The Warden Law Hauling Engine
Hetton-le-Hole Co. Durham

by

J. FREE

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Dissertation submitted as part of the final examination for Pass Degree in Mechanical Engineering Option B, and reprinted without alteration except that certain diagrams and appendices have been omitted.

Acknowledgment is extended to the N.C.B. for permission to undertake this work, and for their assistance at all times.

INTRODUCTION

The engine to be discussed is the Hauling Engine at Warden Law, which was built in 1836 by Murray's of Chester-le-Street, Co. Durham, and is still in use at the present time. The duty of this engine is to haul wagons of coal over a section of permanent way, erected under the supervision of George Stephenson. (1)*

The county of Durham has long been associated with the production of coal. Much of this product is shipped from the North-Eastern seaports to other destinations and therefore the Collieries had to provide means of conveyance of the coal to the docks. So it was, that in 1822 a wagonway was constructed by Stephenson over which wagons of coal were hauled in stages by locomotives and stationary engines from Hetton Colliery to the crest of Warden Law, from whence they rolled down a series of gravity inclines to loading staiths at Sunderland.

Although the company who sponsored this project no longer exists, the coal seams are still worked by the National Coal Board and the wagonway is still used in the same manner as it was when first inaugurated 134 years ago. The present engine is not the original, but a replacement erected fourteen years after the line was opened.

*Figures in parentheses refer to the list of references at the end of the article.

ENGINE SPECIFICATION

Single Cylinder, Double Acting, Non-condensing Beam Engine.

Cylinder Diameter	3′ 3″
Stroke	6′ 2″
Working Pressure	35 p.s.i. gauge
Working Speed	30 r.p.m.
Mean Brake Horse Power	97.5
Estimated Indicated Horse Power	197

Valve Mechanism—Short slide valve operated by eccentric.

GENERAL DESCRIPTION OF ENGINE

The engine cylinder is of Cast Iron and its design is symmetrical about a plane perpendicular to the line of stroke. The steam ports break into the cylinder walls at the ends of the swept portion, and connection to the valve chest is made at the flange joints as shown in *fig.* 1. The cast iron upper cylinder cover is retained by twenty $1^1/_4$″ dia. bolts and embodies a stuffing box through which the $5^5/_{32}$″ dia. steel piston rod passes. The lower cover is attached by the same means, this cover acting as a mounting base, being secured to foundations by four bolts. A general view of cylinder and valve chest is illustrated in *fig.* 1.

Steam is supplied by two Lancashire type boilers operating at 65 p.s.i. gauge, supply pressure to the engine being reduced to 35 p.s.i. gauge by a reducing valve. From this valve the supply passes to a pilot operated regulator which controls admission of the steam to the valve chest, which houses a short D slide valve (2) having an 8-inch stroke. Exhaust steam passes to a feed water economiser which is in the form of a large cylindrical receiver with an opening to atmospheric pressure. Water is drawn from a natural reservoir to header tanks and is passed through the economiser by a steam pump.

The piston is of cast iron and carries two metallic packing rings. This is not the original piston but a replacement which was fitted in conjunction with a new piston rod, the latter being needed due to damage of the original. (The original piston employed hemp packing.)

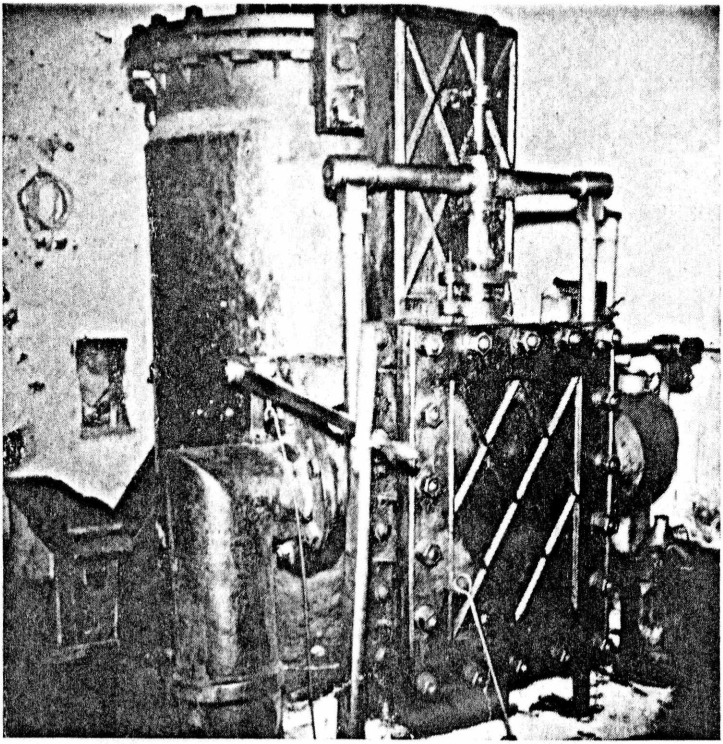

FIG. 1.
Engine Cylinder and Valve Chest.

