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Roasting and Chloridizing of Bolivian Silver-tin Ores

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(~~Lake Superior~~ New York Meeting, ~~August~~ Feb., 192~~0~~)

In the metallurgical treatment of sulfide silver-tin ores mined at Oruro, Potosí, and Chocaya, the most important and difficult step is chloridizing-roasting. The ores are chiefly mined from veins in rhyolite, a detailed description of which can be found in most textbooks on ore deposits. The chief gangue minerals are Pyrite and quartz, and the silver content is derived from tetrahedrite, jamesonite, stibnite, and cylindrite. Most of the tin is present in the form of a rather impure cassiterite, which forms microcrystalline aggregates of varying richness with quartz and pyrite; occasionally, some tin is found as stannite, cylindrite, and other complex sulfantimonates. The silver content of the minerals that compose the ore is approximately as follows: Pyrite, 3 to 5 oz. per ton; jamesonite, 30 to 50 oz. per ton; stibnite, 30 to 150 oz. per ton; cylindrite, 200 to 300 oz. per ton; tetrahedrite, 500 to 3000 oz. per ton. Occasionally, some ruby silver ore is found, but it is very rare. In the mines of Oruro, which are the deepest in the sulfide zone, tetrahedrite has nearly disappeared, stibnite, jamesonite, and, in the deepest levels, cylindrite taking its place.

At present, there are six mills treating this ore, two at Potosí, two at Chocaya, one at Poopo, and one at Machacamarca. The ore is crushed dry, given a chloridizing roast, leached with water and hyposulfite solution (or with brine) to extract gold, silver and copper, and concentrated for tin with or without regrinding.

Early Ore-treatment Methods

In the earlier days, these ores were treated by chloridizing-roasting followed by amalgamation, with satisfactory results, according to the information now available. Material from old tailing dumps from ore treated by this process, which are found at several places in the vicinity of Oruro, seldom contains more than 5 to 6 oz. of silver per ton. As ore with less than 100 oz. per ton was not treated, the extraction of silver must have been good. Reports of the operating companies published about 1890 asserted that over 90 per cent. of the silver was recovered, but in these calculations, as a rule, no allowance was made for silver lost dur-

ing roasting and the figure referred only to the extraction of silver by amalgamation from the roasted ore.

Between 1890 and 1900, amalgamation was replaced by leaching with either hyposulfite solution or brine. It is remarkable that tailings from high-grade ore treated by amalgamation and those derived from ores of much lower grade that have been leached contain about the same amount of silver, namely, from 5 to 7 oz. per ton. The percentage of chloridizing that can be obtained is not directly proportional to the silver content of the ore, but it seems as if the quantity of silver that cannot be converted into chloride is more or less constant. For instance, after roasting an ore containing 25 oz. per ton, the amount of silver that cannot be chloridized will be 5 to 6 oz. per ton; whereas, with ore of 100 oz. per ton, after roasting, there will be from 8 to 9 oz. of insoluble silver. The silver that has not been chloridized and is left in the tailing after amalgamation or leaching cannot be dissolved by cyanide or any other commercial solvent known to the writer. Only a small proportion of it is contained in sulfides that have remained undecomposed owing to imperfect roasting; if these tailings, after fine grinding, are treated by flotation, a small amount of concentrate having about the same silver content as the original ore can be obtained but the amount extracted is insufficient to pay for this treatment.

On account of the difficulty, expense, and silver loss connected with chloridizing-roasting, more direct treatments have been tried for these ores. Agitating the raw ore with cyanide or bromine cyanide after fine grinding is absolutely ineffective; neither can commercial results be obtained by attempting to decompose the sulfantimonates with metallic aluminum, followed by cyanide treatment. This experimenting was carried out chiefly by one of the best known ore-testing laboratories in the United States. Cyanide consumption on either raw or roasted ore was excessive, and the extraction obtained by agitating the finely ground roasted and chloridized ore with cyanide was not better than by leaching the same material at 16-mesh with hyposulfite. Therefore, thus far the old method has proved to be the only way of treating these ores; and to increase the mill capacity and decrease the cost, it was necessary to find a mechanical furnace that would perform roasting and chloridizing as well, or better, than the old hand-rabbled reverberatory furnaces.

