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SIR BENJAMIN BAKER, K.C.M.G., LL.D., F.R.S., President,
in the Chair.

(Paper No. 2882.)

“The Manufacture of Aluminium by Electrolysis: and the
Plant at Niagara for its Extraction.”¹

By ALFRED EPHRAIM HUNT, M. Inst. C.E.

THE Niagara River flows as a comparatively quiet stream from the outlet of Lake Erie at Buffalo to within about 1 mile of Niagara Falls. From this point there is a rapid descent of 56 feet to the brink of the Falls, where the water, with an average depth of about 20 feet at the crest of the Horse-shoe Falls, suddenly descends a distance of 160 feet into the gorge below. Upon the plateau above the Falls and opposite to navigable water just above the rapids, on the site of the old French Fort Schlosser, are situated the new works of the Pittsburgh Reduction Company, engaged in the production of aluminium. Part of the energy in the stream flowing past the works is now conducted from the turbines of the Niagara Falls Power Company, situated half a mile further down the stream, back along the river bank in the form of electric energy, and expended in the work of electrolysis of the refractory oxide, alumina, which is the substance here used as an ore for the production of aluminium.

ALUMINA.

The pure sesqui-oxide, alumina (Al_2O_3), containing 52·95 per cent. of aluminium, is the best compound of aluminium for use

¹ Owing to the curtailment of the last Session the reading of this communication, which was received in February, 1895, was postponed until the above date; and in the interval descriptions of the Niagara Power Works, which form the subject of a part of the Paper, have appeared elsewhere.

in reduction to the metallic state; not only on account of the character of the by-product, oxygen, and the ease with which this by-product can be eliminated, but also on account of its comparative cheapness, and the facility with which a high degree of purity can be attained in its manufacture on a commercial scale. This can be accomplished by processes that are strictly chemical in character, and which lie, therefore, beyond the scope of this Paper. It has, however, been found that it is necessary to only use alumina that has been so purified, for the hard crystalline anhydrous oxides of aluminium, corundum and emery are too difficult to mine, and are too valuable as abrasive agents to make their use as ores of aluminium practicable; while the rarer ones, such as the ruby and sapphire, are, of course, quite out of the question. The monohydrate of alumina, diaspore, is a hard crystalline mineral which, although a pure oxide of the metal, has not yet been found in sufficient quantities to give it much importance as an ore. It consists of 85 per cent. of alumina with 15 per cent. of water of hydration.

The high heat of formation, and the extreme infusibility of alumina are not much more serious obstacles to its use than those which would be encountered in an attempt to utilize the haloid salts of the metal; and the use of the former body possesses the advantage of permitting continuity in the operation of reduction, which is not found to be possible when the double salts of aluminium with the alkalis or other metals are used, on account of the residual mass that then collects in the pot, and the operations, if conducted on a commercial scale, soon stop from clogging. The halogen salts and the sulphide have, so far, seemed to be the only compounds of aluminium other than the oxide ever likely to be used successfully, and all these substances are more expensive and generally less advantageous. The lower monoxide of aluminium (AlO), containing 63·22 per cent. aluminium, is not a very stable compound; when heated it oxidises to alumina, and practically would be used as alumina in metallurgical operations. The more complex rock minerals, such as felspar or mica, although the most common and abundant sources of the metal, are comparatively poor as ores of aluminium; and, on account of the cost of extraction of the pure salts, are (at least, at present) entirely out of the category of practicable materials.

Alumina is prepared from one or the other of the minerals bauxite, cryolite, native sulphate of alumina alum shales, or from the clays, of which some particulars are given in the Appendix.

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EXTRACTION OF ALUMINIUM FROM ITS COMPOUNDS.

Aluminium is one of the few metals whose oxide is not decomposed by intimate contact with hot solid carbon at the temperature of the regenerative furnace, or below what may be attained in the electric arc. The oxidation, moreover, of an equivalent of carbon does not furnish nearly the amount of energy required to reduce an equivalent of aluminium. The more important chemical laws bearing on the case are these:—A substance will usually only chemically displace another if it evolves more energy in its new combination than is absorbed by the necessary decompositions; also substances which evolve the greatest heat when they enter into combination are difficult to decompose, and absorb the greatest amount of heat when they are broken up—they possess what is termed by chemists, a high “heat of formation.”

Aluminium stands high in the list of metals for its power of evolving heat when entering into combination with the metalloids and with acids, being only exceeded in this respect by caesium, rubidium, potassium, sodium and lithium; and, owing to other circumstances, to be considered later, aluminium is more difficult to reduce in a pure state on a commercial scale than most of the metals. If carbon could have its affinity for oxygen sufficiently increased, or if for two atoms of carbon there could be substituted one with double the reducing power, the reduction of aluminium by its agency would be made easy. Something corresponding with this is, indeed, done in the electrolytic method of reduction, by increasing the electromotive force between the electrodes sufficiently to break up the molecules of alumina; and when the device was adopted of dissolving the ore in a flux which had not a high-melting point and was sufficiently stable, the way was opened for the reduction of many metallic compounds which had previously proved refractory. If, in the future, a lower oxide or a less stable compound of aluminium can be obtained, the probability is that such ore will be equally adapted to its final reduction by electrolysis in a state of solution in a flux, as by the Hall process. The reduction of aluminium from its salts by hot solid carbon, or any other cheap reducing agent, is not only an expensive process, but the metal is difficult to obtain pure; for the reason that any re-agents or set of conditions which will cause its reduction, are sure also to cause that of any other metals whose salts may be present—thus requiring, in most operations that could be devised for the purpose, the employment of not only a pure salt of aluminium to be used

as an ore, but also that of pure reducing agents. To add to this difficulty in the production of pure aluminium, if the reduced metal is heated much above its melting point (627°C.), it develops the troublesome property of occluding the gases with which it may be in contact, thus rendering the product porous, weak, and unsound in structure.

Owing to its lightness, it is difficult in many operations to ensure the separation of aluminium from the by-products the specific gravity of which is nearly the same as its own. This trouble has been encountered when attempts have been made to electrolyze aluminium compounds in electrolytes that have about the same specific gravity as the metal, as well as in the chemical reduction of alumina by means of metallic magnesium. In this latter connection it may be mentioned that an interesting new compound of alumina (the monoxide AlO) is produced, besides some finely divided aluminium, when alumina is heated with magnesium. The properties of this easily oxidizable brownish-black monoxide of aluminium have not yet been established, but when this is done, a cheaper method for the manufacture of the metal may possibly be devised.

A well-known fact in connection with the production of aluminium may here be noted, viz., that potassium will reduce the halogen compounds of all of the metals, even of those whose oxides cannot be reduced by either carbon or hydrogen. The cheaper production of the electro-positive metals, potassium, sodium, aluminium and magnesium will in the future undoubtedly lead to their more extensive use as reducing agents; and magnesium is being now successfully made from the mineral carnallite. The high heats of formation and the stability of its oxides and chlorides render the action of magnesium upon the oxide and chlorides of other metals particularly promising as a reducing agent.

The difficulties found in the electrolytic separation of aluminium not only include those due to the necessity for fluidity and conductivity in the mass to be electrolysed, but also those due to the infusible character of all of the practicable salts of aluminium. This especially is the case with the oxide, alumina, and with the fluoride; and not only so, but, as is the case of aqueous solutions of aluminium salts, they are more difficult of decomposition than their solvents. Some fused salts, and even some compound liquids, at ordinary temperatures, are for all practical purposes non-conductors and will scarcely permit the passage of an electric current; many others have so high a resistance as to occasion an altogether

prohibitive loss of energy in overcoming it. The French chemist, St. Claire Deville, suggested the electrolysis of aluminium chloride (Al_2Cl_6); but this salt, when in a heated or molten condition, is, for practical purposes, hardly a conductor of electricity at all. Voltaic action resulting from chemical union (the exact opposite of electrolysis, which occasions dissociation) must of course also be reduced to such proportions as not materially to impede the reduction of the metal. This is a condition difficult of attainment in some processes, for voltaic action is sure to be produced, in many suggested methods, by the substances set free at the electrodes. No considerable quantities of corrosive gases should be evolved by the process, or great expense will be occasioned by the need of frequent repairs to the apparatus; and it is costly to conduct away such gases and to replace the salts whose acids would have been wasted; the gases occasion moreover very serious annoyance. In electrolytic operations where such corrosive gases are formed, the further difficulty of securing a good and insoluble anode has so far proved an insurmountable obstacle to successful operations.

The use of alumina as the ore not only has the advantages which have been enumerated as necessary, but the special advantage that oxygen only is evolved. This gas is liberated in presence of the carbon anode and under the requisite conditions to produce carbonic acid, which is a comparatively harmless waste product that may be allowed to escape into the air of the apartment in which the operation is being conducted.

