SECT. II.—OTHER SELECTED PAPERS.

(Paper No. 2497.)

“An Investigation into the Use of Progressive High Pressures in Non-Compound Locomotive Engines.”

By DUGALD DRUMMOND, M. Inst. C.E.

THIS investigation was instituted to ascertain what increase of efficiency or economy is derived from raising the boiler-pressure in non-compound locomotives, and whether high initial piston-pressures are prejudicial to the mechanism of this type of engine, working under the severe conditions imposed by modern express traffic. The tests took place on the Caledonian Railway between Carlisle and Edinburgh, and *vice versa*, one of the heaviest pieces of main line in the United Kingdom.

The engines selected for this purpose were Nos. 76, 77, 78, 79, built at the Caledonian Railway Company's Locomotive Works, St. Rollox, Glasgow, and put on to traffic in the latter half of 1889. Nos. 76 and 79 have each a working pressure of 200 lbs., No. 77 a working pressure of 175 lbs., and No. 78 a working pressure of 150 lbs. per square inch. They are of the bogie type, with cylinders 18 inches in diameter by 26 inches stroke, and in every respect—except boiler-pressure—identical.

The trains selected for experiment were the 4.30 p.m. *ex* Carlisle from London, and the 10.15 a.m. *ex* Edinburgh to London express. These trains were timed to run at a down mean speed of 51.35 miles an hour; and at an up mean speed of 50.08 miles an hour between terminal stations; the 50 miles between Carlisle and the summit of Beattock incline, with a vertical rise of 947 feet, having a time allowance of one hour.

Thus the conditions under which the trials took place, were of a nature to bring out the respective merits of the engines working under the different boiler-pressures.

TESTS.

The method of procedure adopted was to take indicator-diagrams of the four engines at the same points on the up- and down-

journeys, with, however, some variations in the case of engine No. 76. Upwards of twenty indicator-diagrams, right and left, with simultaneous dynamometer readings, were taken each way. Twelve of these have been selected for the purposes of this investigation. The regulator-handle had a graduated scale attached, to show the amount of opening of the regulator steam-valve. The smoke-box temperature was taken with a Murrie mercurial pyrometer; the position selected for its insertion being at the side, level with the top row of tubes, 9 inches in front of the tube-plate and 3 inches clear of the back edge of the exhaust-nozzle. The steam-chest was fitted with a Bourdon pressure-gauge and a thermometer. The cylinders were also fitted with thermometers. These had to be inserted in pipes, and led above the front foot-plate to facilitate reading. The bulbs were also immersed in a mercury bath, with an iron casing to ensure a safe joint under the high steam-pressures.

The smoke-box temperature was taken before starting, and immediately after arriving at the terminal station, as well as at the points where the engines were indicated. The results obtained point to the advantage of working with early cut-offs. They also show that improved boiler-circulation is required to give more rapid generating-power in producing steam. The difference between the temperatures of the steam-chest and cylinder is given, the thermometers registering under identical conditions of distance and protection from radiation. But the steam-chest thermometer, on account of the comparatively constant pressure, had a small escape-pipe, with a cock placed at the upper end to allow fresh steam to circulate round the bulb. The cylinder-thermometer did not require this, as fresh steam was sent to the bulb at every stroke. The results obtained show that the mean cylinder-temperature is not the mean of the initial- and exhaust-temperatures due to their pressures, as has been assumed. This assumption ignores what is evident in these and similar diagrams of non-compound engines, namely, that the steam-cycle begins at the boiler-pressure, and terminates, not at the exhaust-pressure, but at the pressure due to the compression. The indicator-diagrams show that the final temperature of the compressed steam is in nearly all cases equal to or above the boiler-temperature.

The design of the cylinders is a departure from the normal arrangement with a central valve-face. The steam-ports were moved to the cylinder-ends, and the slide-valve was divided, each having its own exhaust-port. In this way the port-clearance was

reduced to a minimum, and a reduction in back-pressure was effected. The weight of the valve, however, was increased by 70 per cent. The exhaust-passages were increased so that the belt from the lower and top valves extended along the whole length of the cylinder, thus forming an exhaust-steam jacketed cylinder. The blast-pipe, which was of the Vortex type, had likewise a large exhaust capacity with a nozzle equal to a 5-inch opening.

The weight of the engines for all purposes, was taken as the mean between their running-weight before starting and after arrival at the terminal station. The speeds were taken by stop-watch observations between mile-posts, and also by counting the engine-reciprocations from the indicator; and it was found that the latter was the more reliable method, as eye, ear, and touch could be brought into requisition.

The indicator used was of the Tabor form, a type which the Author recommends for high-speed engines. Where diagrams on one side are wanting, the power given out by each cylinder has been assumed to be equal. The HP. absorbed by the blast-pipe resistance, and the compression, as well as that expended in overcoming the train-resistance, and termed "effective," are each computed. The sum of the three is termed the "Total Horse-power." The ratio of each of these to the total HP. has also been calculated.

The train-resistance was recorded by the dynamometer, consisting of two cylinders fitted with rams and charged with oil. The pull of the drawbar was transmitted, through the cross-head and rams, to the fluid, which communicated with a pressure-gauge on the foot-plate. The readings of the gauge were taken by an attendant. It worked satisfactorily, and was capable of measuring pulls from zero, no initial pressure on the gauge being necessary. The gauge-readings taken when indicating, were afterwards converted into the equivalent force in lbs. This was done by transferring the dynamometer and connections to a Pooley weighing-machine, where a series of weighings with ascending and descending pressures were taken. By this means the uncertain element of ram-friction was eliminated. The total resistance of the engine and train combined was computed from the effective HP. The engine-resistance given is the difference between the total and that indicated by the dynamometer.

The measurements to determine the weight of steam used, were taken at 3 inches from the point of cut-off for the steam received. For the steam retained, the measurements were all taken at one-tenth from the end of the stroke during the period of compression.

For the weight of steam saved in percentages at each point of indication, those above zero in diagram No. 3¹ are in favour of the higher pressures; those below zero are in favour of the lower pressures in the engines compared. In taking out the mean saving effected by the higher pressures, No. 11 indicator-diagram of engine 77 has been omitted, as the driver was lubricating the valves when it was taken. The water used was measured in the tender by means of a graduated rod, a glass tube in which was inserted. The quantities given include the loss from the injector and the steam-escape pipe of the steam-chest thermometer, and are therefore approximate.