All these ores contain from 25 to 35 per cent. sulfur. In some plants, it is customary to give the ore, before crushing, a preliminary roast in kilns, which reduces the sulfur content to 8 to 10 per cent.; this has the advantage of making the ore more easy to crush. The partly oxidized ore, after having been ground to about 1 mm. is fed to hand-rabbled reverberatory furnaces where the remainder of the sulfur is driven off and salt is added to complete the process. This second roast has to be carried out with the addition of fuel, because most of the sulfur has been lost by

kiln treatment; and since fuel is expensive in Bolivia, it is cheaper to omit kiln roasting, crushing the raw ore at once to the fineness required (which varies between 2 mm. and 0.6 mm.) and roasting and chloridizing without fuel or with a much smaller amount. In former days, when good crushing machinery was unknown here and the cost of power was nearly prohibitive, kiln roasting was justified, but under present conditions it is not. Besides, it requires more handling than direct crushing and roasting. I have not been able to ascertain whether silver is lost during kiln roasting. A few tests were made with a kiln holding about 750 kg. of ore, which varied in size from 2½ to ½ in. (6.4 to 1.3 cm.), and one quarter of the charge was taken as a sample. One test showed an appreciable loss in silver, but in two others there was a gain in silver, which is impossible, so that the material was too coarse to give a reliable sample.

Early Chloridizing Methods

Chloridizing is simple and quick if salt is added at the correct stage of the roast. If salt is mixed with the ore before nearly all the sulfur has been converted into sulfates, it will retard roasting and increase volatilization losses; besides, salt is consumed unnecessarily. If the salt is added too late, it will fail to react properly and too low a percentage of silver will be converted into chloride. In hand-rabbled furnaces, the correct amount of salt is 3.5 per cent. for an ore of 25 oz. per ton and 5 per cent. for 50-oz. ore. An excess of salt has no particularly harmful effect on the process, but the excess is left undecomposed in the roasted ore, and during the water-wash that precedes hyposulfite leaching, it forms brine which dissolves silver chloride.

Usually the hand-rabbled reverberatory furnace has one continuous hearth, 10 ft. (3 m.) wide, divided into three sections 10 ft. long. There is a drop of 4 in. from one section to the other, the highest being next to the flue, where the raw ore is charged through a drop hole in the arch. A charge of 700 kg. is brought into the furnace and rabbled until it ignites. During normal operation there is a charge in each section of the hearth and care is taken that no ore is rabbled into the section lower down than it belongs. If the charge on the third section is so far roasted that it shows but a few sparks when rabbling, the salt is shoveled into the furnace. The decrepitation of the salt causes violent dusting; therefore, the draft of the furnace is shut off until decrepitation ceases. After the damper is again opened, the charge is rabbled until chloridizing is completed, when the ore will not flow but packs together somewhat like snow and stands up with nearly vertical sides. The chloridizing takes a little less than 1 hr. in these furnaces; once the ore begins to pack, it is useless to continue rabbling, because the percentage of chloridizing is not increased. If worked by two men, one furnace has a capacity of 4 to 4.5 metric tons per 24 hr. A little taquia fuel (llama dung) is used

during chloridizing, because it is not possible to rabble the charge during chloridizing as continuously as during oxidizing, on account of the corrosive fumes that escape through the working doors, for, to keep down the volatilization losses the furnace is worked with a reduced draft.

A charge remains about 4 hr. in each section and is in the furnace altogether 12 hr., of which less than 1 hr. is used for chloridizing. It would therefore be a mistake to try to chloridize continuously, adding salt to the last hearth or section of some kind of mechanical furnace, because the atmosphere in the furnace would be charged with chlorine which retards roasting and attacks the metal parts. Moreover, continuous work has the disadvantage that, if ore with insufficient sulfur enters the chloridizing section poor work will be done until conditions are improved, which will take considerable time with a roasting furnace of some size.

