of the water and superheater surface. Fig. 18 represents

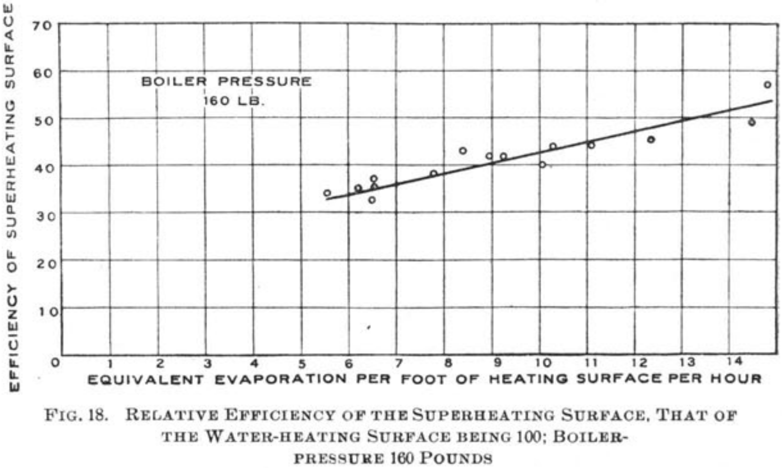


FIG. 18. RELATIVE EFFICIENCY OF THE SUPERHEATING SURFACE, THAT OF THE WATER-HEATING SURFACE BEING 100; BOILER-PRESSURE 160 POUNDS

this quantity plotted against equivalent evaporation per square foot of water-heating surface for a boiler pressure of 160 lb. Referring to this figure, it will be seen that as the rate of evaporation increases, there is a corresponding increase in the ratio of the heat absorbed per square foot of superheater surface to that absorbed per square foot of boiler surface. Thus, the ratio has a value of 34 per cent when the rate of evaporation is 6 lb. of water per square foot of water-heating surface and 53 per cent when the rate of evaporation is increased to 14 lb. The value of this ratio is independent of the boiler-pressure.

21. *Smoke-Box Gases.*—The percentage of excess air is in all cases small (between 20 and 25 per cent in most tests) and it distinctly tends to diminish as the rate of evaporation is increased. The reason for this is to be found in the fact that in locomotive service higher rates of evaporation necessarily involve the use of thicker fires, which offer greater resistance to the admission of air.

The percentage of carbon dioxide (CO_2) present in the smoke-box gases ranges from 10.8 to 14.6. The significance of these results as factors in any general comparison is impaired by the variable quality of the fuel used. Taken as they stand, they do not disclose any well-defined law governing the changes in their value with changes in the rate of combustion. The highest values are, however, those which were obtained in tests under the higher pressures, the average value for all tests at 240 lb. being 14.25, while the average value for all tests at 120 lb. is but 11.70. This may be accepted as evidence that, for some reason not defined

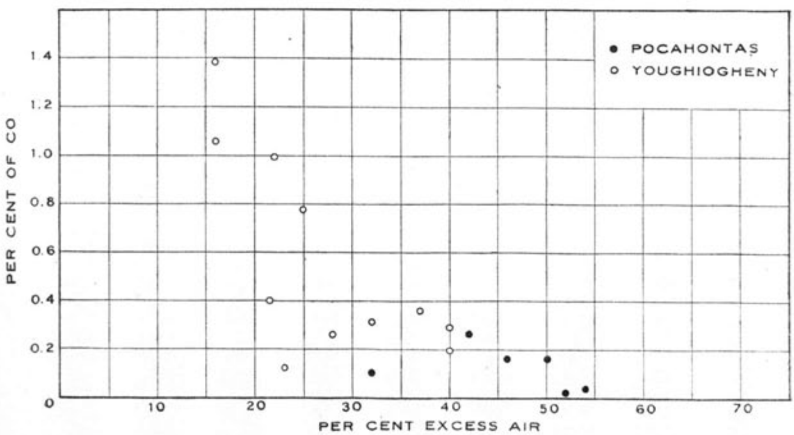


FIG. 19. CARBON MONOXIDE AND EXCESS AIR

the fire was maintained in a more efficient condition during the tests under high pressure than during those at lower pressures.

The percentage of carbon monoxide (CO) present in the smoke-box gases is never great notwithstanding the low percentage of excess air present. At the same time, there are no tests that do not show the presence of a trace or more than a trace of this gas. Its tendency to increase as the percentage of excess air diminishes is well shown by Fig. 19. This figure shows also that under similar conditions, the combustion of the Pocahontas coalis less perfect than that of the Youghiogheny, a result which is more likely to be due to the presence of a greater percentage of fine coal in the Pocahontas than to differences in composition. The tendency of carbon monoxide to increase with increased rates of evaporation is shown by Fig. 20. This tendency is doubtless due to mechanical conditions. It may be accepted also as a function

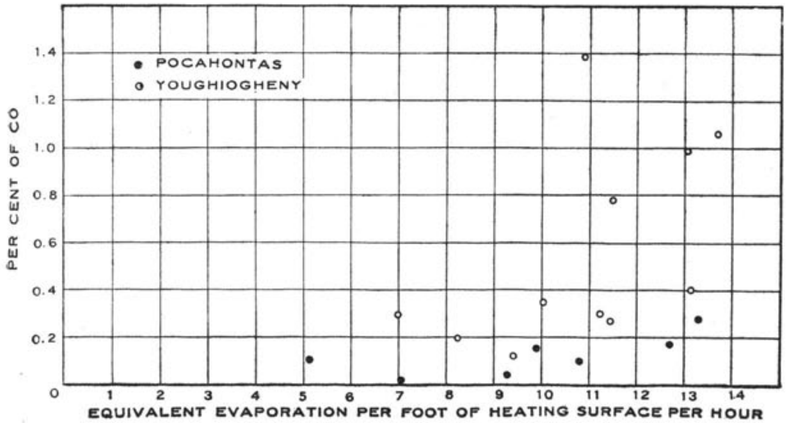


FIG. 20. CARBON MONOXIDE AND RATE OF EVAPORATION

of that tendency to which attention has already been called. Thus, increased rates of evaporation demand higher rates of combustion, and these in turn require more air, which must be supplied by an increase in the strength of the draft-action. In the presence of a stronger draft, the bed of the fire must be thickened, and the thicker fire throttles the passage of air into the fire-box to such an extent that the supply is not commensurate with the increase in the draft-action; hence a reduction in the amount of excess air, and this, as has already been shown, leads to an increase in the percentage of unconsumed gas.

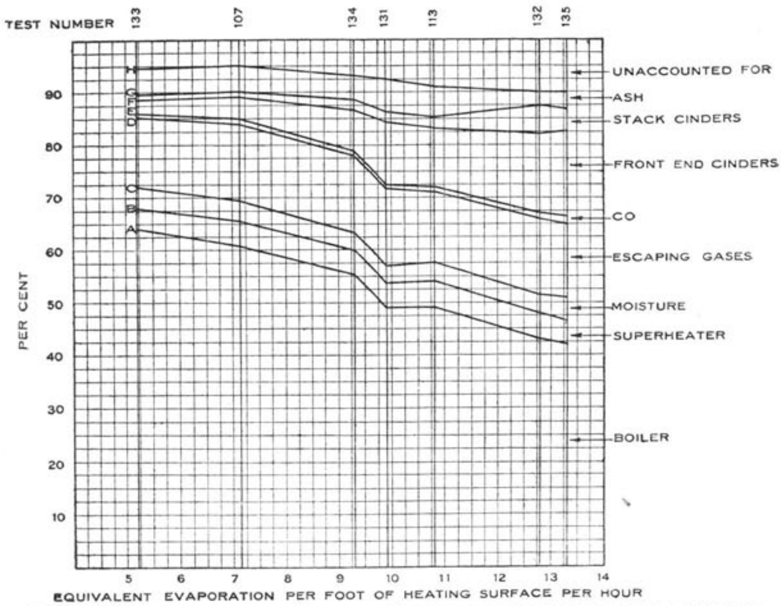


FIG. 21. HEAT-BALANCE OF COMBINED BOILER AND SUPERHEATER AS DERIVED FROM TESTS OF POCAHONTAS COAL

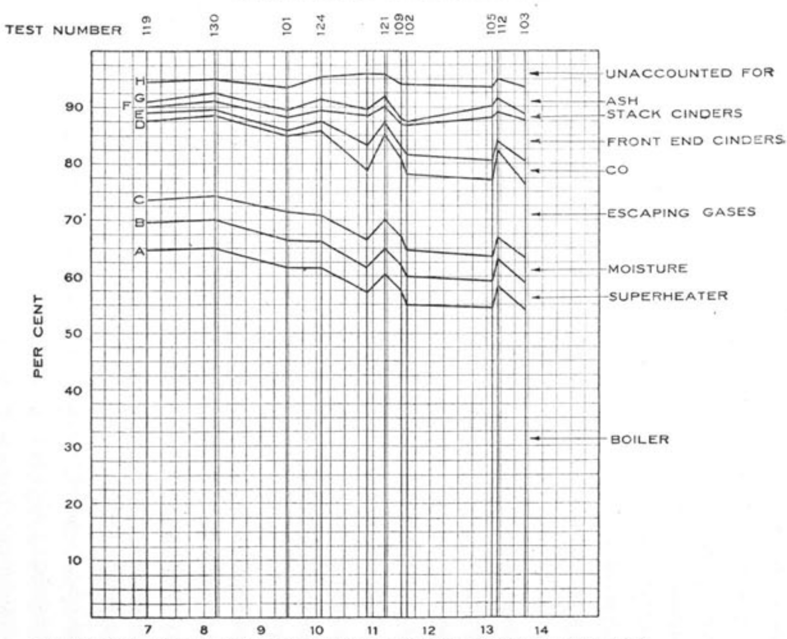


FIG. 22. HEAT-BALANCE OF COMBINED BOILER AND SUPERHEATER AS DERIVED FROM TESTS OF YOUGHIOGHENY COAL

22. *Heat Balance.*—From data obtained, it has been possible to complete a heat-balance for 18 tests. Graphic representations of the heat absorbed and of the heat lost, plotted in terms of the rate of evaporation, are presented by Fig. 21 and 22. The necessity for two diagrams is to be regretted. It has been no part of the purpose of the present work to make tests of coals, and thus far in the discussion, it has been possible to avoid bringing into direct comparison the results obtained from the two varieties employed. The process of making up a heat-balance, however, admits of no compromise, and the discussion which follows necessarily defines the behavior of the coals. In the consideration given this portion of the work, it will be well to remember that the commercial grading of the two coals was not the same. This is well brought out by the following summarized facts concerning them.

The Pocahontas coal used was run-of-mine, and, as such it contained a considerable amount of slack. It was fairly uniform throughout.

The Youghiogheny coal was obtained from two different sources and was less uniform in quality. All tests involving this fuel, run prior to April 12, were fired with a so-called Virginia lump, while tests run after this date were fired with fuel delivered as run-of-mine, but which was screened at the laboratory before being used. Averages of all results obtained from samples of the Pocahontas and Youghiogheny coal are shown in the following statement.