The necessity of continuity of operations, especially in an electrolytic process, has already been referred to. Any process that "clogs up" or requires frequent stoppages, cannot, in the nature of the case, be very successful for the manufacture of aluminium. Indeed, the difficulties, as will be seen in the discussion of the Hall process, are so varied and great, that the ores and reagents which have been so far used successfully in the electrolytic separation of the metal are limited to combinations of a very few halogen salts of aluminium, together with similar salts of some of the metals more electro-positive than aluminium.

MANUFACTURE OF ALUMINIUM BY THE HALL PROCESS.

The Hall process may be described as being the electrolysis of alumina dissolved in a molten bath of the fluoride of aluminium and the fluoride of one or more metals more electro-positive than aluminium, generally sodium or potassium, and calcium. A large continuous electric current is passed through the molten mass

with a small difference of potential, and the deposition of aluminium in a molten condition is thereby brought about. Pure alumina is dissolved in the proportion of about one-third of the weight of the solvent, and is decomposed under the electrolytic action of the current into its elements, aluminium and oxygen, the solvent itself remaining unchanged; the bath is maintained in a constant condition by frequent additions of fresh supplies of alumina. The solvents preferably used are either a mixture of the fluorides of aluminium, sodium and calcium, produced artificially or from the minerals cryolite and fluorspar, or a mixture of the fluorides of aluminium, potassium and calcium, produced by chemical action of hydrofluoric acid upon the compounds of potassium and aluminium, pearl ash and alumina being the salts preferably used, together with a portion of the mineral fluorspar.

The process is carried on in carbon-lined iron pots, *Fig. 1*, placed in series; the pots, with their carbon linings, as well as the reduced metal lying in them, serve to form the negative electrodes or cathodes; and, in the process as usually carried out, the anodes are

of carbon, and dip into the bath. Some of these latter are connected by round copper rods and screw clamps with the omnibus bar of the positive ends of the circuit. The negative connections are made by heavy copper bars, riveted to the iron pots, and are in circuit with the positive poles of the next pot; the current going thus in series from one pot to the other back to the negative side of the dynamo. The carbon anodes are lowered in the bath from time to time as they burn away at their lower ends where the oxygen is liberated from the alumina.

The main electrical circuit is formed of heavy copper bars, which are supported upon insulated slate supports above the

ground. The area, A , of these conductors is determined by the formula

$$A = \frac{C \times N \times D}{E \times V}$$

where C is a constant, and

A = the area of conductor in square inches,

N = the electrical horse-power to be delivered,

D = the length of the transmission line in feet,

E = the electromotive force at the delivery end of the line, and

V = the loss of pressure in volts on the line due to its resistance;

with 10 per cent. added as a factor of safety. The oxygen separated by the electrolytic action attacks the carbon anodes, uniting with them and forming carbon monoxide; the reduced aluminium sinks through the electrolyte, because of its greater specific gravity, and going to the bottom of the pot remains in a molten condition. The fluoride solvent salts are not decomposed by the current, but remain practically unchanged; the small losses being those occasioned by volatilization and by solidification in the form of "cake" at the bottom of the pots. The materials employed in the process are the alumina and the carbon anodes. These latter are used up in a proportion of a little less than 1 lb. of carbon to 1 lb. of aluminium produced. A small quantity of chemical stores is also needed, at a cost of a fraction of 1*d.* per pound of aluminium produced. The pots, with their linings, last for months of continuous work, the carbon linings of the pots not being worn away appreciably. The only other items of cost for the manufacture of the metal, besides general charges, are those of labour and for the electric current.

The electrolytic process for the separation of aluminium is the only metallurgical operation known to the Author for the reduction of a metal from its ore upon a large commercial scale without any loss of metal. The operation is as complete as an assay, every portion of the aluminium added in the form of its oxide being reduced and obtained in ingot form from the reducing pots. There is no volatilization of metal and no loss in the form of slags or other by-products when the process is being properly conducted. The theoretical quantity of carbon anodes necessary for the decomposition of alumina is $\frac{2}{3}$ lb. of carbon to 1 lb. of aluminium produced, according to the equation

The carbon monoxide, when it comes in contact with air, burns to carbon dioxide.

When the amount of alumina in solution in the bath becomes deficient, the electrical resistance is greatly increased; and as the current is kept nearly constant by the dynamos, the difference of potential at the bath rises. When a fresh supply of alumina is dissolved in the bath, the resistance and the voltage rapidly fall again to the normal value. Continuity of operation is one of the essential features in any process for the economical separation of aluminium by electrolysis. It will be safe to say that any process that may be devised for the purpose and that does not possess this feature cannot succeed in competition with one that has it.

The molten aluminium that collects at the bottom of the pots is dipped or siphoned out, as water would be removed from under a layer of oil, due precautions being taken to keep the superincumbent and molten electrolyte from being taken out with the metal. This work is done without interrupting the current passing through the bath. Since the temperature of the molten electrolyte is less than 982° C. it is well within that which a retaining vessel and anodes of metal are able to withstand. The process can therefore be carried on in thick cast-steel pots without carbon linings and with metal anodes. In this case the aluminium produced is somewhat impure, as it becomes alloyed with the iron or other metals with which it is brought into contact. The solvent portion of the electrolyte can be melted in an exterior crucible or furnace, and then poured into the reducing-pots, or it may be readily or conveniently melted in the reducing-pots by the heating action of the current when first commencing work.

It is a comparatively easy task to produce pure aluminium by the Hall process, on account of the few sources of contamination and the ease with which they may be controlled. The fluoride solvent salts are made from commercial products or from minerals; cryolite contains silica in the form of quartz and iron in the form of spathic iron ore, together with a little lead, zinc and copper. The other minerals used, as well as the carbon anodes, contain some silicon and iron in oxidized forms. But as all these metals are electro-negative to aluminium, they are the first to be reduced, and are all removed with the first metal produced in a fresh bath; so that after a couple of days' use, the bath is as good as if it had been made from chemically pure materials. The constant and more serious sources of impurities are the carbon anodes and the alumina, for both contain a small quantity of the oxides of silicon and iron. By care in the preparation of these materials, metal is regularly obtained with an average of 99 per cent. of aluminium; and some has been prepared by the Pittsburgh

Reduction Company with as much as 99·93 per cent. of the metal. The impurity in the metal obtained by the Hall process consists of silicon, partly in the graphitoidal or crystallized form, together with a little iron.

The size of the reducing-pots used in the Hall process varies with the scale of operations, a good rule being that 1 cubic foot of the solvent employed at these works will dissolve sufficient alumina for the production of 1 lb. of aluminium per hour. The number of solvents that can be successfully used is limited.

The requirements that have to be met by a suitable solvent are the following:

1. The solvent, with its considerable charge of dissolved ore, must be fluid at a comparatively low temperature, in order to obtain the necessary conductivity and to allow the reduced aluminium to sink through it to the molten bath below.
2. It must dissolve and keep in solution considerable amounts (at least 20 per cent.) of the ore, at the working temperature.
3. Its "heat of formation" must be such that it will not decompose more readily than the dissolved ore when submitted to electrolysis. This requirement effectually prohibits the use of any aqueous solvent, and practically involves the use of molten salts.
4. Its specific gravity, when molten, must be less than that of the reduced aluminium, both to prevent short-circuiting and also the oxidation of the metal, which would happen if the latter were allowed to come to the surface.
5. There must be no solid by-product to clog the pot and thereby prevent continuity of operation.
6. The molten solvent with its contained ore must be a good conductor of electricity.
7. It must not have any corroding action on the nascent aluminium produced.
8. It must be cheap and readily procurable in large quantities.

Both alumina and fluoride of aluminium alone are too infusible to meet the requirements; and it becomes necessary that the alumina, which is by far the best and cheapest ore of the metal, should be dissolved in fluoride of aluminium to which the fluorides of some of the more electro-positive metals have been added. The electromotive force necessary for the decomposition of alumina is found to be 2·8 volts, but for that of aluminium fluoride, sodium fluoride and calcium fluoride it is much greater, being in each case 4 volts or more. A greater difference of potential is,

however, necessary for conducting the operation on account of the resistance of the bath and of the connections.

The electro-chemical equivalent weight of aluminium is 9.0; that of hydrogen being 1.0, and copper 31.5. Theoretically there should be 0.33912 gram of aluminium produced per ampere-hour, or 0.7476 pound per 1,000 ampere-hours. With the same electric current, under similar conditions, this amount of deposition of aluminium to that of copper would be as 9.0 to 31.5. The theoretical amount of aluminium reduced by any given current is determined by multiplying its electro-chemical equivalent (9.0) by the weight of hydrogen separated by the same current in the same time (0.037296 gram of hydrogen being separated per ampere-hour), and thus the amount of energy required to reduce 1 lb. of aluminium from its oxide is about 5 HP. hours. In practice a very satisfactory approach in output to the theoretical figures is made when the current expended in heating to keep the electrolyte in a molten condition is taken into consideration.

