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“An Investigation into the Heat-Losses in an Electric  
Power-Station.”

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THE published returns of central electricity-stations show very marked differences in the degree of economy attained in the process of converting heat to electrical energy. The replies to an inquiry, sent out in 1903 from Blackburn to thirty-four of the principal generating-stations of the United Kingdom, as to the cost and consumption of fuel per electrical unit generated, yielded figures ranging from 0·13*d.* to 0·83*d.* per unit, and from 3·6 lbs. to 15 lbs. of coal, the average consumption being 7·7 lbs. per unit. Doubtless many of the works referred to have improved in economy since that date, but the figures still represent the results in many of the power-stations in this country.

Roughly speaking it may be assumed that, in all these works, the boilers are capable of evaporating 8 lbs. of water per pound of coal, and the steam-dynamos can generate electrical energy at an average steam-consumption of 28 lbs. per kilowatt-hour. This assumption would mean about 3·5 lbs. of coal per electrical unit; and it would thus appear that half the aggregate fuel-bill of the larger generating-stations in 1903 represented the cost of generating energy which was wasted or consumed in the auxiliary processes.

The fuel-consumption of the Blackburn undertaking was then 10 lbs., costing 0·38*d.* per unit, a performance to be regarded as anything but satisfactory, indicating as it did that about 60 per cent. of the heat-value of the fuel was being absorbed by subordinate uses, and by losses of various kinds. Rough tests made under the existing conditions showed that the water-evaporation per unit generated varied between about 40 lbs., when the station was under

full evening load, and 150 lbs., when the bulk of the plant was shut down and the all-night load was being carried.

The more evident conditions combining to produce such unsatisfactory results were made the subject of tests, and in consequence many improvements were effected. The brickwork setting of boilers, the sides of flues and all economizer-walls were overhauled and repaired; external walls were, when possible, rendered impervious; and finally, better-fitting boiler-dampers were provided, and the firing-operations were more carefully controlled. The steam-piping, which was tortuous and inefficient in arrangement, was simplified, more effectively drained, and more thoroughly lagged.

The abandonment of the steam-ring system alone involved the rejection of 140 feet of 10-inch steam-pipe, with its attendant leakage and condensation; and the provision of greater facilities for drainage permitted the removal of centrifugal steam-driers and separators, which had previously been continuously under steam. Thus the radiating surface of the steam-piping was diminished considerably.

Twelve months after beginning this work, the fuel-consumption had been reduced to 8·5 lbs. per unit, and this improvement in detail was maintained steadily until the figure had fallen to 6 lbs. of coal per unit. While representing an economy of 40 per cent., this still left the fuel-bill undesirably high, which result might be due to one or more of the following causes:—

- (i) Failure to obtain the most economical class of fuel.
- (ii) Failure to obtain the prescribed calorific value in the fuel.
- (iii) Faulty combustion comprising:—
  - (a) Excessive or deficient air-supply.
  - (b) Rejection of combustible material in the ash.
- (iv) Rejection of heat in the gaseous products of combustion.
- (v) Loss of heat by leakage, radiation and condensation.
- (vi) Waste of heat by the main engines.
- (vii) Waste of heat in the auxiliary machinery.

Trials for the determination of the losses occurring from each of these sources were carried out periodically for about 2 years, and a certain amount of progress was made. They were, however, rather trials of individual processes than a general test on the whole plant; and it is probable that where attention is concentrated on the performance of one particular section a higher order of efficiency is obtained than during the ordinary running of the works. By repeating all the specific tests simultaneously, giving to none especial prominence, any error from this source is likely to be obviated. For the purpose, therefore, of throwing the various trials into their true perspective, one week's test of the whole works was arranged.

The more important observations have become more or less a matter of routine, but it was decided to include in these tests some minor processes which had not been considered hitherto. Such investigations were necessary to the completeness of the test, to the compilation of the heat balance-sheets, and to the construction of the curves appended to this Paper. It was felt that all information, even that concerning the smaller details, should be obtained to the greatest possible extent by positive test, rather than by any method of inference.

From the following short description it will be readily appreciated that the Blackburn generating-stations, in common with others of similar date, yield abundant evidence of the evolution of electrical plant during the period of their existence. It was impossible to foresee the development of such an undertaking, and hence the great variety in the type of machinery. These factors would render a comprehensive test in any way approaching to laboratory exactness a matter of extreme difficulty, calling for the provision of much more elaborate apparatus than would have been commercially justifiable, or have been available here.

It was also essential to the practical utility of the inquiry that the normal operation of the plant should be maintained, and it is of course impossible, in the case of a public-supply industry, to prescribe the conditions under which the tests shall be carried out; it was recognized that, under these somewhat unfavourable test-conditions, errors of some magnitude were hardly to be avoided. An attempt has therefore been made to conduct the trials on broad lines, and to preserve throughout the whole investigation a certain degree of accuracy; this accuracy is limited by the difficulties in estimating by weighbridge a coal-consumption of 200 to 300 tons per week, and by the further difficulties of obtaining thoroughly reliable information as to the calorific value and moisture of the fuel.

#### DESCRIPTION OF THE WORKS.

The works comprise two stations, each of approximately 2,300 kilowatts capacity, built on adjoining premises and run in conjunction.

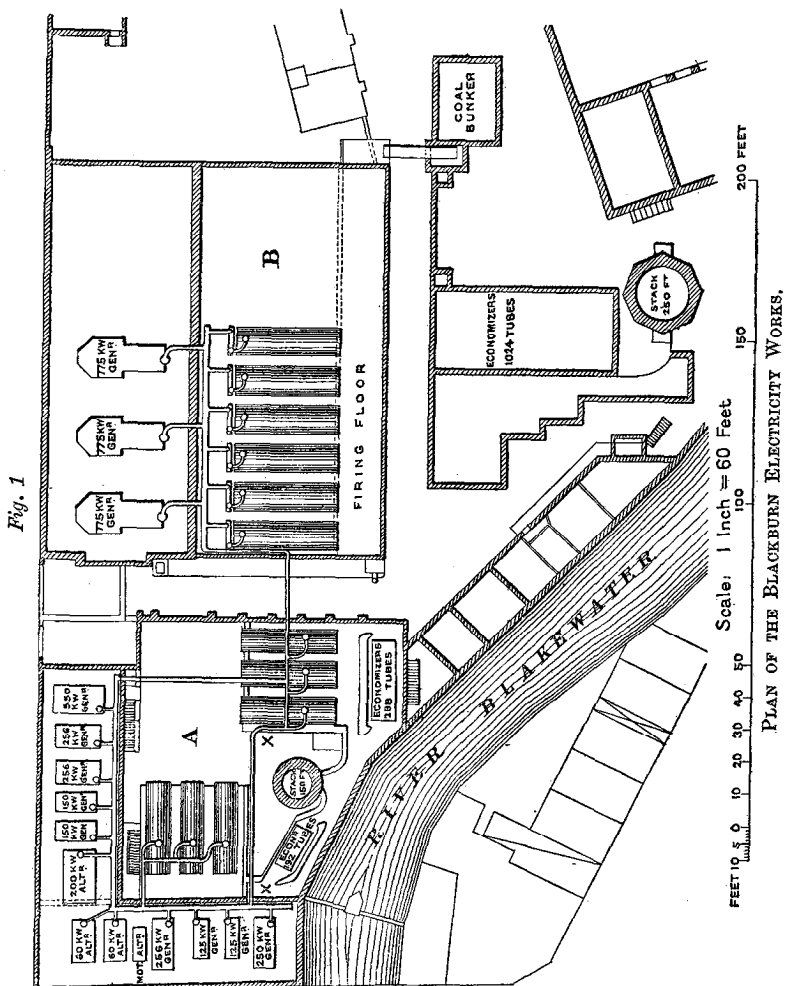
The older station is marked A in *Fig. 1*, and contains :—

*Engine-Room.*—Nine high-speed reciprocating steam-dynamo sets ranging in size from 120 to 550 kilowatts each, for supplying the continuous-current lighting- and tramway-systems.

Three high-speed reciprocating steam-alternator sets with capacities ranging from 60 to 200 kilowatts for the lighting of outlying districts.

One motor-alternator linking the continuous- and alternating-current systems.

One central condenser capable of dealing with 20,000 lbs. of steam per hour.



*Boiler-House.*—Six Lancashire boilers fitted with sprinkling stokers, and working at 130 lbs. gauge-pressure under about  $\frac{3}{4}$  inch water-column draught. No superheaters are used.

Two economizers of 192 and 288 tubes respectively.

Simple steam-driven pumps of the Weir type.

The feed-water is supplied from the condenser-discharge, and is supplemented by drainage from steam-traps and by water from the cooling-tubes in the engine crank-chambers.

*Steam-Pipes.*—The piping under steam ranges from 3 inches to 10 inches in diameter, and is covered with composition 2 to 3 inches thick.

The surface of the piping itself measures 895 square feet, or 0·39 square foot per kilowatt-capacity of the station.

The new station, marked B in *Fig. 1*, contains:—

*Engine-Room.*—Three high-speed reciprocating steam-dynamo sets, each of 775 kilowatts capacity, and each one fitted with its own ejector-condenser.

*Boiler-House.*—Six Lancashire boilers fired by sprinkling stokers, working at 185 lbs. gauge-pressure under chimney-draught. Down-take superheaters are fitted to all boilers.

Two economizers of 512 tubes each.

Two compound steam-driven feed-pumps of the Hall type.

The feed-water is supplied from the condenser-discharge, heated by feed-pump exhaust-steam, and supplemented by drainage from steam-traps, blow-off valves, etc.

*Steam-Pipes.*—The piping is 7, 8 and 14 inches in diameter, with a total radiating surface of 714 square feet, or 0·355 square foot per kilowatt capacity of the station.

*General.*—The two stations deliver current to the same bus-bars, and surplus superheated-steam is delivered from the new works to the old through a reducing-valve.

#### GENERAL SURVEY OF THE TEST.

The trials were made during November, 1907, and throughout the 168 hours of the test every instrument used was read half-hourly, and in addition such constant losses as leakage of water from safety- and blow-down valves were determined.

It was considered desirable, in the case of the observations relating to the calorific value and moisture of the coal, to accept the mean results of the trials carried out frequently during the preceding 12 months, in preference to the much smaller number which could have been obtained during the actual period of the test. The coal, as delivered to the works, was sampled and tested for the amount of moisture contained in it. This sample, obtained daily, was dried and then quartered down to an amount suitable for the determination of its calorific value, a reasonably exact estimate of the available heat being thus obtained.

The distribution of the heat of combustion was arrived at from continuous analysis of the flue-gases, and by observation of their temperature at various points along the flues.

The water-consumption was estimated from a water-meter in the feed-circuit; this was checked by counters on the pumps, and calibrated daily against a measured tank.

The heat used by the main engines was registered by the insertion of thermometers in the condenser-inlets and discharges; and a careful record was kept of the quantity of water in circulation, and of the temperature and pressure of the steam supplied to and discharged from the engines.

A close approximation to the steam-consumption of the auxiliary apparatus was made from direct trials.

The energy metered was that supplied to the external circuits for distribution, that supplied to the electrically-driven auxiliaries in the works, and that required for the lighting of the premises.

In general, all apparatus employed was calibrated against standard instruments, both at the close of the tests and, where possible, during their continuance.