	Pocahontas	Youghiogheny
Moisture (per cent)	3.10	1.89
Volatile matter (per cent)	15.23	31.94
Fixed carbon (per cent)	72.75	57.71
Ash (per cent)	8.92	8.46
Heating value per pound of dry coal (B. t. u.)	14,347	14,047
Heating value per pound of combustible (B. t. u.)	15,802	15,372

In the diagrams, Fig. 21 and 22, the term "heating-surface", as employed in designating the abscissas, includes the heat-transmitting surface of both boiler and superheater. The ordinates of the diagrams represent the percentage of heat in the fuel supplied. Distances measured on ordinates between the axis and the first line *A* represent the percentage of the total heat supplied which is absorbed by the water of the boiler. The line *A* is in fact a definition of the efficiency of the boiler under the varying rates of evaporation represented by the series of tests. While based upon a different unit, it is, as it ought to be, similar in form to curves defining the evaporative efficiency of the boiler, which shows the pounds of water evaporated per pound of coal used. The inclination of all such lines shows the extent to which the efficiency of the boiler suffers as the rate of evaporation is increased. The nature and extent of the losses leading to such a result are to be found in the areas above the line *A*. The fact that the points representing different tests, through which this line *A* is drawn, do not result in a smooth curve is due to irregularities in furnace conditions which were beyond the vigilance of the operator, an explanation which applies equally to other lines, *B*, *C*, *D*, etc., of the same diagrams.

The percentage of the total heat which is absorbed by the superheater is measured by distances on ordinates between the line *A* and the line *B*. It is apparent from the record that the percentage of the total heat absorbed by the superheater is practically constant, whatever may be the power to which the boiler is driven. The normal maximum power of a locomotive may, for present purposes, be assumed to be that power which is represented by an evaporation of 12 lb. of water per sq. foot of heating-surface per hour. Basing a statement on the record as it appears from the rate of power, the superheater, which contains 16 per cent of the total heat-transmitting surface, receives approximately 8 per cent of the total heat absorbed. Distances between the broken line *B* and the axis represent the efficiency of the combined boiler and superheater. Distances above this line *B* account for the various heat-losses incident to the operation of the furnace, boiler, and superheater.

Losses of heat arising from the presence of accidental and combined moisture in the fuel, the presence of moisture in the atmospheric air admitted to the fire-box, and of moisture resulting from the decomposition of hydrogen in the coal are represented by distances measured on ordinates between the lines *B* and *C*. It is of passing interest to note that the heat thus accounted for is practically equal to that absorbed by the superheater.

Losses of heat in gases discharged from the stack are represented by distances measured on ordinates between the lines *C* and *D*. The distances between the lines *D* and *E* represent that portion of these losses which is due to the incomplete burning of the combustible gases. The record shows that this loss is necessarily large, but does not increase with the increased rates of combustion, as has commonly been supposed. In other words, the loss in evaporative efficiency with increase of power does not occur in any degree through the channel of the smoke-box gases. That portion of this loss which is chargeable to incomplete combustion is small under low rates of combustion, but may increase to values of some significance under the influence of very high rates of combustion, as will be seen from the record of the Youghiogheny coal.

Losses of heat through the discharge from the fire-box of unconsumed fuel are represented by distances measured on ordinates between the lines E and H. The loss thus defined is separated into three parts, viz., the heat lost by partially consumed fuel in the form of cinders collecting in the front-end ($E\ F$); the heat lost by partially consumed fuel in the form of cinders or sparks thrown out of the stack ($F\ G$); the heat lost by partially burned fuel dropping throught the grate into the ash-pan ($G\ H$).

The first two of these losses increase with the rate of power developed. They are in fact the chief cause of the falling off of the evaporative efficiency of a locomotive boiler with increased rates of power. This is well shown by a comparison of the two diagrams. In the case of tests with the Pocahontas coal (Fig. 21) the cinder loss is comparatively heavy and the boiler efficiency diminishes in a marked degree under high rates of power, while tests under similar conditions with the Youghiogheny coal (Fig. 22), involving less loss by cinders, show an efficiency of the boiler under high rates of power which is much better sustained.

The cinder loss, expressed as a percentage of the total weight of coal fired, is shown by Fig. 23, and the heating value of the material thus accounted for by Fig. 24. It will be seen that cinders from the Pocahontas coal have more than double the weight, and that each pound has nearly double the heating value of those resulting from the Youghiogheny coal, a result doubtless due in part to the large percentage of fine coal in the Pocahontas and to the absence of such material in the Youghiogheny. The stack cinders from both coals have a higher calorific value than those caught in the smoke-box. Under the practice of the laboratory, in no case was the coal wetted previous to its being fired. Concerning the general significance of the results, it will be well to remember that the fuel used in all tests was of high quality. Lighter and more friable coals are, as a rule, more prolific producers of stack and front-end cinders.

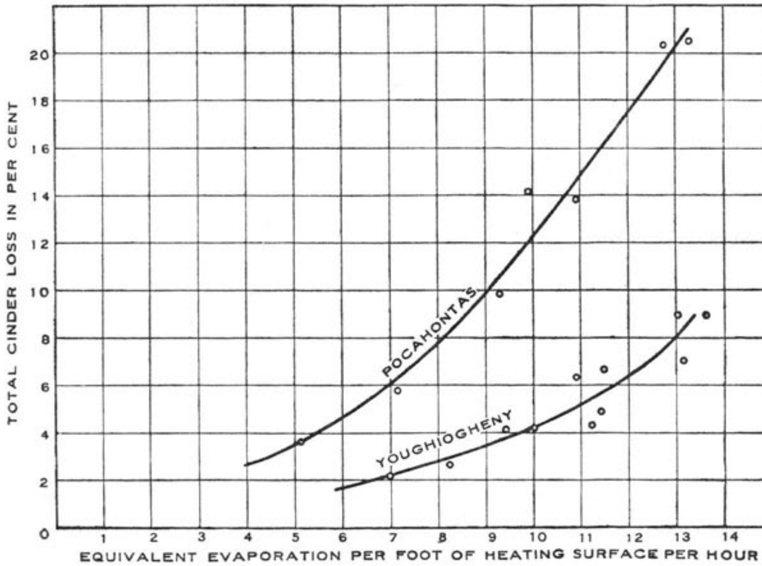


FIG. 23. STACK AND FRONT-END CINDER LOSS, PER CENT OF COAL FIRED

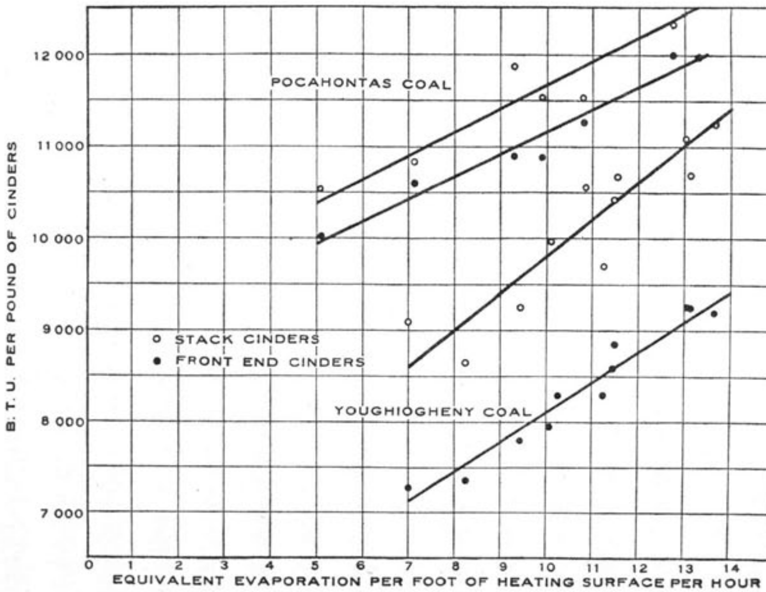


FIG. 24. HEAT VALUE OF STACK AND FRONT-END CINDERS

Radiation, leakage, and all other losses unaccounted for are represented by distances measured on ordinates between the line H and the 100 per cent line of the diagram. The radiation losses are probably from 1 to 2 per cent of the total heat available, the remainder equaling from 2 to 4 per cent, representing leakage of steam or water, or inaccuracy in the determination of quantities already discussed.

23. *A Summarized Statement with Reference to the Distribution of Heat in the Locomotive Experimented upon.*—It is sometimes convenient, for the purpose of fixing values in one's mind, to have an elaborate statement of fact summarized into a few representative values, the relation between which may be easily remembered. Such a summary may be framed in the present case by assuming that the normal maximum power of the locomotive tested is that which involves a rate of evaporation of 12 lb. of water per square foot of heating surface per hour, and by averaging values for this rate of power, from the diagrams, Fig. 21 and 22. The result may be accepted as showing in general terms the action of such a locomotive as that tested when fired with a good Pennsylvania or West Virginia coal. It is as follows:

	Per cent
Total heat available, absorbed by water in boiler	52
Total heat available, absorbed by steam in superheater	5
Total heat available, lost in vaporizing moisture in coal	5
Total heat available, lost through discharge of CO	1
Total heat available, lost through high temperature of escaping gases, the products of combustion	14
Total heat available, lost through unconsumed fuel in the form of front-end cinders	3
Total heat available, lost through unconsumed fuel in the form of cinders or sparks passed out of stack	9
Total heat available, lost through unconsumed fuel in ash	4
Total heat available, lost through radiation, leakage of steam and water, etc	7
Total heat available accounted for	100

V. Performance of the Engine and of the Locomotive as a Whole

24. *Indicated Horse-Power.*—The range in the values of the indicated horse-power for all pressures falls between the limits of 163 and 599 h. p. The maximum horse-power (599) was developed under a boiler pressure of 160 lb. and a speed of 40 miles per hr., with the reverse lever in the eighth notch, corresponding to a cut-off of 35 per cent of stroke. The following table shows the effect

of changes in boiler pressure upon the power output of the engine when run with the reverse lever in the fourth notch at a speed of 40 miles an hour.

