CHEMICAL SECTION.

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DR. JOS. W. RICHARDS, President, in the chair.

THE WETHERILL MAGNETIC CONCENTRATING PROCESS.

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This process was first described by Mr. H. A. J. Wilkens and myself, in a paper entitled "The Magnetic Separation of Non-magnetic Material," presented at the Pittsburgh meeting of the American Institute of Mining Engineers, in February, 1896, and since then published in the *Transactions* of that society. Those who may be more especially interested are referred to the above paper, as it has dealt with the subject somewhat more exhaustively than it is practicable to do here.

It is a process for separating various mineral and chemical substances, of such feeble magnetic permeability, that they have been heretofore generally considered as non-magnetic, from one another and from such accompaniments as are absolutely inert, by means of powerful and specially devised electro-magnets.

The substances that have been found capable of being so attracted are most all of the minerals containing iron and manganese, either alone or in combination; and, likewise, the chemical salts of these metals, either alone or in combination.

Among the minerals are: hematite, limonite, siderite, chromite, menaccanite, rutile, franklinite, pyrolusite, psilomelane, tephroite, rhodonite, garnet, hornblende and many others.

None of these minerals or salts is attracted (in the ordinary sense of being lifted) by the strongest hand magnet or by electro-magnets of equivalent power.

The metals iron, nickel, cobalt, and the minerals magnetite (Fe_3O_4) and pyrrhotite (Fe_7S_8) are the only substances that are magnetic in this ordinary sense, and the only ones which are capable of being separated by the various electromagnetic machines that have been invented prior to the Wetherill machines, such as the Edison, Wenström, Ball and Norton, Conkling, Buchanan, Payne, Chase and other magnetic separators.

It is true that separations have been made of such minerals as red hematite, limonite, siderite and franklinite on some of the above types of machines, but it has invariably been accomplished only after a preliminary conversion of the iron component to its magnetic oxide or artificial magnetite, by means of roasting in an oxidizing or reducing atmosphere.

However, while these minerals and salts are not attracted by the ordinary magnetic powers sufficiently to render their separation possible, it has, nevertheless, been long known in the science of physics that all matter is affected in some way by a magnet.

Coulomb was the first physicist to announce that not only iron, nickel and cobalt, or certain mixtures of these metals with others, were influenced by a magnet, but also that small needles of all other substances, metallic, mineral or vegetable, oscillated under the influence of strong bar-magnets, like small magnetic needles. He, however, erroneously interpreted that this action was due to the universal presence of iron, in quantities so small as to defy detection by the most refined chemical analysis, and did, therefore, not consider that it was a general property of matter in itself to be magnetic.

Nearly twenty years later, in 1824, Becquerel, who had the advantage of utilizing electro-magnets, invented, since Coulomb's time, by Oersted, discovered the repulsion produced by the poles of a magnet on bismuth.

In 1846, Faraday published the results of his very interesting and exhaustive experiments, carried on with the most delicately arranged physical apparatus, showing that all matter, solid, liquid and gaseous, was magnetic; *i. e.*, either

attracted or repelled by the poles of a magnet. He accordingly made the division into paramagnetic and diamagnetic substances, the former including those attracted, and the latter, constituting by far the greater class, those repelled.

He gave the following lists :

Paramagnetics.—Iron, nickel, cobalt, manganese, chromium, cerium, titanium, palladium, platinum, osmium.

Diamagnetics.—Bismuth, antimony, zinc, tin, cadmium, sodium, mercury, lead, silver, copper, gold, arsenic, uranium, rhodium, iridium, tungsten.

Uranium was later found to be paramagnetic (by Verdet); and almost all amorphous and organic substances belong to the diamagnetic class.

The paramagnetic substances may again be subdivided into such as are highly magnetic and such as are only feebly so.

The first class is completed with the substances iron, nickel, cobalt, magnetite and pyrrhotite. It is with the second class that we are especially concerned here.

The knowledge of the paramagnetic property of many substances has been of great scientific interest since the time of Faraday's demonstration.

In 1871, Fouqué, and since then Doelter and other mineralogists, have made use of this knowledge to some extent in the mineralogical laboratory.

But it remained for Mr. J. Price Wetherill, of South Bethlehem, Pa., to design magnets capable of producing a sufficiently concentrated field to make practical the separation of these feebly paramagnetic substances on a commercial scale. Mr. Wetherill, who is the general manager of the Lehigh Zinc and Iron Company, was led to this result in his endeavor to improve the grade of the zinc ore of Sussex County, N. J., used for the manufacture of spelter.