The losses of electrical energy to which the Hall process is subject, beyond the amount actually required for the electrolysis of the alumina, may be apportioned as follows:

1. Energy converted into heat by the resistance of the conductors and the bath.
2. Energy lost in replacing the metal corroded at the kathode (very slight).
3. Loss by counter electromotive force at the surfaces of the electrodes. This loss, if the process is well conducted, is very small. Where hydrogen is added to the electrolytic operation, as has been proposed, the loss under this head is heavy, for hydrogen accumulating around the cathode causes excessive polarization.
4. Loss in transporting the aluminium to the kathode and the oxygen to the anode (very small). There is a good circulation, however, maintained in the electrolyte when the process is working satisfactorily.
5. Loss by secondary reactions between the electrolyte and the products of the electrolysis (small).
6. Losses by short-circuiting the current, so that it does not wholly traverse the electrolyte (small when skilful work is done; but by any process where the reduced aluminium is liable to come to the surface of the bath or to remain intermingled with it, such losses would be considerable).

Losses by leakage of the current through conductors to the ground are, on account of the low voltage of the current employed,

almost entirely prevented when the insulation and all the joints of the conductors are good.

THE PITTSBURGH REDUCTION COMPANY'S UPPER NIAGARA WORKS.

Subway and Conductors.—Owing to the works being only half-a-mile from the dynamos at Niagara, the electric energy used by the Pittsburgh Reduction Company is not raised in potential by means of step-up transformers, as is intended to be the case when transmitting from Niagara to Buffalo and other distant places; but the leads are directly connected to the dynamos. A stone bridge takes these leads over the intake canal of the power-house, and they pass on to the works of the company through a subway built of concrete, the crown of the arch of which is 3 feet below the surface of the ground in order to avoid any action from frost. This subway is $5\frac{1}{2}$ feet high and 3 feet 10 inches wide inside. The bottom of the subway is inclined and is of a curved shape to allow for the drainage of any condensed water. It is intended, however, that this subway should be kept perfectly dry if necessary by the

Fig. 2.

Full size.

continuous passage of warm dry air through it. The walls of the conduit are of Portland cement concrete 10 inches thick with a floor of masonry 1 foot thick. The sides, for a height of about 3 feet, are further protected by stonework 1 foot thick.

The conductors, *Fig. 2*, have an external diameter of $1\frac{1}{4}$ inch. Several cables are already laid temporarily on the wooden floor of the subway. Each cable consists of a large number of strands of pure copper wire, and is equi-

valent to a bar 0.975 inch in diameter. The cables will eventually be supported by brackets well insulated from the walls of the conduit and placed 10 feet to 30 feet apart. The walls of the conduits have apertures at convenient distances, so that the line can be readily tapped at intermediate stations. Manholes 400 feet apart are provided to this conduit from the surface of the ground.

The cables are insulated with rubber and covered with an outer coating of lead. They are made in lengths of 800 feet. When

working under the load for which they are designed, each will carry about 560 amperes. The section of the copper conductors is calculated upon a basis of a current density of 350 amperes per square inch. This density was decided upon, after comparing the cost of cables with the estimated value of power lost, which is estimated in the cables to the works of the company to be one-tenth of one per cent. The drop in potential along the cables will vary with the inductance of the circuit. The distance from the dynamos through the transforming-house of the Power Company to the stationary transformers of the Reduction Company is 2,703 feet. The current is alternating, with two separate circuits differing in phase by 90° , and a maximum difference of potential of 2,500 volts.

The Transformers.—Each set of transformers deals with 500 HP., and comprises two static transformers and one commutating machine. The 2,500-volt alternating currents are first conducted to the pair of stationary “step-down” transformers, by which the potential is reduced to 115 volts at the secondary terminals with a corresponding increase in the current. These transformers consist as usual of a laminated iron core, around which the primary (in this case the high-tension) and the secondary (low-tension) coils are so wound that the core carries the magnetic lines of force from the one set of coils through the other set, just as in the ordinary induction-coil. The primary wires comprise a large number of turns of fine wire, while the secondary coils consist of a smaller number of turns of coarser wire. These static transformers are formed into sections, and the laminated sheets of soft iron are so divided that spaces are left for air-blasts from below to pass up through them as well as through the perforations in the bed-plates of the machine, and thus assist in the dissipation of the considerable amount of the heat developed. The transformers are placed over a long pit, 8 feet wide and 3 feet deep, supplied with air at a pressure of $\frac{1}{2}$ oz. per square inch. The iron cores of the transformers are 27 inches by $39\frac{1}{2}$ inches by 53 inches, and each transformer occupies a floor space of 36 inches by $52\frac{3}{4}$ inches. The magnetic lines of force created by the current in the primary high-tension coils surrounding the iron cores are carried through the convolutions of the secondary coils; the rate at which these magnetic lines of force are cut by the secondary circuit, as compared to the rate in the primary one, determines the relative potentials in the two circuits, matters being so arranged that an electromotive force of 115 volts is produced in the low-tension secondary circuits.

Tests of these fixed transformers have shown that, in a room the temperature of which was 24°C ., and after a nine hours' run with the use of an air-blast supplying 1,040 cubic feet of air per minute, the temperature of the transformers was raised to a maximum of only 61°C .; while a similar test without the aid of the air-blast showed the transformers to be raised to a temperature of 92°C . By the aid of artificial means for cooling, a much greater capacity, as a transformer, per unit weight of apparatus employed is obtained. These machines have an efficiency of over 97 per cent. at full load, and are guaranteed to have a no greater rise in temperature than 40°C . above that of the surrounding atmosphere when working continuously.

Connection between the tunnel leads and the transformer-house is effected by lead-covered copper cables of 1 inch external diameter—the copper rods being each $\frac{1}{2}$ inch in diameter. The cables are divided into four groups, two for each side of the two-phase system employed. These conductors run through the pit beneath the transformers to switch-boards, where they are connected to the static transformers by double-throw switches. The low-potential side of the converters is connected by double-throw switches to 4-inch by $\frac{1}{2}$ -inch copper bars, which are bolted on to insulated slate slabs for support. These omnibus bars connect the transformers already described with the alternating side of the commutating machines, a switch-board for these bars being mounted beside each pair of transformers. The low-tension 115-volt alternating currents thus transformed in the stationary transformers are conducted to the collector side of the commutating machines, which are quarter-phase motor generators with twenty poles. They run at a speed of 150 turns per minute, and each machine produces a direct current of 2,500 amperes. The coils for the continuous current are wound on the same armatures as those for the alternating currents, the former being taken off by a number of brushes from the commutator. The diameter of the armatures is 90 inches, and the machines themselves are 11 feet 6 inches high, with circular field-magnet frames extending a little below the floor-line. Each rotary converter occupies a floor space of 13 feet 6 inches by 9 feet 10 inches.¹

The continuous-current circuit of each machine is connected by cables, with conductors of 1.225 inch equivalent diameter, to the switch-board, and thence to the pot-room of the Pittsburgh

¹ See also *Transactions of the American Institute of Electrical Engineers*, vol. xii. p. 603.

Reduction Company. The current is here measured by ampere-meters, and its potential by volt-meters; all the circuits being coupled in parallel before being conducted by large copper omnibus bars through the brick wall of the transformer-room to the adjacent "pot" or reduction-room. In order to economize space, the indicating instruments on the switch-board have their scales arranged in a vertical plane at right-angles to the switch-board instead of parallel to it, as is generally the case; and the contacts of the field regulators for the motor generators are arranged vertically on a pedestal and their adjustment is made by a rack and pinion. The ampere-meter itself is arranged as a shunt from the main circuit for the same reason.

Measurement of the Electric Energy.—The quantity of energy used by the Reduction Company in their work is capable of measurement in several different ways. First, at the power-house, the turbine can be used as an energy meter. Having once ascertained the discharge of the wheel and consequently the horse-power generated, at the different amounts of gate opening, under a known head, by measurement over a weir, a daily record of the gate openings and head of water acting on the wheel will give data from which the power transmitted to the dynamo is readily computed. The efficiency of the dynamos is known to be 97 per cent., the loss by conduction over the cables to the transforming machinery at the Company's works has been ascertained to be only $1\frac{1}{2}$ per cent., and the 2,500-volt alternating current is known to be subject to a loss of only 3 per cent. at each stage, or a total of less than 6 per cent. for each set of step-down and rotary transformers; it is therefore possible to know, approximately, the energy received at the Reduction Works, from the measurements made at the turbines. Secondly, the energy can be measured by the record of the volt-, ampere-, and watt-meters, which are so constructed as to continuously record the voltage and the current, and the product of these two quantities respectively. The Power Company will charge the Reduction Company on the basis of watts consumed per minute. Thirdly, one means of estimating the continuous current delivered, and the most satisfactory to the Pittsburgh Reduction Company, would be derived from the record of the actual weight of aluminium produced per month, for the weight of aluminium electrolytically produced per horse-power-hour will be well known. By this method the aluminium product from the works would in effect form an electro-chemical meter.

