26 March, 1907.

Sir ALEXANDER B. W. KENNEDY, LL.D., F.R.S., President, in the Chair.

(*Paper No. 3650.*)

"The Application of Hydro-Electric Power to Slate-Mining."

By Moses Kellow, Assoc. M. Inst. C.E.

The slate-mines and quarries of Wales are situated, almost without exception, in the mountainous regions of Merionethshire and Carnarvonshire, and their working forms the staple industry of these counties.

The form of the country, in which high hills alternate with deep valleys, greatly facilitates mining and quarrying, inasmuch as it enables the slate beds, which usually incline at relatively high angles, to be approached and worked by adit-levels and horizontal galleries directly from the hillsides, natural ventilation being also available. These advantages of position, by dispensing to a large extent with the necessity for powerful winding-, pumping- and ventilating-machinery, such as is generally required in collieries and metalliferous mines, have caused the amount of power in use to be small, relatively to the magnitude and importance of the undertakings generally.

There is little doubt that it is due to this fact that the mechanical equipment of slate-mines and quarries—particularly in connection with the generation and distribution of power—has not kept pace with the progress made in other industries.

The conditions under which the slate is being worked tend, however, to become less favourable every year, for, as the workings become deeper, natural drainage is no longer possible, winding from the lower galleries becomes necessary, and satisfactory ventilation is more difficult of attainment. Moreover, mechanical aids in the manufacture, as well as in the mining and quarrying, of slate, tend to become more universal every year.

These changing conditions, by involving an increasing use of power, render the question of the best means of generating and distributing it of considerable importance, especially at the present time, when the stress of foreign competition is so great that the very existence of the industry requires that advantage should be taken of every aid to effective working and cheap production.

By reason of its situation on the west coast, and the high altitude of the mountains comprising the Snowdonian range, which intercept the moisture-laden west and south-west winds, the locality has an exceptionally high rainfall, ranging from 90 inches to as much as 170 inches per annum. The large volume of water which this implies is moreover generally available for storage at a high elevation, so that the two conditions of volume and head, essential to the production of hydraulic power, are present. There is no doubt that, properly developed and applied, there is an abundance of water-power available in the two counties for all the needs of the slate industry.

At present, though in some instances water-power is applied, the bulk of the power for working machinery in the slate mines and quarries is being derived from steam. The disadvantages attendant upon the use of steam-engines, as regards expense and inconvenience, when they are distributed in small units, and especially when situated underground, are so well known to engineers that it is unnecessary to enlarge upon them.

It may therefore be taken that, when the advantages of the economical and convenient source of power in the form of water are more generally appreciated by the mine-owners, and the possibilities of its application to the cheap generation of electricity are fully realized, it will be used almost to the exclusion of any other.

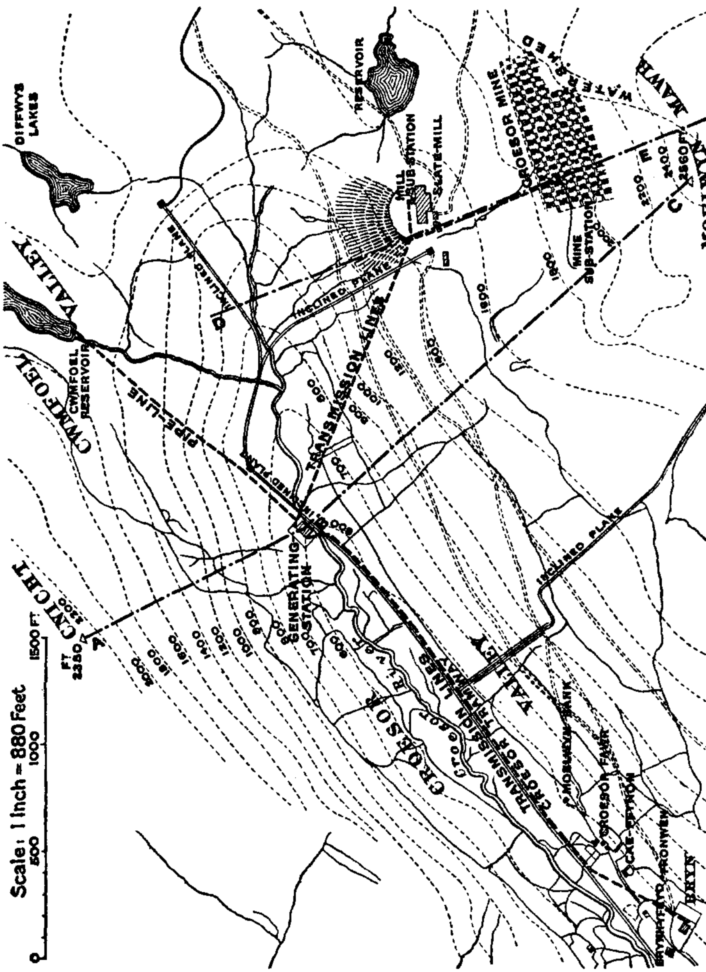
The Author, having designed and installed in North Wales a hydro-electric plant containing features which are in many respects novel, believes that a description of the installation, together with an explanation why the particular forms of apparatus employed were adopted, and some observations upon the application of the principles involved to slate-mining generally, may be of interest.

Hydraulic Installation at the Croesor Quarries.

The property upon which the scheme referred to has been carried out is situated in the Croesor and Cwmfoel valleys, on the slopes of the high mountains of Cnicht and Moelwyn, and in the vicinity of Snowdon. *Fig. 1* is a contoured map of a portion of the property to a scale of 6 inches to the mile. The principal parts of the power-scheme and the position of the mine are also indicated. *Fig. 2* is a section of the Croesor valley through the power-house.

The property contains within its limits all the essentials of a complete power-system—namely, an ample catchment-area having a

Fig. 1.