The coal used was of very inferior quality, as may be seen from its evaporative efficiency; 50 per cent. of that used would have passed through a $\frac{3}{8}$ -inch mesh riddle. To test the persistently low evaporation, the small coal put on the tender of engine No. 79 for the down run was passed through a riddle of $\frac{1}{2}$ -inch mesh, and the fine discarded; the evaporation then rose to 6.94 lbs. of water, but again declined on the following day for the up run, when 40 per cent. of unriddled coal was added to that which had been left on the down run. The evaporation fell to 6.2 lbs. of water per lb. of coal, showing that with the unriddled coal supplied to the other engines the evaporation would have been less than 6 lbs. The Author has no hesitation in saying that 25 per cent. passed into the atmosphere without evaporating 1 lb. of water per lb. of coal. The coal-consumption of the four engines has been compared in terms of an evaporation of 8 lbs. of water per lb. of coal, that being the mean evaporative power of fresh coal supplied to the Caledonian Railway. The coal used in these experiments had mostly been stacked over twelve months. This was due to the collieries being closed consequent on a miners' strike at the time the experiments were begun. An analysis of the comparative coal-consumption of the different engines cannot be given for want of the requisite data, which embraces the determination of the total work and the comparative rate at which it is done by each engine on the up- and down-gradients for every revolution during the entire journey. This can only be obtained accurately from a continuous series of indicator-diagrams. A continuous dynamometer-record is not sufficient, as it gives the work done on the train only. Taken in conjunction, the two records would determine the most economical engine.

¹ The diagrams may be seen at the Institution.—SEC. INST. C.E.

RECIPROCATING PARTS OF THE ENGINE.

These include the piston, piston-rod, cross-head, slide-blocks and connecting-rod. In the engines under consideration, they weigh 830 lbs., or 3.26 lbs. per square inch of the front, and 3.35 lbs. per square inch of the back of the piston. It is in terms of the cylinder-area only that the reciprocating parts have been considered; and their modifying effect on the piston-pressures transmitted to the cranks were constructed for each engine.

This is a subject of paramount interest and importance to engineers, for the high piston-speeds in locomotives are attained with short strokes, and consequently with a high rate of revolution. It is especially interesting at the present time, when increased locomotive efficiency is sought in compounding, and when engines on that principle are run at high speeds. The diagrams showed that the driving-stresses were transmitted to the cranks throughout a complete revolution, with an entire absence of shock. The reversal of pressure on the cranks was accomplished gradually during the terminating stroke, at a point where the tangential pressure nearly vanished; so that all the elements requisite to the maintenance of high speeds over long distances were secured. That high initial steam-pressures are indispensable for high piston-speeds with short strokes, has long been known; and it is clear from the investigation that a steam-pressure of 200 lbs. per square inch, on the piston of an 18-inch cylinder, is by no means the maximum limit from a dynamic point of view. The non-compound engine has always sufficient steam-pressure to start and accelerate its reciprocating parts, at speeds above those attained in modern express traffic; with sufficient compression to gradually reverse the pressures on the cranks for the incoming steam of the following stroke. With separate steam- and exhaust-valves to secure a reduction of pressure, and a longer steam-admission to the back than to the front of the cylinder, the driving-cycle of this type of engine can be made perfect.

ECONOMY OF HIGHER STEAM-PRESSURES.

The method adopted to determine the comparative efficiency of the different pressures, was to ascertain from the indicator-diagrams the weight of steam used per HP. per hour, this being the best method admissible at present in an investigation of this kind. It would have been preferable to have taken a continuous sheet of indicator-diagrams of every stroke from start to finish, as then the

absolute work done by the engines would have been known, and would have been comparable; but the Author does not know of any apparatus of this kind having been arranged for locomotives. The accompanying tabulated statements (Appendix) give the data and results.

The economy obtained by increasing the boiler-pressures, apart from compounding, has been established in traffic as well as in these investigations. Mr. S. Johnson, of the Midland Railway, by raising boiler-pressures from 140 lbs. to 160 lbs. per square inch, effected a saving of fuel of between 11 and 13 per cent. Mr. J. Holden, of the Great Eastern Railway, has verified Mr. Johnson's results by the reverse process in the compound engine, in lowering the boiler-pressure from 160 lbs. to 140 lbs. per square inch. The former saving of 12 per cent. of fuel then dropped to 2 per cent.; and if the low-pressure cylinder of this engine had been $25\frac{1}{2}$ inches in diameter instead of 26 inches, so as to have the same cylinder capacity as the two non-compound cylinders they were tried against, the remaining 2 per cent. would have become negative. Both these results agree closely with the 15 per cent. of steam saved between the Caledonian Railway engines No. 77, with a boiler-pressure of 175 lbs. per square inch, and No. 78, with a boiler-pressure of 150 lbs. per square inch; the weight and speed of the trains drawn by both engines being generally alike. Again, between engine No. 76, with a boiler-pressure of 200 lbs. per square inch, and engine No. 78, the saving effected amounts to 31 per cent., even though the speed and weight of the train were in favour of the latter. Again, between engines No. 76 and No. 77, there is a saving of steam, effected by the higher pressure, of 11·92 per cent.