The piston rod is connected to the main links of the parallel motion by a hollow cast iron "T" piece and is cottered in position. This connection is clearly illustrated in *fig.* 2. The main links connect on each side of the beam and are of a strap construction that provides simple bearing adjustment. The basis of the link is a steel strap enclosing beam and piston rod connection bearings which are separated by a steel rod. Bearings and spacers are drawn tight by the cotters.

The Parallel Link Motion itself is a standard type as first used by Watt in 1782. (3). The motion rods are one-piece forgings which are finished turned. Split brass bearings are employed which are positioned in the rod "eyes" by cotters. The outer lever is pivoted on bearing blocks anchored to the wooden beam supporting the upper floor of the engine house. The degree to

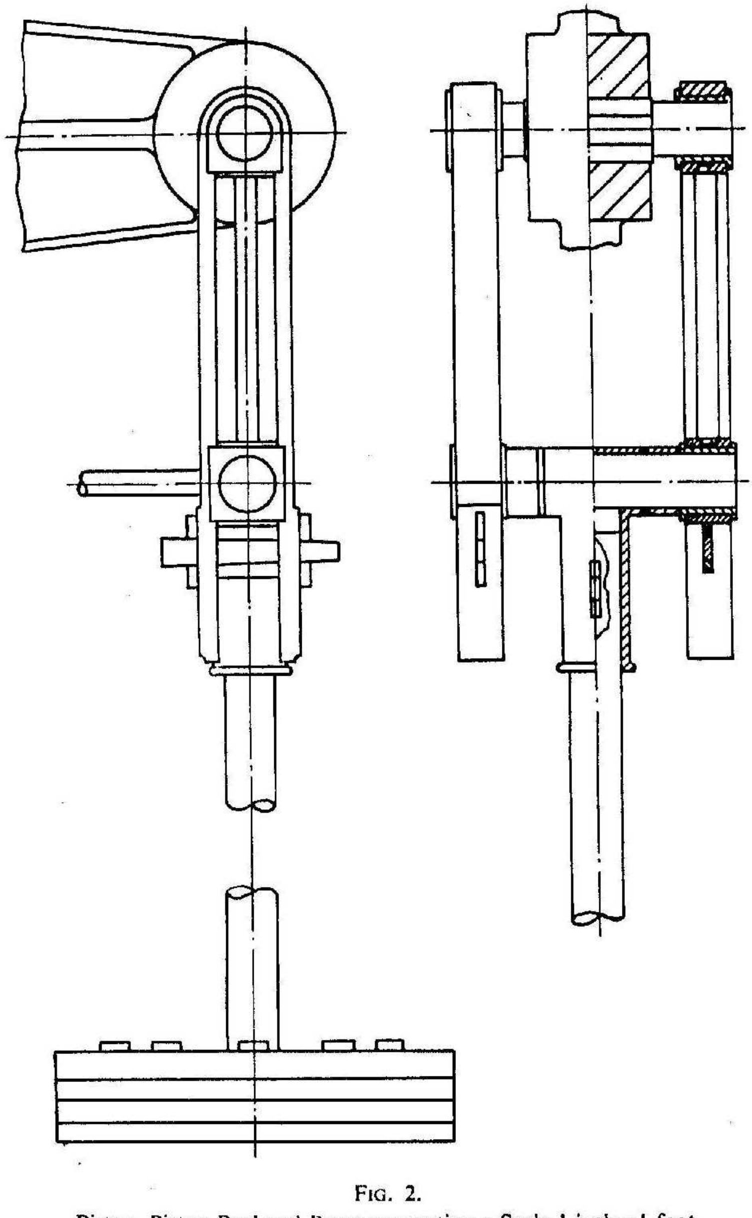

FIG. 2.

Piston, Piston Rod and Beam connection : Scale 1 inch = 1 foot

(*Note cottered strap and bearing separation bar*).

which this link motion is successful in maintaining a straight line path for the head of the connecting rod is illustrated in *fig* 3, and from the limits of the scale to which this drawing has been made, the purpose is shown to be achieved with perfection.

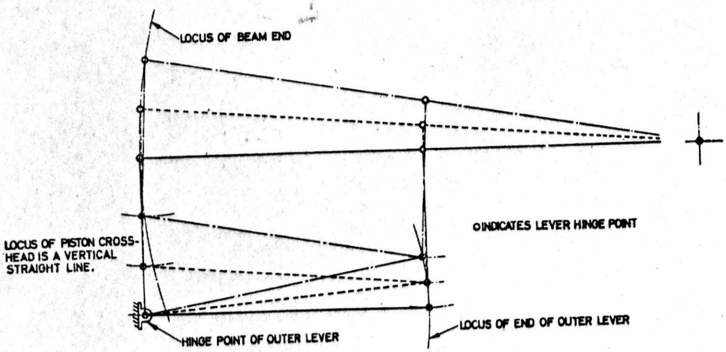

FIG. 3.
Line diagram of Watt's Parallel Motion, Scale 1 inch ≡ 1 Foot.
(Drawing included with acknowledgment to N.C.B. Durham Div. No. 2 Area).