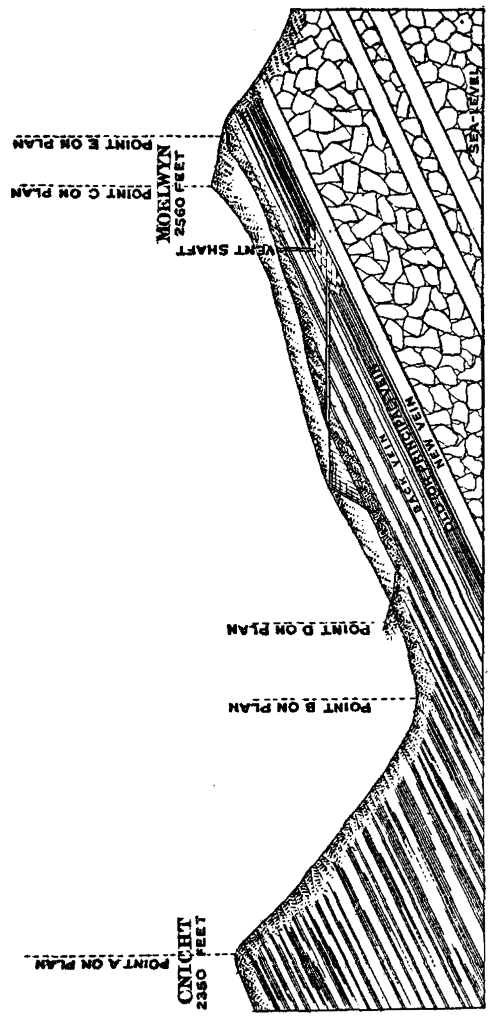


Plan of Croesor Valley.

high rainfall, large water-storage capacity, and high head of water, enabling considerable power to be obtained—as well as the means of employing profitably the power so obtained in the working of the slate-mines.

Two natural lakes, having an area of about 6 acres, exist at an elevation of about 1,100 feet above the power-house, and about 1,700 feet above the level of the sea. At present these, with other feeders, discharge their waters into the Cwmfoel valley, which is

Fig. 2.



SECTION ACROSS CROESOR VALLEY.

enclosed on three sides by high hills. The fourth side, which converges into a narrow opening, has been closed by a masonry dam; and about 12 acres of water have been thereby impounded at an elevation of 860 feet above the power-house, and 1,460 feet above the level of the sea. So far as the Author is aware, there is no previous example of so high a head of water having been utilized in the United Kingdom.

The higher lakes can, when required, be used to supplement the storage of the reservoir, or can be connected directly to the wheels in the power-house, giving them the benefit of the extra fall. A further reserve is provided by a reservoir on the other side of the Croesor valley. This reservoir is more than 5 acres in extent, is 1,050 feet above the power-house, derives its water from a different catchment-area, and has a pipe-line, 1,200 feet long, already laid.

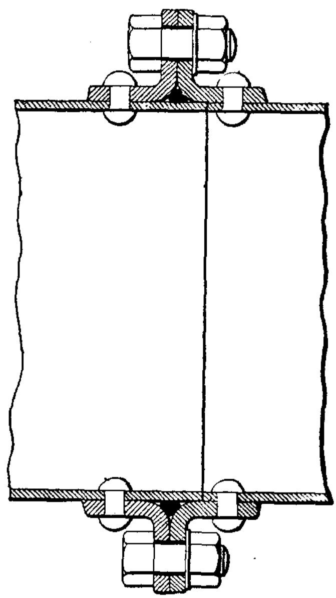
The form in plan of the dam of the principal reservoir in the Cwmfoel valley was determined by the contour of the ground, and by the facilities for obtaining reliable foundations. Its total length is 263 feet. Of this length, 233 feet is built on solid rock, and the remainder on a bed of impervious clay. The dam is 8 feet wide at the top, and rectangular in section for a depth of 4 feet. Below this there is a batter of 2 feet in 5 feet on the outside. Near the sluices the height is 24 feet, and the width at the bottom is therefore 16 feet. As a provision against leakage, a channel about 5 feet deep was cut, and a guard-wall built in it, in line with the inner face of the dam. The inner face of the dam itself, for a thickness of 2 feet 6 inches, consists of dressed blocks of syenite bedded in Portland cement, the joints being also pointed with the latter material. Syenite was selected for this part of the dam because of its imperviousness to water, and consequent non-liability to disintegration by frost. The remainder of the structure consists of slate rubble masonry bedded in hydraulic lime mortar. As a result of the precautions taken, the reservoir is absolutely water-tight, not a single drop escaping, so far as can be ascertained.

The necessary sluices and three outlet-pipes have been fitted; and to one of the latter a steel pipe-line 3,200 feet long has been connected, extending down to the power-house at the bottom of the Croesor valley; and the water from the reservoir is there applied to driving two impulse-wheels, one of 375 B.HP. and the other of 25 B.HP.

The high pressure of 373 lbs. per square inch necessitated the use of a special form of joint. A recess to retain the packing-material was essential; but the flanges being of wrought steel, and therefore thin, a turned groove in their faces would have weakened them. The plan adopted was to form the pipes with male and female ends, and to utilize the space formed by the curvature of the flanges for the packing material. This avoided weakening the flanges; and, by securing uniformity of section in the pipes, obviated the considerable losses due to eddies in the water, which would otherwise have been formed at each joint. A section of the joint is shown in *Fig. 3.* The pipe-losses were further reduced by the use of welded steel, coated with preservative compound, which gave a very smooth interior surface.

The pipe-line has been provided with an air inlet-valve and expansion-joints, and at its lower end, to minimize pressure-variations, with an air-vessel of a capacity of about 30 cubic feet. As the water-pressure was more than 25 atmospheres, it was necessary to provide means for filling it with air at an equivalent pressure. This is accomplished hydraulically by means of a charging-chamber and accessory parts forming the base of the air-vessel. As this is of original design, an explanation of its construction and working may be of interest. The air-chamber is in connection with the pipe-line by a vertical pipe, which passes centrally through a cylinder which forms the base of the apparatus (*Figs. 4*). The annular space between the vertical pipe and the walls of the cylinder forms a charging-chamber. Two cocks and an outlet-valve, controlled by a single lever, enable the charging-chamber to be put into communication with the pipe-line and the air-chamber, or with the atmosphere and the exhaust. When put into communication with the pipe-line, the air contained in it is compressed to a pressure corresponding with that of the water; and, by reason of its lower specific gravity, it rises into the air-chamber above. A movement of the lever closes the passages from and to the pipe-line and air-chamber respectively, and opens the outlet-valve and passage communicating with the atmosphere, thus enabling the water to escape, and a fresh charge of air to be admitted. The outlet-valve is operated through a cam, so as to avoid the necessity for lifting it against the pressure of the water. Gauge-glasses are provided to indicate the height of the water in the air- and