Pressure	Corresponding horse-power
lb.	
120	179
160	343
200	445
240	551

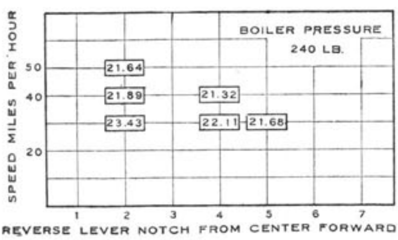


FIG. 25. STEAM PER INDICATED HORSE-POWER HOUR; BOILER PRESSURE 240 POUNDS

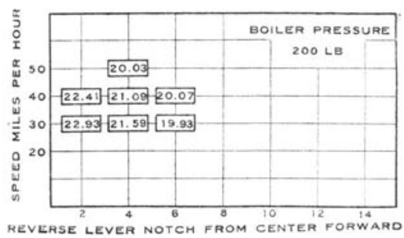


FIG. 26. STEAM PER INDICATED HORSE-POWER HOUR; BOILER PRESSURE 200 POUNDS

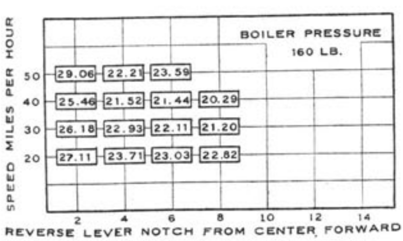


FIG. 27. STEAM PER INDICATED HORSE-POWER HOUR; BOILER PRESSURE 160 POUNDS

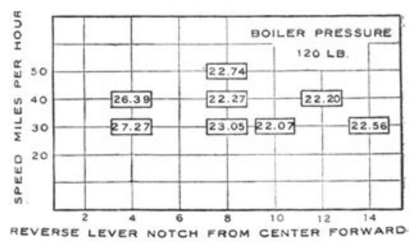


FIG. 28. STEAM PER INDICATED HORSE-POWER HOUR; BOILER PRESSURE 120 POUNDS

25. *Steam Consumption per Indicated Horse-Power.*—The steam consumption per indicated horse-power is presented graphically by Fig. 25 to 28. These diagrams show clearly the effect of speed and cut-off on the steam consumption of the cylinders. The most complete exhibit is that of tests run at a pressure of 160 lb. In this series, the full range of speed and cut-off possible under a wide-open throttle has been carried out, and, consequently, the exhibit of results for this pressure discloses a record of the maximum and minimum performance under a wide-open throttle. The maximum steam consumption for any test of record is 29.06 lb. and the minimum is 20.29.

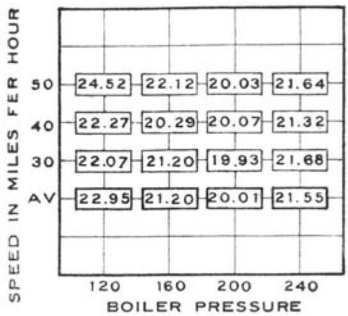


FIG. 29. LEAST STEAM CONSUMPTION FOR EACH OF THE SEVERAL SPEEDS AT DIFFERENT PRESSURES

The least steam consumption per horse-power hour for each of the several pressures at which tests were run is shown by Fig. 29.

For the purpose of securing a statement of the steam consumption of the engine, as set forth by the data presented, values for all pressures have been plotted upon a single sheet. In making up this figure, values for the second-notch tests at 160 lb. have been excluded, since these tests were at a very low power and there are no corresponding tests at other pressures. In a few cases, values for other pressures, not covered by the data, have been derived by extrapolation. The least steam consumption for each of the several pressures as represented by the average values given in Fig. 29, is indicated by points designated by crosses, while the average of all accepted values for each given pressure is represented by circles. In order that the steam consumption of the engine may be defined by a single series of values, a line (AB, Fig. 30) has been drawn through the average points represented by the circle. It is proposed to accept this line as representing the steam consumption of the experimental engine under the several pressures employed. It should be noted that it is not the least consumption or the maximum, but that it is the average of a group of results all of which represent normal working conditions, and none of which represents a consumption more than 4 lb. above the minimum.

From the curve it appears that the minimum normal consumption is obtained under a pressure of 200 lb., and that at this pressure it amounts approximately to 21.6 lb. per indicated horsepower hour.

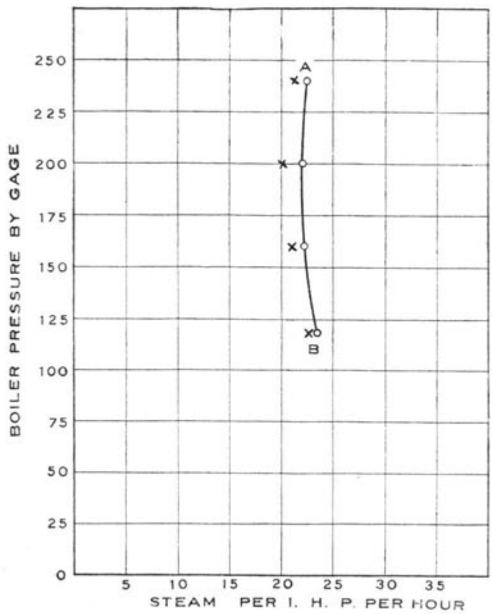


FIG. 30. STEAM CONSUMPTION UNDER DIFFERENT PRESSURES

26. *Steam Shown by Indicator.*—If, for any test, it should appear that there is present in the cylinder more than 100 per cent of mixture, it is to be accepted as evidence that for that test the steam was superheated at release. The data show that such a condition is not closely approached for any of the high-pressure tests, all of which were necessarily run under comparatively short cut-off. As the pressure is reduced, and the cut-off is lengthened, the percentage of steam accounted for increases, and for two tests under a pressure of 120 lb. the actual presence of superheated steam is shown. This applies to tests for which the cut-off was not less than half stroke.

For these tests, also, the percentage of steam accounted for by the indicator was greater than that accounted for by the tank, which is conclusive evidence that the exhaust was superheated.

A comparison of the percentages of the total mixture, which are shown by the indicator at release with similar values taken from the performance of the saturated-steam locomotive Schenectady No. 2, is presented in Table 1.

TABLE 1

PERCENTAGE OF MIXTURE SHOWN AS STEAM AT RELEASE BY INDICATOR-CARDS (SPEED, 30 MILES PER HOUR)

Cut-off, Reverse-lever Notch from Center Forward	Percentage of Mixture Shown As Steam at Release by Indicator-cards							
	Boiler-pressure 240 lb.		Boiler-pressure 200 lb.		Boiler-pressure 160 lb.		Boiler-pressure 120 lb.	
	Super-heated	Sat-urated	Super-heated	Sat-urated	Super-heated	Sat-urated	Super-heated	Sat-urated
I	II	III	IV	V	VI	VII	VIII	IX
2	82.8	75.0	85.2	72.9	85.7	....	....	....
4	82.2	76.7	86.2	77.5	87.4	75.7	89.8	72.0
6	....	....	89.7	75.5	86.0	77.0	....	....
8	....	....	....	....	90.9	80.0	89.7	74.6
12	....	....	....	....	....	....	93.5	....
14	....	....	....	....	....	....	106.0	84.7

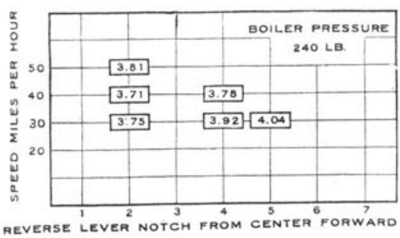


FIG. 31. COAL PER DRAW-BAR HORSE-POWER HOUR; BOILER PRESSURE 240 POUNDS

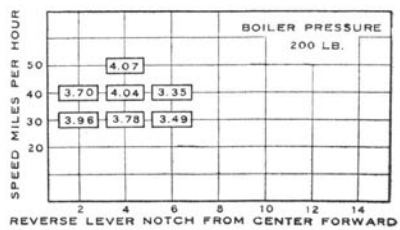


FIG. 32. COAL PER DRAW-BAR HORSE-POWER HOUR; BOILER PRESSURE 200 POUNDS

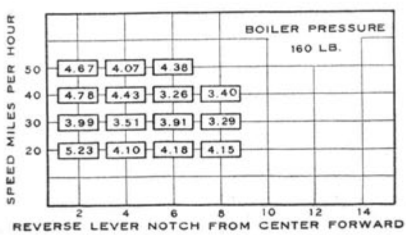


FIG. 33. COAL PER DRAW-BAR HORSE-POWER HOUR, BOILER PRESSURE 160 POUNDS

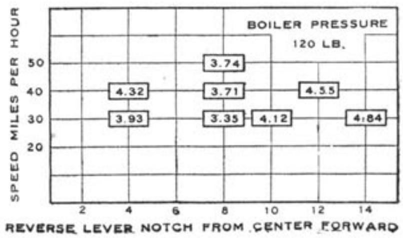


FIG. 34. COAL PER DRAW BAR HORSE-POWER HOUR; BOILER PRESSURE 120 POUNDS

27. *Coal Consumption.*—The coal consumption per indicated horse-power hour is, under favorable conditions, approximately 3 lb., the minimum value of record being 2.8 lb. In 2 tests only, of the 38 tests of record, does it reach a maximum of 4 lb. The coal consumption per draw-bar horse-power hour appears graphically in Fig. 31 to 34. These values are based upon direct observations. They include no accounting for differences in the quality of fuel; these and irregularities arising from other sources are dealt with in paragraph 28.

28. *Comparing the Performance of the Locomotive, Assuming Incidental Irregularities in the Tests To Have Been Eliminated.*—It is apparent that any series of values based directly upon experimental observations will present irregularities. In the course of the preceding discussion, it was sought to eliminate the effect of certain of these irregularities, and to define the performance of the boiler, of the superheater, and of the cylinders of the locomotive experimented upon, in terms which have resulted from a careful summarization of all the data available. Making use of the statements of performance thus secured, it is possible to compile Table 2, which is a table of engine performance based upon the experimental data but freed from its inconsistencies.

Obviously, the exhibit of such a table will have the highest value for purposes of comparison. Thus, the equation defining the performance of the boiler and superheater combined is $E = 11.706 - 0.214\,H$, and that defining the performance of the superheater is $T = 123 - 0.265\,P + 7.28\,H$, and the performance of the engine is defined by the curve *AB*, Fig. 30.

Column 1.—Test number.

Column 2.—Laboratory symbol.—The first term of this symbol represents the speed in miles per hr., the second term represents the position of the reverse lever upon its quadrant, expressed in notches from the center forward, and the third represents the steam pressure.

Column 3.—Equivalent steam to engine per hr., feed-water at a temperature of 60° F. = steam supplied the engine per hour $\times$ (B. t. u. taken up by each pound of water in the boiler and superheater + temperature of feed-water, in degrees F. $-$ 60) $\div$ 965.8.

Column 4.—Equivalent evaporation per lb. of dry coal, assuming the evaporative efficiency of the boiler to have been represented by the equation $E = 11.706 - 0.214$ H, where E is the equivalent evaporation per lb. of coal and H is the rate of evaporation per ft. of water and superheating surface per hr. For values in question, H = columns 3 ÷ 1216.

Column 5.—Dry coal fired per hr., assuming the evaporative efficiency to be that shown by the equation = column 3 ÷ column 4.

Column 6.—Dry coal per indicated horse-power hour = column 5 ÷ indicated horse-power.

Column 7.—Equivalent steam per indicated horse-power hour = column 3 ÷ indicated horse-power.

Column 8.—Machine friction in terms of mean effective pressure.—The purpose of this column is to eliminate irregularities in action due to variations in lubrication, etc. The values given are those determined by the previous experimental work upon *Schenectady No. 2*[1].

Column 9.—Machine friction horse-power is the power equivalent, assuming the friction M. E. P. to have been that shown by column 8.

Column 10.—Machine friction, per cent of indicated horse-power = 100 × column 9 ÷ indicated horse-power.

Column 11.—Dynamometer horse-power = indicated horse-power − column 9.

