COMBUSTION AND HEAT BALANCES IN LOCOMOTIVES.*

By Lawford H. Fry.

The heat losses in a locomotive boiler divide themselves into three main groups:—

1. Loss of heat in the products of combustion.
2. Loss of heat by external radiation.
3. Loss of heat by imperfect combustion.

These three losses with the heat usefully employed in the production of steam must account for all of the heat contained in the coal, and complete the heat balance.

(1) *Loss of Heat in the Products of Combustion.*—The products of combustion consist of certain dry gases, as shown by the analyses of the flue gases, and in addition to these a considerable amount of water-vapor from the water of combustion of the hydrogen in the coal, and from the moisture in the coal and in the air. There is also a trace of sulphuric acid from the combustion of the sulphur. In the St. Louis tests, the water of combustion with the sulphuric acid amounted to 0.40 lb. per pound of coal burned. The moisture in the coal was always in the neighborhood of 1 per cent., and therefore the water-vapor produced, per pound of coal burned, may be taken with sufficient accuracy as 0.41 lb. This comprises the water of combustion and the moisture in the coal as fired. In addition to this vapor, the moisture in the air admitted for combustion must be taken into account. The percentage of moisture in the air can be determined from the wet and dry thermometer readings which were taken.

The mean figures thus obtained are:—

Series 100	1.25	per cent. moisture.
Series 200	1.18	" " "
Series 600	0.62	" " "
Series 800	0.48	" " "

These show that there was a considerable variation in the condition of the various series of tests, but in each series the individual tests do not show a wide variation from the mean.

The weight of the dry gaseous products of combustion per pound of coal burned is 0.54 lb. more than the weight of air supplied per pound of coal.

The amount of heat carried off by the products of combustion depends on the weights of dry gas and water vapor produced per pound of coal burned; on the temperature at which they escape to the smoke-box; and on the specific heat of these substances.

(2) *Loss of Heat by External Radiation.*—This loss was not measured in the St. Louis tests, and, as the loss by unburnt coal was not measured, the radiation loss cannot be determined by difference. It seems, however, permissible to assume that the loss by external radiation is 5 per cent. of the heat utilized by the boiler in evaporation. This cannot introduce any essential error, and it harmonizes with the little that has been published on this subject. Professor Hitchcock shows a loss up to 3.61 per cent., which is 6.3 per cent. of the heat of evaporation. Professor Goss says that experiment has shown that a locomotive running at 28 miles an hour loses by external radiation about 2 per cent. of the power developed.

(3) *Loss by Imperfect Combustion.*—This falls under two heads:—

(i) Loss by production of carbon-monoxide.
(ii) Loss by escape of unburnt coal at chimney and ashpan.

(i) The first-mentioned loss can be calculated from the analysis of the flue gases. The Pennsylvania report shows the percentage of loss in each test by the production of CO. There is a general tendency for the loss by CO to increase as the rate of combustion is increased, but except in Series 100 there is no very serious loss on this score. In Series 100 one individual test shows a loss of 16.33 per cent. by CO. This is due to the rapidity with which the air-supply falls off as the rate of combustion is increased. Evidently the difficulty of getting air to the fire limited the power of this boiler and prevented the rate of combustion being pushed above 90 lbs. of coal per square foot per hour. The relation between the loss of heat by CO and the rate of combustion in this case varies so much that it is difficult to draw a mean curve to express this relation with proper accuracy.

(ii) The loss of heat by the escape of unburnt coal is the most important loss in the heat balance when the boiler is working at full power. The coal escapes unburnt in three ways:—

(*a*) Partially unconsumed as sparks.
(*b*) Partially unconsumed in the ashpan.
(*c*) As unconsumed gas in the products of combustion. This last entails a secondary loss by
(*d*) The sensible heat of the unconsumed gas in the smoke-box.