A consideration of the conditions under which the steam does its work in both engines will not show any superiority for the compound over the non-compound engine. On this subject the phraseology of the marine engineer has been adopted and developed, although the working conditions of the marine and locomotive engine are widely different in two of the most important elements of economy, *i.e.*, quality of steam and piston-speed. In the locomotive, the steam reaches the cylinder through the highly heated atmosphere of the smoke-box, and must be in a very different condition from that finding its way into the high-pressure cylinder of a marine engine. This is manifest from the investigations of the Research Committee of the Institution of Mechanical Engineers.¹ It has sometimes been assumed that

¹ Proceedings of the Institution of Mechanical Engineers, 1889, p. 235.

cylinder-condensation and re-evaporation occur to a serious extent in non-compound inside-cylinder engines. But the steam absorbs heat from the smoke-box in passing to the cylinders, and must reach them very dry, at a temperature above that of saturation. On entering the cylinder, the steam from the boiler mixes with compressed steam at or above the boiler-temperature. The cylinders also form part of the smoke-box, and heat is conducted through the cylinder-walls as well as being generated by the friction of the piston-rings. When to these is added a piston-speed of 1,000 feet per minute, equal to a train-speed of 55 miles an hour, which gives a duration of one-fourth of a second for a revolution, the necessity for expanding steam in two cylinders, to prevent condensation and re-evaporation, is greatly reduced. It is difficult to conceive how more favourable conditions for the transformation of heat-energy can exist in the steam-engine. The principal factor in preventing cylinder-condensation and re-evaporation is high piston-speed; a speed of 1,527 feet per minute was reached during these trials with engine No. 76, at a train-speed of 81·8 miles an hour.

Modern express traffic therefore offers a guarantee that condensation and re-evaporation in inside-cylinder non-compound locomotives must be an infinitesimal quantity; and this is verified by the high mean cylinder-temperature and the weight of steam used per H.P. per hour—the latter comparing favourably with the best marine practice in triple-expansion condensing-engines. The advantage of reduction of the thermal range in each cylinder of compound locomotives is not apparent, since the steam is maintained twice as long in contact with the cylinder-surfaces, and the surfaces are nearly trebled in area. Although the high-pressure cylinder exhaust absorbs heat in passing through the receiver, it is difficult to see how a high thermal efficiency can exist under these disadvantageous conditions.

During part of the running of engine No. 76, five expansions were made, the efficiency increasing to the highest point. As the whole question of engine-economy resolves itself into the number of times steam can be expanded, and as in this case five expansions were within the economical limit in a single cylinder, compounding within this limit appears to be unnecessary. If, however, the thermal and dynamical conditions of the non-compound are superior to those of the compound engine, how is it that those who favour the latter system have attained superior results? The reply must be that the two systems have not been compared on a fair basis. In the first place, the boiler-pressure of the compound

locomotive has been usually higher. In the second place, the driver of the compound engine is obliged to keep up the boiler-pressure, as there must be considerably less range of mean cylinder-pressure than in the non-compound engine, which can expand steam as low as one-and-a-quarter times, and all starting from stations is so done—whereas the compound locomotive cannot expand less than two-and-a-half times. This reduction of range in the power of the latter engine, is undoubtedly the cause of reduced coal-consumption over what is due to higher boiler-pressure. Other things being equal, coal-consumption is the measure of the work done by an engine, and if the compound engine cannot run so fast in express traffic, or has to be assisted on up-gradients, the result should not be credited to increased efficiency. The Author is of opinion that in a comparative trial of the simple and compound systems, the boiler-pressures should be alike. The minimum number of expansions should be alike; and the low-pressure cylinder of the compound-engine should be equal to the combined areas of the non-compound cylinders. On this common basis only, should the trials be conducted, and no analysis offers greater advantages than the one adopted here. He suggests that such a test should be made with engines on the compound principle against non-compound engines, say for a month's duration, in order that their respective merits may be tested in a way that will settle doubts existing on the question.

Viewing the question of steam-pressures broadly, the Author has come to the conclusion that for the present, until drivers appreciate the value and take advantage of higher pressures for ordinary locomotive engines working main-line traffic economically in all respects, the pressure should not be less than 150 lbs. nor more than 170 lbs. per square inch. Pressures of 200 lbs. per square inch can, he believes, only be economically used with engines working heavy suburban passenger-traffic, whereby speed can be got up quickly when leaving stations. By this means a larger amount of traffic can be worked in a given time, than by engines with pressures of 140 lbs. per square inch, which is the average now used in working such trains.

The Paper is accompanied by eight tracings, including a longitudinal section of the line, and indicator-diagrams, which may be consulted at the Institution.

APPENDIX.
TABLE I.—COAL- AND WATER-CONSUMPTION.

UP JOURNEY.—10.15 A.M. EXPRESS PASSENGER TRAIN <i>ex</i> EDINBURGH TO CARLISLE.										DOWN JOURNEY.—4.30 P.M. EXPRESS PASSENGER TRAIN <i>ex</i> CARLISLE TO EDINBURGH.										DOUBLE JOURNEY.			
—										—										Carlisle to Edinburgh.			
Number of Engine.	Dis- tance in Miles and Chains.	Total Weight of Engine and Train.	Mean Speed in Miles per Hour.	Mean Con- sump- tion of Water per Mile.	Total Dis- tance.	Mean Coal Con- sump- tion per Mile.	Mean Water Exapo- rated per Lib. of Coal.	Edinburgh to Carlisle.		Dis- tance in Miles and Chains.	Total Weight of Engine and Train.	Mean Speed in Miles per Hour.	Mean Con- sump- tion of Water per Mile.	Total Dis- tance in Miles and Chains.	Mean Coal Con- sump- tion per Mile.	Mean Water Exapo- rated per Lib. of Coal.	Mean Coal Consump- tion Evapo- rating 8 Libs. of Water per Lib. of Coal.						
								M. C.	Lbs.									M. C.	Lbs.				
Edinburgh to Strawnfrank Junction.	76	27 68	153	49.147	33.213	101 1	..	..	..	73 13	228	51.043	29.072	101 1	..	..	..						
	77	"	138	50.636	32.420	"	41.72	5.980	"	"	217	46.207	31.540	"	47.120	5.835	44.42						
	78	"	137	49.147	37.770	"	53.22	5.430	"	"	246	43.679	36.900	"	53.220	5.893	53.22						
	79	"	138	52.218	31.050	"	43.52	6.208	"	"	217	49.601	29.860	"	41.029	6.945	42.27						
Strawnfrank Junction to Carlisle.	76	73 13	268	51.043	25.31	..	..	..	..	27 68	153	53.903	21.544	Strawnfrank Junction to Edinburgh.									
	77	"	259	52.258	22.12	..	..	..	..	"	138	56.644	16.840	Strawnfrank Junction to Edinburgh.									
	78	"	237	52.571	25.51	..	..	..	..	"	151	53.903	16.800	Strawnfrank Junction to Edinburgh.									
	79	"	275	53.861	25.46	..	..	..	..	"	138	50.678	24.810	Strawnfrank Junction to Edinburgh.									