Column 12.—Draw-bar pull = 33,000 × column 11 ÷ (18.063 × r. p. m.,)

Column 13.—Coal per dynamometer horse-power hour = Column 5 ÷ column 11.

Column 14.—Equivalent steam per dynamometer horse-power per hr. = column 3 ÷ column 11.

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[1] "*High Steam-Pressures in Locomotive Service*", Publication No. 66, Carnegie Institution of Washington. Abstracted in Bulletin No. 26, Engineering Experiment Station.

TABLE 2

COMPARATIVE PERFORMANCE OF THE LOCOMOTIVE ASSUMING IRREGULARITIES IN THE RESULTS OF INDIVIDUAL TESTS TO HAVE BEEN ELIMINATED.

Designation of Tests		Corrected Locomotive Performance											
No.	Laboratory Symbol	Equivalent Steam to Engine per hour Feed Water at 60°F.	Equiv. Evap. per lb. of dry coal by Equation $E = 11.706 - 0.214\ H$	Dry Coal Fired per hour Corrected by Equation	Dry Coal per i. h. p. per hour	Equiv. Steam per i. h. p. per hour	Machine Friction M. E. P.	Machine Friction H.P.	Machine Friction Per cent i. h. p.	Dynamometer horse-power	Draw-bar pull	Coal per D. H. P. per hour	Equivalent Steam per D. H. P. per hour
1	2	3	4	5	6	7	8	9	10	11	12	13	14
		lb.		lb.	lb.	lb.					lb.	lb.	lb.
101	30-2-240	11,308	9.716	1164	3.14	30.59	6.5	46.45	12.58	323.31	4020	3.60	34.97
102	30-4-240	13,853	9.268	1495	3.13	29.07	8.5	58.49	12.27	418.19	5396	3.58	33.13
103	30-5-240	15,187	9.034	1681	3.07	27.79	8.9	61.95	11.33	472.12	6022	3.56	32.17
103a	30-5-240	......	.....	......	......	......	.....	......	..	......	......	......	......
104	40-2-240	11,786	9.632	1224	2.95	28.40	6.5	61.12	14.72	353.97	3343	3.46	33.30
105	40-4-240	15,467	8.984	1722	3.12	28.06	8.5	79.69	14.45	471.67	4465	3.87	34.77
106	50-2-240	13,129	9.396	1397	3.01	28.31	6.5	77.24	16.65	386.63	2865	3.61	33.96
107	30-2-200	8,312	10.242	812	2.90	29.64	6.5	46.38	16.54	234.06	2910	3.47	35.51
108	30-4-200	10,815	9.802	1103	2.88	28.21	8.5	60.37	15.74	323.07	4037	3.41	33.48
109	30-6-200	13,571	9.318	1457	2.82	26.26	9.3	66.86	12.94	450.11	5559	3.24	30.15
110	40-2-200	9.007	10.121	890	2.87	29.10	6.5	61.42	19.84	248.16	2331	3.59	36.30
111	40-4-200	12,865	9.442	1363	2.92	27.58	8.5	81.29	17.43	385.22	3579	3.54	33.40
111a	40-4-200	.. ...	.....	......	......	......	.....	......	. ....	......	......	.....	.....
112	40-6-200	15,622	8.957	1744	2.96	26.54	9.3	89.82	15.26	498.81	4584	3.50	31.33
113	50-4-200	12,803	9.453	1355	2.78	26.27	8.5	96.99	19.90	390.47	3039	3.47	32.80

114	20-2-160	5,929	10.911	414	2.48	35.55	6.5	30.67	18.39	136.10	2559	3.04	43.56
115	20-4-160	7,070	10.462	676	2.91	30.45	8.5	40.08	17.26	192.07	3611	3.52	36.81
116	20-6-160	8,969	10.128	885	2,95	29.88	9.3	44 02	14.66	256.14	4802	3.45	35.01
117	20-8-160	10,811	9.803	1103	3.01	29.49	8.4	59.83	10.86	326.88	6115	3.37	33.08
118	30-2-160	6,421	10.824	463	2.42	33.53	6.5	46.24	24.14	145.29	1811	3.19	44.91
119	30-4-160	8,443	10.220	826	2.89	29.58	8.5	60.06	21.04	225.33	2830	3.67	37.47
120	30-6-160	11,156	9.743	1145	2.96	28.81	9.3	66.01	17.04	321.35	4019	3.56	34.72
121	30-8-160	13,363	9.354	1429	2.97	27.74	8.4	59.69	12.39	422.13	5272	3.39	31.66
122	40-2-160	6,886	10.760	500	2.36	32.56	6.5	62.72	29.66	148.74	1362	3.36	46.30
123	40-4-160	9,587	10.019	957	2.79	27.93	8.5	80.94	23.58	262.34	2447	3.65	36.54
124	40-6-160	12,011	9.592	1252	2.91	27.95	9.3	88.21	20.52	341.59	3199	3.67	35.17
125	40-8-160	15,944	8.900	1792	2.99	26.63	8.4	79.68	13.31	519.02	4857	3.45	30.72
126	50-2-160	6,688	10.784	486	2.70	37.10	6.5	76.78	42.60	103.46	778	4.70	64.63
127	50-4-160	9,882	9,967	992	2.89	28.81	8.5	100.30	29.24	242.75	1827	4.09	40.71
128	50-6-160	16,344	8.830	1851	3.56	31.43	9.3	110.04	21.16	409.99	3076	4.52	39.87
129	30- 4-120	5,649	10,712	527	3.23	34.60	8.5	60.37	36.97	102.93	1287	5.12	54.89
130	30- 8-120	9,924	9,960	996	2.97	29.60	8.4	60.13	17.93	275.14	3412	3.62	36.07
131	30-10-120	11.766	9,637	1221	2.98	28.72	6.9	48.65	11.87	361.07	4546	3.38	32.59
132	30-14-120	15,296	9,014	1697	3.28	29.56	3.0	21.28	4.11	496.21	6208	3.42	30.83
133	40- 4-120	5,989	10,652	562	3.15	33.54	8.5	80.32	44.97	98.26	922	5.72	60.96
134	40- 8-120	11,074	9.757	1135	2.96	28.93	8.4	79.39	20.74	303.50	2851	3.74	36.49
135	40-12-120	15,925	8,904	1789	3.27	29.09	5.0	47.27	8.63	500.30	4698	3.58	31.83
136	50- 8-120	12,159	9,566	1271	3.09	29.53	8.4	99.51	24.17	312.29	2339	4.07	38.94

It is now possible to determine the coal consumption per indicated horse-power per hour by assuming the efficiency of the locomotive to be that defined in the above relationship. The derived results are given as Table 3, which follows.

TABLE 3

LOCOMOTIVE PERFORMANCE UNDER DIFFERENT PRESSURES.

Boiler-pressure	Pounds of Superheated Steam per i. h. p. per hr.; Values from Curve	B. t. u. per lb. of Steam; Feed 60° and Superheat from Equation	Equivalent Pounds of Steam per i. h. p. hr.	Equivalent Pounds of Water per Pound of Dry Coal	Pounds of Coal per i. h. p. hr.
1	2	3	4	5	6
lb.					
240	22.6	1258.7	29.45	9.426	3.12
220	21.8	1261.8	28.48	9.501	3.00
200	21.6	1263.1	28.25	9.518	2.97
180	21.9	1261.7	28.61	9.491	3.01
160	22.3	1259.3	29.07	9.455	3.08
140	22.9	1256.4	29.79	9.399	3.17
120	23.8	1252.7	30.87	9.316	3.31

Column 1 in Table 3 gives the boiler-pressure.

Column 2 gives the steam consumption per indicated horse-power per hour for the several pressures, as defined by the curve *A B*, Fig.

Column 3 gives the number of thermal units in the pounds of steam at the several pressures, assuming the feed-water temperature at 60° F. and the degrees superheat that represented by the equation $T = 123 - 0.265\ P + 7.28\ H$.

Column 4 gives the number of pounds of water from and at 212° F. per indicated horsepower hour. It equals column 2 times column 3 ÷ 965.8.

Column 5 gives the pounds of water evaporated from and at 212° F. per pound of coal and is calculated as follows: Assuming that a fair average load for the locomotive tested is 440 horse-power and that this unit of power is developed under all pressures, the corresponding rate of evaporation may be found by multiplying this value by those of column 4 and dividing by the area of water-heating surface plus superheating surface; that is, rate of evaporation = 440 × column 4 ÷ 1216. The equivalent pounds of water per pound of coal is found by substituting the rate of evaporation found for H in the equation $E = 11.706 - 0.214\ H$.

Column 6 gives the pounds of coal per indicated horse-power hour and equals column 4 ÷ column 5.

From the values given in the table it will be seen that the coal consumption per indicated horse-power hour varies from 2.97 to 3.31. The minimum value 2.97 is found at 200 lb. boiler-pressure.

VI. ECONOMY RESULTING FROM THE USE OF SUPERHEATED STEAM

29. *Comparisons Involving Boiler and Superheater.*—The whole discussion, as presented in the preceding chapters, has been developed with a view to establishing in concise terms the performance of the locomotive experimented upon, while operating under

superheated steam. The method of expressing results and the units of measurement employed have been so chosen that a comparison may readily be made with those which have previously been derived for the same locomotive when, as *Schenectady No. 2*, it was operated with saturated steam. The changes in the extent of heat-transmitting surface resulting from the application of the superheater are described in detail in paragraph 12. Data concerning the performance under saturated steam, which are made a basis for comparison, are drawn from a previous report[1]. Youghiogheny coal or its reduced equivalent has been used in all cases.

30. *Boiler Performance.*—The boiler of *Schenectady No. 2*, designed for delivering saturated steam, gave an efficiency expressed by the equation

$$E = 11.305 - 0.221\ H$$

while the boiler as equipped with a Cole superheater, *Schenectady No. 3*, gave an efficiency expressed by the equation

$$E = 11.706 - 0.214\ H$$

Obviously, on the basis of these equations, the superheating boiler has the advantage. The comparison is, however, not a fair one, since in both cases the equations are based on the extent of heat-transmitting surface, and in *Schenectady No. 3* such surface was sacrificed in making room for the superheater. To make the comparison fair, the term in the equation representing equivalent pounds of water per square foot of heating surface must be expressed in terms of total power delivered by the boiler. Comparisons on this basis, showing the performance of the boiler in one case, and of the boiler and superheater in the other case, expressed in terms of the equivalent evaporation, are shown diagrammatically by Fig. 35.

It will be seen that even upon this basis the efficiency of the combined boiler and superheater is superior to that of the boiler alone, the increase averaging between 3 and 4 per cent. The reason for this is not entirely apparent. An examination of related data suggests that the lines of Fig. 35 should not be far apart. Draft values plotted in terms of the rate of evaporation are lower for the superheating locomotive than for the locomotive using saturated steam, but when these are reduced to equivalent values representing an equal amount of power, they are identical for

[1]Publication No. 66, Carnegie Institution of Washington; Abstract in Bul. 26, Eng. Ex. Sta.

both locomotives—a condition which implies equality in the fuel lost in the form of cinder and spark. Similar comparisons involving smoke-box temperature lead to identical conclusions.