One important series of observations, which would have occupied a prominent place in the records obtained, had to be omitted; the coal-measuring apparatus fitted to the storage-bunkers has proved totally unworkable when dealing with fine wet slack, the measuring-chambers being neither completely filled nor entirely emptied. Data of the rate of fuel-consumption, therefore, have been unobtainable.

Three curves were constructed from the half-hourly readings and from the continuous records taken throughout the week, which show broadly the efficiency of the works at all times throughout the whole of the average day.

So far as possible, the data obtained have been entered on the Form for a Complete Steam-Plant Trial prescribed by the Institution Committee on Steam-Engine and Boiler-Trials.<sup>1</sup> Some slight modification of this Form has been made on account of the unusual nature of the tests. The efficiency of the plant being, of course, variable with the wide changes of load, the adoption of a hypothetical hour or minute for the statement of results would, in this case, convey a false impression. It has been thought preferable, therefore, to enter the figures obtained from the test as a whole, rather than reduce them to an average which is possibly not representative of the performance at any one period of the trial.

The results of the trials are also set forth in the Heat Balance-

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<sup>1</sup> Appendix II.

Sheets<sup>1</sup> which relate to various sections of the plant, and from which the principal Balance-Sheet has been compiled.

The Trial-Form and Balance-Sheets may be considered as the result of the integration of the curves.

### SPECIFIC TESTS.

*Fuel Selection.*—The particular class of fuel to be used was decided upon after the following trials. Several coals were selected, which were tested for calorific value and for proportion of incombustible matter. Those fuels which showed the best results, having regard to price, were chosen for an actual working-trial, one week's supply of each (200 tons to 300 tons) being taken. During such a trial, the weight of coal used, the water evaporated, and the output of electrical energy were noted carefully, the draught being adjusted with the aid of flue-gas analysis. At the end of the test the cost of fuel was compared with the water-evaporation, and the amount of ash produced was noted.

This running-test, showing the behaviour of the fuel in the furnace, was regarded as the only safe basis upon which to make the final decision. The calorimetric determinations, while useful as a preliminary guide, have not been found very reliable as an index to the relative values of different fuels in actual use. No definite information is yielded by the calorimeter on such questions as the smokiness of the coal; as to whether it is free and open-burning, or will cake and adhere to the fire-bars; or again, as to the amount and nature of the clinker formed, whether easy or difficult of removal from the furnace.

Table I shows the comparative results obtained by the two methods for one series of trials. From inspection of this Table it would appear that, regarding the calorimeter-results only, coal Nos. 5 and 6 are both more economical than coal No. 1. The working-tests, however, show that this view is inaccurate, and further that coal No. 5 is entirely unsuited to the conditions.

It is considered that, by these methods, the selection of the most suitable local fuels has been satisfactorily accomplished.

The next consideration is the provision that the quality of the bulk supply of fuel shall be equal to that of the sample upon which the contract is based; unless, of course, some arrangement is effected whereby the price becomes a function of the quality. It is stated to be the practice of some large power-stations to adjust the price of

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<sup>1</sup> Appendix III.

TABLE I.

Calorimetric Determinations.				Actual Working-Tests.		
Number of Coal.	B.Th.U. per Lb. Mean of Six Tests.	B.Th.U. per Penny.	Percent- age of Ash by Ignition.	Cost of Coal in Pence per electrical Unit.	Percent- age of Ash removed.	Remarks on the Working of the Coal.
1	13,200	364,670	7.3	d. 0.255	10.3	{ Coal works easily. Clinker thin and hard.
2	13,970	352,350	6.43	0.265	16.0	{ Coal clogs. Large amount of combustible in ash.
3	14,080	290,750	5.9	0.318	11.8	{ Coal difficult to work. Forms large balls in the fires.
4	13,750	354,820	6.7	0.270	10.4	{ Coal easy to work. Clinker hard.
5	13,860	369,600	..	..	..	{ Test unfinished. Coal too smoky to use.
6	13,090	374,530	7.92	0.262	11	{ Coal dirty but clinker easy to remove.

the fuel to the calorific value by means of a sliding scale, each consignment being sampled and tested in the calorimeter. Such a procedure may be possible if the station is in a position to dictate the terms of sale; but it is found in Lancashire that the colliery-proprietor strongly prefers to sell coal as coal, rather than as heat-units. This method of buying, even if desirable, would thus appear to be difficult of realization, especially for moderate-sized undertakings. It was thought, however, that the use of the calorimeter would constitute the best means of checking the uniformity of supply, and daily tests of the calorific value were made for some considerable time. This has since been discontinued, partly owing to the refusal on the part of the collieries to recognize the application of such methods, but principally because it was found that a variation in quality was more speedily detected in actual working. Thus several tons of coal may be burnt while a calorimetric investigation is being carried out, and further the test sample forms such a very small proportion of the whole consignment. In the undertaking under consideration a sample of 25 lbs. is taken from about 40 tons delivered daily, a small quantity being abstracted from each load while on the weighbridge; from this sample an amount of about 6 grammes is selected by successive quartering for testing in the calorimeter. The ratio between the weight tested and the total supply is about 1 to 7,000,000, and it is difficult to accept the results of such a test with any confidence. It was nevertheless necessary,



in order to bring the various heat-losses into their relative significance, to accept the indications of the calorimeter as the basis of the heat-units supplied to the boiler-fires.

*Estimation of Moisture in Coal.*—The process adopted for estimating the amount of moisture in the coal must necessarily suffer from the same defects as the calorimeter test, i.e., the smallness of the sample tested in comparison with the bulk supply. There would appear, however, to be no practicable means of eliminating this uncertainty.

With a view to restrict, within the closest limits, any error from this source, precautions were taken to carry out the process of sampling on the widest possible scale. From each load of coal delivered about 1 lb. was taken, and the resulting 25 to 30 lbs. was mixed at the end of the day, carefully weighed, and spread thinly on an iron plate; the plate was then exposed to the air in an atmosphere of about 110° F. for 24 hours, after which the contents were again weighed, the loss of weight constituting the correction for moisture in the fuel. This operation was carried out daily for 12 months.

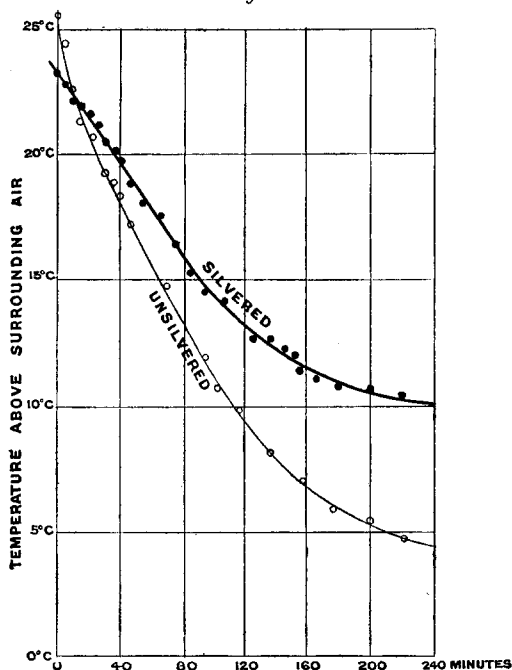
The expulsion of moisture by this method was found by further test to be incomplete; after exposure to the warm atmosphere, samples were heated for 1 hour to a temperature of 220° F., and subsequent weighing showed the elimination of about 1 per cent. of additional water. These supplementary tests yielded results very consistent in character, and no hesitation is felt in accepting the figures thus obtained.

The average moisture in the fuel appears from these trials to have been 5 per cent., and this correction, augmented by a further 1 per cent., has been applied to the scheduled weight of coal delivered, and also to the calorimetric determination of the thermal value available.

*Determination of Calorific Value.*—Before accepting the indications of the heat-value as revealed by the calorimeter, the latter instrument was examined with a view to estimate its degree of accuracy, and to reduce its possibilities of error. The tests were made by means of a Thompson calorimeter, with certain modifications which proved to be desirable. The most probable errors in an instrument of this class appear to be due to:—

- (i) Radiation from the calorimeter.
- (ii) Irregular supply of oxygen, resulting in spasmodic combustion.
- (iii) Insufficient provision for extracting all the heat of the gases.
- (iv) Uncertainty as to the combustion of the whole of the sample

The question of radiation was first investigated. A cooling-curve of the calorimeter was obtained by filling the instrument with water, and noting the rate of fall of its temperature with reference to that of the surrounding atmosphere; the external surface of the glass containing vessel was then silvered and the cooling experiment was repeated. The result of these two tests are shown in *Fig. 2*, and a considerable diminution in the radiation will be observed.

*Fig. 2.*

COMPARATIVE COOLING-CURVES OF THE THOMPSON CALORIMETER.

Using the calorimeter in its original form, i.e., obtaining the supply of oxygen from a mixture of potassium chlorate and nitrate with the fuel, it would seem that the radiation-error is of trifling moment, the time of combustion for a 2-gramme sample of fuel under these conditions being only 60 to 90 seconds. Owing to uncertainty as to the completeness of, and regularity in the rate of combustion, it was found desirable to supply the oxygen directly from a gas-cylinder and to extend the time of combustion to about 10 minutes. A glass combustion-chamber replaced the copper vessel previously

used, rendering the operations visible, and electric ignition was adopted in place of the cotton fuse. These alterations ensured thorough combustion and transfer of heat to the water but increased the liability to radiation-error; however, by taking due precaution as to the relationship between the temperature of the calorimeter and that of the surrounding air, and by the adoption of external silvering, appreciable inaccuracy in this direction was minimized.

In this connection the Author is uncertain whether the cooling-curves obtained (*Fig. 2*) are entirely reliable as an interpretation of the radiation loss occurring in the actual use of the instrument. It is, of course, well known that glass is diathermanous in a greater or less degree according as the heat-rays proceed from a source of high or low intensity; in use, the radiated energy is emitted from a body at high temperature, while the cooling-curves represent the action of a body at low temperature. It is possible, therefore, that the advantage accruing in use from the external silvering is understated by the curves.

The mean calorific value, deduced from seventy-three tests made on the particular coal supplied, was 13,180 B.Th.U. per lb. This figure applies to the dried coal, and when corrected for 6 per cent. of moisture expelled, the available heat becomes 12,310 B.Th.U. per pound of the fuel as actually fired.

*Flue-Gases: Analysis and Measurement.*—The use of a Krell CO<sub>2</sub> recorder enabled the efficiency of combustion to be controlled, and this was checked periodically by means of the Orsat apparatus.