The main links of the Parallel Motion are connected to the cast iron beam at cantilever journals. The journals are turned portions at the ends of an octagonal bar which is wedged into a cast octagonal hole in the beamboss. This construction is illustrated in *fig.* 2 and the octagonal portion can be seen in *fig.* 4.

The beam is a one-piece iron casting (4) estimated to weigh six and a half tons. It is elliptical in elevation and of "I" section plus a lateral stiffening web. A general view of the beam is shown in *fig.* 4.

The main bearing journal of the beam is also fitted by adoption of octagonal bar (5). Over the years of use the wedges positioning the beam on the bar repeatedly loosened and steel clamps around the octagonal projecting portion on either side of the beam are now employed to keep the wedges home. This can be seen in *fig.* 4. The $9^3/_4''$ dia. beam journal is supported by two plummer blocks fitted with brass bushes. Lubrication of this bearing was originally by oilways drilled vertically through the bearing cap but these have been replaced by screw-down grease lubricators. The bearings are mounted on wooden beams which are in turn carried by a cast iron crossbeam supported by two cast-iron

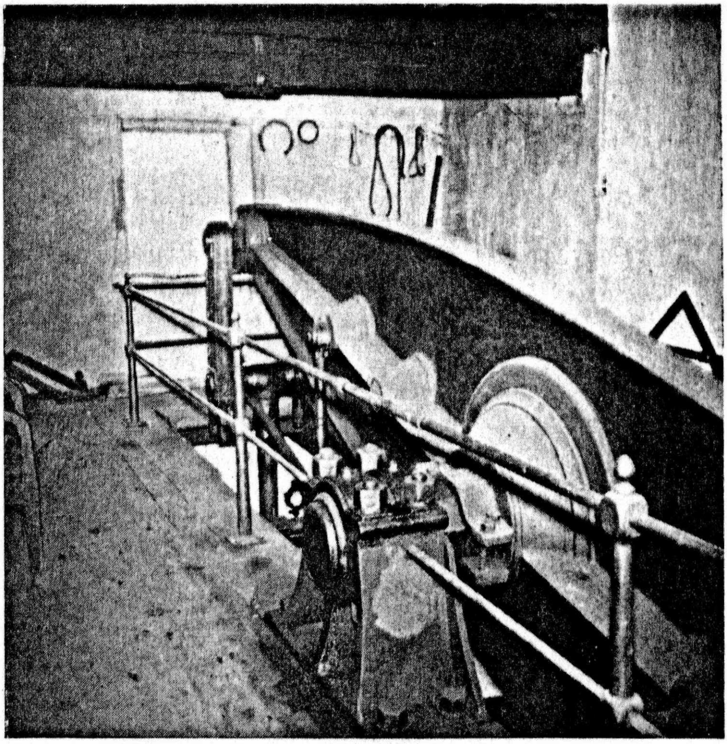

FIG. 4.
General view of Engine Beam taken from the Connecting Rod end.

pillars set in the engine-house foundations. Through-bolts are adopted passing through the bearing flange and the iron beam flange.

The connecting rod is of cast iron and is yoked at one end in order to connect to the journals on each side of the beam. The brass bearings of this upper connection are retained by a steel strap on each arm of the yoke, the strap being cottered in position. The cotters are held firm by set screws as shown.

The lower end of the connecting rod is connected to the overhung crank journal by a similar cottered strap retaining a split brass bush. This is clearly shown in *fig.* 5.

The crankshaft is supported in two 13″ dia. bearings of the plummer block type, both being mounted on wooden beams set on a stone foundation. *Fig*. 5 shows the crank-end shaft bearing and its mounting beam. The shaft was originally of square section cast iron but was replaced in 1934 by the present steel component. The crankshaft and crank (also of steel) were replaced after damage had occurred to the drive gears. Continued use of the iron shaft

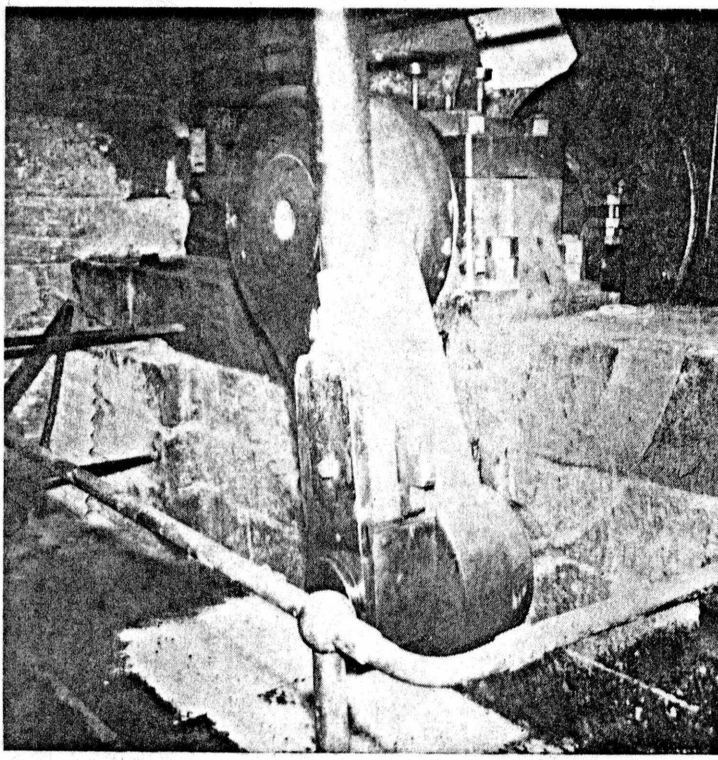

FIG. 5.
Connecting Rod, Big End and Crank.