Continuity of Supply.—Notwithstanding its magnitude, the installation is one of comparatively simple machinery, and during

the six months that have elapsed since the works commenced to deliver energy the supply has been uninterrupted and satisfactory in every way.

THE NEW KENSINGTON WORKS OF THE PITTSBURGH REDUCTION COMPANY.

The Pittsburgh Reduction Company have another large plant for the manufacture of aluminium at New Kensington, on the banks of the Allegheny, near Pittsburgh, Pennsylvania. At these works the dynamos are driven by steam-engines, coal being the source of energy at some times, and natural gas at others. The best quality of Pittsburgh steam coal only costs, in the form of slack with less than 8 per cent. of ash, 2s. 8d. per ton delivered, and it is automatically handled and fed by mechanical stokers to the furnaces under the boilers. Pipes also connect the works with the gas mains from one of the largest natural gas districts of Western Pennsylvania, and which are within a distance of 10 miles. In the summer season there is an excess in the supply of gas over the general demand for it in the district, and it is then used as even a cheaper fuel than the coal.

At New Kensington the company are able to pump excellent water from the adjacent river, and as their engines are of one of the most approved high-speed compound types, with labour and general costs comparatively low, the large units of steam power at these works are probably produced under as favourable conditions as are to be found anywhere else in the world. As an instance of the low cost, it may be mentioned that their boiler repairs only cost about 2d. per HP. during the year 1894. The high-speed dynamos at these works are satisfactory in their working, and their repairs for the year 1894 only amounted to a rate of 6s. 3d. per E.H.P. The various items of cost of this installation are carefully watched and tabulated, and the records of the volt-meters and ammeters not only give a good measure of the electrical power generated, but the amount per month or year of aluminium produced under constant electrolytic conditions is also one of the best indicators of the average HP. expended, so that it is possible to obtain accurate knowledge of the amount of energy used and of its cost.

The competition, therefore, in the use of power from the two different sources at New Kensington and at Niagara Falls respectively will be very interesting, and the general public will be able to gain some idea as to the results, by noting "the survival of the fittest," so to speak, and observing where the

Pittsburgh Reduction Company may, in the future, choose to increase their plant to accommodate their rapidly growing business.

THE NIAGARA POWER WORKS.

The Falls of Niagara recede up the river at a varying rate as the water erodes, at the brink of the Falls, the soft shale, or the harder Niagara limestone, or the still harder slate rock of the district. The average yearly rate of recession of late years has been about 12 inches, and the works of the Niagara Falls Power Company have consequently been placed at a considerable distance above the Falls, so as to be unaffected by the probable changes in the cataract for many centuries. The water-power is obtained from a mill-pond formed by the chain of the five great lakes of America, the united area of which exceeds 90,000 square miles. These lakes have a drainage area more than twice as great as the combined area of Great Britain and Ireland, with a yearly rainfall of about 31 inches. The mill-dam is the great ridge of limestone that stretches across the country between Lakes Erie and Ontario. Over the top of this ridge, the Niagara River, with a flow of some 270,000 cubic feet of water per second, has in the past cut its way, and this large volume of water plunges over the Falls, a distance of 216 feet from the level of the still water above to that of the gorge below.

The Lake Survey Board, U.S. Engineer Corps, estimates the average flow to be about 270,000 cubic feet of water per second, which is approximately equivalent to over 1,000,000,000 lbs. per minute. Reckoning the available fall to be 161 feet, then the horse-power would be approximately about 5,000,000, equivalent to the energy of about 200,000 tons of coal per day, or, as is estimated, of about the daily output of fuel of the entire world. Assuming the flow of water over the Falls to be 16,200,000 cubic feet per minute and the capacity of the tunnel is intended to be 500,000 cubic feet per minute, it will be seen that only 3 per cent. of the water of the Niagara Falls is to be utilized by the Niagara Falls Power Company with their new plant. Major E. H. Ruffner, of the Corps of Engineers, U.S.A., in charge of the work of the new Chicago Drainage Canal, designed to turn a portion of the water of the Great Lakes along an old glacial outlet through the Chicago, Desplaines and Illinois rivers into the Mississippi river, and which will probably be completed in about three years, estimates that it will lower the level of the water in the lakes $\frac{1}{10}$ foot;

Fig. 3.

LONGITUDINAL SECTION OF WHEEL-PIT.

Fig. 4.

Scale
Feet 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 100

CROSS-SECTION OF WHEEL-PIT.

a very much larger amount of water will then be diverted from Niagara Falls than by the works now under consideration.

The Niagara Falls Power Company has obtained rights of way and powers to construct another tunnel, which will at least double, if not quadruple, the capacity of the one already driven. What is practically the same company, though under the name of the Canadian Niagara Falls Power Company, has obtained from the Dominion Government the right to construct a 250,000-H.P. tunnel on the Canadian side of the Falls, and is under agreement to utilize power there before January 1898. Although the amount of energy transmitted backwards up the stream at Niagara for the purpose described in this Paper is but a very small part of the vast supply available from the water flowing down the river at this point; yet, compared with the electric energy so far generated by dynamos, it is one of the largest supplies flowing through any single set of conductors in the world; and the electric generators that transform the power from the rotary shaft above the turbines are the largest yet built. Three of the dynamos are now placed over

the shafts from the turbine-pit, each being of 5,000 horse-power.¹ Ultimately, ten such dynamos are to be placed in one long pit cut through the solid rock down to the tunnel level, and forming the largest wheel-pit ever undertaken. So far it has been excavated for a length of 180 feet; it is 21 feet wide at the top and 16 feet wide at the bottom and 180 feet deep, and will be continued in a direction parallel to the intake canal until it has a total length of 414 feet.

The water is taken from the Niagara River by an inlet canal, commencing at a point about $1\frac{1}{4}$ mile above the "American Falls." The canal is 188 feet wide at the river end and 100 feet wide at its termination. It extends up stream from the river and the water backs into it under a floating boom, by which arrangement it is kept free from ice. The inlet canal will ultimately be about 1,500 feet long. It has a uniform depth of 17 feet, the water in it being 12 feet deep. Its present length is 1,260 feet. The sides of the canal are built of masonry, and are 7 feet thick at the base and 3 feet thick at the top, on which there is a coping 30 inches wide. The masonry of the upper portion of the turbine-pit is formed with apertures 17 feet deep and 14 feet wide, connecting it with the intake canal. Each aperture is controlled by gates and guarded by iron gratings, through which the water is admitted to the penstocks, each 7 feet 6 inches in diameter, and in this manner is conducted by vertical pipes to the turbines in the wheel-pit, *Figs. 3 and 4*, the fall to the turbines being 136 feet.

The Tunnel.—After the water has done its work at the turbines, it passes into a tunnel that serves as a tail-race for the 500,000 cubic feet of water which, it has been stated by the late chief engineer of the Cataract Construction Company, will flow through it per minute, when used to its full capacity.

Ground was first broken on the 4th of October, 1890; and the contract for constructing the first 6,700 feet of the tunnel was carried out by Messrs. Rogers and Clement of New York, the remainder by Mr. A. C. Douglass. The portal, where the water of the tunnel is discharged into the river, rests on a ledge of sandstone, 40 feet below the level of the river in the gorge, and the floor of the opening of the tunnel is 205 feet below the sill of the gate to the main canal. It is constructed in a very massive and solid manner of masonry. The lower half of the tunnel for a

¹ Work has now been commenced on the enlargement of the wheel-pit for the second installation of the three 5,000-HP. wheels, December 1895.

Fig. 5.

distance of 100 feet from its mouth is, moreover, lined with heavy steel plates.

The tunnel already executed, *Fig. 5*, falls into the Niagara River at a point a little below the carriage suspension bridge, and 1,150 feet below Prospect Point on the eastern side of the American Falls. Its total length will be about 9,500 feet. It has an average gradient of 36 feet to the mile, and it is expected that when in full service, the water will flow through it at a speed of 26 feet 6 inches per second. The portion of the tunnel near the wheel-pit has a gradient towards its mouth of 4 in 100, and in the portion nearer its outlet a gradient of 7 in 100. Its cross-section, *Figs. 6*, is of horse-shoe form, 21 feet high, 18 feet 10 inches wide at its widest part, and 14 feet 9 $\frac{1}{4}$ inches wide at the bottom. When

Figs. 6.

Scale, $\frac{1}{16}$ inch to 1 foot.