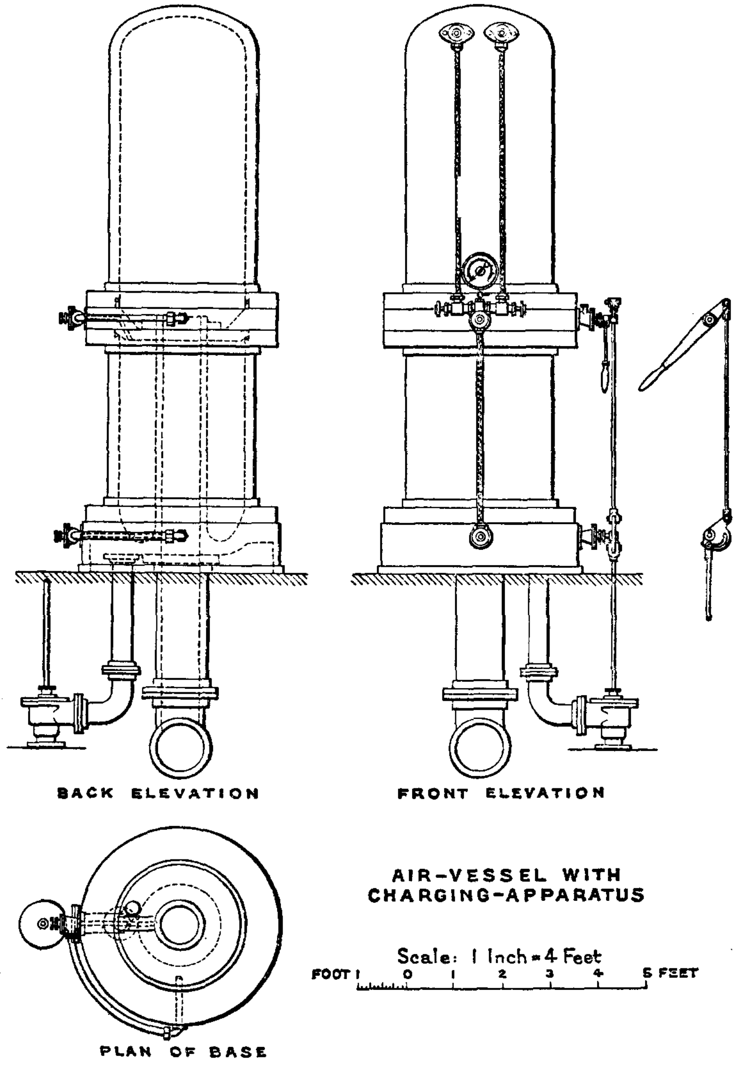
Fig. 3.



PIPE-JOINT.

charging-chambers respectively, and thus to guide the operator in manipulating the lever.

Figs. 4.



Eight relief-valves with knife-edges, giving a minimum of difference between the opening and closing pressures, have also been fixed at the lower end of the pipe-line, to provide against dangerous rises of pressure.

Some form of impulse-wheel was essential for the high head of 860 feet; but before settling the final form of the buckets, nozzles, etc., the Author carried out a large number of experiments with various forms of each, and under different conditions as regards speed, etc., and having the means at hand for readily and accurately measuring the power developed electrically, a considerable body of data was collected, enabling the following conclusions to be arrived at:—

(1) That the friction of the water against the internal surface of the nozzle retards its velocity, and that the difference of velocities in the centre and at the periphery of the jet introduces a dispersive element, which materially reduces the efficiency of the jet, if its point of application be far removed from the orifice of the nozzle; and that therefore the nozzle should be fixed as near to the buckets of the wheel as possible.

Fig. 5 shows a section of the jet obtained from a nozzle constructed in accordance with Molesworth's formula, and illustrates this dispersive tendency.

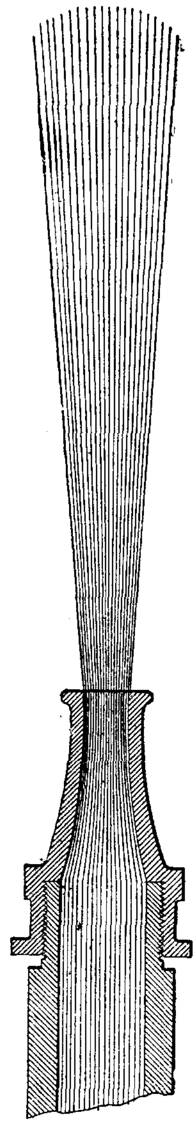


Fig. 5.

Jet from a Nozzle designed according to Molesworth's Formula.

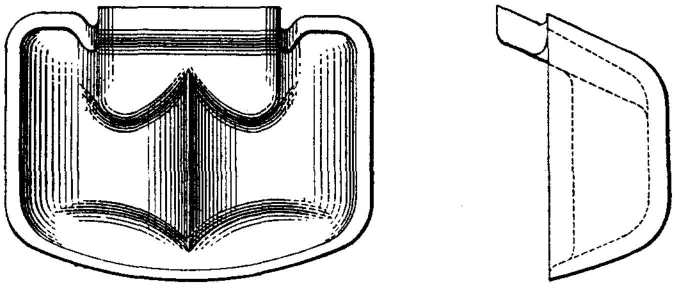
(2) That a pointed spear, or needle, introduced into the centre of the nozzle for the purpose of contracting the orifice has the effect of minimizing the dispersive action, by retarding the velocity of the water in the centre as well as at the periphery, and so making it more uniform; but, as a reduction of the velocity, either at the centre or at the periphery, involves a loss of energy, the efficiency is reduced thereby.

(3) That if such a spear be used, its position in the nozzle must be absolutely central, or the form and efficiency of the jet will be prejudicially affected.

(4) That it is essential to support the spear at a point near the nozzle, as any lack of rigidity renders it liable to vibration, with a consequent distortion of the jet and loss of efficiency.

(5) That a bifurcated bucket with a lip, such as the Pelton bucket,

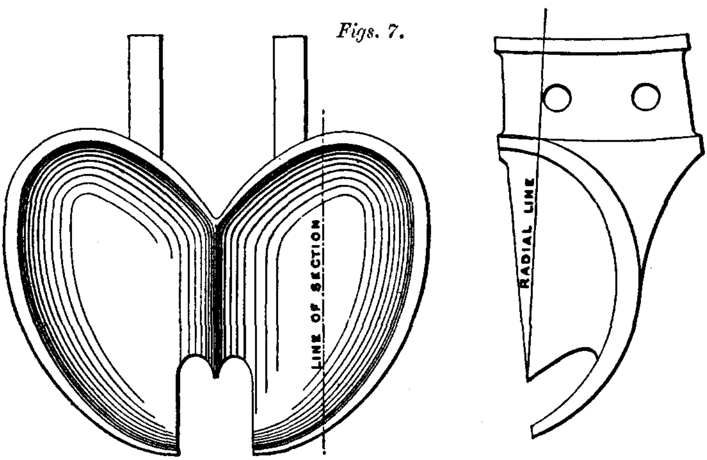
Figs. 6.