This ore is a crystalline granular aggregate of franklinite (FeO , ZnO , MnO) (Fe_3O_4 , Mn_3O_4), willemite (Zn_2O , SiO_2) and calcite, with smaller amounts of zincite (ZnO), fowlerite (MnO , ZnO , SiO_2), tephroite (Mn_2O , SiO_2), and garnet.

It was the object to obtain the zinc-bearing minerals willemite and zincite as free as possible from the franklin-

ite, garnet, tephroite and fowlerite, the iron- and manganese-bearing minerals, as the presence of the latter is fatal to the direct metallurgical production of zinc.

After repeated and painstaking experiments, Mr. Wetherill finally succeeded, in the latter part of 1895, in accomplishing this result to perfect satisfaction, and patents have since been granted in the United States, Canada, England,

FIG. 1.—Plan of Wetherill electro-magnet.

Germany and other European countries, for the method of, and apparatus for, separating paramagnetic substances of very low magnetic permeability or susceptibility.

The accompanying illustrations show the form and arrangement of the magnets, as well as the principal features of the mechanisms for effecting the separation of substances subjected to their influence.

The electro-magnets are arranged in the general form of a horseshoe, as shown in plan (*Fig. 1*), and consist of five parts, made of soft forged iron; two cores and bobbins *C*, joined together by a yoke *Y*, and having attached to each of their other faces, by means of brass clamps *B*, a pole-piece *P*, as shown. The yoke is $31\frac{1}{4}$ inches long by $10\frac{3}{4}$ inches wide by $2\frac{1}{2}$ inches thick. The cores are $12\frac{1}{2}$ inches long by $10\frac{3}{4}$ inches wide by $2\frac{3}{8}$ inches thick, made rectangular in cross-section, with the long edges rounded to a radius of one-half the thickness. These cores are wrapped with nineteen layers of No. 5 insulated copper wire, making 915 ampère-turns. The pole-pieces are $15\frac{1}{2}$ inches long by $10\frac{3}{4}$ inches wide by $2\frac{1}{2}$ inches thick, and are tapered at the free ends at

FIG. 2.—Vertical view of horizontal magnet type.

an angle of 30° , the points being rounded. The total weight of this magnet complete is 1,259 pounds.

The mechanisms for effecting the separation of minerals are of two principal types, as shown in the drawings, representing vertical views (*Figs. II and III*).

(1) The horizontal magnet type (*Fig. II*) in which the material is fed by means of hoppers, in a thin layer on canvas belts *a*, revolving in the directions shown by the arrows about each pole-piece *P*, and is delivered directly into the opening between the two pointed pole-pieces. Two shutters *S*, made of brass and of the same width as the pole-pieces, are situated one beneath the point *T* of each pole; they are adjustable so that the magnetic particles, which adhere slightly to the belts as they round the pole-points,

are carried to one side by the moving belts, while the non-magnetic particles fall vertically in the central space between the two shutters.

The result desired can be regulated by changing the position of the shutters, the speed of the feed belts, the distance between the pole-points, or the ampèrage of the electric current through the coils.

(2) The inclined magnet type (*Fig. III*) in which the material enters on the feed belt *a*, revolving about a brass roller *R*, and is delivered in close proximity to the space between the poles. The magnetic particles are withdrawn and lifted up into the highly intensified field existing at this point, and they are removed by the horizontal belt *b*, revolv-

FIG. 3.—Vertical view of inclined magnet type.

ing around the lower pole point in the same direction as the feed belt; while the non-magnetic particles fall vertically from the brass roller. The revolving belt *d* around the upper pole simply serves the purpose of keeping that point brushed free from magnetic particles that would otherwise have a tendency to stick to the bare points, and ultimately choke the opening.

The intensity of the magnetic attraction can be accurately adjusted by changing the distance between the poles, the distance of the brass roller from the poles, or the ampèrage of the electric current.

The question of paramount interest is: How are these magnets capable of effecting a separation that has not been

FLAT MAGNET CONCENTRATING MACHINE IN THE PLANT OF THE STERLING IRON AND ZINC COMPANY, AT
FRANKLIN FURNACE, NEW JERSEY.

practicable heretofore? How is it that substances possessing such infinitesimal magnetic permeability, that they have been commonly considered as non-magnetic, are attracted here, and actually lifted by the poles of the magnets?