CROSS-SECTIONS OF THE TUNNEL.

the driving of this tunnel was commenced, it was hoped that the use of lining could be avoided, the first 1,200 feet of the excavation being through a comparatively hard rock with seams of slate; whilst the remainder of the work was through a compact shale, underlying the Niagara limestone at a depth of about 130 feet. But it was found that this material, although hard when first exposed to the air, disintegrated and slackened when weathered, and caused dangerous falls of large masses of partially decomposed rock. It was, therefore, necessary to line the 7,000 lineal feet of tunnel with four to six rings of brickwork laid in cement. More than 14,000,000 bricks and some 45,000 barrels of Portland cement were used for this work, which not only occasioned an extra expense of £100,000, but reduced the capacity of

the tunnel as a tail-race from the first estimate of 120,000 HP. to 100,000 HP.

Three shafts were sunk for the purpose of driving the tunnel; one at the lower end, one at 2,600 feet (No. 1), and one at 5,200 feet from that point (No. 2), leaving 1,700 feet to reach the wheel-pit; and since the larger portion of the work had to be done from the latter shaft, its equipment was the most complete. Headings were driven in both directions from Nos. 1 and 2 shafts; one from the turbine-pit and one from the lower end or portal. The headings were driven the full width of the tunnel and the remainder of the rock was removed in two benches, the "centre-cut" system being employed, with four to six rock-drills at each heading driven by compressed air at a pressure of 75 lbs. to 100 lbs. per square inch. The excavating machinery employed consisted of three 18-inch by 30-inch duplex air-compressors and twenty-five Little Giant rock-drills made by the Rand Drill Company. The exhaust of these drills served to provide satisfactory means for ventilation. The explosive used was dynamite. The average progress made was over 10 feet of finished tunnel per day during the twenty-three months occupied in driving and lining it; 166,577 cubic yards of material were taken out, sufficient to fill in and reclaim about 31 acres of ground on the river front, and 1,854,453 cubic feet of timber were used in the construction of the tunnel, shafts and turbine-pit. The alignment in the tunnel was in every way satisfactory throughout, although the clearance allowed between the timbers and brickwork was only 4 inches. This alignment was produced by the aid of two steel wires extending down the vertical shafts, with 30-lb. plumb-bobs attached, which were suspended in oil at the foot of the shafts.

The Niagara Falls Paper Company has been the first to utilize the new tunnel, having built a turbine-pit and erected three 1,100-HP. turbines. These wheels were constructed by Messrs. R. D. Wood & Co., of Philadelphia, and designed by Mr. E. Geyelin. They are of an inverted Jonval type, with vertical shafts. The water is admitted below the wheels, and thus the up-pressure counterbalances the weight of the 10-inch diameter shaft, 175 feet in length, with bevel gear. The wheels make 260 revolutions per minute, and the penstock supplying them is 13 feet 6 inches in diameter and is intended to supply one and possibly two more turbines. Two of those now in operation grind each from 18 to 20 tons of pulp every twenty-four hours. The third turbine drives the general machinery in the mill, such as pumps, rag machines, dynamos, &c. After twenty-five months' steady work

of twenty-four hours per day these turbines continue to perform their duties satisfactorily.

The Turbines.—The turbine principally used hitherto in the United States has been of the twin form, arranged with a horizontal axis projecting from the wheel-case in such a manner as to permit direct connection with other machinery, or the attachment of pulleys by which belts or ropes may be driven. These turbines have been used wherever large volumes of water were obtained with a comparatively small fall.

The form of water-wheel arranged for high falls, which finds most favour in the United States, is that known as the Pelton wheel. This has always been built with a horizontal axis. It was not, however, considered advisable to employ it at Niagara, where a Pelton wheel with a vertical axis, and provided with the large number of nozzles necessary for the development of 5,000 HP. at each shaft, was considered too great an innovation to be adopted with safety.

The great space required underground for belts or ropes, if either of those means for transmission of power from wheels with horizontal axes were adopted, and the expense and trouble of placing the dynamos in damp chambers entirely dependent on artificial means for illumination, were thought to offer such serious sources of difficulty, that it was decided to use vertical shafts which should transmit the power to the surface from turbines with vertical axes. The chief difficulty that then remained to be met was the construction of suitable bearings, or footsteps, by which to sustain the pressure due to the column of water, as well as the weight of the shaft and that of the revolving parts of the dynamo attached to it. Several methods were proposed by various designers who competed for the supply of the machinery. Some arranged for oil- and water-bearings distributed along the line of the shaft; others preferred hollow shafts, provided with an oil-bearing on the top of the supporting column, terminating near the top of the turbine (using the so-called "Fontaine step"); a water-piston bearing found favour in other quarters, while some designers suggested the use of two wheels, one larger in diameter than the other, and placed vertically over it, so that a resultant upward pressure of the wheel should neutralize the weight of the super-incumbent load.

The plan finally adopted, involving the use of several of these proposed features, is as follows:—Two Fourneyron turbine-wheels, each in three stories, are placed in the same vertical axis; one wheel is above, and the other below the guide-wheel casing, in which the elbow from the supply-pipe terminates. The upper

guide-wheel is perforated, so that the disk of the upper turbine-wheel forms the top of the chamber, and receives the pressure of the water on the whole of its under surface. The lower guide-wheel, on the contrary, is solid, and forms the floor of the casing through which the central shaft passes for the attachment of the lower turbine-wheel outside. The resultant downward pressure in the guide-wheel chamber is thus transferred to the foundation, while the upward component acts directly on the shaft and serves to relieve the bearings of its weight.

The constant pressure of the water in the penstock discharging between the twin turbine-wheels serves to support the entire superincumbent weight of the revolving parts of the apparatus, so that when the load is light the upward thrust of the water is 3,500 lbs. in excess of the weight on the shaft, and as the load increases to its maximum the resultant upward thrust disappears and becomes a downward pressure of 3,500 lbs. These varying pressures are taken up by thrust-blocks.

The speed of the turbines is controlled by a cylindrical casing surrounding each wheel, and capable of being moved up and down as occasion requires, forming a valve to throttle the discharge on the outside of the wheel. The wheels are stopped by closing the gates between the top of the water column and the intake canal. Each guide-wheel has thirty-six buckets, whereas the turbine-wheel has thirty-two, and the buckets are thicker in section at the centre. The turbine-wheel sections are in single castings, with both rims and buckets in one piece of bronze of the same quality as that usually adopted for the propeller-blades of steamships.

Each one of these turbines will discharge 430 cubic feet of water per second, and works under a head of 136 feet from the upper surface of the water to the central plane between the upper and lower wheels. They are designed to revolve at 250 revolutions per minute, and to then develop 5,000 horse-power with an efficiency of 75 per cent. These wheels were designed by Messrs. Faesch and Piccard, of Geneva, Switzerland, and were constructed by the I. P. Morris Company, of Philadelphia, Pennsylvania. The assemblage and erection of this machinery was carried out under the direction of Mr. De Courcy May. The first, or preliminary installation, as it is called, is of three of these turbines with their superimposed dynamos, of which two are now in successful operation.

The Vertical Shafts.—Each shaft is a steel tube, built of sections about 38 inches in external diameter, except at the three points

where it is received by the bearing. The journal is there made solid, and is 11 inches in diameter. The weight of the vertical shaft, 166 feet in length, with the portions of the dynamo that are attached to and revolve with it, is 152,000 lbs. A water-cooled thrust-bearing, to resist thrust in both vertical directions, is provided at the upper end of the main shaft to receive the resultant pressure along the shaft, which varies with the speed of the wheel, as well as to keep the apparatus in a fixed position in a vertical direction. When the wheels are running at full speed, a freer outlet is afforded the water. This leads to the slight diminution in the vertical component of the pressure on the upper turbine-wheel as already noticed. The thrust-bearing at the turbines consists of a series of steel rings on the main shaft, fitting into corresponding grooves in a babbit metal collar, secured to the framework of the foundation.

The Power-House.—The power-house is built of Queenston limestone, is 195 feet long, and is capable of extension for a further length of 300 feet; and its side walls are 40 feet in height from the floor-level. It has a steel-trussed roof with a clear span between the side walls of 61 feet. The building consists of a steel skeleton frame, and stone walls, constructed independently of the framework and designed to carry only their own superincumbent weight, the weight of the roof trusses being carried by steel columns. The loads due to the 50-ton electric travelling-crane are also carried by steel columns. This crane commands the whole floor of the house and has unusually long steel wire-rope connections capable of reaching to the bottom of the turbine-pit. The power-house was designed by Mr. Stanford White, to accommodate ten turbines. The present house is only built of sufficient length to contain four turbines, the end of the building being closed for the present by a wooden partition.