As the necessary observations were not taken, it is not possible in the present tests to determine the separate value of each of the four items of the loss by unburnt coal, but the total amount of heat lost can be determined by the method which is described below, and which is illustrated by the following example:—

In Test 8,006 there is known	Per cent.
Heat of evaporation	47.20
Heat lost by external radiation	2.36
Heat lost in the production of CO	0.70
	50.26
This leaves as the loss to be divided between the products of combustion and unburnt coal	49.74
	100.00

The heat lost in this test in the products of combustion is 19.30 per cent. of the total heat of the coal *actually burned.* Now, if for example, 25 per cent. of the coal were to escape unburnt, the loss in the products of combustion would apply only on the remaining 75 per cent. actually burned, and would be 0.75×19.3, or 14.5 per cent. of the heat of all the coal fired. Consequently, if P is the percentage of heat lost by coal escaping unburnt, the loss in the products of combustion is $\frac{100 - P}{100}$ 19.3 per cent. of the total coal *fired,* or calling this P_1 we have

$$P_1 = \frac{100 - P}{100} 19.3$$

$$\text{and} \quad P_1 + P = 49.74$$

whence, by simple algebra, it is found that P, the loss by unburnt coal, is 37.70 per cent.

The general case is as follows:—

The calculations determine the loss in the products of combustion (including excess air) as a percentage of the total heat of the *coal actually burned.* In the heat balance this loss must be expressed as a percentage of the total heat of *all the coal fired.* If of the coal fired, P per cent. escapes unburnt, the figures must be reduced in the proportion* $\frac{100 - P}{100}$ to show the loss of heat in the products of combustion as a percentage of the heat in the coal fired. Represent this percentage by P_1. Then, if X be the quantity required to complete the heat balance as in the above example,

$$P + P_1 = X.$$

Let P_2 be the percentage of heat lost in the products of combustion per pound of coal burned; then, as explained above,

$$P_1 = \frac{100 - P}{100} P_2 \qquad (4)$$

$$\text{thence} \quad P + \frac{100 - P}{100} P_2 = X;$$

$$\text{and} \quad P(100 - P_2) = 100(X - P_2);$$

$$\text{and} \quad P = \frac{100(X - P_2)}{100(-P_2)} \qquad (5)$$

and X and P_2 being known, P, the loss by unburnt coal, can be found. Having found P from equation (5), P_1, the loss by the products of combustion per pound of coal fired, is found from

* Extracts from a paper presented before the Institution of Mechanical Engineers at the meeting on March 27, 1908.

* This is an approximate factor to simplify the calculation. The exact factor would be $\frac{100 - P + d}{100}$, where d is the loss by the sensible heat in the unconsumed gas as a percentage of the total heat in the coal fired. The effect of d is so small that it is negligible.

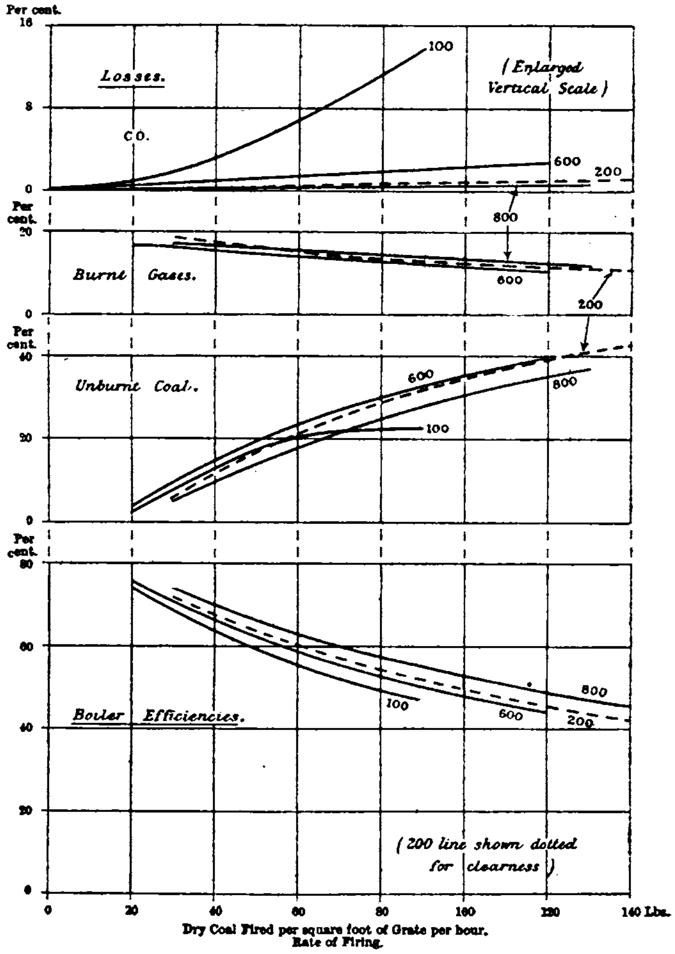
equation (4). The losses thus found complete the heat balance.