was considered unwise even though it had performed approximately 100 years satisfactory service. The original crank would have been wedged on to the square shaft, but the present crank is shrink fitted.

Flywheel and eccentric are mounted between the crankshaft bearings and can be seen in *fig*. 6. The eccentric is of the Loose Sheave type which facilitates reversal of the crankshaft rotation.

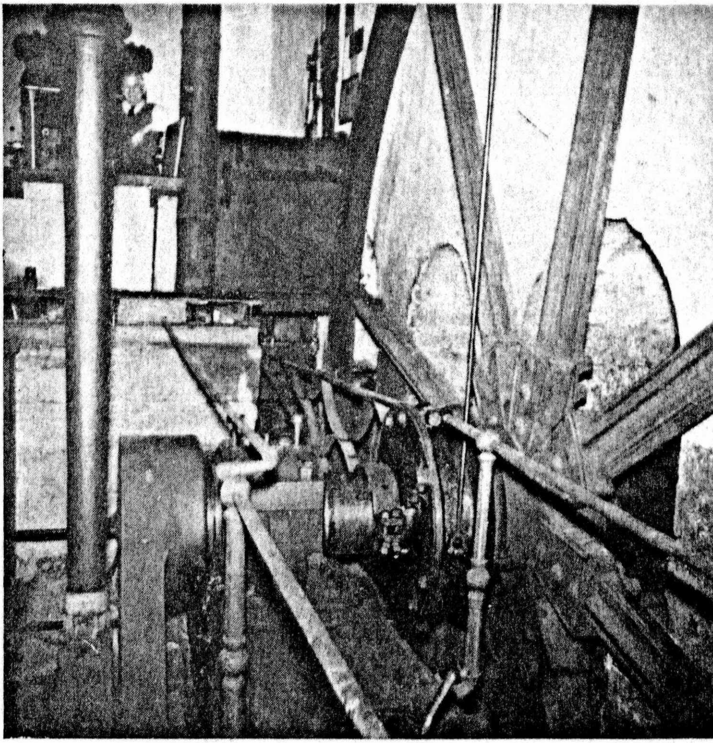

FIG. 6.
Crankshaft assembly showing Connecting Rod, Crank, Bearings, Eccentric and Flywheel.

The steel side plates of the eccentric are firmly fixed to the crankshaft and are positioned by use of strap clamps, see *fig.* 6. On each side plate are two driving dogs as shown in *fig.* 7, which is included to illustrate the method of reversal. The eccentric sheave is loose on the crankshaft and has one dog on each side. As the crankshaft rotates, the side plate dogs pick up the sheave dogs to drive the eccentric. The eccentric "rod," as can be seen in *fig.* 6, is an ornate piece of wrought ironwork. Its connection to the eccentric sheave is made possible by use of a split big end. The end of the eccentric rod remote from the sheave is provided with a notch or "Gab" (6) which engages the bell-crank driving the valve gear. Motion is transmitted to the slide valve by twin connecting links joining the opposite bell-crank arm to a crosshead attached to the valve spindle.

To reverse the crankshaft rotation, the piston is brought to rest at approximately mid stroke, and the Gab is disengaged by depressing the footpedal connected to the disengagement linkage. (This is shown diagrammatically in *fig.* 7.) The slide valve is then worked by the hand lever to rotate the engine back through 180°. The Gab is then re-engaged. The valve motion relative to the piston remains unchanged because the eccentric shift is exactly 180°. When steam is supplied to the cylinder the piston moves as previously yet the crank is driven in the reverse direction.