The Dynamos.—The dynamos, *Figs. 3 and 4*, are about 13 feet 6 inches both in height and in diameter, and are compact machines. They are arranged to give two equal alternating currents differing in phase by an angle of 90° , each current having the comparatively low frequency of twenty-five complete cycles per second. The wave phases give slightly flattened sinusoidal curves. The two circuits are quite distinct one from the other; the difference of potential amounts to 2,400 volts in each circuit at the terminals, but the machines may be worked sometimes at as low a difference as 2,100 volts. The normal speed is 250 revolutions per minute, and they have been designed to work continuously at full load without their temperature rising 40° C. above that of the atmo-

sphere. They belong to the type in which the field magnets revolve, whilst the armature coils are fixed, a mode of construction that offers much advantage when the machine is of large size. The frame of each machine consists of a cylindrical casting resting on a circular foundation plate, which is in turn supported by heavy masonry arches built over the turbine-pit. The frame has external flanges by which the armature is retained in position, and its inner surface has inverted conical seatings that receive the four-armed castings carrying two bearings for the upper vertical shaft situated in the third gallery above the turbines. These bearings are bushed with babbit metal, and spiral grooves are provided through which a current of oil is caused to circulate under pressure, arrangements being also made by which the bushes can be cooled in case of need by the circulation of a current of water through exterior channels.

On the top of the shaft a six-ribbed steel casting or "spider" is keyed, and this carries a massive nickel steel ring 11 feet 6 inches in diameter. This ring with its attachments weighs 80,000 lbs., and serves as a fly-wheel; it is $4\frac{7}{8}$ inches thick, and 51 inches wide. The material has an ultimate tensile strength of 80,000 lbs. per square inch, with an elastic limit of 48,000 lbs. per square inch, and, at its normal speed of working, 250 revolutions per minute, its outside surface travels at the rate of about 2 miles per minute. The rings of all the machines were made at the Bethlehem Iron Works, Pennsylvania, from solid cylindrical ingots, which, after being forged under the steam-hammer, were bored and then forged into shape under an hydraulic press. Nickel steel is particularly suited for this purpose, not only on account of its great strength and toughness, but also on account of its electrical properties. Attached to the inner surface of this cylinder are twelve open-hearth steel pole-pieces, each one being secured by six iron bolts $1\frac{1}{2}$ inch in diameter. These pole-pieces are wound with two copper bars, air insulated, and covered externally with brass casings. The weight of each pole-piece with its bobbin is 2,800 lbs. They are excited by a continuous current obtained from the main alternating ones by 200-kilowatt rotary transformers placed in the power-house; the energy so employed is equal to 10 H.P., or 0.2 per cent. of the main output. This exciting current, a direct one, at a potential of 175 volts, is carried to the field-magnets from the transformer through covered conduits beneath the level of the floor, through the foundation and up one of the hollow iron columns that supports the bridge across the top of the machine, along this bridge and to the revolving shaft, by two fixed copper

brushes that rub on two hardened copper rings, suitably insulated and fixed on the top of the shaft. These rings are directly connected with the windings.

The core of the armature is built up on the cylindrical framing of the machine already referred to, and lies wholly within the revolving system of field-magnets. It is formed of thin plates of soft iron, the surfaces of which are oxidized, and the whole mass is held together by nickel steel bolts. In the outer surface of this armature, 187 vertical rectangular recesses are formed to receive the armature winding. This latter consists of copper bars $\frac{1}{2}$ inch by $1\frac{1}{4}$ inch in cross-section, two bars being placed in each recess. The insulation is of mica. It will thus be seen that the winding is wholly on the outside, enabling ready access to be obtained in case of need. The bars are connected in series so as to give two independent circuits, and separate cables connect each circuit with the switch-board.

The design of the dynamos with fixed armatures allows the coils to be more securely wound and to be free from the mechanical stresses induced by centrifugal action. Currents can also be taken from the machines without the intervention of cumbersome brush-holders, or of commutators, which, with very large currents, involve problems of serious difficulty.

By means of the field-magnets on a metal ring with their poles projecting radially inward and weighing about 70,000 lbs., a fly-wheel is obtained, and the magnetic stress between the fields and the armature acts as a partial counterbalance to the centrifugal force. A further advantage, in the design adopted, is that space is afforded to the workmen in which to attend to the bearings. In the tests of the first machine a man was stationed inside the armature space during the running of the machine, with telephone connections to the office outside by which to communicate the conditions of the bearings. There is, indeed, a clear space, 5 feet in diameter, in the middle of the machines. This feature of the design is of great advantage in allowing the replacement, by the aid of the electric cranes, of portions of the turbine shaft or other machinery beneath the dynamos whenever required, without the necessity of dismantling the dynamos more than by the removal of the field-magnet system and shaft, which is very readily performed. In these dynamos the centrifugal tendency of no part of the revolving system is restrained by bolts or keys—an important advantage. The formula used in designing the parts of the revolving machinery was that the sum of the weight of each part, multiplied by the square of its velocity in feet per second, should

equal 1,100,000,000. Great care was exercised in balancing the revolving parts, so that the machinery would run true at the highest speeds it would ever be subjected to in practice.

When the first dynamo was put in operation at full speed it was found that the moving parts continued to revolve for thirty-nine minutes by their own inertia. As it was considered important to be able to stop the machine quickly, the ingenious device was adopted of reversing the fields by means of a current in the opposite direction, in this way putting on a load which served as an electrical brake, by which the revolving system can be stopped almost instantly. It has been found that the power required to overcome friction and drive the motor and generator without load is 76 HP.

The Niagara Falls Power Company, which has a charter from the State of New York, constituted, in 1889, a subsidiary company, the Cataract Construction Company, by whom the plans for the utilization of Niagara have been decided on and carried out. Mr. E. D. Adams is the President of this company, and Mr. William B. Rankine is the Secretary. In 1890 this company invited various firms in America and Europe to submit plans for the hydraulic utilization of the power and its electrical distribution. A sum of \$22,000 was set apart to be awarded to competitors who furnished plans in accordance with the invitation. To decide on the merits of these plans a Commission was formed, consisting of Sir William Thomson (now Lord Kelvin) as Chairman, with Dr. Coleman Sellers, of Philadelphia, Lieut.-Col. Theodore Turrettini, of Geneva, Switzerland, and Professor E. Mascart, of the College of France, as members, and Professor W. C. Unwin, F.R.S., as Secretary. Subsequently revised plans for the turbines were obtained from two of the competitors, and one of these was selected, and has been carried out in the installation at Niagara. The dynamos are of the type and general construction proposed by Professor George Forbes and the engineers of the Cataract Construction Company, to whom the installation of the general plant for the Niagara Falls Power Company was entrusted.

The general design and details of the dynamos have been worked out with great care, under the direction of Mr. Albert Schmid, the general superintendent of the Westinghouse Electric and Manufacturing Company, the firm by whom they were built. The efficiency of these large dynamos is remarkable, and Mr. L. B. Stillwell, the Chief Electrical Engineer of the Westinghouse Company, under whose immediate supervision the work was done, has furnished the Author with the following information bearing upon this point :—" When operating with a difference of potential of

2,100 volts at the alternating current terminals, the total electric and magnetic losses will not exceed 2 per cent. The mechanical losses—that is, losses in dynamo bearings and air friction—will be less than 1 per cent., and will probably approximate three-quarters of 1 per cent. The net efficiency of the generator will therefore exceed 97 per cent. and will probably very closely approximate $97\frac{1}{4}$ per cent.” As an example of the small loss due to mechanical friction, the occasion on which the dynamo ran for more than half an hour after power had ceased to be applied may here be again mentioned.

The circuits of the machines already erected are carried independently in cables to the stationary transformers of the Pittsburgh Reduction Company. The commutation of the two currents in quarter-phase difference can be more easily arranged for electro-metallurgical use than would be the case with a single current, and it must be remembered that the two circuits may also be kept perfectly independent and used to supply separate motors. The low frequency of 3,000 alternations per minute, adopted as the one best suited to the requirements of the installation, has occasioned increased cost in the static transforming machinery; but as the unit for the supply of power will always be large, the disadvantage is more than balanced by the increased efficiency of the low-frequency currents when employed for motors, by the reduced cost of the rotary transformers, and by a decrease in the difficulty of dealing with insulation and eddy-currents. It is easier also to run the dynamos in parallel.

It is the practice to run dynamos in parallel, and to have them interchangeable so that the machines can relieve one another. This will be necessary in order to insure continuity in the supply of energy to the electro-metallurgical works. The low frequency of the current at this installation would occasion flickering, if used direct for arc or incandescent lamps, but will not affect the electro-metallurgical work, the alternating current being first transformed to a continuous one by the motor generators or rotary transformers. It is possible to use the current as now supplied to the plant of the Pittsburgh Reduction Company in any required manner, either by the employment of synchronizing alternating motors without transformers, or by direct current motors or rotating phase-induction motors. The conductors from the dynamos are all placed in conduits under the floor of the power-house.