TESTS AT ALTOONA WITH BITUMINOUS COAL.

At the close of the St. Louis Exhibition, the Locomotive Testing Plant was transferred to the shops of the Pennsylvania Railroad, where it is now in regular operation. A series of tests were made with one of the standard Pennsylvania Railroad single-expansion Atlantic type locomotives which has cylinders 20½ inches in diameter, with 26 inches stroke, and driving wheels 6 feet 8 inches in diameter.

Three series were run: (a) with the full grate area of 55.5 square feet; (β) with the front of the grate covered with fire-brick so that the effective grate area was reduced to 39.5 square feet, the ratio of grate area to heating surface being 1 to 58.7; (γ) with the effective grate area still further reduced to 29.76 square feet, giving a ratio of grate area to heating surface of 1 to 77.9.

In each of the series four tests were run, one at 80 revolutions per minute with a nominal cut-off at 15 per cent. of the



LOSSES OF HEAT IN LOCOMOTIVE BOILERS—ST. LOUIS TESTS.

stroke, one at 120 revolutions with 20 per cent. cut-off, one at 160 revolutions with 25 per cent. cut-off, and one at 160 revolutions with a cut-off of 32 per cent. This last combination of speed and cut-off taxed the boiler to its maximum capacity.

The coal used contained more volatile matter than that used at St. Louis (35 per cent. instead of 16 per cent.) and was less friable. An ultimate analysis was not made. The proximate analysis of the coal was:—

Fixed carbon	57.2 per cent.
Volatile combustible	35.0 " "
Ash	6.7 " "
Moisture	1.1 " "

[The author here analyzed the processes of combustion in the three series of tests by the same methods used for the St. Louis tests.]

In analyzing this series of tests the rate of combustion has been measured by the total weight of coal fired per hour, and not as for the St. Louis tests by the weight of coal fired per square foot of grate area per hour. This has been done because it was found that if any given quantity of coal, as for instance 4,000 pounds, is fired per hour, the boiler efficiency is independent of the grate area, being practically the same whether the coal is burned on the grate of 55.5 square feet at 72 pounds per square foot, or on the grate of 29.76 square feet at 134 pounds per square foot per hour. The reason, of course, is that in the three series of tests the firebox volume is the controlling factor in the combustion, and is constant; so that a given quantity of coal has in all three tests practically the same opportunity of complete combustion irrespective of the rate at which it is fired per square foot of grate.

SUMMARY OF RESULTS.

St. Louis Tests.—The calculations which have been described have determined for various rates of firing for each locomotive the values of the five items of the heat balance.

(1) Loss by formation of CO.
(2) Loss of heat carried off in the products of combustion.
(3) Loss by coal escaping unburnt.
(4) Loss by external radiation (assumed).
(5) Useful heat of evaporation.

The various values found for these items (with the exception of the radiation) are shown by the accompanying curves. From an examination of these it will be seen that they are calculated for rates of firing of from 20 to 140 lbs. of dry coal per square foot of grate per hour, and that within these limits the four chief items of the heat-balance are affected as follows by an increase in the rate of firing:—

The loss by CO increases from a trace up to about 2 per cent. except in series 100, which is abnormal in this respect, and shows losses up to about 13.8 per cent.

The loss of heat in the gaseous products of combustion decreases from about 18 per cent. to about 11 per cent.

The loss by unburnt coal increases from about 4 per cent. to about 40 per cent.

The boiler efficiency, being affected by the combination of the above changes, decreases from about 74 per cent. to about 43 per cent.

The heat-balances show the result of two separate operations within the boiler, viz., the production of heat by combustion in the fire-box and the absorption of heat by the heating surface. It is interesting to separate the efficiencies of these two operations.