The answer lies in the extremely condensed magnetic field at the pole-points, which is produced by means of the correctly proportioned cores, yokes and pole-pieces employed, and especially by the tapering ends of the latter. These ends being of less sectional area than the magnet cores, a vast number of magnetic lines are forced through and across the points.

The amount of ampère necessary to generate these lines in sufficient number is comparatively small. The magnetizing power of a magnet may be attained either by increasing the ampère of the current, or by increasing the ampère-turns, *i. e.*, the number of turns of the coil on the core, the one or the other of these functions remaining constant.

In the Wetherill magnets the latter fact is taken advantage of, and with 915 ampère-turns of No. 5 wire the quantity of current or ampère is reduced to an economic minimum.

The No. 5 wire is capable of carrying a current of 25 ampères, but this quantity is rarely necessary for most minerals.

For instance, limonite and pyrolusite, which are perhaps among the most stubborn of the feebly magnetic minerals, require from 10 to 20 ampères; red hematite and garnet are usually attracted with from 4 to 8 ampères; and franklinite and siderite with as low as 1 to 4 ampères.

The amount of voltage is an inconsequent factor, depending solely on the size and length of wire and the number of ampères used; *i. e.*, it represents the pressure requisite to drive the necessary ampère through the magnets. For coils wrapped with No. 5 wire the voltage is equal to about twice the number of ampères used; *i. e.*, the resistance is 2 ohms; for coils wrapped with No. 10 wire the resistance is 5 ohms.

To illustrate the intensity of the magnetic field it may

be mentioned that the current of a single bluestone cell (such as is used in telegraphy) is usually too powerful to permit of a satisfactory separation of the highly magnetic substances magnetite or pyrrhotite, the particles adhering to the points so tenaciously that the moving belts are incapable of pulling them off. For this purpose it is found best to reduce the strength of the current by means of resistance coils.

The ability to delicately adjust the magnetic intensity of the field permits, in many cases, the successive isolation of several products, showing a slight difference in permeability from a mixture containing the same. For instance, in the New Jersey zinc ore, franklinite can first be separated at 1 to 3 ampères, and then the garnet at 4 to 8 ampères.

This brings up the interesting question of the possibility to tabulate the minerals in distinct groups capable of being magnetically separated from one another, *i. e.*, in the order of their relative attractability. It is, however, a matter of very considerable difficulty to do this accurately, for the reason that the magnetic permeability of each mineral, in itself, is subject to wide variations; for instance, some particles of franklinite will be attracted at 1 ampère, while others will require as high as 4 ampères; some garnets will be lifted at 3 ampères, and others not until 6, 7 or 8 ampères are reached.

Nevertheless, various attempts have been made in the past by physical investigators, with more or less success and reliability of results, to determine the magnetic permeability of substances, and it may be of interest to give some of their determinations.

Delesse (*Annales des Mines*, IV Ser., Vol. XIV, p. 429) gives, among many others, the following comparative values, taking the magnetic attractability of steel at 100,000.

Magnetite	65,000
Siderite	120
Hematite	93 to 43
Limonite	72 to 43

Plücker (*Pogg. Annalen*, Vol. LXXIV, 1848) gives, taking metallic iron at 100,000:

Magnetite	40,227
Red hematite	134
Hydrated ferric oxide	156
Proto-sulphate (vitriol) of iron	98
Pyrite	150
Hydrated Mn_2O_3	70
Mn_3O_4	167

These results verify one important point, namely, the undoubted existence of a wide gap between the strongly and the weakly magnetic substances, according to which the paramagnetics are divided into two classes, as mentioned in the beginning of this paper.

The accuracy and value of the figures, otherwise, is extremely doubtful, and in some instances they are known to be absolutely erroneous and misleading, so far as experience with the Wetherill magnets goes. A striking instance of discrepancy is furnished by pyrite and iron vitriol, the former of which Plücker rates at 150, and the latter at 98. Yet the fact is that iron vitriol is attracted with ease at 8 ampères, while iron pyrites is the only iron-bearing mineral that does not, so far as present experiments have gone, come within the attracting limit of the magnets at all, although it is still hoped that it will be possible to further increase the intensity of the field by which it will be made effective upon a wider range of minerals than has been successfully treated so far, including iron pyrites.

Again, whereas Plücker places the permeability of the manganese salts not far from, and even below that of pyrite, their attractability is, in reality, far greater. It is, indeed, a curious and interesting fact that the manganese salts are, as a rule, more magnetic than the corresponding iron salts; for instance manganous sulphate (c. p.) requires only 1 ampère, while ferrous sulphate (c. p.) requires 8 ampères to be attracted.