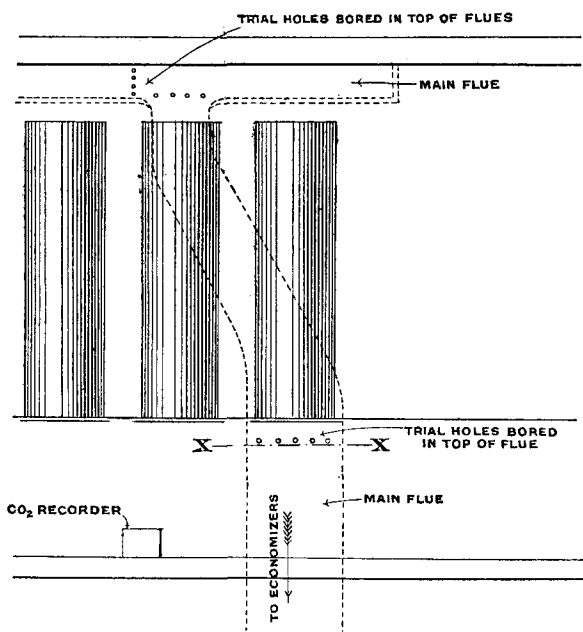
The Krell instrument consists essentially of two vertical tubes of equal height, connected at the upper extremities through one pipe to the apparatus used for extracting the gases from the flue, e.g. a fan or air-ejector. The lower end of one tube communicates directly with the flue, and that of the other is open through a diaphragm to the atmosphere. When the fan or ejector is in operation, the flue-gases are drawn up one limb and air up the other, to meet at the top in the common pipe. At the base of each tube connection is made to a delicate manometer, which registers the relative weights of the columns of gas and air.

The instrument was connected to the main flue beyond the boiler-exit dampers, thus yielding a record of the average composition of all the gases from the fires. This plan is not entirely satisfactory, for, while the main flue is underground and is thus free from in-leakage of external air, a record obtained at this point includes the leakage through the boiler-brickwork. To ensure conclusive information, however, would have entailed the provision of one recorder for each boiler-downtake, a quite impossible condition.

From time to time analyses of the products of combustion in the boiler-flues were made by means of a portable Orsat apparatus, and these were compared with the simultaneous record obtained from the main flue. It was thus possible to apply a correction to the latter, so as to render it a fairly reliable index to the process of combustion itself.

Great difficulty was experienced in the selection of the point from which to obtain gases truly average in character; the simultaneous insertion of pyrometers in a series of holes drilled across the top plates of the main flue, as shown in *Fig. 3*, yielded a variety of

*Fig. 3.*

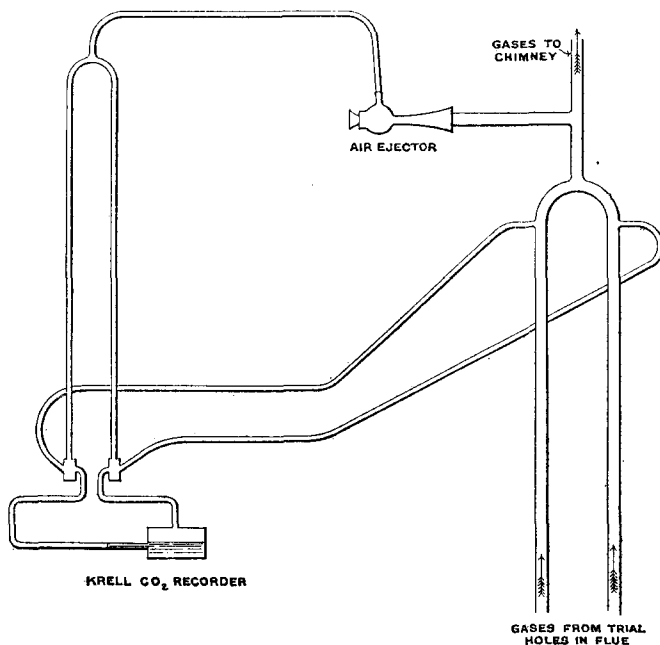


POSITION OF TRIAL-HOLES USED FOR OBTAINING SAMPLES OF FLUE-GAS.

temperature-readings, pointing to the possibility of stratification of the gases in the flue. This condition was further indicated by the fact that the opening of the furnace-doors of any one boiler for a considerable period did not produce an equal fall in the readings of the several pyrometers; and definite proof of the existence of this peculiarity was obtained by connecting the Krell recorder to two of the points in such a manner that the gases derived from the one were balanced against those from the other.

A skeleton diagram (*Fig. 4*) illustrates this method of employing an instrument. Connected as shown, it is obvious that no movement of the liquid can take place if the constituent gases of both tubes are of the same composition, while any variation from homogeneity will produce movement at once. By this method differences in the composition of the gases to the amount of 4 per cent. of  $\text{CO}_2$  were indicated at the various points tested. At the point marked X in *Fig. 3*, the mixture of the gases appeared from this test to be

*Fig. 4.*



METHOD OF COMPARING GASES OBTAINED FROM TEST-HOLES.

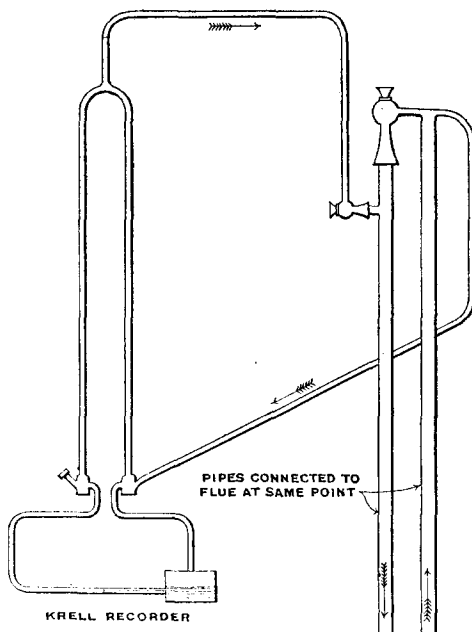
intimate, and a sample drawn from a perforated pipe at this point would be fairly representative in character.

The experiments undertaken in this direction also demonstrated another interesting effect, namely, the centrifugal tendency imparted to the heavier constituents of the flue-gas by curves in the direction of the line of flow. The gases, after leaving the boilers, describe an easy curve on their way to the chimney; and the tests showed clearly that they were about 2 per cent. richer in  $\text{CO}_2$  on the outer than on the inner perimeter of the curve. This effect, obvious of

explanation when observed, was for some time overlooked, and may serve to indicate the extreme care to be taken in procuring gas for analysis.

The method of taking the sample of gas was also the subject of considerable experiment, and it was found impossible to achieve reliable results with the Krell instrument on the lines proposed for the tests of the Admiralty Boiler Committee, and referred to in the Report of the Institution Committee on Steam-Engine and Boiler-Trials.<sup>1</sup> Most of the difficulties encountered, and the failures to

*Fig. 5.*



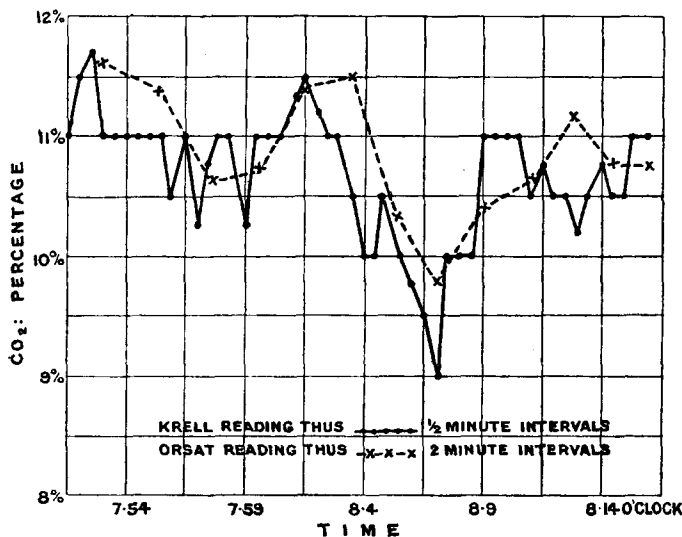
ARRANGEMENT FINALLY ADOPTED FOR SAMPLING FLUE-GASES.

overcome them satisfactorily, have been intrinsic to the type of analyser adopted. It is essential to correct working that the degree of tension of the flue-gas in the one column and of the air in the other should be nearly equal; with a variable atmospheric pressure, and an alteration, from time to time, of perhaps  $\frac{3}{4}$  inch water-column in the draught, this equality has been somewhat difficult of attainment. When a fan is used for the extraction of the gas, the

<sup>1</sup> Minutes of Proceedings Inst. C.E., vol. cl, p. 261.

tension of the latter is dependent jointly on the pull exerted by the fan, and the extent of vacuum in the flue; as the latter quantity is variable, and in fact is changed with every manipulation of the dampers, a sufficiently constant tension in the gas passing through the analyser was not obtainable by this means. The plan finally adopted to overcome the difficulty was found to give good results, and consisted in causing the pull to become a function of the draught in the flue only, eliminating all external agencies; and by the employment of an air-ejector it was possible to maintain a constant flow of gas under comparatively wide variations of draught. *Fig. 5* shows this arrangement, and numerous tests have proved that

*Fig. 6.*



COMPARATIVE CURVES FROM TWO CO<sub>2</sub> RECORDERS.

the accuracy of the Krell instrument so connected is conformable to all practical requirements.

On several occasions a trial of 1 hour's duration was carried out, during which the gases were analysed by means of the Orsat apparatus every 2 minutes, and a curve of the percentage of CO<sub>2</sub> was plotted from the records (*Fig. 6*). This curve was compared with that traced on the drum of the Krell instrument during the same period of time, and demonstrated the very close agreement between the two types of apparatus. The volume of gas drawn through the pipe from which the test-sample was extracted was metered, and found to be

about 37 cubic feet per minute, which bears a reasonable ratio to the total volume of flue-gas.

The mean percentage of  $\text{CO}_2$  in the gases at the boiler-exit dampers was found to be from nothing to 2 per cent. higher than that recorded in the main flue at the point of test; as it was impossible to maintain a continuous record from all the boilers individually, the main-flue reading, corrected from periodical tests on the boilers, is accepted as representing the average composition of the furnace-gases. The correction for the week of test was 0.6 per cent. of  $\text{CO}_2$ .

It is an open question whether or not the specific heat of simple gases increases with their temperature. The specific heats of superheated steam and of  $\text{CO}_2$  do so increase, but their values are to some extent a matter of conjecture, and in any case are compiled from laboratory experiments possibly under conditions different from those obtaining in actual work. Even if the chemical composition of the flue-gases is known accurately, there seems to be some doubt as to the accuracy of computing their mean specific heat from that of their several constituents, particularly under conditions where possible molecular changes, the presence of particles of incandescent fuel and flue-dust, and the possible absorption by these particles of some of the constituents of the gases, may all be prevalent.

In the investigation these questions had to be ignored, and the specific heat of the flue-gases was estimated from analysis of the coal and of the gases; it was also assumed to be independent of such changes of temperature and volume as are encountered between the boiler-flues and the chimney-base. Any error thus introduced was considered small in comparison with that due to uncertainty as to the exact chemical composition of the gases.

The temperature of the flue-gases was continuously observed in the main flue immediately beyond the boilers, and at the entrance to and exit from the economizers. For this work four certified mercury-pyrometers, one fitted with a recording drum, were available.

As the superheaters are fitted to the boiler down-takes, it was impossible to obtain temperature-readings of the flue-gas before and after passing them; the heat given up by the gases to the superheaters, therefore, cannot be separated from that abstracted by the boilers. Moreover, as the dryness-fraction of the steam delivered to the superheaters is unknown, this separation of the two quantities would be of little use.