"A" Bucket.

does not fulfil the conditions essential to maximum efficiency, as the lip and central wedge deflect the jet in two planes, nearly at right angles to each other, and as the resultant paths cross, the interference of the streams dissipates energy uselessly.

Figs. 7.



"B" Bucket.

(6) That it is advantageous to omit the portion of the lip which is in the line of the jet; but to avoid the escape of water through this opening the path of the water along the bucket must be directed obliquely backwards.

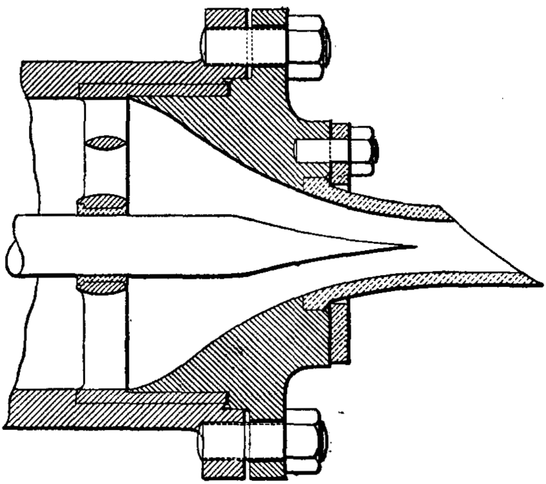
(7) That the peripheral speed of the wheel has an important influence on its efficiency, and that the best results are obtainable at lower peripheral speeds relatively to the spouting velocities of the water than are generally adopted for this type of wheel.

(8) That where a spear is used to control the volume of water passing through the nozzle, there is a wide variation in the best peripheral speeds with different degrees of opening.

For the efficiency-tests, the water was discharged into a tank and accurately measured, the power developed being ascertained electrically for full, three-quarter, half, and quarter volumes of water, and over a range of speeds in each case.

Figs. 6 and *7* show buckets of the two types referred to, and *Fig. 8* shows the form of nozzle and spear adopted.

Fig. 8.



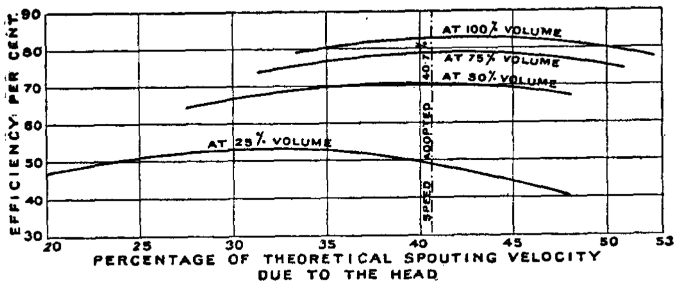
NOZZLE AND SPEAR.

Fig. 9 gives the results of the tests of the wheel when furnished with buckets with closed lips ("A" type) and *Fig. 10* gives corresponding results obtained when buckets with open lips ("B" type) were substituted. The efficiencies are plotted as ordinates; the peripheral speeds as abscissæ. An examination of the curves shows clearly the superiority of the "B" type of bucket, the considerable advantage of working with a fully-open nozzle, and the importance of adopting the best peripheral speed.

The "B" type of bucket was adopted by the Author for each of the two impulse-wheels, with a peripheral speed of 40·7 per cent.

of the theoretical velocity due to the head of water, as indicated by a pressure-gauge attached to the pipes at a short distance from the nozzle. This speed was adopted with a view to obtain the highest efficiency when the plant was working at or near its full load; but this does not coincide with maximum efficiencies at smaller loads.

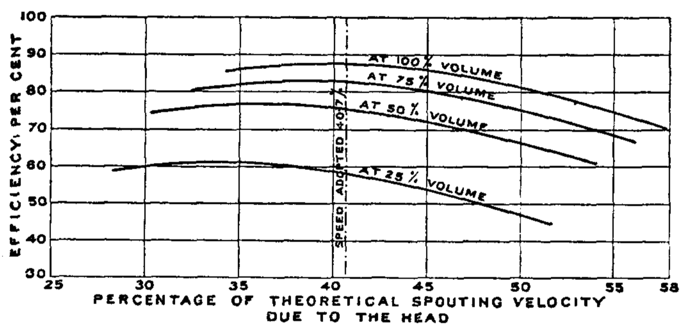
Fig. 9.



EFFICIENCIES OF IMPULSE WHEEL WITH "A" BUCKET (*Figs. 6*).

Fig. 11 shows the wheel-efficiencies at various volumes of water at a constant peripheral speed of 40·7 per cent. for both "A" and "B" types of buckets. Pipe-efficiency, combined hydraulic efficiency, and horse-power curves have also been added.

Fig. 10.

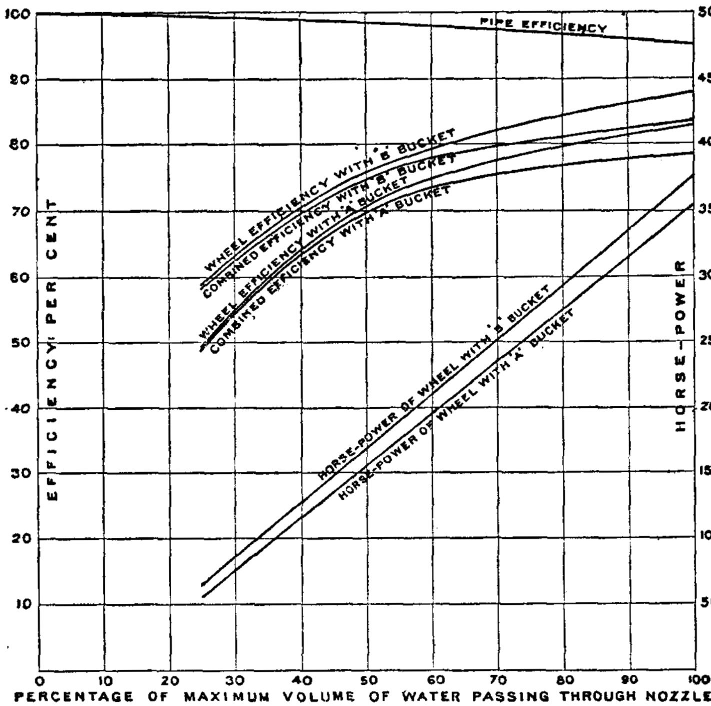


EFFICIENCIES OF IMPULSE WHEEL WITH "B" BUCKET (*Figs. 7*).