It does not appear then that the magnetic permeability necessarily depends upon the amount of iron in a substance, or upon the chemical condition of that iron in a ferrous state, as has been thought by many. But how is this property of matter best explained?

Without here desiring to enter into a discussion of the

theories concerning the magnetic properties of matter, it may be stated briefly that, in view of existing facts, the magnetic molecular theory seems the most satisfactory to us. This theory accounts for the magnetism of bodies by the existence of magnetic molecules and explains the variation of permeability as due to the arrangement and structure of these molecules.

The ratio of the sum of the volumes of the magnetic molecules to the entire volume of a body is the magnetic density of that body. It is upon this that the capacity of a body for magnetism seems to depend, and it has been shown to vary with the temperature and other physical and chemical conditions.

In conclusion, I will give some actual results obtained in concentrating different ores by the Wetherill process :

ZINC ORES.

From Franklin, N. J.

	Percentage by Weight.	ZnO Per Cent.	Fe Per Cent.	Mn Per Cent.
Original ore	—	31'09	20'34	9'34
Franklinite, garnet, etc. (magnetic heads) .	56	24'38	35'50	13'62
Willemite and zincite (non-magnetic tails) .	28	60'00	1'50	6'10
Calcite (non-magnetic tails)	16	4'00	—	—

From Austinville, Wythe County, Va.

	Percentage by Weight.	Fe Per Cent.	Zn Per Cent.
Original ore	—	18'60	29'57
Limonite (magnetic heads)	33	49'45	5'58
Calamine (non-magnetic tails)	67	3'41	41'40

RED HEMATITE IRON ORES.

(From the Birmingham district, Alabama.)

	Percentage by Weight.	SiO ₂ Per Cent.	Fe Per Cent.
Original	—	27'14	45'32
Magnetic heads	49	12'29	56'47
Non-magnetic tails	51	41'41	34'60

(From the Pewabic Mine, Michigan.)

	Percentage by Weight.	SiO ₂ Per Cent.	Fe Per Cent.
Original	—	43'49	37'87
Magnetic heads	37	7'76	63'55
Non-magnetic tails	63	64'11	23'05

BROWN HEMATITE ORE.

(From Iron Gate, Va.)

	Percentage by Weight.	SiO ₂ Per Cent.	Fe Per Cent.
Original	—	31'29	43'98
Magnetic heads	63	11'24	51'04
Non-magnetic tails	37	66'00	31'74

SILVER-LEAD ORE.

(From Monterey, Mex., consisting of galena in a limonite gangue.)

	Percentage by Weight.	Ag, ozs. Per Ton.	Pb Per Cent.	Fe Per Cent.	SiO ₂ Per Cent.
Original ore	—	6'41	12'04	35'42	12'68
Magnetic heads	81	0'90	2'90	43'00	14'10
Non-magnetic tails	19	29'90	51'00	3'10	6'60

MANGANESE ORE.

(From Cave Spring, Ga.)

	Percentage by Weight.	SiO ₂ Per Cent.	Mn Per Cent.
Original	—	43'00	28'78
Magnetic heads	52	20'85	40'91
Non-magnetic tails	48	67'20	15'54

Among the materials, besides those mentioned above, which have been separated successfully, are :

(1) A mixture of apatite and rutile, occurring in a deposit near Charlottesville, Va.

(2) Monazite sand from North and South Carolina, from which rutile and garnet were completely removed.

(3) Garnetiferous rocks and schists, from which it was desired to obtain the pure garnet.

(4) Garnetiferous copper ore from Mexico.

(5) Corundum ores, from which garnet and other deleterious ferruginous minerals were to be removed.

(6) Ores containing siderite, as in cryolite from Greenland, and the foreign zinc-blende ores.

DISCUSSION.

PROF. F. LYNWOOD GARRISON:—For the past three or four years a magnetic process for the concentration of copper and zinc ores (sulphides) has been in operation at Pitkäranta, Finland.

The ores used for this purpose are so lean, and mixed with so large a proportion of worthless material, that they cannot be worked by the ordinary methods of concentration and smelting. They are essentially mixtures of pyrite, chalcopyrite and zinc-blende, often associated with magnetite.

This lean copper ore, which, under ordinary circumstances, would be thrown away, containing about 1 per cent. copper, is crushed by ordinary Blake crushers and then granulated by rolls to a size of about 0.75 millimeters.