*Evaporation of Feed-water and Distribution of Steam.*—The estimation of the work done by the boilers and superheaters was carried out in the following manner:—



The total feed-water pumped was measured by a meter placed in the suction-pipe, and working under a 12-foot head. This meter was calibrated daily against a measured tank, and a rough check was provided by the counters on the feed-pumps. The tank had a capacity of about 4,000 gallons, and was carefully gauged throughout its depth from smaller accurately-measured tanks. Each day about 2,000 gallons of water was pumped under observation, the meter-error and the average duty per pump-stroke being thus determined; this operation was performed at various definite rates of pumping, and curves were constructed showing the correction to be applied to the meter-reading. The average speed of the pumps was obtained half-hourly from the records of the counters taken throughout the test.

In this connection a curious error was met with, due to the type of water-meter employed. On the suction-pipe between the meter and the pumps, an air-vessel had been fitted to steady the water-supply; and it was found that the meter was fast at all rates of pumping, the extent of inaccuracy ranging from 5 per cent. on full duty to nearly 100 per cent. when pumping very slowly. By fitting a water-gauge to the air-vessel it was seen that the water, after passing the meter, returned at the end of the pump-stroke to the feed-tank without reversing the meter; and a large quantity of water was thus being measured repeatedly. The error was eliminated by placing a non-return valve between the feed-tank and the water-meter. The Author considers that, having regard to the constant check which was maintained, the corrected indications of the water-meter may be accepted as a true statement of the amount of water pumped.

The losses due to leakage, condensation and radiation, in addition to the water required for driving the main engines and auxiliary plant, are included in the meter-readings. To separate these items special tests of about 10 hours' duration were made on several occasions, advantage being taken of the light load in the small hours of Sunday morning to transfer the load on to one station while the other was under trial.

The boiler water-gauges being marked, and the boilers filled to the prescribed levels, steam was shut off at the engine stop-valves and water at the pump delivery-valves; the leakages from boiler- and economizer-valves, and from all steam-traps were drained into separate vessels.

The depth and temperature of the water in the feed-tank was noted so as to check any slight return of water through the pump-valves, and the tightness of the engine stop-valves was ensured by removal of the throttle-valve lubricating-cocks. Steam was main-

tained at full pressure for about 10 hours, and at the end of that time the boilers were pumped to the original levels with measured water. As the water-leakages from boilers and from economizers were determined separately, the remaining loss may be considered as steam-leakage and condensation, the discharge from the steam-traps forming an additional check on the latter item.

The condensation in the whole pipe-system under these trials amounted to an average of 953 lbs. of water per hour. This is equivalent to about 810,000 B.Th.U. per hour, which figure divided by the total radiating pipe-surface gives a heat-loss of 473 B.Th.U. per square foot per hour. It should be pointed out that the radiation cannot be quite correctly arrived at in this manner, for in practice the pipes carry superheated steam at a temperature varying between 450° and 650° F., while in the test the steam was saturated, and, probably, very wet, at a temperature of about 380° F. Several attempts have been made to estimate the quantity directly by observing the fall in temperature of a known weight of superheated steam passing through the pipes in a definite period of time. In a 72-foot length of 14-inch piping, it was found repeatedly that a flow of 16,000 lbs. of steam per hour, at a temperature of 580° to 600° F., was accompanied by a fall in temperature of 15°. The same weight of steam traversing a 10-inch pipe, with consequently double the velocity of the previous case, appeared to experience a smaller diminution of temperature, an effect contrary to expectation but confirmed by repeated trials. The two pipes were exposed to much the same external temperature, were coated to equal thickness with the same covering material, and were both of steel and approximately of equal thickness; each was thoroughly clean internally, and free from constrictions or other obstruction to the free flow of steam, the 14-inch pipe consisting of one straight length, and the 10-inch of two straight lengths at right angles and coupled by an easy bend. It was thus anticipated that the greater friction, consequent on the higher velocity, would have occasioned a greater loss of temperature in the smaller pipe.

The results observed would appear to constitute an argument for the reduction of pipe-area, apart from the diminution of radiating surface occasioned thereby. The tests have been necessarily rough in character, and the Author does not care to place undue reliance on the figures obtained; they have been thought worthy of mention, however, as the data yielded were consistent, and while perhaps inaccurate in an absolute sense seemed to be true relatively. It is proposed to subject the matter to further investigation at a later date.

The loss of heat in these experiments with superheated steam is  
 $16,000 \times 15 \times 0.48 = 115,200$  B.Th.U. per hour,  
 assuming the usual value for the specific heat of steam.

The radiating surface in these cases being 306 square feet, the heat-loss per square foot per hour is thus 376 B.Th.U. From the experiments of Messrs. Knoblauch and Jakob, of the Royal Technical University, Munich,<sup>1</sup> the specific heat of steam, at the temperatures and pressures employed, would appear to have a much higher value than is here assigned to it.

If this higher figure be adopted, the heat-loss mentioned becomes

$$\begin{aligned} 16,000 \times 15 \times 0.545 &= 130,800 \text{ B.Th.U. per hour.} \\ &= 427 \text{ B.Th.U. per square foot per hour.} \end{aligned}$$

There is thus some considerable disparity between the figures obtained by the condensation-test and those obtained by the test with superheated steam, the results, repeated for ease of comparison, being as follows:—

By condensation test,

473 B.Th.U. per square foot of radiating surface per hour.

By fall-of-temperature test—

(i) assuming the specific heat to be 0.48,  
 376 B.Th.U. per square foot per hour.

(ii) assuming the specific heat to be 0.545,  
 427 B.Th.U. per square foot per hour.

Owing to the uncertainty attaching to the question of the specific heat of superheated steam, and the doubt as to the correctness of the data obtained from the experiments, the Author has considered it advisable to accept the quantity as determined from the condensation tests.

*Steam-Consumption of Auxiliaries.*—The only auxiliary purposes to which steam is devoted are the supply to the jets under the boiler grate-bars, that to the feed-pumps, and that to some domestic appliances, e.g., bath and steam-kettles for workmen.

The figure representing the quantity of steam utilized by the grate-jets was obtained by connecting all the jet-pipes to one boiler, and observing the rate of evaporation for this purpose alone. Before and after this test the boiler was left standing for some time

<sup>1</sup> *Mitteilungen über Forschungsarbeiten* 1906, p. 109 (Nos. 35 and 36). See also *Engineering*, vol. lxxxiii, pp. 227 and 472.

with closed valves, to ensure that it was neither receiving nor delivering steam or water through the valves. It was found that this demand amounted to practically 2 per cent. of the total water evaporated, and that this figure remained approximately true for all rates of evaporation. It was impossible to measure the steam consumed by the jets throughout the trials by direct means, and this quantity has accordingly been allocated to them. The steam supplied is considered as being evaporated twice, once in the boiler and again in the furnace which it reaches in the form of a fine spray of condensed particles rather than as a steam-jet proper. These two operations are shown in the boilers account.

The steam-supply to the feed-pumps was arrived at by the condensation of their exhaust into a known weight of water, and by determination of the increase in weight of this water for varying duties of the pumps. The mean speed of the latter being recorded by the half-hourly reading of their counters, it was possible with very fair accuracy to decide on the weight of steam abstracted for driving the feed-pumps. A rough check on this determination was also provided by the observation of the heat given up by the pump-exhausts to the feed-tank, although as the steam is very wet when rejected from the pumps, this evidence is of comparatively small value.

As the greater portion of the heat in the steam used by the pumps is returned to the feed-water, a considerable miscalculation in the estimate of its amount would have little effect on the balance of heat. It is thought, however, that the tests made have allowed but little scope for the occurrence of any appreciable error.

The consumption of steam for the domestic purposes is small, and frequent direct tests permitted its estimation without risk of serious inaccuracy.

*Steam-Consumption of Main Engines.*—The calculation of the steam used by the main engines was a matter of difficulty, and some doubt is felt as to the reliability of the deductions. The employment of the ejector- or jet-condenser at once prohibits the application of any process of direct measurement to the quantity of condensed steam; assuming, however, the condition of dry exhaust from the engines, reliable results may be obtained from this type of condenser. The quantity of circulating water may be estimated very exactly from a knowledge of the effective pressure across the injection-nozzles and of their area. It was recognized that the dryness of the exhaust was the crucial point in determining the accuracy of the calculations, and tests were accordingly made to discover whether or not this condition was satisfied, thermometers

being placed in the exhaust-pipes close to the engine exhaust-chambers. From the indications of the thermometers combined with those of mercury columns attached at the same point, the inference was drawn that the steam was not only dry but slightly superheated. This result was surprising, and would seem very improbable under any but full-load conditions. It was nevertheless decided to proceed with the attempt to arrive at the steam-consumption directly from the condensing-operations; for, while the method might fail as a means of measuring the heat supplied to the engines, it would be correct and of value as an estimation of that rejected by them.

The tests were conducted in the following manner :—

The quantity of water passing through the condensers was measured accurately by fitting mercury-gauges immediately across the water-nozzles, and observing the effective head of water. The water is supplied from an overhead tank containing about 50,000 gallons, and calibration of this tank to an accuracy of  $\frac{1}{4}$  inch provided an effective means of checking periodically the information deduced from the mercury-gauges. It was found possible to deal with the whole load throughout the day, with only three or four alterations to the quantity of water passing through each condenser : this is due to the fact that the ejector-condenser is capable of very little adjustment as regards water-supply, depending, under small external heads, upon the kinetic energy of the condensed steam for the preservation of vacuum. The lighting- and power-load, which is steady in character, has been carried with a water-head of only 3 feet, while the traction-load with its rapid fluctuations required a head of 8 feet.

By the careful logging of all adjustments made to the effective pressure it was possible to determine accurately the volume of water used. The condensers discharge into a common rectangular pipe 40 inches wide and 10 inches deep. Holes were drilled across this pipe for the insertion of thermometers into the discharge-water ; it was found that the water from the several condensers was imperfectly mixed, and considerable variations were encountered in the temperature of the water at different points across the pipe. It was therefore decided to construct a thermometer the bulb of which should extend the entire width of the pipe, and should be thus exposed to the effect of the whole of the water passing. Owing to the widely fluctuating demand for steam occasioned by the tramways load, it was found necessary to fit recording apparatus in the form of a pen and rotating drum ; such a thermometer was devised, and its operation was found satisfactory. The instrument as arranged is shown in *Figs. 7*, and a chart obtained from it is shown in *Fig. 8*. As a check on its

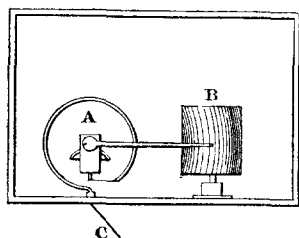
record, the mercury-thermometers inserted in the various test-holes and individual condenser-discharges were read half-hourly throughout the trials. The temperature of the injection-water was subject to little variation, and was also recorded half-hourly. Thus a very accurate calculation of the quantity of heat rejected by the engines has been possible.

As mentioned, the test fails to indicate the amount of steam supplied to the engines if the appearance of dryness at the exhaust is fallacious in character. This would seem to be at least possible, and, in that event, the only alternative method of estimating the steam used by the engines is to measure all other demands and subtract them from the total water evaporated. Thus in balance-sheet H an amount of 30,840 lbs. of water has been unaccounted

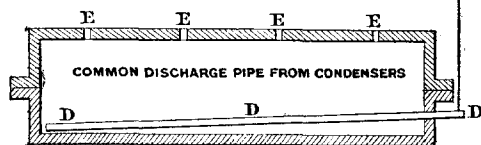
for, and the alternative method of calculating the steam-consumption of the engines would involve the addition of this figure to the quantity determined by the foregoing test.