Satisfactory metallurgical results are obtained from hand-rabbled furnaces worked by competent men; formerly, these could be found as chloridizing roasting was practiced in Boliva for generations. The average silver loss caused by dusting and volatilization during a period of several years was calculated to be 6 to 7 per cent. at Machacamarca; if the furnace is worked carefully, the loss can be reduced to a lower figure as was proved by an experiment described later. The cost of roasting was not high, being around $2 (U. S. currency) per metric ton, including everything, but as the plants grew in size and tin mining drew a large percentage of the men away from the silver mines, it became imperative to use mechanical furnaces.

Roasting Huanchaca Ore

The Compañía Huanchaca de Bolivia led the way in installing a mechanical roasting plant. The Huanchaca ore is a heavy sulfide with a large proportion of blende; it carries no tin but contains similar silver minerals and is treated by the same process as the ores referred to in this paper; therefore, a short description of the plant is of interest. The ore was given an oxidizing roast in Kaufmann furnaces, which are small circular, superimposed hearth furnaces of the McDougall type, and the product from several of these was fed to a furnace of the same type where it was mixed with salt and chloridized. This installation was not satisfactory, the loss of silver through dusting and volatilization was much higher than in the hand-rabbled reverberatories and chloridizing was not as good. The latter was due to changes in conditions in the oxidizing furnaces; the slightest change in fineness or sulfur content of the ore, or of the temperature of the furnaces would result in a product with either too much or not sufficient sulfur being delivered to the chloridizer. Further, because of continuous contact of the furnace shaft and rabbles with chlorine fumes, these parts corroded quickly and had to be replaced

every four or five months. The furnaces were only air cooled; if water cooling had been used the material might have given longer service. For these reasons, the chloridizing furnace was abandoned and the product from the oxidizing roasters was fed to ordinary hand-rabbled reverberatories and chloridized in the old way. Although this arrangement dispenses with considerable labor, it requires strong and skilled workmen. It also has the same disadvantage as the mechanical system; that, if conditions in the first stage of roasting are not kept strictly uniform, and it has been proved that this is not possible, chloridizing will be unsatisfactory. I am indebted for this information to Mr. L. Wurhaft, formerly metallurgist to the Huanchaca Co.

First Mechanical Furnace at Machacamarca

The first mechanical furnace installed at the Machacamarca plant of the Compañía Minera de Oruro was a six-hearth McDougall with an inside diameter of 14½ ft. (4.4 m.). It was first used in connection with two hand-rabbled chloridizing furnaces, where the calcines were mixed with salt. The furnace was fed with ordinary run-of-mine ore which contained about 35 oz. of silver per ton and 30 per cent. sulfur; the product from the McDougall contained from 4 to 4.5 per cent. sulfur. It was soon evident that the silver losses in the McDougall furnace were much higher than in the reverberatory furnaces. The loss of weight during roasting is from 18 to 20 per cent. on an ore with about 30 per cent. sulfur; therefore, if the raw ore assays 35 oz. per ton, the roasted ore should contain approximately 42 oz. per ton if no silver were lost during roasting. Instead of this, the product from the McDougall furnace assayed, usually, a little less silver than the raw ore, which proved that at least 20 per cent. of the silver passed through the stack. Later tests proved this loss to be much higher. The capacity of the furnace was 20 metric tons per 24 hr. when roasting from 30 per cent. sulfur to about 4 per cent. Water cooling was used, because on a 30 per cent. sulfur charge, the furnace would run so hot that if no particular care was taken, the ore would sinter on the third hearth, causing frequent breakage of rabble teeth. The higher the temperature, the heavier were the silver losses through volatilization. The economy in labor was not as great as had been expected, because one attendant was needed for the McDougall and four furnacemen were required at the reverberatories for chloridizing. These men could have roasted and chloridized 9 tons per day, using the reverberatories without the McDougall, so that the cost of labor was only reduced to about 45 per cent.