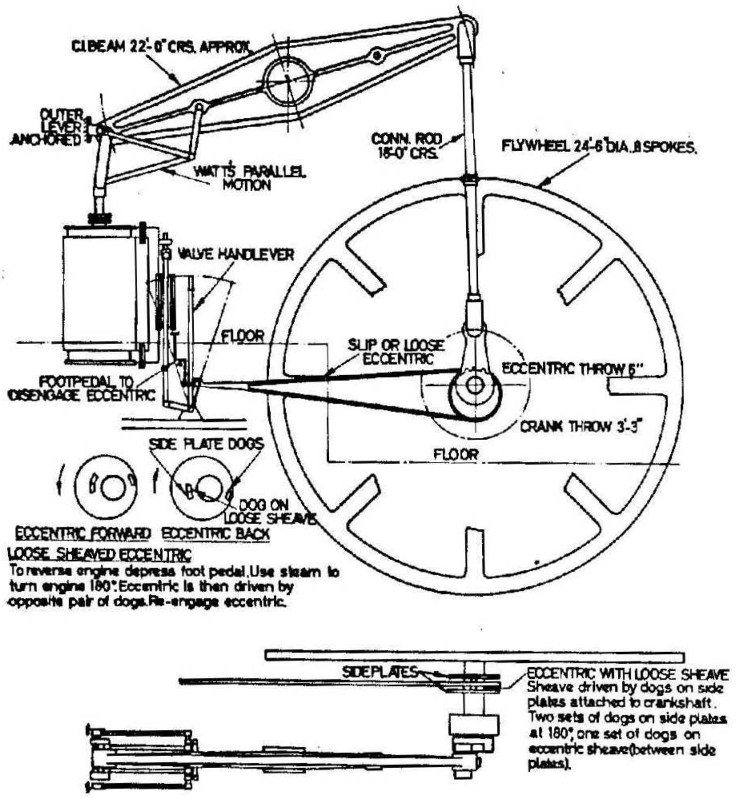

FIG. 7.
Reversing Details.

Drawing included with acknowledgment to N.C.B. Durham Div. No. 2 Area.

To ensure that the Gab does not become disengaged during automatic working a counterbalance system is fitted which forces the notch on to the bell-crank journal.

The 24′ 6″ dia. flywheel is built up from a centre hub, spokes and segmented rim. The flywheel rim (7) is constructed from eight cast iron sections having a thickness of 6″ and a depth of 10″. Connection to the star-shaped centre hub is by eight tapering cast iron spokes. All joints are bolted. The centre hub is a one-piece casting fitted to a square section of the crankshaft. It is positioned and fastened by wedges.

A brake-band operates on the flywheel rim. The fixed end of the band is secured to a wooden crossbeam at the connection remote from the engine cylinder. Brake application is made by depressing a footpedal. A ratchet engagement facilitates locking of the brake. This arrangement is not an engine brake but merely an anchorage to maintain the piston at mid-stroke when not working. This practice is adopted in order that the crank is positioned to render max. turning moment available at the commencement of winding. Were it not for this brake the weight of the piston and link motion are sufficiently in excess of that of the connecting rod and crank to cause the crank to be rotated to the position where connecting rod and crank are in line, *i.e.* turning moment zero.

The transmission gears are of cast iron and employ cycloidal teeth. Each is made in two halves which are bolted together. The gear teeth have not been machined but have been run as cast. The crankshaft pinion and the intermediate wheel have pitch circle diameters of 6 feet, each having 65 teeth, and the drum shaft gears are of approximately 9 feet diameter with 97 teeth. The original gears were of almost identical construction to the existing gears, but all employed square cast iron shafts and the wedge method of securing. In 1933 the main pinion failed. A similar failure occurred in 1946 and now only one of the original gears remains, this being one of the drum shaft gears. All the gear shafts are now of circular section steel. The present method of securing the gears to their shafts is by a single key.

The winding drums are not the originals, but replacements fitted in 1934. The previous drums were completely of cast iron whereas those now fitted are of steel. The drum diameters are

8′ by 2′ 6″ wide, the side plates being 10′ 6″ diameter. As with the gearing, wedge fitting was employed originally, a single key now being used for retaining the drums fast on the shafts.

The bearings of all shafts in the transmission are mounted on timber set in "windows" in the stone walls of the engine-house. The drum shaft bearings are also adjustable in position, in that a mechanical linkage is provided by which the bearing pairs may be moved parallel to the centre line passing through them. This is shown in the Plan View, *fig.* 8, and may be explained as follows.

The bearings of the drum shafts are of the C.I. plummer block type housing split brasses. Each bearing is mounted in a cast iron tray which is bolted to the timber beam supported on the stonework. Attached to each bearing is a 2″ dia. pull-rod. The other end of this rod is connected to a lever on a cross-shaft as shown in Plan View, *fig.* 8. The length of these levers is 4″. Also connected to this cross-shaft is a 6′ long operating lever. Movement of this lever can either separate the drum shaft gears

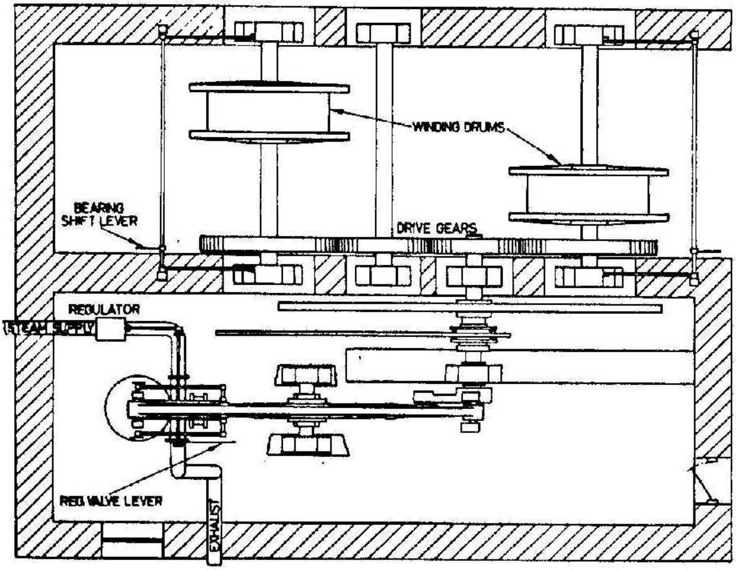

FIG. 8.
Plan View, Warden Law Hauling Engine (For elevation see Fig. 7).