It should be mentioned that the mean temperature of the walls of the engine exhaust-chamber was nearly 20° F. higher than that of the steam itself; this would seem to be caused by conduction of heat from the crank-chambers, whose average temperature is 140° F., and con-

*Figs. 7.*



- A. Steam gauge movement
- B. Rotating drum
- C. Copper capillary tube
- D.  $\frac{3}{4}$  bore copper tube, inside of which is fitted a  $\frac{1}{2}$  copper rod. The annular space is filled with water.
- E. Test holes for insertion of mercury thermometers.



ARRANGEMENT OF RECORDING THERMOMETER.

duction from the cylinders would also have some effect. It is suggested, as a possible explanation of the high temperature observed in the exhaust, that the close proximity of the thermometer-pockets to the exhaust-chambers may have permitted some transfer of heat from the latter to the thermometers. Opportunity has not as yet arisen for ascertaining whether or not such an influence exists.

The existence of an aspirating effect on the mercury vacuum-gauges, due to the passage of steam at a high velocity across the mouth of the gauge-pipes, may also be expected to produce a low reading of the pressure.

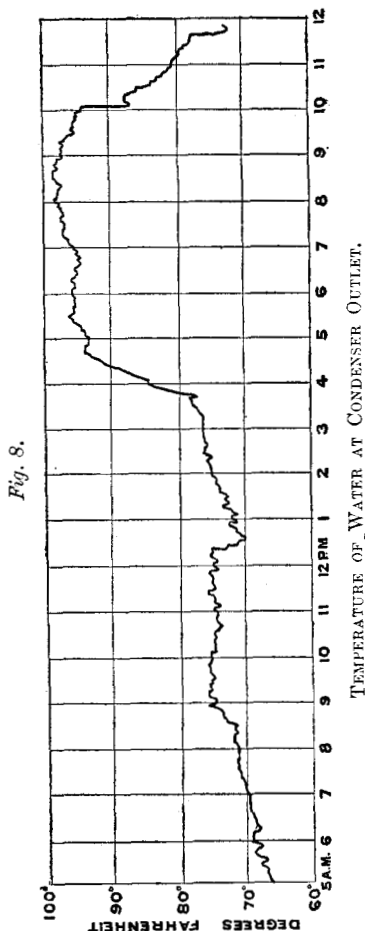
*Measurement of Output.*—The electrical measuring instruments used during the trials were carefully calibrated, and the Author has entire confidence in their accuracy to within 2 per cent.

The traction-output passes through three meters in series, the mean of the three indications being accepted. These meters are of guaranteed accuracy within the above-mentioned limits, and their performance in series for a period of 12 months has abundantly justified the guarantee.

The continuous-current power- and lighting-meters are of a similar type to those used on the traction-circuits, and their correctness on steady load was further established by the insertion of a Kelvin electrostatic wattmeter.

The high-tension alternating-current meters were also calibrated against a Kelvin electrostatic wattmeter, as were the various meters used for estimating the works' consumption of power.

In general, the output, however constant in amount, was on no circuit left to conjecture, and all energy used was



passed through carefully-tested meters.

## GENERAL SUMMARY.

In the light of these tests, it may be well to recapitulate the causes suggested as the possible sources of loss, in order to see how they may be held individually responsible for the poor thermodynamic performance of the works as a whole.

(i) *Failure to obtain the most Economical Class of Fuel.*—The very indifferent evaporative duty, averaging only slightly over 7 lbs. of water per pound of coal, would appear to indicate scope for some improvement in this particular. The working-tests, however, to which the various fuels were subjected may be held to have decided this point, and the comparatively unsatisfactory nature of the results is due rather to the conditions under which the fuel is consumed than to any shortcomings in the coal itself.

The wide variations in the load on the station and the short duration of the period of heavy load, which militate strongly against economical work, are circumstances peculiar to the character of the industry, and for this reason unavoidable. The necessity of maintaining steam-pressure in boilers for 22 or 23 hours, to permit of their use during the remainder of the day, involves a relatively enormous radiation-loss, and demands the combustion of a large quantity of fuel with no corresponding useful evaporation of water.

(ii) *Failure to obtain the prescribed Calorific Value in the Fuel.*—There can be little doubt that, having regard to the calorific quality of the samples upon which the annual contracts have been placed the character of the total supply leaves something to be desired. The seam from which the slack is obtained is thin, and there is considerable fluctuation in the value of the coal at the pit-mouth. The journey of 20 miles either by canal or rail, with the accompanying exposure to the weather, has also a deleterious effect.

For reasons already stated, no means have as yet been arranged to throw the onus of these conditions upon the colliery-proprietors, except at an increase of price which would more than outweigh the advantage gained.

(iii) *Faulty Combustion.*—This has been checked as indicated, and the efficiency of firing has been raised to as high a point as would seem to be commercially desirable. It has been found that a higher percentage of  $\text{CO}_2$  in the flue-gases involves smoke, and the rejection of a larger proportion of combustible in the ash.

(iv) *Rejection of Heat in the Gaseous Products of Combustion.*—The amount of heat lost in the chimney-gases is considerable, and the temperature at the base is far higher than is necessary to produce the



requisite draught. The length of the boiler-grate has been reduced from 6 to 5·25 feet, and internal feed-heaters are being tried as a means of reducing the final temperature still further, but no data as to the efficacy of the latter are yet available.

(v) *Loss of Heat by Leakage, Radiation and Condensation.*—A slight loss is encountered under the heading of leakage, including the waste of water from safety- and blow-down valves, and leakage of steam from safety-valves, joints and defective drains. A large quantity of water escapes constantly from the boiler blow-down valves, which are difficult to keep tight when regularly operated, owing to the scouring action of the sludge discharged through them at high velocity. The water thus rejected is too dirty to permit of its commercial recovery and delivery into the feed-tank.

The tests made have covered the investigation of the radiation- and condensation-losses in so far as they relate to the steam-pipes. It is difficult to see in what direction they are capable of much reduction, although they represent an annual loss of the order of £250, taking the average effective evaporation at 7 lbs. of water per pound of coal.

A greater but indeterminate loss is incurred by radiation from the boilers and brickwork during periods of light load, and also by leakage of air through the division-walls between the boiler-flues. The latter is avoided as far as possible by working adjacent boilers when the others are banked.

(vi) *Waste of Heat by Main Engines.*—This may be regarded as inevitable, except where it can be modified by care in the selection of generating machinery for the particular loads carried at various times; it has accordingly not been made the subject of special tests.

(vii) *Waste of Heat in the Auxiliary Machinery.*—This is not serious, as the steam is delivered to the feed-water. The steam used by the grate-jets, however, is considerable in amount and entails an expenditure of about £85 per annum. No satisfactory means of obviating this loss has as yet been devised.

The performance of the works for the particular week under test may be expressed in a tabular form, showing the disposal of the heat available, although as mentioned, such a statement is not a correct average over the year, the conditions varying at different seasons.

It may be of interest to compare Table II (p. 26) with one given by Mr. H. G. Stott<sup>1</sup> in January 1906, relating to the performance of one of the largest and most efficient of the American steam-driven power-stations (Table III).

<sup>1</sup> "Power-Plant Economics." Proceedings of the American Institute of Electrical Engineers, vol. xxv, p. 3.

TABLE II.

Heat energy in the coal (as used) . . . . .	B.Th.U. $6,287 \times 10^6$ .	Percentage 100.
Converted into useful work . . . . .	$339 \times 10^6$	5.39
Rejected to chimney . . . . .	$842 \times 10^6$	13.36
Radiation and leakage from steam-pipes . . . . .	$135 \times 10^6$	2.15
Rejected in hot ashes (combustible) . . . . .	$256 \times 10^6$	4.07
Losses (net) by auxiliary processes . . . . .	$189 \times 10^6$	3.10
Rejected (net) in condensing water . . . . .	$3,187 \times 10^6$	50.62
Rejected by blow-down valves of boilers . . . . .	$8 \times 10^6$	0.13
Evaporating and superheating grate-jets . . . . .	$87 \times 10^6$	1.38
Losses unaccounted for, <i>e.g.</i> , radiation of boilers, brickwork, including errors of observation, being balance . . . . .	$1,244 \times 10^6$	19.80
Total . . . . .	$6,287 \times 10^6$	100.00

TABLE III.—ANALYSIS OF THE AVERAGE LOSSES IN THE CONVERSION OF ONE POUND OF COAL INTO ELECTRICAL ENERGY. (*H. G. Stott*.)

	B.Th.U.	Per cent.	B.Th.U.	Per cent.
1. B.Th.U. per pound of coal supplied . . . . .	14,150	100.0	..	..
2. Loss in ashes . . . . .	..	..	340	2.4
3. Loss to stack . . . . .	..	..	3,212	22.7
4. Loss in boiler radiation and leakage . . . . .	..	..	1,131	8.0
5. Returned by feed-water heater . . . . .	441	3.1	..	..
6. Returned by economizer . . . . .	960	6.8	..	..
7. Loss in pipe-radiation . . . . .	..	..	28	0.2
8. Delivered to circulator . . . . .	..	..	223	1.6
9. Delivered to feed-pump . . . . .	..	..	203	1.4
10. Loss in leakage and high-pressure drips . . . . .	..	..	152	1.1
11. Delivered to small auxiliaries . . . . .	..	..	51	0.4
12. Heating . . . . .	..	..	31	0.2
13. Loss in engine friction . . . . .	..	..	111	0.8
14. Electrical losses . . . . .	..	..	36	0.3
15. Engine radiation losses . . . . .	..	..	28	0.2
16. Rejected to condenser . . . . .	..	..	8,524	60.1
17. To house auxiliaries . . . . .	..	..	29	0.2
	15,551	109.9	14,099	99.6
	14,099	99.6		
Delivered to bus-bar . . . . .	1,452	10.3		

In conclusion, the Author regrets the inadequate treatment which was accorded to many of the incidental sources of loss, the tests made having indicated a much larger field for profitable and interesting exploration than has been covered by them. In the first instance, however, the investigation was conceived with a

specific commercial end in view, and time did not permit of wide digression from the prescribed lines. Thus with the instruments, the time and the assistance available, it was impossible to do more than merely glance at many details which would yield much to a fuller and more thorough research.

The analysis and thermometry of flue-gases, and the calculation of their specific heat and weight, provide problems whose solution is difficult of realization.

The estimation, whether by calorimeter or analysis, of the mean calorific value of such a variable commodity as coal in large quantities, would appear to be very uncertain when accomplished by the testing of relatively microscopic samples.

The extent to which the radiation of steam-pipes depends, in actual work, upon whether superheated or saturated steam is employed, would in itself furnish very interesting ground for experiment.

These and many other similar suggestions arising out of the tests were extraneous to the purpose of the trials, and have thus been left untouched.

In so far as the practical object of the investigation is concerned, the results achieved may be held to have constituted some measure of success : from the point of view of scientific accuracy the results leave much to be desired. If, however, the investigation has indicated some of the difficulties encountered in the application of scientific tests to an essentially commercial operation, and if stimulus has been given to some spirit of scepticism regarding many of the methods commonly employed, the trials may not have been wholly fruitless.