It was therefore evident that the furnace should be used in some other way. For some time, the attempt was made to assist chloridizing by feeding salt continuously into the furnace on the fifth hearth. The rabbles are so set that on this hearth the ore is moved from the periphery to

the center, so that, if salt was fed through one of the working doors on the fifth hearth chloridizing was carried on on the entire surface of the fifth and sixth hearths. But at this point the ore was not sufficiently roasted to react well with the salt, and the final product from the furnace contained too much sulfur and unchloridized silver to allow dispensing with finishing in the reverberatories. Later, in order to reduce the heavy losses of silver, the furnace was used only for roasting ore containing from 12 to 15 oz. of silver per ton with about 25 per cent. sulfur, but even on this material the silver losses were entirely too high.

The charge for the McDougall furnace is now prepared by mixing low-grade fines of run-of-mine ore with high sulfur content with silver-tin ore which carries only 15 to 20 per cent. sulfur. When working on this ore the furnace has a maximum capacity of 22 metric tons per 24 hr. and delivers its product to one reverberatory furnace for finishing and chloridizing, instead of to two furnaces as was the former practice. On ore with more than 30 per cent. sulfur, the capacity is only 17 tons. No fuel is used in the McDougall, but a small amount must be supplied to the reverberatory furnace so as to keep its temperature high enough for continuous chloridizing. The difficulty common to all continuous chloridizing is experienced here—slight variations in the McDougall furnace caused by different composition of the ore, etc., is at once reflected in the results. An attempt to remedy this was made by placing a small bin between the McDougall and the reverberatory, where the partly roasted ore could be stored, if it came down with too much sulfur. With this arrangement, two men working at the reverberatory furnace could finish roasting to the desired point without having to add the salt, and if the ore came down with too much sulfur, the charge to the furnace could be at once reduced. But it takes several hours to bring the McDougall furnace back to proper conditions, and if too much half-roasted ore was held in the bin, it became too cold for chloridizing, so that this arrangement was not satisfactory. Often some of the ore had to be chloridized before it was properly roasted to prevent its becoming so cold that it would spoil the work of the reverberatory roaster altogether. If, on the other hand, the ore came down too far oxidized, chloridizing would be bad because the salt could not react properly with the ore; there was no remedy for this, except mixing with elemental sulfur before chloridizing, which procedure is far too complicated and too expensive for practical work.

Losses Through Dusting and Volatilization

Losses of silver through dusting and volatilizing can be prevented by passing the roaster gases through a Cottrell precipitator. Experiments made by a representative of the International Precipitation Co. showed that 9500 cu. ft. of gas containing 0.32 gm. of solids passed each minute out of the stack of the McDougall furnace. Therefore, 4300 kg. of dust

were carried away per 24 hr. At that time the feed to the furnace was 22,400 kg. per 24 hr. of ore carrying 670 gm. silver per ton. The sample collected in the filter assayed 1070 gm. per ton; therefore, a little over 30 per cent. of all the silver that goes to the furnace is lost through the stack. The flue dust is a mixture of totally oxidized, half oxidized, and raw ore, and contains considerable antimony trioxide. The erection of a Cottrell treater alone would not have solved the problem, for the chief difficulty was the disposal of the dust. (1) It might be returned to the furnace feed; (2) it might be fed, together with raw ore, to one or more of the hand-rabbled reverberatory furnaces; (3) it might be treated separately, without further roasting, by some hydrometallurgical process.

The first method has the advantage of simplicity, but as the gases leave the McDougall furnace at about 180° C., all antimony trioxide driven off would be collected by the Cottrell treater and, since it cannot remain in the furnace on account of the high temperature it would accumulate between the outlet of the McDougall and the Cottrell apparatus, making it necessary to clean the conduits quite frequently, thus causing great irregularity in operating the furnace. It was suggested that the gases be kept so hot that antimony trioxide would not be condensed during their passage through the treater, but this would have been very delicate, and the furnace construction did not allow the construction of the Cottrell treater directly on top of it.