The losses by CO and by unburnt coal are due to incomplete combustion and affect the efficiency of that process only, while the loss of heat in the gaseous products of combustion determines the efficiency of the heat-absorption.

It appears from these figures that the efficiency of the absorption of the heat is practically independent of the rates of combustion and evaporation, so that under all conditions of working the heating-surface absorbs about 81 per cent. of the heat produced by combustion. Approximately, the same figure is obtained for all four boilers, although they vary considerably as regards design and ratio of heating-surface to grate area. The figures show that the efficiency of the boiler, as a whole, is mainly determined by the efficiency of the combustion, which falls rapidly as the rate of combustion is increased.

Although the smoke-box temperature at which the products of combustion escape increases as the rate of combustion increases, the percentage of the total heat carried away by these gases is reduced. This is due to the reduction of the weight of gas produced per pound of coal burned. When the rate of firing is increased from 30 to 130 lbs. per square foot of grate, the weight of the products of combustion is reduced from about 18 lbs. to about 8.5 lbs. per pound of coal fired. For complete combustion about 11 lbs. of air are required, so that when the boiler was forced it was not possible to get enough air through the fire to burn all the coal fired.

The figures obtained show that the locomotive of series 100 is particularly choked for want of air. The author learnt with much interest, after writing the foregoing, that since the tests, the Pennsylvania Railroad has increased the area of the air-inlets in the ashpan of this locomotive, with the result that it steams much more freely and efficiently.

Altoona Tests.—The heat-balances in these tests are calculated for rates of firing ranging from 2,000 to 5,000 pounds of coal per hour. Within these limits, which correspond to the range covered by the tests at St. Louis, the four chief items of the balance are affected as follows by an increase in the rate of firing:—

The loss by CO increases from 0.4 to 2.4 per cent.

The loss of heat in the gaseous products of combustion decreases from about 18 per cent. to about 15 per cent.

The loss by unburnt coal increases from about 10 per cent. to about 28 per cent.

The boiler efficiency decreases from about 68 per cent. to about 52 per cent.

The efficiency of the absorption of the heat actually produced, is, as found in the St. Louis tests, practically independent of the rates of combustion and evaporation, varying only from 78.4 to 79.7 per cent. That is, under all conditions of working, the boiler absorbs about 79 per cent. of the heat produced by combustion, while the boilers at St. Louis showed a constant efficiency of absorption of about 81 per cent.

The Altoona coal, having a higher percentage of volatile matter than that used at St. Louis, did not give quite such a high boiler efficiency at the lightest loads, but it enabled the boiler to be forced to a higher rate of evaporation, and gave a higher efficiency at the maximum boiler power. In the St. Louis tests the highest rate of evaporation obtainable was about 16.3 pounds of water from and at 212° F. per square foot of heating surface per hour, the corresponding boiler efficiency being about 46 per cent. The tests at Altoona show a maximum evaporation of 18.6 pounds of water per square foot of heating surface per hour, with a boiler efficiency of about 51 per cent.

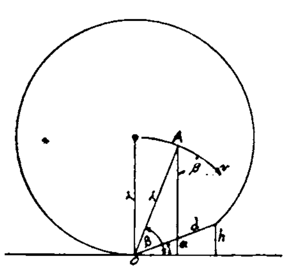
In examining the effect of the variation of grate area in the Altoona tests, it is found that at any given rate of evaporation there is very little difference between the efficiencies of the three series. At the lower rates of evaporation the largest grate gives the lowest efficiency and the smallest grate the highest efficiency; while at the high rates of evaporation the reverse is the case, the largest grate giving the highest efficiency. This is due to the fact that the resistance to the passage of the air through the grate is least with the large grate and greatest with the small grate. At low rates of combustion the most important losses are those due to an excess of air; consequently the large grate has the lowest efficiency. At the high rates of combustion the most important losses are those due to coal escaping unburnt from a lack of sufficient air for proper combustion, and hence the largest grate by admitting the air most freely gives the highest efficiency.

ALLOWABLE LENGTH OF FLAT SPOTS ON CAR AND LOCOMOTIVE WHEELS.*

By E. L. Hancock, Purdue University.