In all the diagrams, wheel- and nozzle-efficiencies are taken together.

For both wheels, very sensitive governors, pivoted on knife-edges and acting through hydraulic relays, control the positions of the spears in the nozzles; and in the case of the larger one, an oil dashpot is also brought into use, whereby the speed of withdrawal, or insertion of the spear, can be separately controlled and also steadied. Except under severe fluctuations of load, when the relief-valves come momentarily into operation, the variations of pressure in the pipe-line, due to the action of the governors, are kept within

Fig. 11.



Efficiencies and Power developed by an Impulse Wheel.

(Head = 61 feet; volume of water used per minute = 276 cubic feet; peripheral speed (constant) = 40·7 per cent. of theoretical spouting velocity due to head.)

very narrow limits by the air-vessel, and therefore the quantity of water wasted is negligible.

The power-house has been made of sufficient capacity to accommodate three generating-sets, and it is intended to lay additional pipe-lines from the reservoirs when the demand for extra power renders such a course necessary.

The Application of Electricity to Slate-Mining.

As regards the electrical part of the scheme, the Author proposes first to consider the general principles governing the application of electricity to slate-mining, and then briefly to state how these principles were embodied in practice in the plant designed by him.

The electrical systems possible may be broadly divided into (*a*) Continuous Current; (*b*) Alternating Current.

Continuous Current.—With continuous current, a voltage must be adopted which is suited to the generators, the transmission-lines, and the motors, or lamps, as the case may be; and as the requirements of these various elements are not identical, the designer has to adopt what appears to be the best compromise in view of all the conditions of the case. Moreover, the difficulties of commutation in connection with generators and motors place practical limitations upon high voltage.

As, all other conditions being equal, the efficiency of transmission varies as the square of the voltage, high voltage is the very essence of efficient transmission. Therefore when transmission has to take place to any great distance, say 1 mile or upwards, this factor is one of considerable importance, and may become the determining element in the system to be adopted.

For voltages above 1,000, the continuous-current generator is not a suitable machine; so that, where it is desirable to use high tension up to 3,000 volts, or extra-high tension up to say 11,000 volts, to obtain efficient and economical transmission, the use of continuous current becomes practically impossible.

The comparatively high voltages which are generally desirable from the point of view of transmission, are objectionable from the point of view of application; for to have motors and other plant carrying current at a fatally high potential in use by men who generally are not electrical experts, under conditions where there is liability to mechanical injury to insulation, deterioration from wet, and other sources of injury such as prevail in slate-mines, is to incur risk of serious accident to the men, and of damage to the plant.

It is, however, generally assumed that continuous current has advantages over alternating current in the following respects:—

(1) Uniformity of voltage at the point of application, obtainable by over-compounding the generators to balance the ohmic drop in the transmission-lines.

(2) Storage of electrical energy by means of accumulators to equalize the peaks of the load.

(3) Variability of speed, without material sacrifice of efficiency, by varying the excitation of the motors.

(4) High initial torque, and consequent quick acceleration of loads, as applied to winding, haulage, and traction, obtainable by the use of series-wound motors.

(5) Simplicity of the overhead system in connection with traction on tramways, a single conductor overhead only being required.

(6) The positive value of all the current passing, i.e., a power-factor of unity.

In this Paper, however, it is in its applicability to slate-mining, rather than in a general sense, that the subject is being considered. Dealing with these points in the order named above :—

(1) For motors which represent the bulk of the power used, though uniform pressure is a very desirable condition in continuous-current motors, as their speed-regulation depends upon it, comparatively wide variations of pressure do not materially affect the speed of alternating-current motors, as this depends principally upon the periodicity. It is, therefore, in connection with the relatively small lighting element that good pressure-regulation is of consequence in the alternating-current system.

The attainment of this is primarily easier with continuous current than with alternating, by reason of the demagnetizing influence of the lagging currents, which are generally associated with the latter, upon the field system of the alternator, and of the fact that, at least until very recently, compounding and over-compounding had not been successfully applied to alternators. Recent developments, both in alternators themselves and in voltage-regulators, which correct for power-factor as well as for ohmic drop, indicate, however, that the lead which continuous current has in this respect is disappearing.

(2) The extent to which power can be stored electrically is inconsiderable, unless a large outlay is incurred; and, moreover, a very considerable loss is involved in charging and discharging accumulators.

In the slate districts of North Wales, where water is the source of power, it is generally possible to store it, and to generate power as required to meet the varying conditions of load. This, where practicable, is simpler, much cheaper, and more efficient than the storage of energy by means of secondary batteries.

(3) Variable-speed motors would, in any event, be limited to the driving of sawing- and dressing-machinery. It would be desirable in many cases to vary the speed of these machines, to adapt them to different degrees of hardness in the material operated upon; but

a difficulty of application arises from the fact that the machines individually require too small a power to justify a separate motor for each, and with group-driving, the difficulty would be to adjust the speed to suit the several machines constituting the group.

(4) The feature of high initial torque, which characterizes the series-wound motor and gives the power to accelerate loads quickly, is held by many to fulfil the principal requirement of winding and haulage so completely that no other type of motor can hope to compete with it. For winding from a deep vertical shaft, such as an ordinary colliery-shaft, where the attainment of maximum speed in minimum time is the object aimed at, this view is probably correct; but in slate-mines vertical shafts are practically unknown, and haulage on inclined planes, following the dip of the slate-beds, is the usual condition encountered.

Very high speeds are not advantageous; about 750 feet per minute marks the practical limit. At this, and lower speeds, the power required to accelerate the load is not very considerable; and though the high initial torque, which is characteristic of this type of motor, is advantageous so far as it meets the requirements of acceleration, it is generally so much in excess of these requirements that it has to be considerably reduced rheostatically, in order to start the loads without throwing them off the rails.