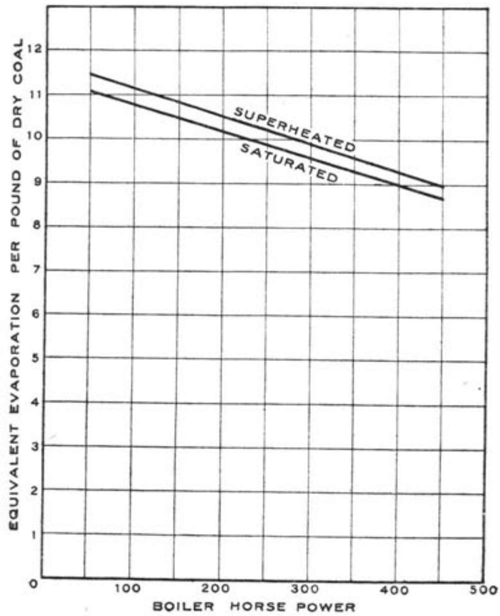

FIG. 35. BOILER EFFICIENCY

Upon the basis of these statements, the relation defined by Fig. 35 is not confirmed by collateral evidence. This statement, however, does not discredit the record, which is in fact one of no small significance. The line of performance for the superheating locomotive (Fig. 35) depends upon results of 38 tests and that for the saturated-steam locomotive upon results of 40 tests. It is therefore difficult to see how either could have been affected to the extent indicated by any incidental cause or causes. Whatever the conclusion may be with reference to this matter, it is clear that the combined boiler and superheater of *Schenectady No. 3* are not less efficient than the boiler of *Schenectady No. 2*, while being worked at the same rates of power, and the face value of the data shows its efficiency to be higher by 4 per cent.

31. *Comparisons Involving the Performance of the Engine.*—The steam consumption per indicated horse-power hour for the superheating locomotive, as determined by the results of 38 tests, has been defined as the line *A B*, Fig. 30. A similar line based upon the results of 100 tests of the saturated-steam locomotive estab-

lishes the cylinder performance of that machine. Replotting the results upon a single sheet gives the diagram Fig. 36. This exhibit (or better, perhaps, the numerical values given by columns 2 and 4, Table 4) shows well the saving in water realized by substituting steam superheated approximately 150° F. for steam which is saturated. The saving ranges from 18 per cent when the boiler-

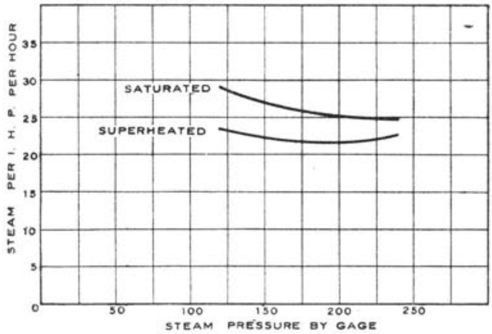

FIG. 36. STEAM PER INDICATED HORSE-POWER HOUR

pressure is 120 lb. to 9 per cent when the boiler pressure is 240 lb. It appears, also, from the diagram that with superheating, the least consumption of water, 21.6 lb. per horse-power hour, is secured when the boiler-pressure is approximately 200 lb., and that variations in the consumption resulting from changes in pressure are slight (column 4, Table 4). For example, the water consumption for all pressures between 160 and 220 lb. ranges between 21.6 lb., the minimum value obtained, and 22.3 lb., a range of approximately 4 per cent.

The saving of water in locomotive service is always a matter of moment; it diminishes the exactions of certain conditions in operation; and in some districts, where water is bad or hard to obtain, it tends to simplify difficult problems either in locomotive maintenance or in the maintenance of the water-supply. The fact, therefore, that superheating affords a material saving in the amount of water required, is not to be overlooked in estimating the value of superheating as a practice. But the saving in heat is not proportional to the saving in water, for each pound of superheated steam must have more heat imparted to it than a pound of saturated steam at the same pressure. As an indication of the thermal advantage to be derived from the use of superheated steam in comparison with that of saturated steam, it is desirable to reduce the steam in each case to the same thermal basis. This has been shown graphically by Fig. 37 and numerically by columns 3 and 5, Table 4.

TABLE 4

STEAM PER INDICATED HORSE-POWER HOUR

Boiler-pressure lb.	Saturated Steam		Superheated Steam	
	Pounds of Steam per i. h. p. per hr.	B. t. u. per i. h. p. per min.	Pounds of Steam per i. h. p. per hr.	B. t. u. per i. h. p. per min.
1	2	3	4	5
240	24.7	483	22.6	474
220	25.1	491	21.8	459
200	25.5	498	21.6	455
180	26.0	507	21.9	461
160	26.6	517	22.3	468
140	27.7	537	22.9	481
120	29.1	563	23.8	497

Upon this basis the saving effected by the use of superheated steam is 12 per cent when the pressure is 120 lb., and 2 per cent when the pressure is 240 lb. Under a boiler-pressure of 180 lb. the substitution of superheated steam improves the efficiency of the engine 9.1 per cent.

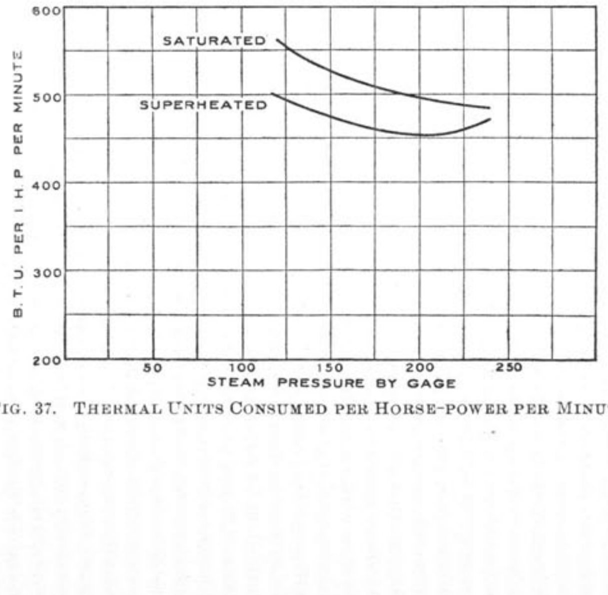

FIG. 37. THERMAL UNITS CONSUMED PER HORSE-POWER PER MINUTE

32. *Comparisons Involving the Performance of the Locomotive As a Whole.*--The performance of the locomotive as a whole, as expressed in terms of coal consumed per indicated horse-power hour, both for saturated steam and superheated steam, and the saving effected by the substitution of superheated for saturated steam, is given as Table 5. These results, since they combine the performance of both engine and boiler, represent a definition of the improvement in the performance of the locomotive experimented upon as the result of the substitution of superheated for

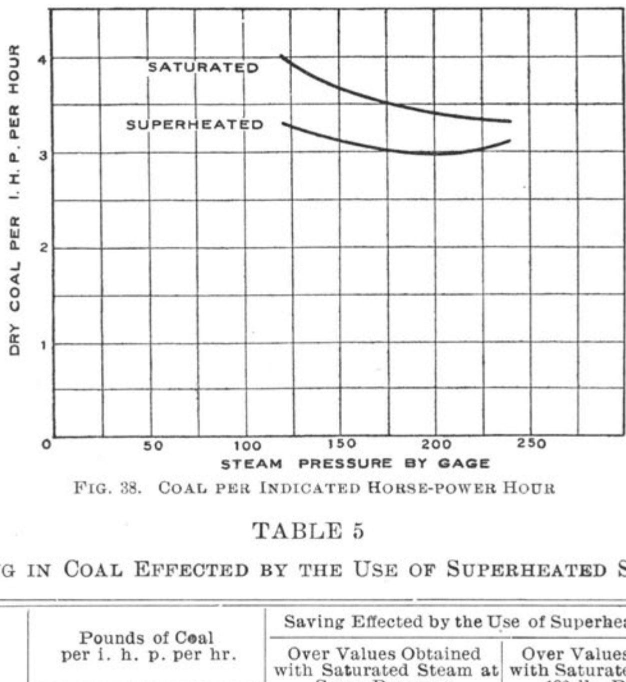

FIG. 38. COAL PER INDICATED HORSE-POWER HOUR

TABLE 5

SAVING IN COAL EFFECTED BY THE USE OF SUPERHEATED STEAM

Boiler-pressure lb.	Pounds of Coal per i. h. p. per hr.		Saving Effected by the Use of Superheated Steam			
			Over Values Obtained with Saturated Steam at Same Pressure		Over Values Obtained with Saturated Steam at 180 lb. Pressure	
	Saturated Steam	Superheated Steam	Pounds per i. h. p. per hr.	Per cent	Pounds per i. h. p. per hr.	Per cent
1	2	3	4	5	6	7
240	3.31	3.12	0.19	5.72	0.38	10.86
220	3.37	3.00	.37	10.98	.50	14.29
200	3.43	2.97	.46	13.31	.53	15.15
180	3.50	3.01	.49	14.00	.49	14.01
160	3.59	3.08	.51	14.21	.42	12.00
140	3.77	3.17	.60	15.98	.37	10.57
120	4.00	3.31	.69	17.25	.19	5.43

saturated steam. They show that the gain is most pronounced at the lower pressure; thus, at a pressure of 120 lb. it is 17 per cent, while at a pressure of 240 lb. it is but 6 per cent. They show also that the performance of the locomotive using superheated steam is only slightly affected by changes of pressure; for the entire range of pressure from 120 lb. to 240 lb., the difference in coal consumption from minimum to maximum is but a third of one pound, while for pressures between 175 lb. and 225 lb., it is practically constant and always near the minimum value. The least coal consumption per indicated horse-power hour, as it appears in the summarized statement, is 2.97 lb., and was obtained under a steam-pressure of 200 lb.

The results sustain a claim which has been put forward by advocates of the practice of superheating, to the effect that the adoption of such practice permitted the steam-pressure to be materially reduced over that now employed in locomotives using saturated steam without material sacrifice in efficiency. A detailed numerical statement showing the saving in coal resulting from a change from saturated to superheated steam is set forth by columns 4 to 7, Table 5. Columns 4 and 5 present results obtained by comparisons based on equal pressures, and columns 6 and 7 those obtained by comparing values obtained with superheating under the several different pressures employed with those obtained from saturated steam at a pressure of 180 lb.

33. *Comparisons Involving the Capacity of the Locomotive.*—The maximum power presented by the data derived from the locomotive using superheated steam is not to be accepted as a measure of its capacity. Except in the case of the series of tests run at 160 lb. pressure, the number of tests was insufficient to permit the establishment at each speed of a maximum cut-off for which the boiler could be made to supply steam. But while direct evidence is lacking, the data contain much which goes to show that the superheating locomotive is a more powerful machine than the locomotive using saturated steam. For example, it has been shown that for the development of equal amounts of power, the combined boiler and superheater of the superheating locomotive have an efficiency which equals or exceeds that of the saturated-steam boiler; hence the boiler-power which it may be made to deliver as a maximum equals or exceeds that which the boiler of the saturated-steam locomotive can be made to deliver. But each unit of power delivered from the boiler in the form of superheated steam is more effective in doing work in the cylinders than a similar unit of

power delivered in the form of saturated steam; hence, at the limit, the superheating locomotive is more powerful than the one using saturated steam, and the difference is that which measures the difference in the economy with which the cylinders use steam.