TABLE II.—SMOKE-BOX, CYLINDER, FEED-WATER AND ATMOSPHERIC TEMPERATURES.

SMOKE-BOX.					Engine No. 79. Temperature in Steam-chest above Temperature of Cylinders.
No. of Diagram. ¹	No. of Engine.				
	76	77	78	79	
<i>Starting from Edinburgh</i>	° F. 430	° F. 400	° F. 375	° F. 400	° F. ..
1	820	812	850	795	20
2	900	960	935	945	13
3	750	780	950	815	2
<i>Starting from Strav- frank Junction . . . }</i>	460	500	500	470	..
4	830	820	870	820	13
5	850	905	1000	990	12
6	830	905	985	960	..
7	800	890	940	860	5
8	810	915	985	880	2
9	800	915	980	870	3
10	680	830	895	905	25
11	650	615	885	620	..
12	570	645	790	685	25
<i>Arriving at Carlisle .</i>	510	540	450	575	..
<i>Temperature of Water in Tender. . . . }</i>	47	46	48	48	..
<i>Temperature of Atmo- sphere. . . . }</i>	44	47	48	52	..

¹ Nos. 1 to 7 and 10 to 12 were taken on the up journey, and Nos. 8 and 9, while ascending Beattock Summit, on the down journey.

TABLE III.—WEIGHT

Up Journey.—10.15 A.M. Express Passenger-Train *ex* Edinburgh

Date. 1889.	Number of Engines.	Working Steam-Pressure.	Edinburgh to Strawfrank Junction—27 miles, 68 chains.								
			No. of Vehicles and Weight of Train.				Running of Train.				
			Number of Vehicles.	Weight of Vehicles in Tons.	Mean Weight of Engine and Tender in Tons.	Total Weight of Engine, Tender & Train in Tons.	Left Edinburgh.	Arrived at Strawfrank Junction.	Running Time in Minutes.	Mean Speed in Miles per Hour.	Remarks on Running.
29 Oct.	76	Lbs. 200	4-5½	75	78	153	10.15	10.49	34	49.147	Stopped by signal.
2 Nov.	77	175	3-4½	61	77	138	10.15	10.50	33	50.636	
5 „	78	150	3-4½	61	76	137	10.15	10.49	34	49.147	
12 „	79	200	3-4½	61	77	138	10.16	10.48	32	52.218	

Down Journey.—4.30 P.M. Express Passenger-Train *ex*

Date. 1889.	Number of Engines.	Working Steam-Pressure.	Carlisle to Strawfrank Junction.											
			No. of Vehicles and Weight of Train.				Running of Train.							
			Number of Vehicles.	Weight of Vehicles in Tons.	Mean Weight of Engine and Tender in Tons.	Total Weight of Engine, Tender & Train in Tons.	Left Carlisle.	Passed			Arrived at Strawfrank Junction.	Running Time in Minutes.	Mean Speed in Miles per Hour.	Remarks on Running.
								Lockerbie.	Beattock.	Summit.				
29 Oct.	76	Lbs. 200	8-11	150	78	228	4.37	5.7	5.22	5.39	6.3	86	51.043	
1 Nov.	77	175	7-10½	140	77	217	5.1	5.35	5.52	6.12	6.36	95	46.207	
4 „	78	150	9-12½	170	76	246	4.46	5.19½	5.34	6.0	6.26½	100½	43.679	
11 „	79	200	7-10½	140	77	217	4.31½	5.3½	5.18	5.36	6.0	88½	49.601	

NOTE.—All eight-wheeled carriages of the West Coast

AND RUNNING OF TRAINS.

to Carlisle.—Bogie Passenger-Engines, Nos. 76, 77, 78, 79.

Strawfrank Junction to Carlisle—73 miles, 13 chains.												Weather.	
No. of Vehicles and Weight of Train.				Running of Train.									
Number of Vehicles.	Weight of Vehicles in Tons.	Mean Weight of Engine and Tender in Tons.	Total Weight of Engine, Tender & Train in Tons.	Left Strawfrank Junction.	Passed			Arrived at Carlisle.	Running Time in Minutes.	Mean Speed in Miles per Hour.	Remarks on Running.	Rain.	Wind.
					Summit.	Beattock.	Lockerbie.						
10-14	190	78	268	10.51	11.24	11.34	11.47	12.17	86	51.043		Showers.	Strong(head).
9-13½	182	77	259	10.53	11.25½	11.35½	11.50	12.17	84	52.258		None.	{ Very strong (side).
8-12	161	76	237	10.52½	11.23½	11.33½	11.47½	12.16	83½	52.571		Showers.	Light (head).
10-14½	198	77	275	10.55½	11.26½	11.36	11.50	12.17	81½	53.861		Showers.	{ Light to strong(side).

Carlisle to Edinburgh.													
Strawfrank Junction to Edinburgh.											Weather.		
No. of Vehicles and Weight of Train.				Running of Train.									
Number of Vehicles.	Weight of Vehicles in Tons.	Mean Weight of Engine and Tender in Tons.	Total Weight of Engine, Tender & Train in Tons.	Left Strawfrank Junction.	Arrived at Edinburgh.	Running Time in Minutes.	Mean Speed in Miles per Hour.	Remarks on Running.	Rain.	Wind.			
4-5½	75	78	153	6. 5	6.36	31	53.903	Stopped by signal.	Showers.	Strong (side).			
3-4½	61	77	138	6.38½	7.11	29½	56.644		Heavy.	Very strong (side).			
4-5½	75	76	151	6.33	7. 4	31	53.903		Showers.	Light (head).			
3-4½	61	77	138	6. 3	6.31	28	59.678		Light.	Light to strong(head).			

Joint Service are reckoned as 1½ vehicle.