The Author desires to acknowledge his indebtedness to Mr. Henry A. Mavor, M. Inst. C.E., for valued suggestions in regard to the arrangement of Appendix III.

The Paper is accompanied by thirteen drawings and five photographic curves, from which Plate I and the Figures in the text have been prepared ; also by the following Appendixes.

## APPENDIXES.

## APPENDIX I.

*Fig. 9. Economizers, Temperature, Draught and CO<sub>2</sub>.*

THE position in which the pyrometers were inserted was selected after some considerable experiment so as to give a reading as nearly average in character as possible. The simultaneous insertion of three pyrometers in the same trial-hole, so that the bulbs were in contact with the gases at different depths in the flue, constituted one test. The records thus obtained showed variations of as much as 30° F. in the temperatures at different depths.

Absolute accuracy cannot therefore be claimed for the figures adopted, but they are as nearly correct as could be achieved with the mercury type of thermometer. More exact information would perhaps be gained by observing the change in electrical resistance of a platinum wire stretched across the flue, although it would appear that the deposit of soot on the wire at low temperatures might introduce error.

*Fig. 10. Feed-Water used and Units Generated.*

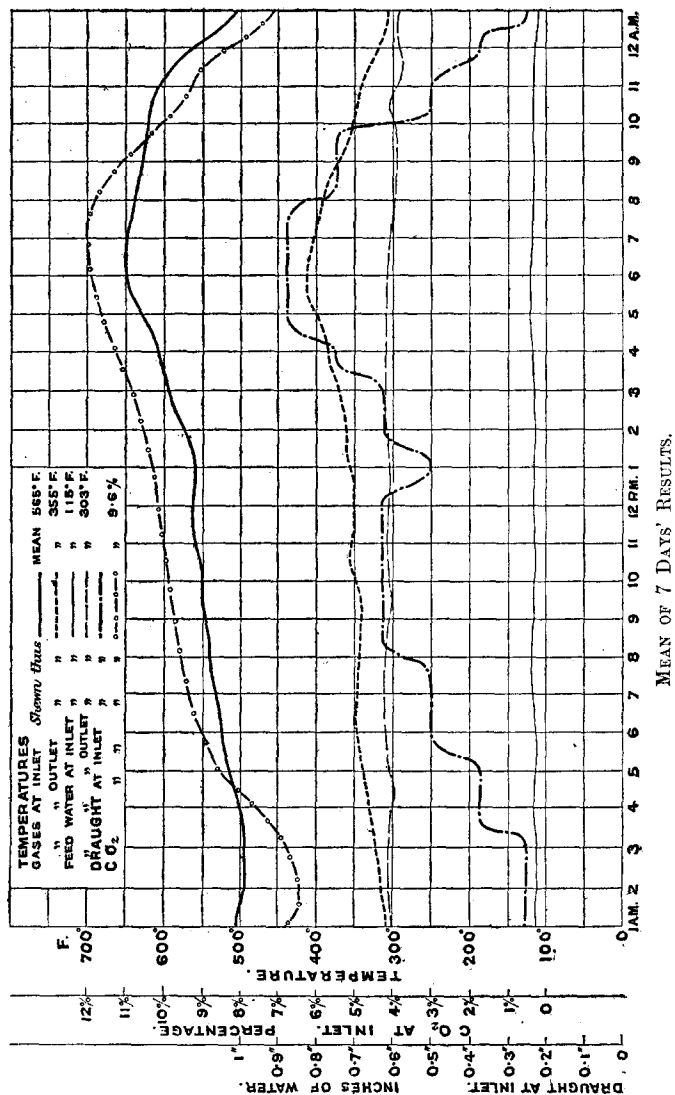
It will be noted that the amount of water used is not at all times the same for equal loads. One of the most interesting features is the difference in economy with which a rising load is carried as compared with a falling load; in the one case engines are warmed and put to work in anticipation of the demand, and it is not possible to allow one generating set to become fully loaded before switching in another; in the other case, with the declining output, one set after another is cut out, those remaining being thus operated at their highest efficiency.

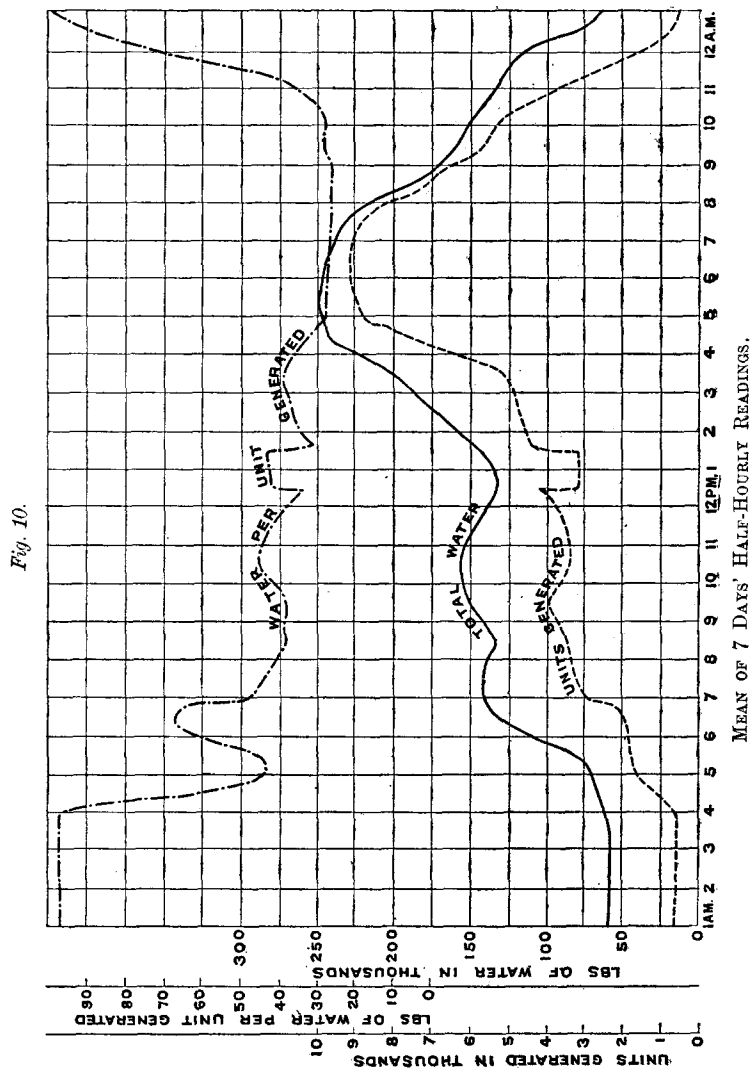
*Plate 1. Feed-Water and Steam.*

The items composing this Figure are obtained from the tests as indicated earlier in this Paper. Any ordinate, say, at 10 a.m. will represent the aggregate of all the 9.30 to 10 o'clock readings taken throughout the week. It will be seen that the area representing the condensation of steam vanishes at 3 p.m. to reappear at 9 p.m.; this is to be attributed to the fact that, at the higher loads, the radiation loss is supplied from a larger volume of steam, and the superheat, therefore, is not entirely lost; the condensation was discharged from the steam-traps and measured half-hourly. Between the hours mentioned the radiation loss does not appear in the curve; in the balance-sheets it has been necessary to assume, as indicated earlier, that this loss is the same in amount when superheated steam is employed, as is shown by the actual condensation with saturated steam.

The small area designated leakage of steam was determined by measurement of the steam-condensation on iron plates from such leakages as were visible.

Fig. 9.





# APPENDIX II.

## BOILER. SHEET I. GENERAL DESCRIPTION AND DIMENSIONS.

Type of Boilers Lancashire. Made by Messrs. Yates and Thom.  
 Maker's rating of the output of the Boilers, 8,000 to 10,000 lbs. of steam per hour.  
 Test made at an various outputs of lbs. of steam per hour.  
 Object of the Trial Estimation of general efficiency and losses.

Refer- ence No.	GENERAL DESCRIPTION OF BOILER AND LEADING DIMENSIONS.	
1	<i>Boilers under steam at time of trial were five 33' 0" × 8' 6" working at 185 lbs pressure ; one 30' 0" × 8' 0" banked for emergency at 130 lbs. ; one 28' 0" × 7' 6" banked for emergency at 130 lbs.</i>	
2	Method of starting and stopping the Test. <i>Coal bunkers empty at commencement and end of trials. Boilers filled to marked levels at commencement and end of trials. Full steam-pressure maintained throughout trial.</i>	
3	Method of stoking and average thickness of fire. <i>Mechanical sprinkling. Steam-jets used for cooling the grates. Fires about 4 inches thick working, and 7 to 9 inches thick banked.</i>	
4	Production of draught. <u>By chimneys.</u>	
5	Chimney heights { <u>250</u> } ft. Area at bottoms { <u>95</u> } sq. ft. ; tops { <u>95</u> } sq. ft.	
6	Total grate-surface (excluding dead plate)	sq. ft. _____
7	Grate area occupied by air-space between bars	sq. ft. _____
8	Total effective heating surface (fire-box _____ sq. ft., tubes _____ sq. ft.) sq. ft. _____	
9	Capacity of water-space	} at _____ inches { c. ft. _____ } in gauge-glass. { c. ft. _____ } sq. ft. _____
10	„ steam-space	
11	Area of water-surface in boiler	
SMOKE DIAGRAM.		
5	<i>Negligible.</i>	
Very black		
4		
Black		
3		
Darker grey		
2		
Dark grey		
1		
Light grey		
0		
No smoke		

NOTE.—The Numbers in the first column of each Form have reference to Appendix II of the "REPORT OF THE COMMITTEE ON STEAM ENGINE AND BOILER TRIALS," Minutes of Proceedings Inst. C.E., vol. cl, p. 266.

The words and figures in ordinary type are those of the printed form ; the Author's alterations are indicated, and his figures etc. are shown, in italics.

## BOILER. SHEET II. DATA DEDUCED FROM OBSERVATIONS.

Refer- ence No.	Particulars of Observations.	Abstract of Observa- tions.	Remarks.
12	Duration of trial <del>from</del> <del>to</del> 168 hours		
	FUEL.		
13	Short description . . . . .	Wigan fine slack.	
14	Fired <del>per hour</del> during trial . . . . . tons lbs.	228	{ Includes 13·7 tons moisture.
15	Analysis by weight of dried fuel—		
	"    "    carbon . . . . . per cent.	74·6	{ By indepen- dent analy- sis.
	"    "    hydrogen . . . . . "	5·1	
	"    "    sulphur . . . . . "	1·6	
	"    "    ash . . . . . "	7·4	
	"    "    oxygen and other matters "	11·3	
16	Moisture in fuel as fired . . . . . per lb.	0·06 lbs.	{ Mean of 12 months' tests.
17	Calorific value of dried fuel ("lower" value) B.Th.U.	13,180	
18	Carbon value per lb. of dried fuel . . . . .	0·91	
	ASH AND CLINKER.		
19	Total <del>per hour</del> during trial . . . . . tons lbs.	24·6	{ 3·44 per cent. of total fuel fired.
20	Carbonaceous matter in ash <del>per hour</del> . . . . . "	7·57	
	FLUE-GASES.		
	Analysis of dry flue-gases, carbonic acid . per cent.	By Vol. 10·2	{ Corrected mean of con- tinuous analy- sis maintained throughout trials.
21	"    "    carbonic oxide . . . . . "	By Wt. 14·9	
	"    "    oxygen . . . . . "	9·0	
	"    "    nitrogen (by difference) "	80·8	
22	Average temperature leaving boiler flues. . . ° F.	610°	{ Mean of contin- uous record.
23	Mean specific heat of products of combustion B.Th.U.	0·247	
	AIR AND DRAUGHT.		
24	Temperature of outside air (mean) . . . . . ° F.	45°	
25	Barometric pressure ( ins. mercury) lbs. per sq. in.	..	
26	Pressure in ash-pit (if forced air supply) ins. of water	..	
27	"    over fire ( " " ) " "	..	
28	Draught at gas exit from boiler . . . . . "	As per Fig.	
29	"    base of chimney . . . . . "	1·25	
30	Weight of steam per hour used in producing draught) lbs. }	..	
	FEED-WATER.		
31	From pump, economizer or feed heater <del>per hour</del> during trial lbs.	3,479,000	
32	Temperature of feed to boiler (mean) . . . ° F.	303°	
	STEAM.		
33	Gauge pressure . . . . . lbs. per sq. in.	185	
34	Absolute pressure . . . . . " "	200	
35	Total moisture in steam . . . . . per lb. }	*Not determined.	
36	Temperature of saturation . . . . . ° F.	382°	
Note to line 31.—The figure given is the actual water fed to boilers. It is subject to deduction			
for the regular blowing down of the boilers, and also for leakage from blow-down valves.			
The water evaporated was 3,376,440 lbs.			