The same question may be dealt with through another series of facts, as follows: It can be shown that the power of any locomotive is limited by its capacity to burn coal, and coal-burning capacity is a function of the draft. The data show that for the development of a given cylinder power, the draft values of *Schenectady No. 3* (superheating) were in all cases less than those of *Schenectady No. 2* (saturated). The extent of these differences

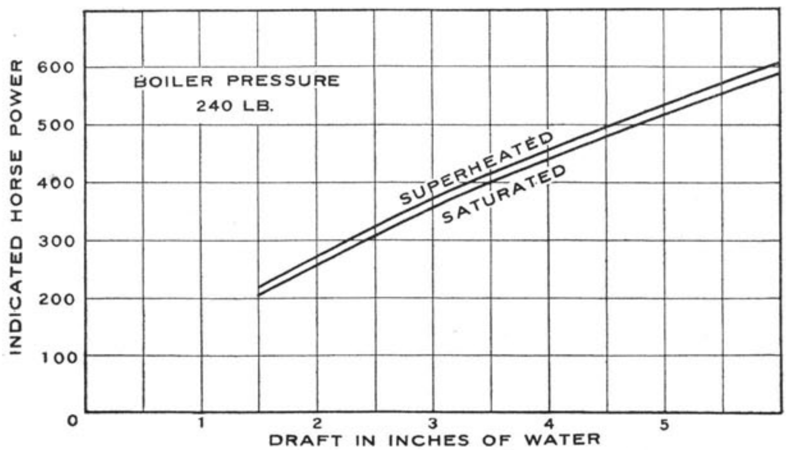

FIG. 39. INDICATED HORSE-POWER: BOILER PRESSURE 240 POUNDS

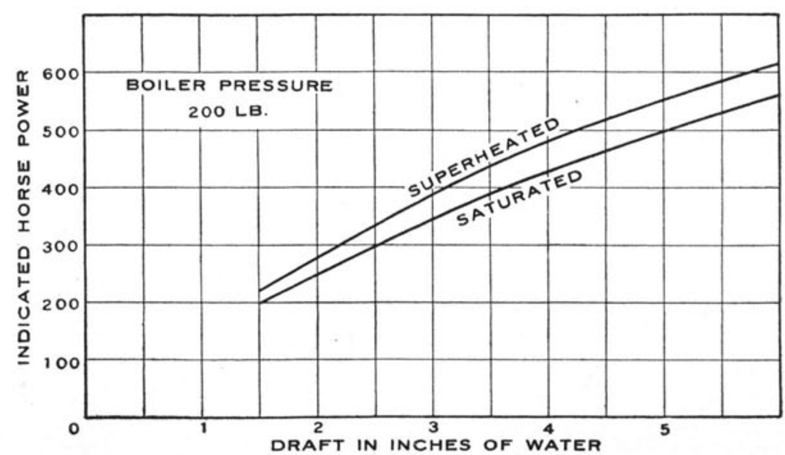

FIG. 40. INDICATED HORSE-POWER: BOILER PRESSURE 200 POUNDS

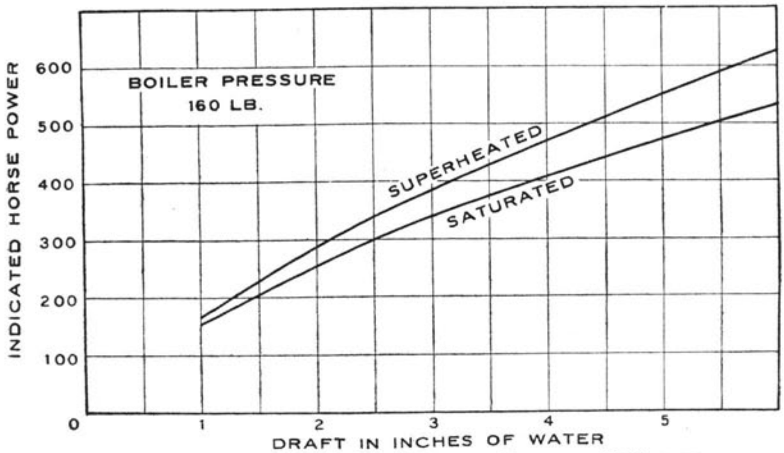

FIG. 41. INDICATED HORSE-POWER; BOILER PRESSURE 160 POUNDS

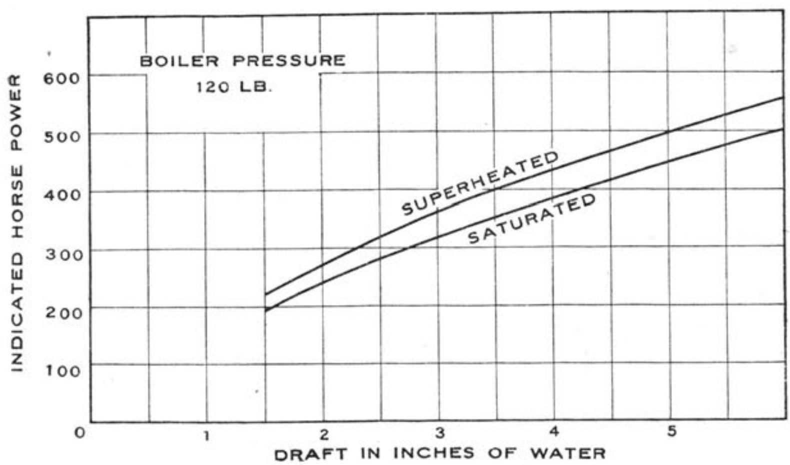

FIG. 42. INDICATED HORSE-POWER; BOILER PRESSURE 120 POUNDS

is well shown by Fig. 39 to 42. They are of small value for tests under high pressure, but as a rule they increase as the pressure is reduced. Tests at 160 lb. (Fig. 41) show that the power developed in return for a given draft is from 10 per cent to 16 per cent greater for the superheating locomotive than for the saturated-steam locomotive. Obviously, there is no reason why the draft for the former should not be increased to limits practicable with the latter, and when this is done the power developed by the superheating locomotive will exceed that which is possible with the saturated-steam locomotive.

34. *The Possible Economy Which May Result from the Use of Superheated Steam in Locomotive Service.*[1]—In the preceding paragraphs an attempt has been made to define with accuracy the increased efficiency resulting from the substitution in locomotive service of steam superheated to approximately 150° for steam which is saturated. The facts upon which comparisons have been based have been derived by careful processes, and the results can safely be accepted as the measure which has been sought. All discussion might well end with the presentation of the facts referred to, were it not that out of them arises a group of questions of great practical significance. To some of these attention must be given.

As a general proposition, the gain which in any service will result from the introduction of a superheater is a function of the degree of superheat employed, and this in turn is limited by the ability of the materials composing the superheater and the exposed parts of the engine to withstand the temperatures which are involved. The Prussian State Railway prescribes a boiler-pressure of 180 lb. and a temperature of steam of 300° C., which temperature may rise above 300°, but must never be allowed to exceed 350°. That is, a degree of superheating of 190° F. is regarded as satisfactory, while the maximum limit never to be exceeded is fixed at 280° F. Under normal running conditions, the degree of superheating is considerably above 200° F.

Comparing the superheating effects described by these statements with the degree of superheat obtained from the Purdue locomotive when working under a pressure of 180 lb. (Fig. 13), it appears that those of the latter may be increased by at least 33 per cent of their present value without exceeding the limit which has been proved practicable in the every-day practice of German railroads. The means to be employed in securing such a degree of superheat are, of course, matters of detail which concern the design and proportions of the superheater. The savings in water and fuel resulting from the presence of the superheater, as set forth by data already presented, would have been greater had the degree of superheat been higher. In the absence of data derived from experiments, it may be assumed that the possible increase in the savings will be proportional to the increase in the degree of superheat.

[1] Information resulting from later experiments, tending to confirm the statements of this section, is presented in the Appendix.

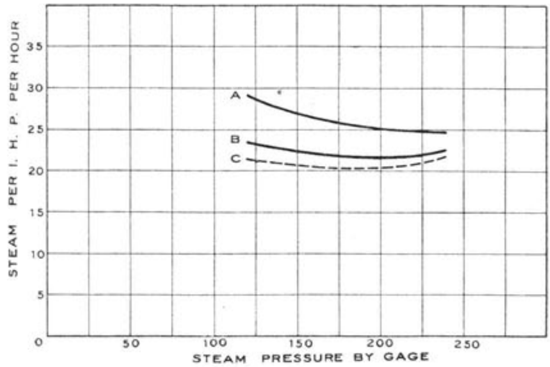

FIG. 43. STEAM PER INDICATED HORSE-POWER HOUR, SHOWING POSSIBLE GAIN BY INCREASING SUPERHEATING 33 PER CENT

On the basis, therefore, of the experimental results already presented and of these statements, the possible gain in water and fuel which may result from the adoption of the superheater is seen by Fig. 43 and 44, respectively. In these figures, the upper line *A* is that of saturated steam as derived from tests of locomotive *Schenectady No. 2;* the next below, *B*, is that of superheated

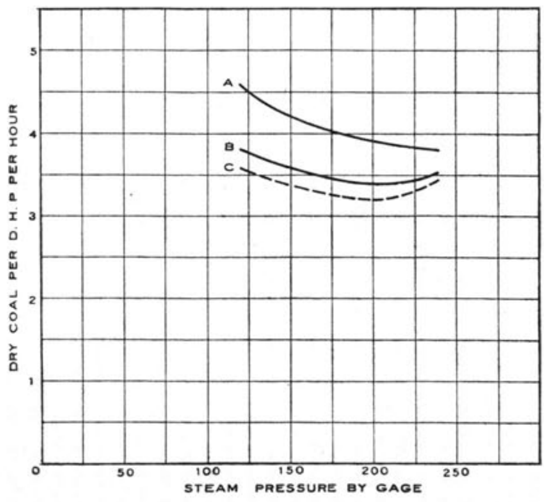

FIG. 44. COAL PER DRAW-BAR HORSE-POWER HOUR, SHOWING POSSIBLE GAIN BY INCREASING SUPERHEATING 33 PER CENT

steam as derived from tests of locomotive *Schenectady No. 3*, and the dotted line *C* is that which is assumed to represent the performance which *Schenectady No. 3* would have given had the degree of superheating been 33 per cent greater than that actually obtained. These are not maximum savings, but are such as are to be expected under normal conditions of continuous full-power operation. From this exhibit, it appears that for boiler-pressure of 180 lb., the substitution of superheated steam for saturated steam may result in a reduction of water consumption from 26 lb. to 20.5 lb. a saving of 21 per cent, and in a reduction of coal consumption per draw-bar horse-power of from 4 lb. to 3.25 lb., a saving of 19 per cent. These values may be accepted as representing what should reasonably be expected of superheating in American locomotive service, so far as the experiments herein described define them.