TABLE IV.—WEIGHT OF STEAM USED AS SHOWN BY THE INDICATOR,

Indicator Diagrams Nos. 1 to 7 and 10 to 12 were taken on the Up Journey.							
Number of Diagrams			1.				
Number of Engine			76	77	78	79	
Steam used per Revolution			Lbs. 1·055730	Lbs. 1·084104	Lbs. 1·297053	Lbs. 1·060640	
Steam used per HP. per hour	Total		12·85	14·35	15·19	12·84	
	Effective		18·42	20·35	22·29	18·05	
Economy due to Higher Steam-Pressures.							
—	Pressure.	No. of Engine.					
Steam saved per cent. per effective HP. per hour.	Lbs. per Square Inch. 200 to 175	76-77	10·5	..	..	..	
		79-77	..	..	..	12·7	
	200 to 150	76-78	21·1	..	..	..	
		79-78	..	..	..	23·5	
	175 to 150	77-78	..	9·6	..	..	
	200 to 200	76-79	..	..	..	2·1	
Steam saved per cent. per effective HP. per hour.	200 to 175	76-77	11·9	..	..	..	
		79-77	..	..	..	10·2	
	..	76-78	31·0	..	..	..	
	..	79-78	..	..	..	24·5	
	175 to 150	77-78	..	15·0	..	..	
	200 to 200	76-79	8·4	..	..	..	

AND ECONOMY EFFECTED BY THE HIGHER STEAM-PRESSURES.

Nos. 8 and 9 Diagrams were taken ascending Beattock Summit on the Down Journey.

2.				3.				4.			
76	77	78	79	76	77	78	79	76	77	78	79
Lbs.	Lbs.	Lbs.	Lbs.	Lbs.	Lbs.	Lbs.	Lbs.	Lbs.	Lbs.	Lbs.	Lbs.
1·268167	1·338671	1·512939	1·415501	0·535854	0·645332	0·911626	0·618346	1·513220	1·644577	1·554835	1·659281
13·51	15·85	16·61	14·39	9·68	13·07	14·77	10·33	14·79	15·51	15·91	14·88
18·88	22·16	23·49	19·87	20·72	24·42	27·52	19·04	19·26	19·65	21·78	18·61
17·3	..	..	..	17·9	..	..	..	2·1	..	..	..
..	..	..	11·5	..	..	..	28·2	..	..	..	5·6
24·3	..	..	..	32·8	..	..	..	13·1	..	..	..
..	..	..	18·2	..	..	..	44·4	..	..	..	17·0
..	6·0	..	..	..	12·7	..	..	..	10·8	..	..
5·2	..	..	..	..	..	..	8·8	..	..	..	3·4

TABLE IV.—WEIGHT OF STEAM USED AS SHOWN BY THE INDICATOR,

Indicator Diagrams Nos. 1 to 7 and 10 to 12 were taken on the Up Journey.							
Number of Diagram			5.				
Number of Engine			76	77	78	79	
Steam used per Revolution			Lbs. 1·109122	Lbs. 1·201870	Lbs. 1·381139	Lbs. 1·361074	
Steam used per HP. per hour	Total		12·50	14·53	15·96	15·18	
	Effective		17·69	20·26	24·18	21·34	
Economy due to Higher Steam-Pressures.							
—	Pressure.	No. of Engine.					
Steam saved per cent. per effective HP. per hour	Lbs. per Square Inch.						
	200 to 175 {	76-77	14·6	..	..	..	
		79-77	..	5·4	..	..	
	200 to 150 {	76-78	36·6	..	..	..	
		79-78	..	..	..	13·3	
	175 to 150	77-78	..	19·4	..	..	
	200 to 200	76-79	20·6	..	..	..	

AND ECONOMY EFFECTED BY THE HIGHER STEAM-PRESSURES—*continued.*

Nos. 8 and 9 Diagrams were taken ascending Beattock Summit on the Down Journey.

6.				7.				8.			
76	77	78	79	76	77	78	79	76	77	78	79
Lbs.	Lbs.	Lbs.	Lbs.	Lbs.	Lbs.	Lbs.	Lbs.	Lbs.	Lbs.	Lbs.	Lbs.
1·142596	1·265071	1·428089	1·275993	1·511382	1·399033	1·570469	1·212407	1·056358	1·048538	1·500963	1·160629
12·86	14·78	15·53	14·55	15·31	15·77	17·03	14·95	11·31	13·36	16·10	12·94
17·82	20·36	22·27	20·46	19·56	20·55	22·45	19·13	15·68	18·89	22·39	17·99
14·3	..	..	..	5·1	..	..	..	20·4	..	..	..
..	0·5	..	..	..	..	..	7·4	..	..	..	5·0
24·9	..	..	..	14·8	..	..	..	42·7	..	..	..
..	..	..	8·9	..	..	..	17·3	..	..	..	24·4
..	9·4	..	..	..	9·3	..	..	..	18·5	..	..
14·8	..	..	..	..	..	..	2·2	14·7	..	..	..

TABLE IV.—WEIGHT OF STEAM USED AS SHOWN BY THE INDICATOR,

Indicator Diagrams Nos. 1 to 7 and 10 to 12 were taken on the Up Journey.							
Number of Diagram			9.				
Number of Engine			76	77	78	79	
Steam used per Revolution			Lbs. 1·825868	Lbs. 1·704577	Lbs. 2·258626	Lbs. 1·759440	
Steam used per HP. per hour	Total		15·34	15·69	19·14	15·37	
	Effective		19·08	18·68	23·48	18·85	
Economy due to Higher Steam-Pressures.							
—	Pressure.	No. of Engine.					
Steam saved per cent. per effective HP. per hour	Lbs. per Square Inch.						
	200 to 175	76-77	..	2·1	..	..	
		79-77	..	0·9	..	..	
	200 to 150	76-78	23·1	..	..	..	
		79-78	..	..	..	24·5	
	175 to 150	77-78	..	25·6	..	..	
	200 to 200	76-79	..	..	..	1·2	

AND ECONOMY EFFECTED BY THE HIGHER STEAM-PRESSURES—continued.