BOILER. SHEET III. HEAT ACCOUNT AND DEDUCTIONS.

Reference Number.		B.Th.U.	Per Cent.
	HEAT ACCOUNT (per lb. of dried fuel).		
37	Total heat value of 1 lb. of dried fuel . . .	13,180	100·0
38	Heat transferred to the water (thermal efficiency)	6,905	52·39
39	Heat carried away by products of combustion .	1,579	12·06
40	Heat carried away by excess air . . . . .	1,041	7·9
40a	Heat carried away by moisture of steam-jets . .	186·4	1·41
41	Heat lost in evaporating and in superheating } moisture mixed with fuel . . . . .	84·8	0·64
42	Heat lost by incomplete combustion . . . .	Nil.	
43	Heat lost by unburnt carbon in ash . . . .	533	4·04
44	Balance of heat account : Errors of observation, and unmeasured losses such as—those due to radiation, escape of unburnt hydro-carbons, superheating moisture in air, loss in hot ashes, etc. . . . .	2,850·8	21·62
	Total of lines 38 to 44, equal to line 37	13,180	100·0
	DEDUCTIONS.		
45	Heat transmitted per square foot of heating } surface per hour . . . . .	B.Th.U.	
46	Weight of fuel fired per square foot of grate } per hour . . . . .	lbs.	variable
47	Weight of dried fuel fired per square foot of } grate per hour . . . . .	lbs.	"
48	Water evaporated and superheated per pound } of fuel as fired . . . . .	lbs.	6·175
48a <sup>1</sup>	Water evaporated and not superheated per } pound of fuel as fired . . . . .	lbs.	0·45
49	Equivalent evaporation from and at 212° Fahr. } per pound of fuel as fired . . . . .	lbs.	6·73
50	Water evaporated and superheated per pound } of dried fuel . . . . .	lbs.	6·57
50a	Water evaporated and not superheated per } pound of dried fuel . . . . .	lbs.	0·48
51	Equivalent evaporation from and at 212° F. } per pound of dried fuel . . . . .	lbs.	7·16
52	Equivalent evaporation per pound of carbon } value of fuel from and at 212° F. . . . .	lbs.	7·87
53	Weight of feed from and at 212° F. per square } foot of heating surface per hour . . . . .	lbs.	
54	Velocity of steam across water surface . . . }	feet per } second }	
55	Air used per pound of dried fuel . . . . .	lbs.	18·13
56	Ratio of air used to air theoretically needed . . . .		1·746

Lines 48 to 52. See Note on p. 41.

<sup>1</sup> Line 48a.—The steam for the grate-jets and for the feed-pumps did not pass through the superheater.

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D

## ECONOMIZER AND SUPERHEATER. SHEET I.

## GENERAL DESCRIPTION AND DIMENSIONS.

Reference Number.	ECONOMIZER. (Heating of feed by flue-gases.)		
57	General description of economizer, and arrangement of flues, etc. <i>Economizers of Green's make, consisting of 1,024 tubes, arranged in two batteries, and heated in parallel by the flue-gases. Scrapers motor-driven. Also one battery 288 tubes and one of 192 tubes.</i>		
58	Heating surface of economizer ( <i>external surface of tubes</i> ) . . . . .	sq. feet	<u>13,450</u>
SUPERHEATER.			
59	General description of superheater and of method of heating it. <i>McPhail-Simpson Superheaters, fixed in down-take at back of boilers.</i>		
60	Heating surface ( <i>each superheater</i> ) . . . . .	sq. feet	<u>about 300</u>
DATA DEDUCED FROM OBSERVATIONS.			
	ECONOMIZER.	Abstract of Observations.	Remarks.
61	Weight of feed water entering economizer <i>per-hour during trial</i> . . . . . lbs.	3,479,000	} Mean of 336 half-hourly observations Mean of continuous record.
62	Temperature of feed into . . °F.	115°	
63	" " out of . . °F.	303°	
64	" of flue-gases into . °F.	565°	
65	" " " out of . °F.	355°	
66	Analysis of dry flue-gases leaving economizer—	By Volume. By Weight.	
	Carbonic acid . . . per cent.	9 13·23	
	Carbonic oxide . . . "	11 11·78	
	Oxygen . . . . . "	80 74·99	
	Nitrogen (by difference) "		
67	Mean specific heat of flue-gases leaving economizer . B.Th.U.)	0·242	
SUPERHEATER.			
68 <sup>1</sup>	Weight of steam entering superheater <i>per-hour during trial</i> lbs.)	3,145,640	} Assumed nil. Mean of 336 half-hourly observations
69	Steam pressure (absolute) into lbs. per sq. inch)	200	
70	Moisture of steam into . per lb.	not taken	
71	Temperature of steam into . °F.	382°	
72	" " out of . °F.	508°	
73	" of flue gases into . °F.	..	
74	" " " out of . °F.	..	
75	Analysis of dry flue-gases leaving superheater—	By Volume. By Weight.	
	Carbonic acid . . . per cent.	..	
	Carbonic oxide . . . "	..	
	Oxygen . . . . . "	..	
	Nitrogen (by difference) "	..	
76	Mean specific heat of flue-gases leaving superheater . B.Th.U.)	..	

<sup>1</sup> Line 68. See Note to Line 48a.

ECONOMIZER AND SUPERHEATER. SHEET II.

HEAT ACCOUNT AND DEDUCTIONS.

Reference Number.	HEAT ACCOUNT (per lb. of dried fuel).	B.Th.U.	Per Cent.
	ECONOMIZER.		
77	Heat received from boiler flues, in gases and steam, per lb. of dried fuel (reckoned from air temperature) . . . . .	2,595	100·0
78	Heat transferred to the water (EFFICIENCY OF ECONOMIZER) . . . . .	1,362	52·5
79	Heat carried off in the chimney gases . .	1,754	67·6
80	Balance of Heat Account, including errors of observation, and difference of heat contained in brickwork at beginning and end of tests, etc. . . . .	..	..
	Total of lines 78 to 80, equal to line 77	3,116	120·1
	SUPERHEATER.		
81	Heat received from flue-gases and steam, per lb. of dried fuel (reckoned from air temperature) . . . . .	..	100·0
82	Heat transferred to steam (EFFICIENCY OF SUPERHEATER) . . . . .	..	..
83	Heat carried off in the chimney gases . .	..	..
84	Balance of Heat Account, including errors of observation, etc. . . . .	..	..
	Total of lines 82 to 84, equal to line 81	..	100·0
	DEDUCTIONS.		
85	Heat transmitted per square foot of heating surface of economizer per hour (mean) . .	B.Th.U.	288
86	Heat transmitted per square foot of heating surface of superheater per hour . . . .	B.Th.U.	..
87	THERMAL EFFICIENCY of boiler and economizer combined . . . . .	per cent.	62·8

ENGINE. SHEET I. GENERAL DESCRIPTION AND DIMENSIONS.

Types of Engine {  $\frac{\text{High-speed compound}}{\text{and triple.}}$       Made by {  $\frac{\text{Belliss and Morcom,}}{\text{Willans and Robinson.}}$

Maker's rating of the power 100 to 1,200 B.H.P. at 430 to 180 revolutions per minute and 115 to 175 lbs. per square inch, stop-valve gauge pressure.

Test made at *varying output* I.H.P.

Character of load      *Supply of electrical energy.*

### Object of the trial

Reference Number.					
88	General description of engine and leading dimensions.— <i>Willans Engines.</i> <i>Two and three-crank compounds.</i> <i>Three-crank triples.</i> <i>Speeds 180 to 430 revolutions per minute.</i> <i>Belliss Engines.</i> <i>Two and three-crank compounds.</i> <i>Speeds 325 to 330 revolutions per minute.</i>				
89	Type of valves.— <i>Standard types.</i>				
90	How governed.— <i>Throttle valves.</i>				
91	Method of measuring steam consumption.— <i>By rise in temperature of measured condensing water. See Note to line 120.</i>				
	Particulars of cylinders :—	H.-P.	I.-P.	—	L.-P.
92	Diameters of cylinders . . . inches				
	"    " piston rods . . . "				
	Strokes of pistons . . . . . "				
93	Volumes swept by pistons per stroke (mean of two ends) . }				c. ft.
94	Clearance volumes per stroke (mean of two ends) . . . }				per cent.
95	Clearance surfaces per stroke (mean of two ends) . . . }				sq. ft.
96	Proportion of clearance surfaces jacketed . . . . . }				per cent.
97	Proportion of barrel surfaces jacketed . . . . . }				"
98	Receiver or reheater or inter-heater, volume of . . . }				c. ft.
99	Receiver or reheater or inter-heater, heating surface of . }				sq. ft.



## ENGINE. SHEET III. HEAT ACCOUNT AND DEDUCTIONS.

Reference Number.	HEAT ACCOUNT (from 32° F.).	B.Th.U.	Per Cent.
		Millions.	
120 <sup>1</sup>	Gross heat supply entering engines <i>during trial</i> <del>per minute</del>	3,620	100·0
121	Heat equivalent of <i>units generated during trial</i> <del>I.H.P. . . per minute</del>	338·7	9·35
122	Heat leaving engine in jacket drain „	..	..
123	Heat leaving engines in exhaust steam . . . . . }	3,260	90·06
124	Balance of Heat Account (errors of observation, losses by radiation, etc.) . . . . }	21·3	0·59
	Total of lines 121 to 124, equal to line 120	3,620	100·0
	DEDUCTIONS (reckoned from exhaust temperature).		
125	Heat supplied per minute per I.H.P. . . . .	B.Th.U.	
126	Thermal efficiency . . . . .	per cent.	
127	Heat theoretically required per minute by the “Institution of Civil Engineers standard of comparison” per I.H.P. (Rankine’s cycle) }	B.Th.U.	
128	Efficiency ratio . . . . .		
129	Heat supplied per minute per B.H.P. . . . .	B.Th.U.	
130	Pounds of steam used per I.H.P. per hour . . . .	lbs.	
131	Equivalent pounds of steam used per I.H.P. per hour at 1,100 B.Th.U. per lb. . . . . }	lbs.	