Acknowledgment to N.C.B. Durham Division No. 2 Area for details from which this drawing was prepared.

from the main and intermediate pinions or, conversely, force the gears into mesh. This arrangement aids maintenance and erection and also allows mesh correction for wear. When the requisite positioning is obtained by this manner of adjustment the bearings are firmly fixed to the tray by four bolted clamps.

It is apparent from inspection of *fig* 8, that the winding drums rotate in opposite directions to each other. The reason for employing contrary rotating drums is best described by an explanation of the winding sequence, which follows this description of the engine.

WINDING SEQUENCE

Consider the winding sequence to commence under the conditions shown in *fig*. 9.

A loaded set of wagons (five wagons each containing twelve tons of coal) denoted at "A" has been hauled to the crest of Warden Law by drum "B," whilst an empty set, "C," has descended as controlled by drum "D" to the lower flat. The loaded set "A" is now disconnected from the haulage cable and attached to the cable of the gravity controlled system, "A" now becoming signified as "A^1." "A^1" is now allowed to descend the incline, thus drawing empty set "E" to the crest. Set "E" is then connected to the cable link from which "A" was disconnected. By this time the empty set "C" will have been exchanged for a loaded set "C^1." The engine is now put to work in reverse to the previous rotation so that the winding operation hauls the loaded set "C^1" to the crest whilst lowering empty set "E" to the lower flat.

The sets consist of five wagons each carrying twelve tons. Prior to the introduction of twelve ton wagons in 1931 the sets consisted of twelve four ton wagons, though when the railways first began the wagons would be of the two and a half ton chauldron type.

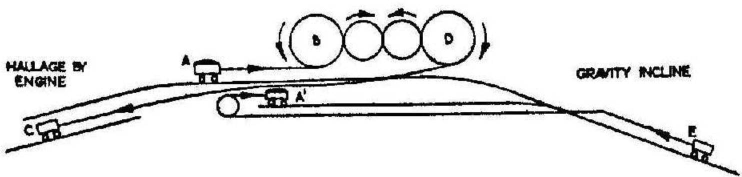

FIG. 9 Winding Sequence (Schematic)

METHOD OF OPERATION OF THE ENGINE

For the purpose of this description it is assumed that the engine is to be used for its first wind of the day, since mention is to be made of the initial warming of the engine prior to working.

Boiler steam has been raised, an empty unbraked set of wagons has been attached to the short cable at the crest of the gradient and a loaded set has been connected at the bottom. To facilitate coupling of both sets there is sufficient slack in the cable which the engineman allowed on the previous wind. Before winding is commenced, the valve chest, porting and the engine cylinder must be warmed to avoid undue condensation which would cause unnecessary loss of power during the hauling operation. The warming process is carried out as follows.

The flywheel brake is released and the eccentric gab is disengaged by depression of the footpedal referred to in the engine description. The regulating valve is then opened and the valve hand lever worked back and forth allowing steam to circulate through the valve and cylinder to exhaust. When the engineman is satisfied that sufficient pre-heating has been carried out (which is usually judged to occur when water ceases to be blown past the valve rod gland at the top of the valve chest) the engine is ready to wind and the regulating valve is closed.

When the loaders at the lower flat have connected the loaded set to the haulage cable, they inform the engineman via a bell system. The engine is started by disengaging the eccentric and working the slide valve by the hand lever, and regulating valve control. The gab is held disengaged by the right foot, regulator controlled by right hand and valve positioning accomplished with the left hand.

The initial acceleration of the engine is restricted by the acceleration of the empty set down the incline, it being necessary to keep the paying out cable taut. The conditions of the uncoiling cable is signalled to the engineman by a "whistler," who is a man who stands by the winding drums and blows a blast on a whistle when the cable falls slack. At each blast of the whistle the engineman restricts his engine speed slightly but allowing a gradual overall acceleration of the system. When the empty set has gathered speed the whistling ceases, the gab is engaged and the regulator fully opened. Engine speed then increases to its maximum working value.

The position of the wagons on the incline is indicated to the engineman by a cord indicator driven from the drum shaft. As the loaded set approaches the crest, the indicator alone may be relied on to judge the stopping position, the driver prefers to work in conjunction with hand signals of the brakemen on the line whom he can observe from the driving position. It is the duty of the brakemen to apply the hand-brake to the wagon when the gradient is surpassed and to change rope connections.

As the loaded set approaches the summit the engine speed is reduced gradually by partially closing the regulator. When the engine is running slowly the eccentric is disengaged and the engine brought to rest by manual control of the valve. The brakemen apply the hand-brakes of the raised set, and the engineman then lets out sufficient slack to allow cable disconnection.