It will be a mistake, however, for anyone to assume that a railway company's bills for locomotive fuel may be diminished by the percentages set forth in the preceding paragraph merely by the introduction of the superheater. It should be clear, for example, that no part of the fuel used in raising the steam of a locomotive or of its wastes which occur between the round-house and the starting of the locomotive at the head of its train can be saved by the application of a superheater to a locomotive. Assuming that the fuel thus used is 15 per cent of the total for the run, a conservative estimate, the amount which remains subject to the influence of the superheat is 85 per cent of 19 per cent, or 16 per cent.

Again, the fuel used in maintaining a normal temperature of all parts of the machine when the locomotive is at rest at stations and at passing-points is fuel over which the superheater can exert no influence. The amount of fuel thus used is a function of the schedule of the train. The results set forth in Chap. IV show that in some classes of service upon American railways it will be so small as to be negligible, but in other classes of service it will constitute a considerable percentage of the total coal used. A review of Chap. IV will suggest the difficulty which confronts one in an attempt to fix numerical values covering fuel thus to be accounted for. Again, fuel used in generating steam which is discharged through safety-valves can not in any way be affected by the presence of a superheater. In none of the experimental work, the results of which are recorded in the preceding chapters, has there been any loss by safety-valves. This loss in practice is necessarily indefinite. In some classes of service it is so small as to be negligible, and in others it involves a considerable percentage of the total coal used. Finally, attention should be called to the fact that the question at issue involves the whole problem of maintenance. Steam leaking past valves and pistons or coming out by leaky glands or through leaky cylinder-cocks or steam-joints wherever located causes losses which remain undiminished in the presence of the superheater.

Summarizing the preceding statements, and making such deductions from the known performance of the superheater as will suffice to remove from the calculations all expenditures of heat normal to the American locomotive, which are beyond the influence of the superheater, the actual net reduction in the amount of fuel needed for locomotive use, by a railroad having all its locomotives equipped with satisfactory superheaters, over that which would be required if all employed saturated steam, will not be far from 10 per cent. This value is not to be accepted as of strictly scientific import, but merely as an estimate based upon such facts as have appeared in the course of a rather careful study of the problem.

APPENDIX

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APPENDIX

A COMPARISON OF RESULTS OBTAINED WITH SATURATED STEAM AND WITH FOUR DIFFERENT DEGREES OF SUPERHEATED STEAM[1]

35. The tests reported in the preceding pages were completed in the summer of 1907. Since that date, the Purdue Laboratory has been engaged in investigations, involving the use of different superheaters, the results of which are to be accepted as the latest information available concerning the value of superheated steam in locomotive service. A brief abstract of a paper presented jointly by Dean Benjamin and Professor Endsley follows.

36. *Superheaters.*—Tests have been run with locomotive *Schenectady No. 3* equipped with four different superheaters, which have been designated as follows:

Cole A—193 sq. ft. of heating surface in the superheater
Cole B—151 sq. ft. of heating surface in the superheater
Cole C—109 sq. ft. of heating surface in the superheater
Schmidt—324 sq. ft of heating surface in the superheater

Cole A was the superheater used during the tests reported in the preceding pages.

The boiler dimensions were the same for all the Cole superheater tests, but in order to install a Schmidt superheater, with a larger amount of superheating surface, the number of small 2-in. flues was reduced from 111 to 107, and the large 5-in-flues were increased in number from 16 to 21. This change in the number of flues increased the water-heating surface from 897 sq. ft. to 956.5 sq. ft. With the above exceptions, the boiler and engine were the same for all the testing upon the four different superheaters.

37. *Basis of Comparison.*— It seems logical to compare the results obtained with the four different degrees of superheated steam and with saturated steam, since all the series of the tests so far run have been under the same steam pressures and cut-offs, developing approximately the same horse-power, the only difference being the area of the superheating surface and the area of the water-heating surface. As the area of the water-heating surface

[1] An abstract of a paper presented before the American Master Mechanics' Association at Atlantic City in June 1911 by Dean C. H. Benjamin and Professor L. E. Endsley, of Purdue University.

of the boiler with the Schmidt superheater is approximately only 47 sq. ft. greater than with the Cole superheater, it would seem that this difference would not be enough to affect the relative efficiency of the boiler. In the comparisons which follow, therefore, no allowance is made for differences resulting from different water-heating surfaces.

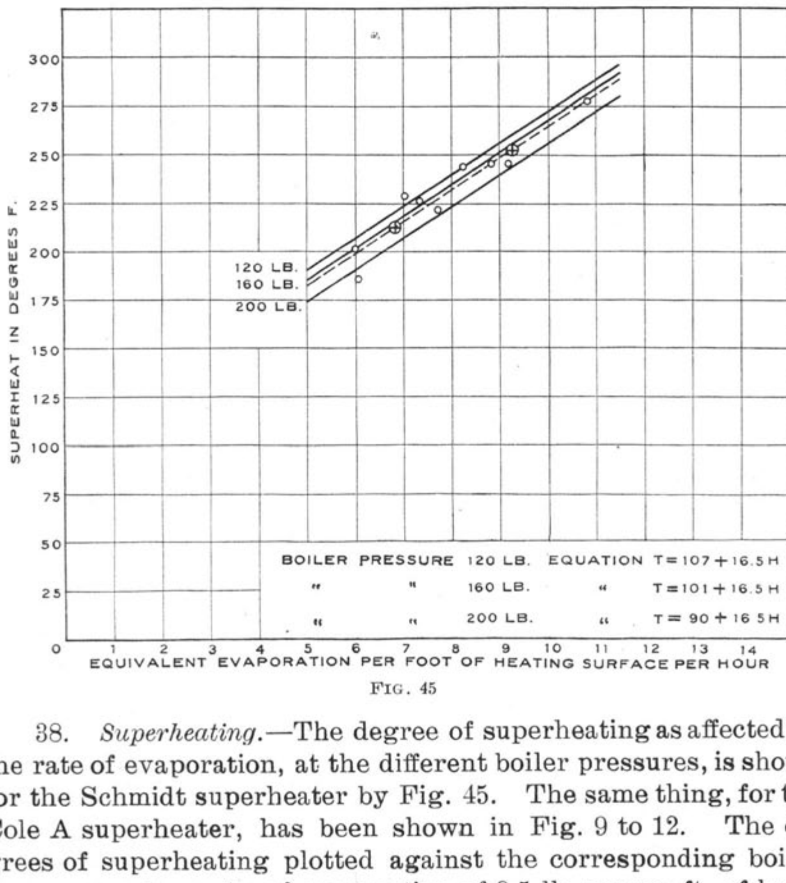

FIG. 45

38. *Superheating.*—The degree of superheating as affected by the rate of evaporation, at the different boiler pressures, is shown for the Schmidt superheater by Fig. 45. The same thing, for the Cole A superheater, has been shown in Fig. 9 to 12. The degrees of superheating plotted against the corresponding boiler pressures, at a rate of evaporation of 8.5 lb. per sq. ft. of heating surface per hour, is shown, for all four superheaters in Fig 46.

39. *Comparison of Engine Performance.*—The steam consumption of the locomotive operated under saturated steam and the four different degrees of superheated steam represented by Cole A, Cole B, Cole C and Schmidt are shown graphically in Fig. 47.

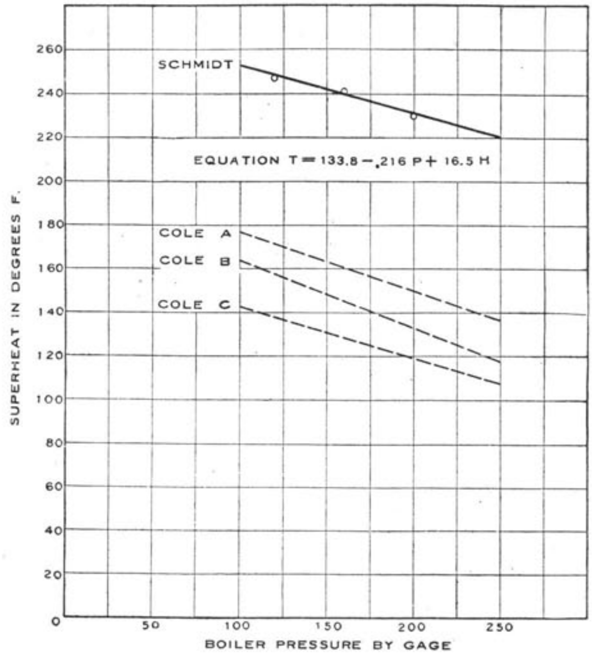
SCHMIDT
EQUATION T = 133.8 − .216 P + 16.5 H
COLE A
COLE B
COLE C
SUPERHEAT IN DEGREES F.
260
240
220
200
180
160
140
120
100
80
60
40
20
0
50
100
150
200
250
BOILER PRESSURE BY GAGE

FIG. 46

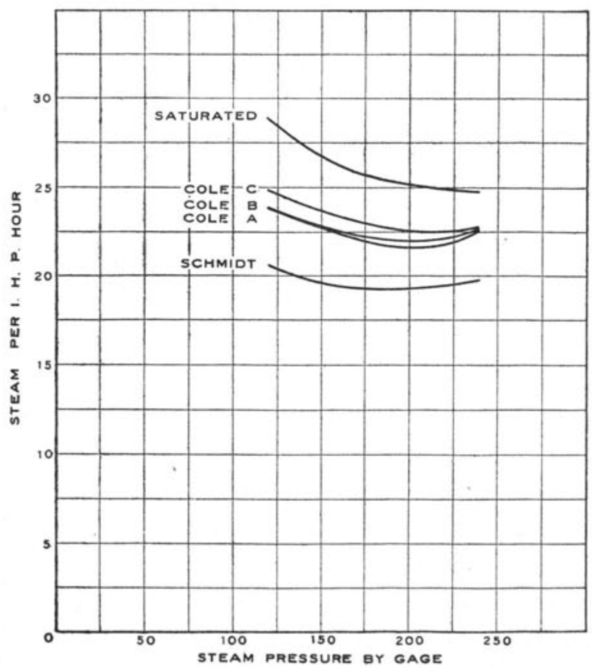
SATURATED
COLE C
COLE B
COLE A
SCHMIDT
STEAM PER I. H. P. HOUR
30
25
20
15
10
5
0
50
100
150
200
250
STEAM PRESSURE BY GAGE

FIG. 47

The numerical values are given in Table 6. From an inspection of these curves, it is seen that the tests with the Schmidt superheater, i. e., the one giving the highest degree of superheat, gave the lowest water consumption.

The curves showing the relation between the B. t. u. per i. h. p. per minute for the different conditions of tests are given in Fig. 48.