The conditions that suit the peculiarities of the series-wound motor are also that heavy loads are wound at a low speed, and light loads at a high speed. If these conditions are not fulfilled, rheostatic control again becomes essential. In slate-mines it is the character of the load and not its weight which limits the speed at which it can be drawn up. Blocks of slate intended for the dressing-mills, and constituting a fair proportion of the total traffic, are frequently of awkward shapes and difficult to balance on the trollies. With the displacement of the centre of gravity due to the trollies coming on to an incline, this difficulty becomes accentuated.

As therefore, both at starting and in the subsequent winding, the successful operation of the motor depends upon the entire current (armature and field) working it being controlled rheostatically, the efficiency is necessarily considerably reduced; and the Author, while recognizing the advantages of this type of motor for winding-gears generally, does not by any means regard it as a *sine quâ non* under the particular conditions which exist in slate-mines. On the other hand, for traction along the tramways, on the galleries, and in the levels of slate-mines, series-wound continuous-current motors, arranged so that they can be run alternatively in series or in parallel, are superior to any other type, as is proved by their almost universal adoption in street-tramway work, where the conditions are similar.

(5) A single overhead conductor, with rail return, affords the maximum of simplicity combined with economy in the transmission of power to the motors of a locomotive.

(6) The advantage of a power-factor of unity, and therefore no disparity between apparent and real watts, and the effect of this on the general efficiency of the system, is undoubtedly an important point to be taken account of; but it is only one factor out of many, and exaggerated importance must not be attached to it.

Alternating Current.—In comparison with continuous current, a point which stands out conspicuously is, that the voltages of generation, transmission, and distribution can each be determined independently of the other, and therefore that best suited to the circumstances can be adopted in each case. This is rendered possible by the use of the static transformer, which can be used to step up, or step down, the voltage as required, either at the generating or at the distributing end of the transmission-line.

Between single-phase and polyphase systems, as applied to slate-mining, the predominance of the motor element as compared with the lighting, practically determines the question in favour of the latter. Polyphase motors are superior to single-phase in every point upon which a comparison can be made—cost, starting-torque, efficiency, power-factor, overload-capacity, and weight in relation to power. On the other hand, the current required for lighting, being taken from a single phase, or between phases, necessitates some care in arranging the circuits, so as to distribute the load equally between the various phases, and avoid throwing the system out of balance, if a polyphase system be adopted.

Polyphase systems are practically restricted to two-phase and three-phase. Two-phase has the advantage, when it replaces continuous current or single-phase alternating current, of enabling existing conductors which have been laid in pairs, to be utilized, and is for this reason frequently adopted for converted systems; but for an entirely new plant it has no advantage which is not possessed by three-phase, and is in some important respects inferior to it.

The advantage obtained by the three-phase relation as regards transmission is a factor of prime importance. The algebraic sum of the currents in the three-phases being always zero, the ends of the various phase-windings in the generators and motors may be connected together; a single conductor thus sufficing for each phase and no returns being necessary. For the three-phase system, star connected, the transmission-losses are only one-fourth as great as in a continuous-current system; the basis of comparison being the virtual voltage between line and neutral in the case of three-phase, and the voltage between lead and return in the case of continuous current, the weight of copper being the same in both cases. In view, therefore, of the superiority of the three-phase system, the Author will confine his remarks chiefly to it.

The choice of periodicities in connection with slate-mining is practically confined to 25, 40, and 50 cycles. The principal considerations affecting this choice are the following:—

(1) For a given number of poles in the stators of the motors, the speed varies directly as the periodicity, therefore a low periodicity is suited to low-speed motors, which are most commonly required in slate-mining.

(2) The characteristics of motors in general, and their power-factor in particular, are better at low than at high periodicities.

(3) A low periodicity facilitates the parallel running of generators (where required) and a smaller fly-wheel effect is necessary than at higher periodicities, as the permissible value of the cyclic irregularity of the prime movers is greater. This is chiefly applicable to cases where the generators are engine-driven, as the cyclic irregularity with turbine driving is almost negligible.

(4) A low periodicity is essential to the working of rotary converters. At 25 cycles the performance of these machines is quite satisfactory, at 40 cycles it is practicable, but above 40 cycles the use of a motor-generator, which is less efficient, becomes a necessity. Generally speaking, however, this is not of much importance, as it only affects the question so far as it may be necessary to transform three-phase to continuous current; moreover the adoption of rotary converters frequently necessitates the use of special transformers, to obtain the correct ratio between the voltages on the alternating- and continuous-current sides of the machines.

(5) High periodicities give a correspondingly larger range of available speeds for motors than lower ones.

(6) High periodicities are more favourable for lighting than lower ones. Arc-lighting is impossible, and incandescent lighting is indifferent, at 25 cycles; but both are available and fairly satisfactory at 40 or 50 cycles.

(7) Static transformers are considerably less bulky and expensive at high than at low periodicities.

In the Author's opinion the periodicity best suited to slate-mining is 40 cycles, but 50 cycles is only slightly inferior, and the standardization of the latter figure will probably render its adoption advisable in the majority of cases.

The revolving-armature and inductor types of alternator are now practically obsolete, the latest practice involving the use of the stationary-armature revolving-field type. The enormous advantage of taking the current from the stationary element in the machine, instead of the rotating element requiring the use of collecting devices, the other good electrical characteristics, and the excellent mechanical construction possible, have been, no doubt, the principal factors in popularizing this type.

As there is not the least difficulty in building generators of this kind for voltages up to 11,000 volts (this being now standard), which is ample for efficient transmission to any distance within the slate-districts, only step-down transformers are required in any case; but in the event of its being possible to generate electricity, say within $\frac{1}{2}$ or $\frac{3}{4}$ mile of the point of application, it will be better to dispense with transformers altogether, and to generate at the distribution voltage.

Whether the source of power be water or steam, direct driving should be adopted, if at all possible. Where a steam-engine supplies the motive power, the generator, when directly driven, is necessarily of low speed, and therefore a bulky and expensive machine in proportion to its output, the speed being limited by what the engine is capable of running at. With water-turbine driving, however, the only limit to the speed of the generator is that imposed by the ultimate mechanical strength of the rotating-field system; and this being high, a very compact, cheap, and efficient machine is possible. The performance of such a machine is, in fact, superior to that of a larger and more expensive one, by reason of the better fly-wheel effect obtained at the higher speed.