The flywheel brake is then applied and the engine is ready to wind the next set.

ENGINE MAINTENANCE

The routine maintenance of the engine consists of four classes :

(*a*) Bearing lubrication.

(*b*) Checking level of oil in the lubricator mounted on the inlet steam line.

(*c*) Lubrication of piston rod gland and valve rod gland.

(*d*) Lubrication of gearing.

The following table lists the methods of lubrication.

Item	Lubricant and method of application
Crank Shaft Bearings	Grease - Screw-down Lubricator
Connecting Rod - Beam connection bearings	ditto
Drum-shaft bearings	ditto
Intermediate shaft bearings ...	ditto
Main beam bearing	Medium viscosity oil in oilways
Connecting Rod - Big end bearing	ditto
All link motion bearings	ditto
Valve motion link bearings including eccentric	ditto
Gland packings	Medium viscosity oil in annular cups
Gear Teeth	Grease - applied to tooth face

Gland packings are replaced when necessary. Asbestos cord packing is employed for valve rod and regulator valve rod, and until recently for the piston rod gland. A substitute for the latter has been a hard synthetic rubber packing. Subsidence of the foundations beneath the engine cylinder has caused the piston rod to be approximately $\frac{3}{4}''$ out of line with the cylinder centre line when piston is at top of stroke, and this eccentricity caused rapid wear of the asbestos gland-packing, rendering sealing defective in a short time after replacement. The rubber packing has been found more suitable for this purpose, as it retains its resilient properties even under the temperature subjection and presence of oil. Under certain conditions an audible squeal is noticed from the metal-rubber rubbing surface, but this only occurs during the first few strokes from starting. It is assumed that injected oil provides the suitable non-injurious lubricant.

ALTERATIONS, MODIFICATIONS AND REPLACEMENTS

The engine was built in 1836. The first record of a replacement of any type is that of a rope renewal in 1879. Since this date, the records show that ropes are replaced at an average interval of three years.

The following records are listed in chronological order :-

1925 Lubricator fitted to steam supply line.

1927 Secondhand Lancashire Type Boilers installed.

1930 Joists built in to walls above winding drums to assist in future maintenance.

1931 New bearing brasses fitted throughout.

1933–1935 Broken Pinion and bent piston rod. Damage also caused to the intermediate pinion. Three gears were replaced and a new piston and piston rod fitted.

All gearshafts and crankshafts were changed from square section cast-iron to circular section steel. New winding drums manufactured and fitted, the replacement items being entirely of steel construction as opposed to the iron originals. Crankshaft bearing blocks complete replaced, and holding down bolts lengthened to pass through masonry as well as timber.

The original holding bolts passed through timber only. Engine-house flooring relaid.

1937 Connecting rod brasses renewed, and screw-down grease lubricators fitted to beam connection connecting rod bearings.

1946 Broken Pinion replaced. Only one of the original gears remains in use, this being the front drum spur wheel.

1954 Eccentric Sideplates fractured. These were renewed and a new sheave fitted. The sideplates are now each made up of a two piece steel casting, the originals being in one piece with square hole fixing to shaft.

ENGINE PERFORMANCE FIGURES

It was not possible to take an indicator diagram from this engine, but a hypothetical diagram was constructed with careful consideration and it is upon this diagram that many of the following figures have been established. The author does not offer any limits of accuracy in this assumed diagram, but is confident that figures quoted give satisfactory values which enable various stresses and pressures to be compared with present-day allowances.

Engine Speed		30 r.p.m.
Brake Horse Power as measured at Winding Drum		97·5
Indicated Horse Power		197
Overall Mechanical Efficiency		49·5%
Overall Brake Thermal Efficiency	with feed water economiser	1·3%
Engine Brake Thermal Efficiency	with feed water economiser	1·8%
Rankine Efficiency		9%
Overall Plant Efficiency		0·1668%
Boiler and Transfer Efficiency		0·1283%
Transmission Efficiency (including power absorbed by valve gear)		72·5%
Fluctuation of Speed under normal running conditions		$\pm 1\frac{1}{4}$ r.p.m.
Steam Consumption at rated speed		198lbs./H.P.hr.

ESTIMATED WEIGHT OF MAJOR COMPONENTS

Beam		6·5 tons
Piston and Piston Rod		1·73 tons
Flywheel		11·5 tons
Gears :	Pinion	1·9 tons
	Spur Wheel	2·85 tons
Crank		1·28 tons

STRESSES IN WORKING PARTS

Estimated Stresses in Bearing Journals

(Maximum stress under **normal** working conditions).

	Max. Bending Stress		Shear Stress	
	Actual	Allowable (8)	Actual	Allowable
Beam Support	6,500lb/sq.in.	56,000	442	42,000
Beam Ends	4,750 „	56,000	542	42,000

Estimated Stresses — lb./sq.in.

(Maximum stress under **normal** working conditions).