In the absence of experimental data as to the impact to which rails are subjected because of flat spots on car and locomotive wheels, the author has made a theoretical analysis. The development of a formula for the energy with which a flat wheel strikes the rail is as follows:

Let the diagram represent the wheel, of radius, r, having a flat of length, d. Represent the velocity of the train by v. At any instant it may be considered that the kinetic energy of the wheel, with its weight, considered as rotating about the point, O, is the same as if the mass supported by the wheel be regarded as concentrated at its center, that is, its kinetic energy is $\frac{1}{2}Mv^2$, where M is the combined mass of the car and wheel and v is the velocity of train. When the flat spot is in contact with the track the center of the wheel is at the point A. distant below the original position approximately $\frac{1}{4}h$, which is equal to $d^2 \div 4D$, where d is the length of the flat spot and D is the diameter of the wheel. At the point A the mass has a downward velocity equal to $v \cos \beta$.



But $\cos \beta$ equals $d \div D$, so that the kinetic energy with which M strikes the rail is $\frac{1}{2} Mv^2 \cos^2 \beta = \frac{Mv^2 d^2}{2D^2}$, where v is the velocity of train in feet per second, d the length of flat spot in feet and D the diameter of the wheel in feet.

It is assumed that the permissible kinetic energy of the blow caused by the flat spot should not exceed the kinetic energy with which the weight strikes a rail in the prescribed drop test. Hence the energy of the impact as deduced is equated to 380,000 foot-pounds, the energy of a 2,000-pound weight falling through 19 feet.

The weight upon a car wheel being assumed to be 10,000 pounds and the diameter of the wheel 33 inches, the formula becomes

$$d = \frac{29.4}{v} \quad \text{(A)}$$

While the energy of impact will be slightly increased by reason of the action of gravity increasing the velocity of the mass during the fall through the distance of A below the center, approximately $\frac{h}{4}$, it is found that this is so small as not appreciably to affect the results.

A formula corresponding to (A) for a 72-inch driving wheel, assuming a load of 25,000 pounds on the driver, is:

$$d = \frac{40.6}{v} \quad \text{(B)}$$

The following table shows the values of d for various speeds:

LENGTH OF FLAT SPOT PERMISSIBLE.

	33-inch wheel—Formula A.		72-inch wheel—Formula B.	
Speed v, in m. p. h.—	d in ft.	Factor of safety of 10, d in in.	d in ft.	Factor of safety of 10, d in in.
10	2.90	3.48	4.06	4.87
20	1.42	1.68	2.03	2.43
30	0.96	1.15	1.35	1.62
40	0.73	0.87	1.01	1.21
50	0.59	0.70	0.81	0.97
60	0.49	0.58	0.67	0.80
70	0.42	0.50	0.58	0.69
80	0.36	0.43	0.50	0.60
90	0.32	0.38	0.45	0.54
100	0.29	0.34	0.41	0.49

* From a paper presented before the Indiana Engineering Society, January 17, 1908.

Comparison of Alcohol and Gasolene Engines.—A very complete set of tests on the relative value of gasolene and alcohol as producers of power has recently been made by the Technologic Branch of the United States Geological Survey. Over 2,000 tests were made and it is stated that the results show that correspondingly well designed alcohol and gasolene engines, when running under the most advantageous conditions for each, will consume equal volumes of the fuel for which they are designed. The minimum fuel consumption value thus obtained is .8 of a pint per hour per brake h.p. Considering that the heat value of a gallon of denatured alcohol is only about .6 that of a gallon of gasolene, this shows a much better thermodynamic efficiency for the alcohol engine.

Sailors Ride in Railway Gasolene Motor Car.—A feature of the celebration of the arrival of the battleship fleet at San Diego, Cal., was a new gasolene motor car, of the same type as used on the Union Pacific Railway, which the Los Angeles & San Diego Beach Railway has recently installed. The trip of this car to the coast was exceptional for this class of equipment, since it was ordered at such a late date that it was necessary to start it from Omaha without the customary breaking in trials. The car left Omaha on April 9 at 5 a. m. and arrived at Los Angeles at 3 p. m., April 13, having made the entire run without mishap or delay of any kind.