Mounting the exciter upon the alternator-shaft has the merit of making a neat and compact combination, but it has the disadvantage of accentuating the effect upon the voltage of variations of speed; for an increase or decrease of speed involves not only the direct rise or fall of voltage corresponding with it, but also that due to the variations in the voltage of the exciter reacting on the alternator-field. On the whole, therefore, especially where lighting is an element, it is better to drive the exciter separately.

Above all things, mining-plant, including electrical, must possess, to the fullest possible extent, the qualities of reliability, first-class mechanical construction, and simplicity of operation.

As regards motors, in the Author's opinion these conditions are fulfilled by the three-phase induction type to a greater extent than by any other.

As compared with continuous-current motors, the application of the current to the stationary, instead of the rotating element, and the consequent elimination of commutators and brushes with their attendant troubles and maintenance, is a point in their favour of very considerable importance.

While induction motors may be broadly divided into two classes—those with wound rotors and those with short-circuited rotors—the further subdivision of which these classes are capable, renders available many varieties of motor, each possessing characteristics which render it suitable, or otherwise, for the varying service required in slate-mining, so that some care has to be exercised in the selection of the right type in each case. The consideration of these will therefore be taken in connection with the nature of the work they have to perform.

Without re-designing the whole of the existing sawing- and dressing-machinery, the units are too small, and their speed is too low, to render separate driving of each machine advisable. On the other hand, where, as in some cases, as many as one hundred machines are contained in a mill, driving by a single large motor, and transmitting the power by long lines of heavy shafting, is equally inadvisable.

In addition to the question of efficiency of driving the machinery, and really of much greater importance, are the questions of economy of men's time and facility of operation. From many causes temporary stoppages of the machinery become necessary, and while the necessity for such a stoppage may arise from a single machine, a stoppage of the whole mill is involved if it is driven by a single large motor. Moreover, the stopping and starting are beyond local control. The best arrangement therefore appears to be the driving of groups, consisting of eight to twelve machines, by separate motors, locally controlled.

Undoubtedly the most mechanical, reliable, and simple type of motor is the one with a squirrel-cage rotor. When constructed for the highest efficiency and power-factor, it is, however, lacking in starting-torque, and takes a heavy starting-current, unless an external device, such as a resistance or an auto-transformer, is used to reduce it, which again further reduces the already low starting-torque. If, however, group-driving be adopted and comparatively small motors be used, it is possible to arrive at a satisfactory compromise by slightly sacrificing efficiency and power-factor, and thus obtain the requisite starting-torque, as also sufficient reduction in starting-current to render the motor independent of any starting-device, beyond a simple switch which can be operated by any inexperienced person.

While this is the simplest and most reliable arrangement, a very good alternative is a motor with wound rotor, and internal starting-resistance, which cuts out automatically as the machine runs up to speed. This is easy to work, and high power-factor, efficiency, and starting-torque are obtainable; but in mechanical strength and simplicity, as well as in first cost, it is inferior to the squirrel-cage type.

For winding up inclined planes, where relatively large motors are employed, and frequent starting, stopping, and speed-control are necessary, it is essential to use wound rotors in conjunction with controllers and outside resistances.

The use of wound rotors (in conjunction with the auxiliary devices referred to) enables the motors to be controlled through their secondary elements, which has the advantage, over control through the primary element, of involving no sacrifice of power-factor, and of rendering available the maximum torque the machine is capable of exerting for starting, and also over the whole range of speeds.

In considering the suitability of a three-phase induction motor for winding, the conditions almost universally prevailing in slate-mines must be borne in mind:—

(*a*) The trucks are being drawn up inclined planes.

(*b*) Several trucks are generally being drawn up simultaneously, and on different roads.

(*c*) The traffic is a mixed one, consisting of rubbish and blocks of slate for the mills.

(*d*) Different speeds of winding are not possible for the two classes of traffic without complicating the winding-arrangements, and therefore a speed suitable to both must be adopted.

(*e*) The speed of winding is fixed by the character and not by the weight of the load or loads to be lifted.

(*f*) Whether one load is being lifted or two or more loads simultaneously, the speed should remain the same.

As the variation of speed with load of a large three-phase induction motor will not exceed 3 to 4 per cent., within its normal working-range, the conditions as to speed required for winding are admirably fulfilled, without involving any rheostatic losses, such as would be involved in similar speed-regulation of a series-wound continuous-current motor.

In all other respects, such as starting-torque, rapid acceleration of load and speed-control, a three-phase motor may be made to fulfil all practical requirements.

The efficiency of the rotor being inversely proportional to slip, that of the whole machine is certainly low, while its speed is materially below the normal; but as in a properly-designed plant, the time during which the motor will be running below its normal speed will be but a small portion of the total, the overall efficiency will compare very favourably with, and probably be superior to, that of any other type of motor it is possible to instal.

For driving reciprocating-pumps it is certainly necessary to use a type of motor which admits of using resistance in the rotor-circuit, in order to obtain the requisite initial torque for starting and accelerating the column of water; but for pumps of the centrifugal type, the multi-stage variety of which, directly coupled, is admirably suited for slate-mining, the short-circuited, or squirrel-cage type, may be used, the starting-current being kept down by an auto-transformer. The difference is that in the latter case no movement takes place in the column of water until the motor is nearly up to speed, and hence the motor practically starts light.

For driving fans, winches, etc., the most suitable type will depend upon the size, starting-torque required, frequency of operation, and cost of current, and will be governed by the same principles as the particular cases already considered.

The methods of starting, either by simple switch, auto-transformer or resistance in the rotor-circuit, or otherwise, for all motors throughout the system, will also be influenced by the importance or otherwise of a high power-factor, and of uniformity of power-factor. The first two methods are inferior to the third in these respects, but render possible a more desirable type of motor.

A low power-factor is disadvantageous, as it involves the partial loading of the plant with wattless current; but as the total losses due to this in any well-designed three-phase system, as regards the generating, transmitting, and transforming apparatus, will not usually exceed 2 per cent., the losses due to the method of starting, being only a small fraction of this, will not be of great importance.

A variable power-factor is disadvantageous, as it renders good voltage-regulation difficult. The lag or lead of the armature-current has a far greater effect on the voltage of the generator than that due to ohmic resistance; and as the power-factor of the current taken at starting by induction motors (when a resistance in the rotor circuit is not used) is usually 0·15 to 0·3, as against, say, 0·85 for ordinary loads, an element of variability is introduced which is not easy to correct. This, however, only affects the question to any practical extent as regards lighting, and a high standard in this respect is not so essential for mines as for town lighting.