TABLE 6

STEAM PER INDICATED HORSE-POWER PER HOUR

Superheater	Boiler Pressure lb. by gauge	Superheat ° F.	Pounds Steam per i. h. p. per hr.	B. t. u. per i. h. p. per min.
I	II	III	IV	V
Schmidt A	240	222.2	19.5	421.4
Schmidt A	220	226.5	19.0	410.7
Schmidt A	200	230.8	18.9	408.3
Schmidt A	180	235.1	18.7	404.0
Schmidt A	160	239.4	18.9	408.0
Schmidt A	140	243.8	19.5	419.8
Schmidt A	120	248.6	21.0	452.3
Cole A	240	139.7	22.6	474
Cole A	220	145.0	21.8	459
Cole A	200	150.3	21.6	455
Cole A	180	155.6	21.9	461
Cole A	160	160.8	22.3	468
Cole A	140	166.1	22.9	481
Cole A	120	171.4	23.8	497
Cole B	240	120.6	22.6	469
Cole B	220	126.8	22.1	460
Cole B	200	133.0	21.8	454
Cole B	180	139.2	22.1	460
Cole B	160	145.4	22.5	469
Cole B	140	151.5	23.0	479
Cole B	120	157.7	23.8	496
Cole C	240	109.9	22.7	469
Cole C	220	114.6	22.5	465
Cole C	200	119.4	22.6	467
Cole C	180	124.2	22.8	472
Cole C	160	128.9	23.5	486
Cole C	140	133.7	24.0	496
Cole C	120	138.4	24.8	512
None	240	0	24.7	483
None	220	0	25.1	491
None	200	0	25.5	498
None	180	0	26.0	507
None	160	0	26.6	517
None	140	0	27.7	537
None	120	0	29.1	563

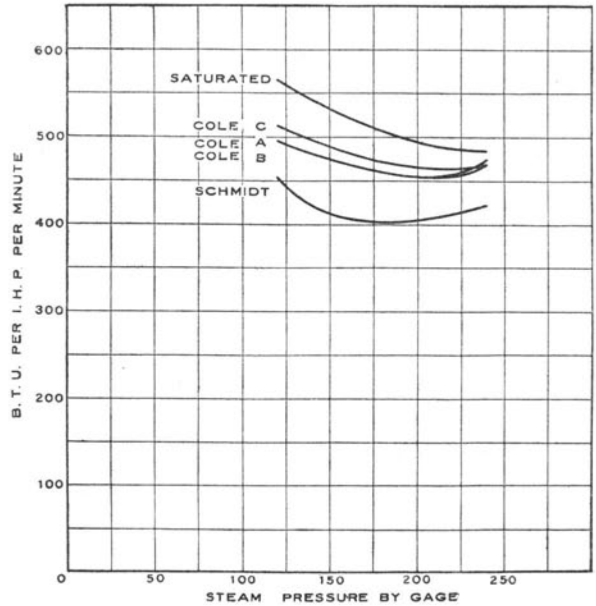
600
500
400
300
200
100
0
50
100
150
200
250
SATURATED
COLE C
COLE A
COLE B
SCHMIDT
B. T. U. PER I. H. P. PER MINUTE
STEAM PRESSURE BY GAGE

FIG. 48

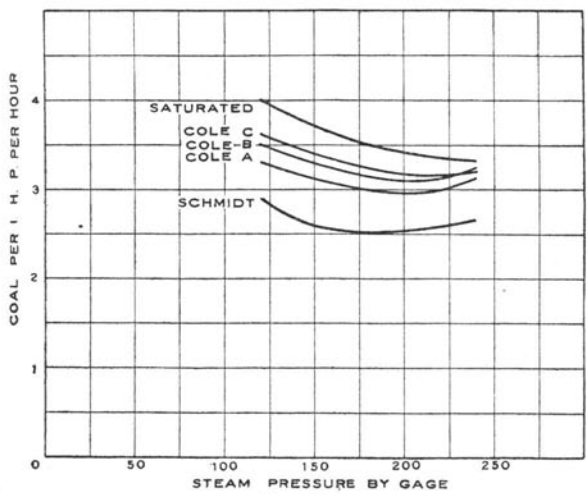
4
3
2
1
0
50
100
150
200
250
SATURATED
COLE C
COLE-B
COLE A
SCHMIDT
COAL PER I H. P. PER HOUR
STEAM PRESSURE BY GAGE

FIG. 49

The relation in coal consumption per i. h. p. per hour for the four different superheaters and for the saturated steam is shown graphically in Fig. 49, the numerical values being in Table 7. Here again the Schmidt superheater results are the smallest, going as low as 2.5 lb. per indicated horse-power per hour.

TABLE 7

COAL CONSUMPTION UNDER DIFFERENT PRESSURES AND SUPERHEATERS

Boiler Pressure Pounds Gauge	Pounds of Coal per Indicated Horse Power per Hour				
	Saturated Steam	Superheater Cole A	Superheater Cole B	Superheater Cole C	Superheater Schmidt A
I	II	III	IV	V	VI
240	3.31	3.12	3.24	3.20	2.63
220	3.37	3.00	3.16	3.16	2.57
200	3.43	2.97	3.11	3.18	2.55
180	3.50	3.01	3.16	3.22	2.51
160	3.59	3.08	3.24	3.35	2.55
140	3.77	3.17	3.33	3.45	2.63
120	4.00	3.31	3.48	3.60	2.89

The consumption of water per indicated horse-power, as affected by the degree of superheat, is well shown in Fig. 50, in which the pounds of steam per indicated horse-power per hour are plotted against the degrees of superheat. The pounds of steam per indicated horse-power per hour were obtained from the curves shown in Fig. 47. The degree of superheat was obtained from the lines shown in Fig. 46. It will be seen that the comparisons are made at 160, 180 and 200 lb. steam pressure, these being the pressures that fall in the center of the field of experiment, and for that reason would be more likely to represent correct results.

It would seem that this relation could be approximately represented by a straight line as shown. It is also seen that the water consumption for all pressures between 160 and 200 lb. for the Schmidt superheater is practically the same.

40. *Coal Consumption.*—The pounds of coal per indicated horse-power per hour plotted against degrees of superheat are shown in Fig. 51. The pounds of coal per indicated horse-power per hour were obtained from the curves of Fig. 49, and the degree of superheat was obtained in the same manner as for Fig. 50.

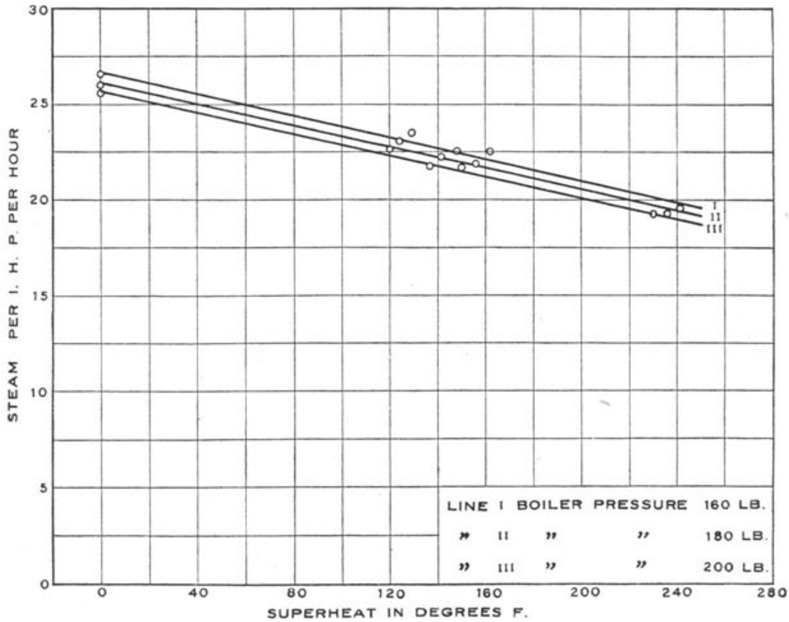
STEAM PER I. H. P. PER HOUR
SUPERHEAT IN DEGREES F.
LINE I BOILER PRESSURE 160 LB.
" II " " 180 LB.
" III " " 200 LB.
I
II
III

FIG. 50

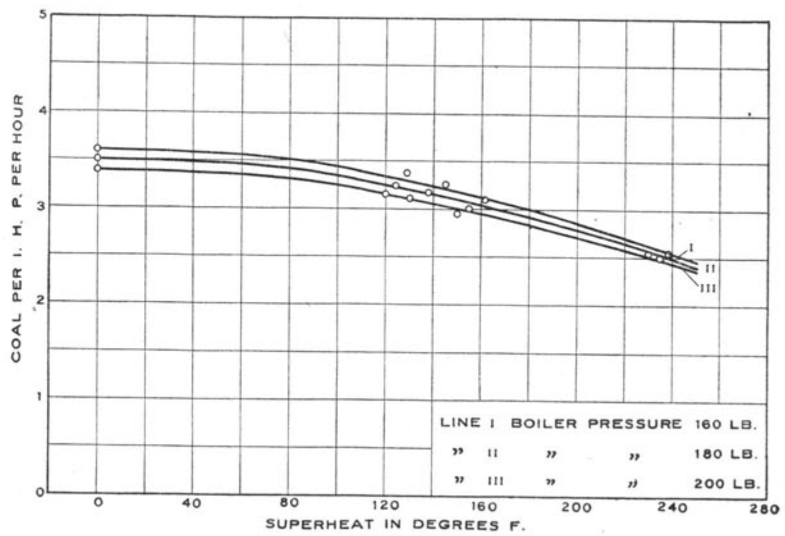
COAL PER I. H. P. PER HOUR
SUPERHEAT IN DEGREES F.
LINE I BOILER PRESSURE 160 LB.
" II " " 180 LB.
" III " " 200 LB.
I
II
III

FIG. 51

The same pressures of 160, 180 and 200 were used in this comparison as in the comparison for steam consumption. This relation between the coal per indicated horse-power per hour and the degree of superheat for pressures of 160, 180 and 200 would seem to indicate that it could be represented by a curve as shown. In other words, the first 80 or 100° of superheat do not make the same proportionate decrease in coal consumption as the second 80 or 100°, and, in like manner, the third 80° increase makes a still greater reduction in the coal consumption. For instance, the coal consumption per indicated horse-power per hour at 180 lb. steam pressure for the locomotive using saturated steam was 3.50 lb., and for 80° of superheat it was 3.4 lb. a gain in efficiency of 2.8 per cent; while the consumption at 160° superheat is 3.05 lb., a gain of 12.8 per cent, and the coal consumption at 240 degrees superheat is only 2.47 lb., a saving of 29.4 per cent over that of the locomotive using saturated steam. Thus, if we take the locomotive using saturated steam as consuming 100 per cent of coal, it might be said that the first 80° superheat will reduce this 2.8 per cent, the second 80°, 10.0 per cent, and the third 80°, 16.6 per cent, making the total reduction for 240° superheat, at 180 lb. pressure, 29.4 per cent. Practically the same results would be obtained for the curves representing 160 and 200 lb. steam pressure.

41. *Conclusions.—a.* A locomotive equipped with a superheater giving from 200 to 240° of superheat will during the time of running, effect a saving in coal consumption of from twenty to thirty per cent over that of the same locomotive using saturated steam.

b. It would seem that the total gain in efficiency which can be obtained from superheat in a locomotive would not be reached until the temperature becomes too high for practical purposes.

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