Nos. 8 and 9 Diagrams were taken ascending Beattock Summit on the Down Journey.											
10.				11.				12.			
76	77	78	79	76	77	78	79	76	77	78	79
Lbs.	Lbs.	Lbs.	Lbs.	Lbs.	Lbs.	Lbs.	Lbs.	Lbs.	Lbs.	Lbs.	Lbs.
0·786390	0·934926	1·088062	0·939610	0·875346	0·448763	0·901309	0·559930	0·584926	0·864709	0·936339	0·814640
11·12	13·27	15·39	12·12	11·63	25·76	14·93	12·61	9·29	13·53	15·19	11·05
17·51	20·02	24·05	18·25	18·06	48·23	26·85	21·92	17·25	21·35	26·43	17·78
14·3	..	..	..	..	..	..	..	23·7	..	..	20·1
..	..	..	9·7	..	..	..	..	..	..	..	..
37·3	..	..	..	48·6	..	..	..	53·2	..	..	..
..	..	..	31·8	..	..	..	22·5	..	..	..	48·7
..	20·1	..	..	..	..	..	..	..	23·9	..	..
4·2	..	..	..	21·4	..	..	..	3·1	..	..	..

TABLE V.—SPEED, HORSE-POWER,
Indicator Diagrams Nos. 1 to 7 and 10 to 12 were taken on the Up Journey.

Number of Diagram		1.			
Number of Engine.		76	77	78	79
Speed, in miles per hour		48·25	47·32	49·18	51·04
Horse Power.					
Horse - power developed and absorbed by train, blast-pipe, and compression	Effective . .	715·24	652·00	739·95	775·56
	Blast-pipe . .	102·80	114·26	163·24	88·79
	Compression . .	207·24	157·96	182·45	226·01
	Total . .	1025·28	924·22	1085·64	1090·36
Percentage of effective blast-pipe and compression horse-power	Effective . .	69·76	70·54	68·16	71·12
	Blast-pipe . .	10·02	12·36	15·04	8·14
	Compression . .	20·21	17·09	16·80	20·72
Tractive Resistance.					
Resistance in lbs. per ton. Train-resistance taken from dynamometer . .	Engine . .	23·23	22·53	53·95	15·21
	Train . .	49·93	56·22	25·24	74·18
	Total . .	36·32	37·43	41·17	41·28

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AND TRACTIVE RESISTANCE.

Nos. 8 and 9 were taken ascending Beattock Summit on the Down Journey.

2.				3.				4.			
76	77	78	79	76	77	78	79	76	77	78	79
46·40	46·40	42·68	51·04	69·60	62·64	71·45	65·42	40·83	38·04	36·19	37·12
805·62	724·90	710·79	940·04	465·38	428·08	612·05	553·13	829·56	833·15	668·16	855·69
111·17	156·44	162·17	166·72	135·80	120·10	230·87	108·72	95·97	116·82	128·50	85·66
209·03	131·80	132·58	191·58	394·90	251·22	297·44	357·27	154·72	105·64	117·85	128·47
1125·82	1013·14	1005·54	1298·34	996·08	799·40	1140·36	1019·12	1080·25	1055·61	914·51	1069·82
71·56	71·55	70·69	72·40	46·72	53·55	53·67	54·27	76·79	78·92	73·06	79·98
9·87	15·44	16·13	12·80	13·63	15·02	20·24	10·66	8·88	11·06	14·05	8·00
18·56	13·01	13·19	14·75	39·64	31·42	26·08	35·05	14·32	10·00	12·88	12·00
26·33	22·85	54·28	23·68	2·70	Negative. 3·67	26·63	Negative. 0·44	15·71	23·62	35·34	13·73
59·40	67·18	34·71	83·31	30·61	46·64	19·45	52·15	33·63	35·11	26·30	38·30
42·54	42·45	45·57	50·04	16·39	18·57	23·44	22·80	28·42	31·70	29·20	31·48

TABLE V.—SPEED, HORSE-POWER,
Indicator Diagrams Nos. 1 to 7 and 10 to 12 were taken on the Up Journey.

Number of Diagram		5.			
Number of Engine.		76	77	78	79
Speed, in miles per hour		44·54	50·11	49·61	52·89
Horse Power.					
Horse - power developed and absorbed by train, blast-pipe, and compression	Effective . .	721·95	768·58	733·32	872·35
	Blast-pipe . .	97·99	147·68	232·68	151·15
	Compression . .	201·55	155·65	144·54	202·30
	Total . .	1021·49	1071·91	1110·54	1225·80
Percentage of effective blast-pipe and compression horse-power	Effective . .	70·67	71·70	66·03	71·16
	Blast-pipe . .	9·59	13·77	20·95	12·33
	Compression . .	19·73	14·52	13·01	16·50
Tractive Resistance.					
Resistance in lbs. per ton. Train-resistance taken from dynamometer . .	Engine . .	15·17	11·12	39·52	4·75
	Train . .	25·75	26·88	15·73	29·37
	Total . .	22·67	22·20	23·37	22·49

AND TRACTIVE RESISTANCE—continued.

Nos. 8 and 9 were taken ascending Beattock Summit on the Down Journey.

6.				7.				8.			
76	77	78	79	76	77	78	79	76	77	78	79
42·68	41·76	44·54	46·40	33·40	41·76	27·84	34·80	36·65	41·76	43·15	40·36
707·76	670·91	738·54	748·35	667·49	735·02	503·58	570·20	638·36	599·31	748·12	673·25
90·14	126·02	202·44	123·56	68·17	111·19	96·86	46·31	92·34	88·19	174·59	93·15
182·48	127·10	117·78	179·97	117·09	111·91	63·72	112·09	154·20	160·10	117·17	169·76
980·38	924·03	1058·76	1051·88	852·75	958·12	664·16	728·60	884·90	847·60	1039·88	936·16
72·19	72·60	69·75	71·14	78·27	76·71	75·82	78·259	72·139	70·70	71·94	71·91
9·19	13·63	19·12	11·74	7·99	11·60	14·58	6·35	10·43	10·40	16·78	9·95
18·61	13·75	11·12	17·11	13·73	11·68	9·59	15·38	17·42	18·88	11·26	18·13
14·54	12·22	38·55	6·89	18·50	11·10	35·30	2·41	9·13	25·32	38·08	27·97
26·74	27·92	20·41	27·85	31·67	31·55	25·45	30·08	38·78	24·50	21·20	29·27
23·20	23·26	26·23	21·99	27·95	25·48	28·62	22·34	28·64	24·79	26·42	28·81

TABLE V.—SPEED, HORSE-POWER,
Indicator Diagrams 1 to 7 and 10 to 12 were taken on the Up Journey.