Summary of Advantages of Three-Phase System.—The advantages of three-phase current, as applied to slate-mining, may be summarized as follows:—

1. The voltages of generation, transmission, and distribution can be separately determined, so as to give the best results obtainable in each case.

2. Higher efficiency of transmission than with any other system.

3. Higher efficiency of the generators, when turbine-driven at high speed.

4. Substantial mechanical construction in generators and motors and consequent immunity from breakdown.

5. Collection of current from, and its application to, the stationary element in generators and motors respectively.

6. Absence of commutators and brushes, which are the most delicate and troublesome elements in continuous-current machines.

7. Simplicity of operation, especially where the power is distributed in small units by squirrel-cage motors.

8. Suitability of motors for the various classes of work requiring to be performed (including winding).

The foregoing are, in the Author's opinion, of such weight when taken collectively that the superiority of the three-phase over any other system is clearly established.

Where long-distance transmission is an element in the question, material advantages are obtained; but the superiority of the three-phase system is not limited to this condition, its reliability and simplicity rendering its adoption preferable for slate-mining work under all conditions.

The Author intends these remarks to apply to the system generally, and does not exclude the use of continuous current for such a special purpose as traction.

In accordance with the conclusions enunciated above, the Author adopted the three-phase system in his power-scheme; and as it is the first, and at the date of this Paper was the only three-phase plant installed and working in a slate-mine in the United Kingdom, a brief description of it may prove of interest.

Electrical Installation at the Croesor Quarries.

The 375-HP. impulse-wheel, referred to earlier in this Paper, is direct-coupled to a 250-kilowatt three-phase alternator; and the smaller impulse-wheel is applied to driving two small continuous-current generators, also directly coupled. The alternator runs at 600 revolutions per minute, and is of the revolving-field, stationary-armature type. Mounted on a single bed-plate of cast-iron, the wheel and alternator make a very compact and effective combination. Similar remarks apply to the smaller set.

Either of the continuous-current generators may be used for excitation, the one not in use for the purpose being employed to light and heat the Author's house, which is about 1 mile distant.

Both alternator- and exciter-sets have heavy steel fly-wheels mounted on their shafts, with the object of securing good speed-regulation.

The alternator is wound for 2,750 volts between phases, and, being star-connected, this corresponds to 1,587 volts per phase. The adoption of 2,750 volts as the voltage between the phases was influenced partly by the desire to keep within the limits of high tension as defined by the Government Regulations. The voltage is automatically regulated by means of a Thury regulator.

The periodicity of the system is 40 cycles per second, the lower speed of the motors thus obtained, as compared with that of 50 cycles, enabling single reduction-gear to be used, instead of double, for the major part of the applications required, the results being gains in efficiency, compactness, and cost.

The transmission-line consists of overhead wires for a distance of 3,200 feet, at which point it branches, one part being continued as an overhead line to the mills, and the other part, consisting of a three-core cable 1,500 feet long, going underground.

At the respective ends of the lines, in the mills and underground, oil-cooled three-phase transformers reduce the voltage to 220 volts between phases for local distribution.

The mill-machinery has been divided into groups consisting generally of eight machines, but in some cases more, each group being driven by a separate 10-HP. motor. These motors are of the squirrel-cage type, designed for an initial torque $1\frac{1}{2}$ times the normal. They are started against load by a simple switch, and it is interesting to note that, notwithstanding the comparatively large size of the motors, not the slightest objectionable feature has ever manifested itself as a result of this method of starting.

The mills are also lighted electrically by two hundred and forty 32-candle-power glow-lamps, connected between the phases.

Underground, a 90-HP. motor, combined with a reversing controller and resistance, is used for winding on an incline. It is capable of dealing with a load of 5 tons, and for a single gallery the complete operation occupies about 20 seconds.

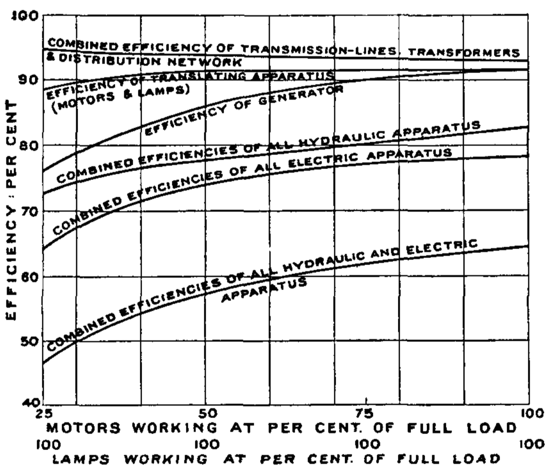
A two-stage centrifugal pump, directly driven by a 35-HP. motor, deals effectively with the mine-water.

A motor-generator produces continuous current for working an electric locomotive, which is, the Author believes, the first one electrically driven applied to mining in this country. It has two series-wound continuous-current motors of 15 HP. each, arranged to work in series or in parallel, and give normally speeds of 4 miles and 8 miles per hour respectively, when hauling a train of 30 tons. Other speeds are available by rheostatic control. In facility of working this locomotive leaves nothing to be desired.

Electrically-driven winches have partially replaced the old hand-operated tripod cranes, and have proved eminently satisfactory.

The main underground level, shunting-siding, main incline, and the approaches thereto, have been lighted by glow-lamps, and arc-lighting, applied experimentally to one of the underground

Fig. 12.



EFFICIENCIES OF HYDRO-ELECTRIC PLANT.

chambers, has given such satisfactory results that its extension to other chambers is contemplated.

Fig. 12 shows graphically the various efficiencies of the system, from which it appears that when the motors are working fully loaded, it is possible to obtain at the mine, in the form of mechanical energy at the motor-shafts (or its equivalent at the lamp-terminals) 64·43 per cent. of the potential energy of the water in the reservoir $1\frac{1}{2}$ to 2 miles distant; and that even at half-load on the motors (a very exceptional condition) the figure is still high, being 61·75 per cent.

The whole plant has been in operation upwards of 2 years; no hitch of any kind has occurred, and the working has been completely successful.

The Author craves indulgence for the introduction of certain matter which is common knowledge to electrical experts, but this Paper has been written for the purpose of considering the question from the point of view of the mining and quarrying, rather than that of the electrical expert; and moreover the statement of some elementary facts has been essential to the full exposition of the Author's views.

The Paper is accompanied by eight drawings from which the Figures in the text have been prepared.