Component	Max. Bending Stress		Shear Stress		Direct Stress	
	Actual	Allowable	Actual	Allowable	Actual	Allowable
Beam	1,050	22,000	660	24,000		
Crankshaft	4,180	56,000	2,890	42,000		
Connecting Rod					514	22,000
Piston Rod					1,240	56,000
Cylinder Cover Bolts					1,340	56,000
Gear Teeth, roots of	7,300	22,000	1,080	24,000		

Estimated Bearing Pressures

(Maximum pressures under normal working conditions).

BEARING	Bearing Pressure lb./sq.in.	
	Actual	(9) Permissible
Crankshaft		
(a) Crank End	215	200
(b) Flywheel End	148	200
Beam Support	282	200 — 700
Connecting Rod		
(a) Big End	470	900
(b) Beam Connection	390	200 — 700
Main Motion Links	390	200 — 700

Estimated Number of Reversals of Beam Stress to which beam has been subjected throughout working life = 108,000,000.

GENERAL REMARKS AND CONCLUSIONS

The Warden Law Hauling Engine has been installed for 120 years. It has performed its winding duties almost continually up to the present date and by virtue of the mammoth service and a knowledge of the generally sound condition of the engine it should have at least as many working years again, before it. The only stoppages have been due not to faults of the engine but to those brought about by gearing failure. Other than these occurrences, only lubrication and bearing replacement has been necessary in maintaining the engine.

Examination of the stresses and bearing pressures calculated, and the comparative ultimate or allowable values reveals that very low stressing is imparted by virtue of the massive construction of the engine throughout. It may well be that the massiveness is the secret of the success and reliability of the engine, the engineers of the period designing on assessment of dimensions by practical experience rather than by theoretical consideration.

The failing of the engine is its efficiency, which is drastically below modern standards. The engine cycle itself promotes a Rankine efficiency of only 9% which is due to the low working pressure of the steam. (10)

In the Engineering Laboratory of King's College there is a quadruple expansion steam engine designed by Professor Weighton in 1894. This type of engine probably represents the pinnacle of achievement in steam engine design. If this engine had replaced the Warden Law engine, it is estimated that a total saving of 63,000 tons of boiler fuel would have been realised in 50 years of working, assuming that the boiler and transfer efficiency of the Warden Law plant remained the same.

The overall mechanical efficiency of the Warden Law engine is estimated as 49·5%. By consideration of the Transmission Efficiency (72·5%) the mechanical efficiency as measured at the crank is then 49·5/0·725 = 69%. The mechanical efficiency of the Weighton Engine is approximately 80%. Thus it is evident that the practical design appreciations of the builders of the Warden Law engines were far in excess of their ideas on the theory of heat engines.

Many engines of the early nineteenth century were fitted with condensers to raise the output. In fact, the Warden Law engine beam is provided with bosses which would presumably accommodate condenser and air pump rods. Had a condenser been employed a net saving of 34,500 tons of boiler fuel could have been attained in 50 years. It has been assumed, for the purpose of estimation, that the effect of condensing would double the thermal efficiency.

The only attempt that has been made to increase plant efficiency is the addition of the feed water economiser. In order to estimate the effect of this apparatus, it is assumed that feed water is raised to boiling point. Choosing a 50 year period in keeping with the previous estimates the economiser would lead to the saving of 12,500 tons of fuel.

However, consumption of fuel does not seem to have been taken into account in the case of colliery engines in general, (11) the excuse being given that the coal burned is unfit for sale.

Efficiency could be increased by employing higher steam supply pressure but this would make for higher working speed of the engine. This is undesirable on two accounts :-

(a) Generally increased working stresses.

(b) Increased winding speed is not necessary since the rate of hauling is restricted by ascent of empty wagon sets up the gravity incline in conjunction with which the engine works. Thus higher working speed could not assist in the overall rate of working of the traffic system.

Therefore, although the Warden Law engine is a great tribute to the ability of the early engine builders, its economy is shameful by modern standards. In its early days, the Hetton Railway system provided rapid transport (by standards at the time) from colliery to seaport, and the employment of the 37 men needed on the system was considered fully justified. The scheme itself is highly ingenious, for which all credit must go to Stephenson. But by modern standards it is completely outdated.

However, in spite of the criticisms of the engine, the reader is asked to think once more of the date of its erection. Yes, 1836. How many machines have been in continual service for a period of 120 years, during which time, this engine's beam has sustained approximately 100 million stress reversals ? (12) It must be admitted that the answer is "Very few". Thus, in the Warden Law Hauling Engine, we have a unique example of the achievements of the early engine builders, the engine serving as a monument to their contribution to development of the steam engine.

With this appreciation, it is with reluctance that the author has to announce that in 1958 the Hetton Railway will be rendered redundant by a more modern transport system.

A final reflection on the tribute that the present existence and employment of the Warden Law engine affords its creators leaves us in no doubt as to why the engineman wears a proud smile.

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11. *Direct Winding Engines for Mines.*—G. Daglish. (Paper read before I.M.E. 1875).

12. *Proc. of I.M.E.* 1914.—M. Longridge.