Number of Diagram		9.			
Number of Engine.		76	77	78	79
Speed, in miles per hour		31·55	26·92	25·05	33·40
Horse Power.					
Horse - power developed and absorbed by train, blast-pipe, and compression	Effective . .	780·80	634·94	623·17	806·27
	Blast-pipe . .	98·58	55·41	95·15	88·34
	Compression . .	91·86	65·65	46·00	94·26
	Total . .	971·24	756·00	764·32	988·87
Percentage of effective blast-pipe and compression horse-power	Effective . .	80·39	83·98	81·53	81·53
	Blast-pipe . .	10·15	7·32	12·44	8·93
	Compression . .	9·45	8·68	6·01	9·53
Tractive Resistance.					
Resistance in lbs. per ton. Train-resistance taken from dynamometer . .	Engine . .	18·42	48·88	46·15	37·41
	Train . .	52·26	36·30	34·21	44·05
	Total . .	40·69	40·76	37·91	41·70

AND TRACTIVE RESISTANCE—continued.

Nos. 8 and 9 were taken ascending Beattock Summit on the Down Journey.

10.				11.				12.			
76	77	78	79	76	77	78	79	76	77	78	79
49·18	58·46	57·53	57·53	51·04	60·32	69·60	59·39	58·46	64·96	62·17	64·96
570·98	705·78	673·00	766·00	639·64	145·13	604·16	392·22	512·64	680·41	569·56	769·72
82·00	119·31	171·60	143·00	86·98	57·57	192·74	33·74	78·87	134·87	178·72	117·62
246·16	239·71	207·22	244·00	266·32	68·97	289·02	256·08	359·61	257·68	242·84	351·04
899·14	1064·80	1051·82	1153·00	992·94	271·67	1085·92	682·04	951·12	1072·96	991·12	1238·38
63·50	66·28	63·98	66·43	64·42	53·42	55·63	57·50	53·89	63·41	57·46	62·15
9·12	11·20	16·31	12·40	8·76	21·19	17·749	4·94	8·29	12·56	18·03	9·49
27·37	22·51	19·70	21·16	26·82	25·38	26·615	37·54	37·81	24·01	24·50	28·34
7·79	7·23	29·84	8·59	7·69	13·36	23·94	12·38	2·66	6·45	26·31	6·14
19·71	21·80	13·15	21·86	21·57	10·50	8·91	17·32	16·21	18·84	8·91	20·04
16·24	17·48	18·50	18·15	17·53	3·40	13·73	9·00	12·27	15·16	14·49	16·15

TABLE VI.—STEAM-PRESSURES AND INFLUENCE
Indicator Diagrams Nos. 1 to 7 and 10 to 12 were taken on the Up Journey.

Number of Diagram		1.			
Number of Engine.		76	77	78	79
Opening of steam-regulator		$\frac{3}{4}$	Full	$\frac{5}{8}$	Full
Steam Pressures.					
Pressures in lbs. per square inch	Boiler . . .	200	170	155	200
	Steam-chest .	200	170	155	200
Mean cut-off in percentage		21	27	33	26
Mean pressures of indicator diagrams in lbs. per square inch	Effective . .	52·18	48·50	52·96	53·50
	Back . . .	7·50	8·50	11·60	6·10
	Compression .	15·12	11·70	8·06	15·50
Initial driving pressure on piston in lbs. per square inch	Front . . .	190·0	152·0	137·5	181·0
	Back . . .	190·0	159·0	139·0	190·5
; Influence of Reciprocating Parts.					
Revolutions per minute		208	204	212	220
Pressure in lbs. per square inch of piston-area required to start reciprocating-parts from rest at dead-centres	Front . . .	60·6	58·2	62·9	67·7
	Back . . .	44·5	42·75	46·1	49·7
Initial driving pressure on piston in lbs. per square inch transmitted to cranks.	Front . . .	129·4	93·8	74·6	113·3
	Back . . .	145·5	116·2	92·9	140·8

OF RECIPROCATING PARTS OF ENGINE.

Nos. 8 and 9 were taken ascending Beattock Summit on the Down Journey.

2.				3.				4.			
76	77	78	79	76	77	78	79	76	77	78	79
$\frac{3}{4}$	$\frac{3}{4}$	$\frac{5}{8}$	Full	$\frac{1}{8}$	$\frac{5}{8}$	$\frac{1}{4}$	Full	$\frac{1}{2}$	Full	$\frac{7}{8}$	Full
200	170	150	195	195	150	145	175	190	175	160	195
200	162	150	195	160	125	125	175	185	175	160	195
21	33	33	27	18	27	33	19	27	33	33	33
61.12	55.00	58.62	64.80	23.54	24.00	30.10	29.50	71.50	77.00	65.00	81.10
8.43	11.87	13.37	11.50	6.87	6.75	11.37	5.80	8.27	10.80	12.50	8.10
15.80	10.00	10.93	13.20	19.97	14.12	14.60	19.20	13.34	9.78	11.46	12.10
185.5	135.0	131.0	171.5	133.5	110.0	104.5	156.0	171.5	148.0	144.0	177.5
187.5	145.0	126.0	161.5	150.0	115.0	107.0	167.5	172.0	152.5	142.0	178.0
200	200	184	220	300	270	308	284	176	164	156	160
56.0	56.0	47.4	67.7	126.0	102.0	132.8	112.9	43.3	36.7	34.0	35.8
41.1	41.1	34.8	49.7	92.5	74.9	97.5	82.9	31.8	27.6	25.0	26.3
129.5	0.8	83.6	103.8	7.5	8.0	28.3	43.1	128.2	110.4	110.0	141.7
146.5	103.9	91.2	111.8	57.5	40.1	9.5	84.6	140.2	124.9	117.0	151.7

TABLE VI.—STEAM-PRESSURES AND INFLUENCE
Indicator Diagrams Nos. 1 to 7 and 10 to 12 were taken on the Up Journey.