It then passes into roasting furnaces. The ore is thus gently roasted, which is a delicate operation, as the temperature must be very carefully regulated. The copper ores appear to require a lower temperature for roasting than the zinc ores, in order to render them magnetic; more or less difficulty has been experienced with the zinc-blende in this respect. When the ore comes from the furnace it is red-hot and glowing; when cold, it is passed by mechanical means to the magnetic separators, which are constructed with the special view of concentrating such magnetic material.

It is claimed that in this way from 70 to 80 per cent. of the copper in the ore is separated out, the refuse containing only about 0.20 per cent. copper. At Pitkäranta, about 600 hundred-weight of ore is treated in twenty-four hours, or about 1 ton per hour.

The results obtained with the concentration of zinc ores have not been so satisfactory, and the work on them is still in an experimental stage. The difficulty appears to be in the roasting, the proper conditions for which do not seem to be entirely, as yet, understood.

MR. NITZE:—Prof. Garrison's description of the magnetic concentrating process as applied to copper and zinc ores containing pyrite, at Pitkäranta, Finland, is very interesting, and corroborates the fact which I brought out in the beginning of my paper, namely, that apparently non-magnetic minerals have been separated on magnetic machines of the ordinary types, but only after a preliminary roasting of the material in order to render it artificially magnetic. It appears from the description that the roasting at Pitkäranta is carried on in a simple oxidizing atmosphere. No mention is made of the addition of coal, carbon, or a reducing gas to the charge. Therefore, the idea aimed at is evidently the conversion of the pyrite into pyrrhotite (the magnetic iron sulphide), by driving off a portion of its sulphur; the roasting must be arrested just at the point where the correct amount of sulphur has been eliminated, and it is for this reason that the operation becomes a most delicate one. If it be carried beyond this point the material will again become non-magnetic to the ordinary magnets. At the best, the uniformity of magnetization of the roasted product must be imperfect.

It must also be considered that, naturally, a partial concentration of the copper in the ore is effected by the roasting operation alone, the weight of the total mass being reduced by the amount of sulphur driven off.

Regarding the conversion of pyrite into pyrrhotite, it may be mentioned that Eustis and Howe (*Trans. Amer. Inst. Mining Engineers*, Vol. X, p. 105) in 1882 suggested the reduction of iron and nickeliferous pyrite to the magnetic subsulphide, but the delicacy of the operation deterred its practical application.

Mr. G. G. Convers, superintendent of the Lehigh Zinc and Iron Company, South Bethlehem, Pa., in (about) 1893, made similar experiments on magnetizing the pyrite con-

tained in a mixture of blende, pyrite and gangue from the Arminius Pyrite Mine, Louisa County, Va. He roasted the material to just the exact point to make pyrrhotite, but he found the operation such an extremely delicate one that he concluded it could not be carried out on a practical scale.

Besides the above, there are others who have experimented in the same direction and with similar results, apparently demonstrating the impracticability of such a delicate roasting operation; and it seems, therefore, the more remarkable that it should be practically successful at Pitkäranta.

However, if the roasting be carried still further, so as to drive off all of the sulphur (dead roast), converting the pyrite into Fe_2O_3 , and the operation be completed in the presence of a reducing atmosphere, such as can be attained by the admixture of carbon in the charge, so as to reduce a portion of the Fe_2O_3 to FeO , the ferruginous material will then be in the condition of artificial magnetite (Fe_3O_4), which can be separated on the usual types of magnetic machines.

The great objection to such a magnetizing roasting, aside from the additional cost of the same, is that it is never perfect; the probabilities are that there will always be some particles which have not become magnetized, and will therefore pass into the tails in the process of concentration.

This disadvantage is eliminated in the Wetherill process, where any previous *magnetizing* roasting becomes not only superfluous, but undesirable, inasmuch as the magnetic permeability of Fe_2O_3 is sufficient to cause its attraction and removal in the highly condensed field of the magnets. In pyritic ores, therefore, the only operation necessary would be a simple dead roast, which can be easily and perfectly attained.

Mr. — (a visitor), in reply to an inquiry by Dr. Wahl, whether the fine sizes of iron ores produced in concentration could be utilized in the furnace, said that this difficulty had been well overcome, as was demonstrated by the successful and practical use of such fine ores in the blast furnaces of the Lackawanna Iron and Steel Company, at Scranton, Pa.