REMARKS : <sup>1</sup> *The figure for line 120 is based on the assumption of entirely dry steam in the exhaust. The simultaneous records of thermometer and mercury column placed close to the exit from the engines appeared to indicate a slight superheat varying with the load from 0° F. to 18° F. This condition would appear improbable, but has been accepted pending further investigation.*

ENGINE ACCESSORIES. SHEET I. GENERAL DESCRIPTION AND DIMENSIONS.

Reference Number.	
	<b>CONDENSER.</b>
132	General description of condensers. <i>Three of the ejector pattern by Körting Bros., fitted close to engine exhaust flanges. One Worthington central jet condenser.</i>
	If a surface condenser—
133	Number of tubes . . . . .
134	Diameter of tubes . . . . . inches
135	Length of tubes . . . . . feet
136	Effective area of cooling surface . . sq. feet
	<b>AIR-PUMPS.</b>
137	General description and method of driving. <i>None.</i>
	<b>CIRCULATING PUMPS.</b>
138	General description and method of driving. <i>No pumps. Water delivered by gravity into overhead tank, and thence to condensers with an available head of 18 feet at the nozzles.</i>
	<b>FEED-PUMPS.</b>
139	General description and method of driving. <i>Compound and simple low-speed steam-driven pumps. Each pump has a capacity of 4,500 gallons per hour at twelve double strokes per minute.</i>
	<b>FEED-HEATER. (Heating of feed by exhaust-steam.)</b>
140	General description of feed-heater, and of connections to exhaust-pipe, feed-pump and boiler connections. <i>No feed-heater as such. Feed-tank fed from condenser discharge, the water being further raised in temperature by the injection into it of the exhaust-steam from feed-pumps, and by the drains from steam-traps, crank-chamber cooling tubes, etc.</i>
141	Heating surface (if any) . . . . . sq. feet
	<b>STEAM-PIPES.</b>
142	General description of steam-pipe arrangements and of methods of draining them, kind of covering, etc. <i>Principal steam-pipes as shown in the plan, Fig. 1.</i> <i>Drained by Sentinel-Geipel steam-traps discharging into feed-tank.</i> <i>Lagged completely (including flanges) with 1 inch thick asbestos and over this 2 inches plastic cork composition</i>
143	Diameter of main steam-pipes 10 to 14 inches. <i>Inches</i>
144	Surface <del>length</del> of main steam-pipe under steam during trial. . . . . } sq. feet <i>1,710</i>

Line 144.—Surface of pipe measured represents bare pipe-surface under lagging.

## ENGINE ACCESSORIES. SHEET II. DATA DEDUCED FROM OBSERVATIONS.

Reference Number.	Particulars of Observations.		Remarks.
CONDENSER.			
145	Cooling water passing through condensers <i>per hour during trial</i> . . . }	lbs.	103,850,000
146	Temperature of cooling water as it enters condenser . . . . . }	° F.	53°
147	Temperature of cooling water as it leaves condenser . . . . . }	° F.	83°
148	Exhaust steam entering condenser <i>per hour during trial</i> . . . . . }	lbs.	2,920,000
149	Temperature of exhaust steam as it enters condenser . . . . . }	° F.	{ Not determinable
150	Temperature of condensed steam as it leaves condenser . . . . . }	° F.	..
151	Vacuum in condenser { — ins. of mercury = lbs. per sq. in. }		27 inches
AIR-PUMP.			
152	Effective volume displaced by air-pump bucket per minute . . . }	cubic feet	
153	Indicated horse-power absorbed in pump . . .		
CIRCULATING-WATER PUMP.			
154	Effective strokes per minute or revolutions per minute if centrifugal . . .		
155	Indicated horse-power absorbed in the pump NOTE.—If the pumps are driven by an independent engine, the records of the tests of this engine should be filled up in an engine sheet.		
FEED-HEATER ( <i>exhaust from pumps, etc.</i> ).			
156	Temperature of feed into . . . . . }	° F.	75°
157	„ „ out of . . . . . }	° F.	115°
158	„ of exhaust steam . . . . . }	° F.	..
FEED-PUMP.			
159	Temperature of feed passing through pump . . . . . }	° F.	115°
160	Steam used by feed-pump (if <i>during trial</i> separately driven) . . . }	lbs. per hour	163,300
STEAM-PIPES.			
161	Steam-pressure (absolute) in boiler . . . }	lbs. per sq. in.	200
162	Steam-pressure (absolute) at engine stop-valve . . . . . }	lbs. per sq. in.	200
163	Temperature of steam at boiler or at superheater ends of pipe . . . . . }	° F.	508°
164	Temperature of steam at engine stop-valve . . . . . }	° F.	468°
165	Moisture in steam at exit from boiler . . . . . }	per lb.	Nil.
166	Moisture in steam at engine stop-valve . . . . . }	„	Nil.
167	Water collected from steam-pipes per hour . . . . . }	lbs.	953

{ Mean of 336 observations  
By recording thermometer checked by 336 observations.

{ Nozzles inaccessible while working.

{ Mean of 336 observations

{ Feed heating by exhaust from auxiliaries.

{ By condensing steam into measured weight of water.

{ Drop inappreciable.  
Mean of 336 observations of each boiler.  
Mean of 336 observations of each engine

{ By trials using saturated steam.



# SUMMARY.

Rated power of the plant 4,518 Kilowatts ~~I.H.P.~~

Test made at 2.2 per cent. up to 60 per cent. of the rated power.

## ECONOMY OF THE COMPLETE STEAM-PLANT.

Reference Number.		
168	Total-heat value of dried fuel in boiler and superheater } per minute during trial . . . . . B.Th.U. }	$6326 \times 10^6$
169	Heat equivalent per minute of I.H.P. developed } B.Th.U. }	..
170	Heat equivalent per minute of <del>B.H.P.</del> developed during } trial of electrical units generated . . . . . B.Th.U. }	$339 \times 10^6$
171	Percentage of heat utilized in I.H.P. developed } per cent. }	..
172	Percentage of heat utilized in <del>B.H.P.</del> developed electrical } energy generated . . . . . per cent. }	5.35
173	Coal fired per <del>I.H.P.</del> per hour kilowatt-hour (averaged) } lbs. }	5.15
174	Carbon equivalent to dry coal fired per <del>I.H.P.</del> per hour } kilowatt-hour (averaged) . . . . . lbs. }	4.41

REMARKS.—Lines 168, 173 and 174 are calculated from the total coal used, part of which has been required for maintaining steam-pressure on banked boilers. The amount thus utilized has been about 18 tons during the period of test.

Lines 48 to 52 are calculated on the same basis and thus show a rather worse performance than is actually obtained.

## APPENDIX III.—

<i>Dr.</i>	STEAM AND WATER
	Lbs.
To Water supplied from engine condensers . . . . .	3,315,700
,, Water supplied from condensation of steam delivered from feed- pump exhausts . . . . .	163,300
	<u>3,479,000</u>
	BOILERS, SUPERHEATERS
	B.Th.U. (Millions)
To Balancing Account for Coal Heat . . . . .	6,287
,, Feed-Pump Account for Feed-Pump Exhaust . . . . .	132
,, Main Engine Account for Heat from condensers to feed-water) (3,315,700 lbs. from 75° to 115° F.) . . . . .	74
	<u>6,493</u>
	PIPE-RANGE
	B.Th.U. (Millions).
To Boilers Account for Steam to main range . . . . .	3,960
	<u>3,960</u>

<sup>1</sup> These Balance Sheets are arranged in a similar manner to those given by Proceedings Inst. C.E., vol. clxiv, p. 18.

## HEAT BALANCE SHEETS.<sup>1</sup>

BALANCE SHEET.	Cr.
	Lbs.
By Steam delivered to engines . . . . .	2,920,000
„ „ „ feed-pump . . . . .	163,300
„ „ condensed and leakage in main steam-piping . . . . .	160,000
„ „ delivered to boiler steam-jets . . . . .	67,500
„ „ „ for domestic purposes . . . . .	34,800
„ Water blown-down from boilers . . . . .	32,000
„ „ leakage from blow-down and safety-valves, etc. . . . .	70,560
„ Steam unaccounted for, being balance . . . . .	30,840
	<hr/> 3,479,000 <hr/>

### AND ECONOMIZERS ACCOUNT.

	B.Th.U. (Millions).
By Pipe-Range Account for Steam to main range . . . . .	3,960
„ Feed-Pump Account for Steam to feed-pumps . . . . .	196
„ Balancing Account for Heat lost as under :—	
Blowing down and leakage . . . . .	8
Unburnt Coal in ash . . . . .	256
Generating Steam for grate jets . . . . .	81
Re-evaporating moisture of jets to chimney temperature . . . . .	87
Chimney Losses . . . . .	842
Unaccounted for heat, e.g., loss by hot ashes, radiation, etc., balance . . . . .	1,063
	<hr/> 2,337 <hr/>
	<hr/> 6,493 <hr/>

### ACCOUNT.

	B.Th.U. (Millions).
By Main Engine Account for Steam supplied to engines (2,920,000 lbs. at 460° F.). . . . .	3,620
„ Radiation and Condensation of main steam range, being 953 lbs. per hour . . . . .	135
„ Balancing Account for Domestic Heating . . . . .	44
„ Loss by difference . . . . .	161
	<hr/> 3,960 <hr/>

Mr. H. A. Mavor in his Paper on “Heat-Economy in Factories,” Minutes of

## APPENDIX

<i>Dr.</i>		MAIN ENGINES
		B.Th.U. (Millions).
To Pipe-Range Account for steam supplied . . . . .		3,620
		<hr/>
		3,620
		<hr/>
		FEED-PUMPS
		B.Th.U. (Millions).
To Boilers Account for Steam to feed-pumps . . . . .		196
		<hr/>
		196
		<hr/>
		BALANCING
		B.Th.U. (Millions).
To Work :—		
Main Engines Account . . . . .	338	
Pipe-Range Account for Domestic Heating . . . . .	44	
	<hr/>	382
„ Losses :—		
Boilers Account, Balance . . . . .	2,337	
Main Engines Account, condenser and radiation . . . . .	3,208	
Pipe-Range Account, radiation . . . . .	135	
Loss by difference . . . . .	161	
Feed-Pumps Account, Balance . . . . .	64	
	<hr/>	5,905
		<hr/>
		6,287

III—continued.

ACCOUNT.	Cr.	B.Th.U. (Millions).
By Balancing Account for work done . . . . .		338
„ Lost to Condenser . . . . .		3,186
„ Radiation and other losses, by difference . . . . .		22
„ Boilers Account for heat returned to feed . . . . .		74
		<u>3,620</u>

ACCOUNT.		B.Th.U. (Millions).
By Boilers Account for Heat in Feed-pump exhausts . . . . .		132
Balancing Account for loss of heat, being work of feeding boilers, by } difference . . . . . }		64
		<u>196</u>

ACCOUNT.		B.Th.U. (Millions).
By Boilers Account for Heat in coal (less heat necessary to evaporate } contained moisture to chimney temperature) . . . . . }		6,287
		<u>6,287</u>