Number of Diagram		5.			
Number of Engine.		76	77	78	79
Opening of Steam-Regulator		Full	$\frac{5}{8}$	$\frac{3}{4}$	$\frac{1}{2}$
Steam Pressures.					
Pressures in lbs. per square inch	Boiler . . .	200	170	155	180
	Steam-chest .	200	165	155	175
Mean cut-off in percentage		18	27	33	33
Mean pressures of indicator diagrams in lbs. per square inch	Effective . .	57·00	54·00	52·00	58·00
	Back . . .	7·75	10·37	16·50	10·00
	Compression .	15·90	10·90	10·25	13·40
Initial driving pressure on piston in lbs. per square inch	Front . . .	183·0	137·0	132·0	153·0
	Back . . .	185·5	148·0	135·0	150·0
Influence of Reciprocating Parts.					
Revolutions per minute		192	216	214	228
Pressure in lbs. per square inch of piston-area required to start reciprocating parts from rest at dead-centres	Front . . .	51·6	65·3	64·1	72·7
	Back . . .	37·8	47·9	47·0	53·4
Initial driving pressure on piston in lbs. per square inch transmitted to cranks.	Front . . .	131·4	71·7	67·9	80·3
	Back . . .	147·7	100·1	88·0	96·6

OF RECIPROCATING PARTS OF ENGINE—*continued*.

Nos. 8 and 9 were taken ascending Beattock Summit on the Down Journey.

6.				7.				8.			
76	77	78	79	76	77	78	79	76	77	78	79
Full	Full	$\frac{5}{8}$	$\frac{1}{2}$	Full	Full	Full	Full	$\frac{1}{2}$	Full	Full	$\frac{3}{8}$
195	170	150	175	180	160	150	147	190	175	150	200
195	170	150	165	180	160	150	147	190	172	150	200
18	27	33	33	23	27	33	33	23	23	33	23
58·37	56·50	58·30	56·70	70·34	61·90	63·60	57·60	61·30	50·50	61·00	58·70
7·40	10·60	16·00	9·37	7·10	9·37	12·20	4·60	8·80	7·40	14·20	8·10
15·00	10·70	9·30	13·60	12·34	9·40	8·00	11·30	14·80	13·49	9·50	14·80
179·5	147·5	128·0	148·5	168·5	136·5	125·0	125·5	173·0	153·0	128·5	184·5
185·0	152·5	126·0	148·0	169·0	141·5	124·0	138·0	177·0	157·5	126·5	189·0
184	180	192	200	144	180	120	150	158	180	186	174
47·4	45·3	51·6	56·0	29·0	45·3	20·1	31·5	34·9	45·3	48·4	42·3
34·8	33·3	37·8	41·1	21·3	33·3	14·8	23·1	25·63	33·3	35·5	31·1
132·1	102·2	76·4	92·5	139·5	91·2	104·9	94·0	138·0	107·7	80·0	142·2
150·2	119·2	88·2	106·9	147·7	108·2	109·2	114·9	151·0	124·2	91·0	157·9

TABLE VI.—STEAM-PRESSURES AND INFLUENCE
Indicator Diagrams Nos. 1 to 7 and 10 to 12 were taken on the Up Journey.

Number of Diagram		9.			
Number of Engine.		76	77	78	79
Opening of steam-regulator		Full	Full	Full	Full
Steam Pressures.					
Pressures in lbs. per square inch	Boiler . . .	195	170	145	185
	Steam-chest .	195	170	145	185
Mean cut-off in percentage		27	27	47	33
Mean pressures of indicator diagrams in lbs. per square inch	Effective . .	87·10	83·00	87·50	84·90
	Back . . .	11·00	7·25	13·30	9·30
	Compression .	10·20	8·59	6·40	9·93
Initial driving pressure on piston in lbs. per square inch	Front . . .	178·0	148·0	115·0	168·5
	Back . . .	175·0	152·5	106·5	166·0
Influence of Reciprocating Parts.					
Revolutions per minute		136	116	108	144
Pressure in lbs. per square inch of piston-area required to start reciprocating parts from rest at dead-centres	Front . . .	25·9	18·8	16·3	29·0
	Back . . .	19·0	13·8	11·9	21·3
Initial driving pressure on piston in lbs. per square inch transmitted to cranks.	Front . . .	152·1	129·2	98·7	139·5
	Back . . .	156·0	138·7	94·6	144·7

OF RECIPROCATING PARTS OF ENGINE—*continued*.

Nos. 8 and 9 were taken ascending Beattock Summit on the Down Journey.

10.				11.				12.			
76	77	78	79	76	77	78	79	76	77	78	79
Full	$\frac{1}{2}$	$\frac{1}{4}$	Full	$\frac{1}{2}$	$\frac{1}{8}$	$\frac{1}{8}$	$\frac{1}{8}$	Full	Full	$\frac{1}{4}$	Full
200	175	150	200	195	180	150	195	200	165	150	205
200	155	130	200	190	25	120	125	200	165	125	205
18	27	33	21	18	64	33	23	13	27	33	22
40·80	42·50	41·00	46·80	44·12	8·28	30·50	23·20	30·80	36·80	32·20	41·70
5·87	7·18	10·50	8·70	6·00	3·37	9·70	2·00	4·75	7·30	10·10	6·37
17·60	14·40	12·60	14·93	18·37	3·90	14·60	15·10	21·60	13·90	13·70	19·00
194·0	139·5	115·0	187·0	175·5	23·0	105·0	125·0	187·5	126·5	107·0	191·0
194·0	140·5	118·0	188·0	178·5	23·0	111·0	124·0	194·5	137·5	114·0	193·0
212	252	248	248	220	260	300	256	252	280	268	280
62·9	88·9	86·1	86·1	67·75	94·6	126·0	91·7	88·9	109·7	100·0	109·7
46·2	65·2	63·2	63·2	49·7	69·4	92·5	67·3	65·2	80·5	73·8	80·5
131·1	50·6	28·9	100·9	107·8	-71·6	-21·0	33·3	98·6	16·8	7·0	81·3
147·8	75·3	54·8	124·8	128·8	-46·4	18·6	56·7	129·3	57·0	40·2	112·5