The Paper is accompanied by numerous drawings and photographs, from which the *Figs.* in the text have been prepared.

APPENDIX.

ORES OF ALUMINIUM.

The Bauxites.—The double- and triple-hydrated oxides, forming the mineral bauxite, are the cheapest and best ores of aluminium. Bauxite consists of sesqui-oxide of aluminium, together with from two to three molecules of water of hydration ($\text{Al}_2\text{O}_3 \cdot 2\text{H}_2\text{O}$ to $\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$), which would yield :—

—	Triple Hydrate.	Double Hydrate.
Alumina	Per Cent. 65·61	Per Cent. 73·9
Water of hydration . . .	34·39	26·1

The best varieties, as found in nature, are contaminated with between 1 per cent. and 5 per cent. of titanio acid and silica, with hydrated sesqui-oxide of iron ($\text{Fe}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$) replacing the hydrated alumina in varying proportions; the red-coloured varieties of the mineral often having as much as 15 per cent. or 18 per cent. of the sesqui-oxide of iron, and sometimes with as little silica as 1 per cent. up to 3 or 4 per cent.; while the white-coloured mineral often has between 10 per cent. and 20 per cent. of silica in it, and the correspondingly low amounts of from 1 per cent. to 3 per cent. of oxide of iron. These latter minerals, high in silica, but low in oxide of iron, are often still rich in alumina, and seem to have a part of the water of hydration replaced by silica; many specimens have only between 18 per cent. and 20 per cent. of water of hydration. These ores are especially adapted for treatment by sulphuric acid of 42° Beaume for the preparation of sulphate of alumina. The bauxites almost always contain between 1 per cent. and 5 per cent. of titanio acid, and often a small amount of vanadium.

The French bauxites, which were the first discovered and mined, have the following composition :—

HYDRARGYLITE.			
Red Bauxites of the Var, with Aluminate of Iron.		White Bauxites of Villeveyrac Hérault, with Basic Silicate of Alumina.	
	Per Cent.		Per Cent.
Alumina	60	Alumina	60
Silica, up to	3	Silica, up to	20
Ferric oxide, up to	18	Ferric oxide, up to	3

Besides these ores, there are large quantities of bauxite minerals ranging from maximum-silicious bauxites, which are basic silicates of alumina, or “fat” clays, to maximum-ferruginous bauxites, which are aluminates of iron. The French

ores are found in the Southern Departments of Var, Bouches du Rhone, Alpes Maritimes, Hérault, and Ariège. They are of massive conglomerate or oolitic structure. The Irish, Styrian, and Austrian bauxites are denser and more earthy minerals. As a rule they carry somewhat higher proportions of silica, but are in other respects similar minerals to the French product. European bauxites are said to occur in the Tertiary and Jura-Triassic formations. Bauxite has been mined since 1872 in France, Messrs. Augé & Co., of Montpellier, being the largest miners and dealers in the mineral.

The bauxites of France are, according to M. Francis Laur, of the firm of Messrs. Augé & Co., a well-recognised authority in the matter,¹ probably residual deposits from the decay of basalt.

Messrs. George Blackwell and Alexander Sutherland have exploited the Irish bauxites upon the land of the Marquis of Downshire at Strain, near Ballyclare, Antrim. Most of the Irish bauxites contain as much as 12 per cent. of silica.

The American bauxites are found overlying the Knox dolomite rock, extending over a considerable area in a north-easterly and south-westerly direction through several countries in the north-west of Georgia and in the north-east of Alabama. The more plentiful ores in this district are similar to those found in Europe, and contain 10 per cent. to 20 per cent. of either oxide of iron or silica, with the usual amount (3 per cent. to 5 per cent.) of titanitic acid common to all bauxites. There are, however, some large and valuable deposits of this mineral from which many thousands of tons of ore have already been extracted, containing less than 3 per cent. of silica and less than 1 per cent. of oxide of iron. The Pittsburgh Reduction Company draw their main supplies of alumina from these sources at the present time. The Georgia deposits were first exploited in 1887, but mining on an extensive scale in that State, as well as in Alabama, has only been developed within the last four years.

The Georgia and Alabama bauxite is found in pocket formations in a belt 30 miles wide and 75 miles long, in the Chattooga, Floyd, Polk and Bartow counties in Georgia; and in the Cherokee, Etowah, Calhoun and Cleburne counties in Alabama. These formations are somewhat similar in character to those noticed in places where manganese and limonite iron ores occur in the Southern Appalachian region. The bauxite is not found in continuous beds or in veins, but in pockets having well-defined outlines and containing compact masses of ore amounting to many thousands of tons each.

The supply of bauxite in Georgia and Alabama is very large, enough without doubt to meet the demand for many years. The ore-bearing formations are surrounded by rocks of the older Cambrian formation, represented by the Rome sandstones below them, and by the Connasauga aluminous shales above them. In the southern portion of the region, the Rome sandstones are replaced by the Weisner quartzite of which both the Weisner and Indian Mountains are composed. Above the Connasauga shale is the Knox dolomite, which is the most uniform and persistent formation of the Southern Appalachian region. The Knox dolomite is of the Upper Cambrian and Lower Silurian period; fossils are almost entirely absent from it; it has a thickness of between 3,000 feet and 4,000 feet. This dolomite is a grey semi-crystalline carbonate of lime and magnesia, containing much silicious matter, which by its disintegration has usually left a heavy residual mantle covering all the outcrops of the formation. The bauxite, as well as the limonite deposits of this portion of Georgia and Alabama, are found associated with the residual materials of this mantle, which is composed

¹ See Paper by Mr. F. Laur on Bauxite, Transactions of the American Institute of Mining Engineers, vol. xxiv., 1894, p. 234.

principally of ferruginous clay. The mantle usually has a depth of between 50 feet and 100 feet, and is remarkable for the large quantities of chert that it contains, both in nodules and in beds. The chert is a dull-coloured subtranslucent and somewhat brittle and impure variety of chalcedony or cryptocrystalline quartz. Immediately above the Knox dolomite the succession of rocks is broken, and the Chickamauga limestone, and, higher still, the Rockmark slates are found. The geological structure of the region is exceptionally complicated, and exhibits many folds and faults.

The north-western limit of the ore-bearing belt is a line of Rome sandstone hills, dipping towards the south-east, and adjoining the Coosa-Oostanaula Valleys, from Calhoun, Georgia, to Mount Weisner. Massive beds of Cambrian quartzite are found upon the southern border of the region. The strata of the whole district exhibit the effects of great compression concentrated upon narrow belts between harder and more resistant rocks. This compression is shown by the existence of many geological faults, among the more important being the Coosa thrust fault, along the line of which the bauxite deposits have been found most abundantly. Dr. C. Willard Hayes, of the United States Geological Survey, who has given the subject careful study, reports that the region has from very early geological time been the seat of oreogenic activity.

The distinctness of the bauxite deposits from the surrounding residual clay in this district contrasts remarkably with what is seen in other deposits of bauxite, which appear to be the residue of decayed rock. The Georgia-Alabama bauxite indeed shows distinct stratification, the material being found in layers of different colours, although no trace of bedding is discernible in the surrounding clay. These beds have usually a steep dip, which exceeds the slope of the surface of the uneven land in which the ore bodies are mined.

The ore varies greatly in appearance; a large portion of it has a very characteristic pisolitic structure of a grey colour, the individual granules usually ranging in size from $\frac{1}{10}$ inch to 3 inches in diameter, the most common size being about $\frac{1}{2}$ inch diameter. The Author has one such pisolite which is more than 2 feet in diameter. In some beds the ore is found in large concretionary lumps of oolitic structure, weighing $\frac{1}{2}$ lb. to 10 lbs. each. This ore is commonly called "donic." Beds of yellow, grey, red, and chocolate-coloured ore of fine-grained texture often alternate with those of pisolitic ore. This fine material usually contains more silicious matter in the form of kaolin than is found in the harder portion of the mineral. The presence of the sesqui-oxide of iron is the chief reason for the varying colour of the material, which runs from a light salmon and grey to dark red, although some of the bauxite also contains organic colouring matter. Some of the material is soft and even plastic as it is mined, while some of the dark-coloured mineral is nearly as hard as quartz. There are some beautifully violet-coloured manganese bauxites amongst those found in Georgia; but so far, no varieties have come under the Author's notice containing further metallic elements as impurity. If such minerals, however, are found, they may prove to be of commercial value, as affording a ready means by which aluminium alloys could be produced when a material harder than pure aluminium is needed.

Mr. Francis Laur considers the bauxites to be natural pigments or inorganic "lakes," and that they are natural bi-hydrates of alumina or hydrargyllites with about 27 per cent. of water. While most of the bauxites of Southern France and of Arkansas, Colorado, and New Mexico of the United States undoubtedly have this amount of water of hydration, yet there are many (in fact, most of the pure ores of Georgia and Alabama) which have more

than 31 per cent. of water of hydration, which would make them triple hydrates.

When the water of hydration is below 31 per cent. in the greyish and white-coloured minerals, it is found in the Georgia and Alabama bauxite that the silica is proportionately higher and has replaced a portion of the hydrated mineral. A bauxite with only 27 per cent. of water of hydration from this region will almost certainly contain as much as 8 per cent. of silica. The bauxites of Georgia and Alabama not only seem to have a different amount of water of hydration, but also appear to differ in their origin from those of France and the Western districts of the United States, where the bauxites are residual deposits from the decay of basalts, granites, &c., and contain remains of the constituent minerals of the parent rock, as well as traces of the original rock structure, the ore being disseminated throughout the eruptive mass.

No eruptive rocks are found in the vicinity of the bauxites of Georgia and Alabama, nor are there any rocks in this region which by weathering could yield bauxites as a residual product, as has been pointed out by Dr. Hayes, of the U.S. Geological Survey. He considers that thermal springs must have been the agent by which the mineral was carried to the surface from the underlying shales in some soluble form through the intermediate fractured strata, being subsequently precipitated where it is now found. He suggests that the water, first heated and containing much ferrous and aluminous sulphate, became highly charged with lime in passing through the Knox dolomite; and that a reaction of calcium carbonate upon aluminium sulphate took place, causing a gelatinous or flocculent precipitate of aluminium hydroxide, the basic sulphates remaining in solution. This action may have taken place at great depth, and the resulting precipitated alumina may in some cases have been brought to its place of deposit in suspension by the water. This explanation accords with the peculiar physical structure and methods of bedding of the bauxites observed in the Georgia-Alabama district.

The Arkansas deposits of bauxite occur as regularly stratified beds in rocks of tertiary origin, near their places of contact with eruptive syenites or hornblende granites. Prof. J. G. Branner, of the Arkansas State Geological Survey, states that the bauxites of the State are formed from these granites. In this opinion Dr. Hayes, of the United States Geological Survey, concurs. There are two theories as to the causes of their formation; one is that these bauxites are sedimentary deposits from mineral springs, while the other supposes the bauxite to be due to the double decomposition of chlorides of alumina and iron in contact with carbonates of magnesia and calcium. The bauxites of Arkansas occur in positions at between 250 and 300 feet above sea-level. As a rule they have no covering, the overlying beds having been removed by erosion, which has removed part of the bauxite in some cases. The deposits lie high enough above the natural level of the country to be readily and economically quarried, and are in the vicinity of Little Rock, Pulaski Co., and near Benton, Saline Co.; but the Arkansas ores have not yet been mined in a systematic manner.

Useful varieties of bauxites are found in Asia Minor and in South America.

Beyond its use as a source of alumina, bauxite is largely used for the manufacture of alum, and in setting the "size" or colour in the process of paper-making and in dyeing. It has further uses as a basic furnace-lining and as a pigment for the bottoms of boats and for other marine work.

Gibbsite.—Gibbsite, the stalactitic modification of the triple hydrate of

aluminium ($\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$), containing 65·4 per cent. alumina and 34·6 per cent. water of hydration, which occurs in the purest beds of bauxite, has a specific gravity of 2·4, and is a purer mineral, freer from oxide of iron, silica and titanate acid, than is bauxite. Unfortunately, it has not been found in very large masses, although much of the better quality of bauxite found in Georgia contains a considerable quantity of gibbsite.

Native Sulphates of Alumina.—Alunogen, or aluminite (sulphate of alumina), and bauxites are also found in strata of volcanic origin in a district upon the Upper Gila River, about 40 miles north of Silver City, New Mexico, U.S.A., the adjacent rocks having been originally highly basic—volcanic porphyries and basalts accumulated in massive beds of brecciated fragments. These rocks have been altered and changed by solfataric action, or by the decomposition of disseminated pyrites, which has led to the occurrence of alunogen in outer crusts and layers, with bauxite beneath in the residual material. They have, in addition, been largely deprived of their silica and alkalis by acid solutions percolating through them. There is another large bed of this native sulphate of alumina, $\text{Al}_2(\text{SO}_4)_3 \cdot 9\text{H}_2\text{O}$ (probably with residual bauxite under it), in Purgatory Valley, 12 miles east of Trinidad, Colorado. This deposit of sulphate of alumina contains about 30 per cent. of alumina in a condition suitable for cheap purification. The difficulties and expense of transport, however, render the New Mexico and Colorado bauxite and alunogen at present commercially unavailable.

Clays as Ores of Aluminium.—The clays vary from tribasic silicates of alumina to pentacid silicates, minerals with at most 65 per cent. of alumina and 35 per cent. of silica, while the more common varieties contain 50 per cent. to 70 per cent. of silica and only 35 per cent. to 50 per cent. of alumina. Pure kaolin contains 39 per cent. of alumina, corresponding with about 20 per cent. aluminium with 40 per cent. of silica and 14 per cent. of water. Now, as silica is much easier of reduction than alumina by all the methods so far used for the production of aluminium, this large amount of silica must be separated from the alumina before the reduction is commenced; otherwise much of the energy and of chemicals used in the reduction will be expended in the reduction of a troublesome impurity. The value of clay, therefore, as an ore of aluminium is small in comparison with that of the richer and purer hydrated oxides of aluminium, which have only small amounts of iron and silica to be removed before they are submitted to the reducing operation.

Pure bauxite ores can be delivered in Pittsburgh, Pennsylvania, at a cost of £1 10s. per ton at present. There seems to be only one method by which "fat" clays like kaolin may be used as aluminum ores, and that is treatment by cold concentrated sulphuric acid. This dissolves the alumina out of most clays, leaving the insoluble silica behind. The same reaction takes place, under favourable conditions, when mixtures of sulphates of the alkalis and alkaline earths with clays are heated and the mass is treated with water. The alumina can be subsequently precipitated from the solution by the addition of an excess of an alkaline reagent. These methods have been the subject of experiment, but so far, alumina has not been produced from them cheaper than from bauxite.

Cryolite.—The mineral cryolite is still used as an ore of aluminium, and is the source of a considerable amount of alumina sold by the Pennsylvania Salt Manufacturing Company to the Pittsburgh Reduction Company. Cryolite is the double fluoride of aluminium and sodium, containing 40·25 per cent. aluminium fluoride and 59·75 per cent. sodium fluoride, and thus corresponds to the formula $\text{Al}_2 \text{F}_6 \cdot 6 \text{Na F}$. It is a massive semi-transparent, white mineral, easily fusible, usually occurs granular or indistinctly crystalline, is cleavable, has a vitreous

lustre, and specific gravity of 2.95 and hardness of 3. The common impurities in cryolite are quartz, siderite, chalcopryrite and galena. This mineral would not seem to be particularly adapted for, or have much importance in the metallurgy of aluminium. It contains only 13 per cent. of aluminium with 32.8 per cent. of sodium and 54.2 per cent. of fluorine, and is only mined at Ivigtuk, on the West Coast of Greenland, in latitude $61^{\circ} 13'$, a distance of some 12 miles up the Arksuk Fiord. This place is, moreover, only accessible to navigation during the early and latter parts of the summer, on account of pack-ice and icebergs. Its chief importance is derived from the fact that, together with the more common and cheaper mineral, fluorspar, and an excess of alumina fluoride, it makes one of the best fluxes in which to dissolve the oxide of aluminium for the purpose of electrolysis. Although it is easy to manufacture the mineral artificially, yet large quantities of it are exported annually from Greenland, the chief American consumer being the Pennsylvania Salt Manufacturing Company. This Company uses the mineral as a source of pure soda suitable for making soap and the soda salts, as well as cryolite glass, alum, aluminium sulphate and alumina. The salts thus made from cryolite have a high reputation for purity.

It is probable that cryolite will not command so large a sale in the future as it has done in the past, since better methods for the purification of bauxite and the production of soda from salt by electrical means are being developed.

At Miask, in the Ural Mountains (which are prolific in minerals that are rare elsewhere), cryolite has been found; but, so far as is known to the Author, the mineral has not been commercially worked there.

The triple fluoride of aluminium, sodium, and magnesium, is found near the top of the South Cheyenne Mountain, in the vicinity of Colorado Springs, in Colorado. It has a composition of—

	Per cent.
Aluminium	13.61
Magnesium	8.91
Sodium	18.05
Silica	1.94
Fluorine	57.49
	<hr/>
	100.00

This mineral dissolves alumina and performs the functions of cryolite in the electrolytic production of aluminium. It exists in several veins, 6 feet to 10 feet thick, in the granite which forms the mountains. As far as is known to the Author, there has not been any pure cryolite found on Pike's Peak, in El Paso County, Colorado.