The second way, feeding the dust to other furnaces, has the disadvantage that a certain proportion of the dust would again be lost; and although this scheme on the whole would be feasible, and has been frequently practised here with dust caught in the dust chamber of the McDougall, it is not practical because it reduces the capacity in the other furnaces.

As the dust is a mixture of raw and roasted ore, it seemed practically impossible to obtain a satisfactory extraction by agitation with brine, cyanide, or hyposulfite solutions. Cyanide and hyposulfite failed to extract appreciable amounts of silver, but nearly 60 per cent. could be dissolved by a prolonged agitation of the dust with hot brine, to which a small amount of copper sulfate had been added. The residue of this agitation-leaching was treated by oil flotation, yielding a product of 41 oz. per ton; this brought the total extraction up to 85 per cent. Afterwards an attempt was made to combine the two processes in one operation by agitating with brine and copper sulfate in the flotation machine and adding oil at the same time, but no mineral froth could be formed.

The proposed hydrometallurgical treatment would therefore have consisted of the following processes: Agitation with brine and copper sulfate, precipitating the solution on copper and iron; decantation of the solvent and washing once or twice with water; oil flotation of the residue, filtering and drying the concentrate and feeding it to the reverberatory furnaces

together with raw ore. The same objection, that a certain amount of this flotation concentrate might be carried away again by the draft in the reverberatory furnaces, could be made here, but the sulfide in the dust is much coarser than the oxidized material, since it comes from the upper hearths of the McDougall furnace, where the draft is strongest, and only the finest of the oxidized grains, which come from lower hearths, will finally reach the stack, the coarser ones being again deposited on hearths higher up in the furnace.

The operation of a plant like that described on a basis of about 4 tons per day would be expensive and inconvenient; besides, this treatment is so complicated that perhaps feeding all the dust back to the reverberatory furnaces would have been preferable. Very likely a Cottrell treater would have been installed and the precipitate from it have been treated in the hand-rabbled furnaces, if there had not been developed, just at that time, a system of roasting which made the Cottrell precipitator superfluous.

There is little information available concerning the treatment of dust collected from roaster gases by the Cottrell process. Where ore or concentrate are roasted prior to smelting, the dust is usually by-passed the roasting furnace and sent to the smelter together with the roasted ore. However, I do not know of an instance where roasting is conducted as a preparation for some hydrometallurgical process, and where the dust collected by the Cottrell treater is either treated by a special process or refed to the roaster. Generally, descriptions of plants of this type state that the dust is collected for future treatment. This is unsatisfactory and it is far better to use a type of roasting furnace that does not blow a large percentage of its charge into the air, as do all circular superimposed hearth furnaces, thus requiring the installation of costly and delicate precipitation apparatus which finally recovers the ore that is carried away in the fumes in such a form that the valuable metals from it cannot be recovered.

Straight-line Reverberatory Furnace

The only type of furnace from which any result could be expected was the straight-line reverberatory Edwards or Merton. Furnaces of the revolving drum type, which were formerly extensively used for chloridizing roasting, make as much dust as the superimposed-hearth furnaces of the McDougall type, if not more. Blast roasting could not be used on account of the high sulfur content, and even after having reduced the sulfur by kiln-roasting, there was enough of it left to prevent sintering in the blast-roasting furnace. Moreover, chloridizing was not satisfactory with this treatment.

The next step in experimenting with mechanical roasters at Machacamarca was the erection of a straight-line, one-hearth Merton furnace

with five spindles as shown in Fig. 1. This type of furnace was selected because it fitted best in the plant, the hand-rabbled reverberatories having about the same dimensions. In order to get a good idea of the movement of the ore through the furnace, the ironwork was completely erected before the arch was built. Every spindle had but one rabble arm, which was 5 ft. long, and the rabble teeth were so placed on the arm that one-half of them project forwards about 6 in. and the other half are 6 in. backwards. These teeth are alternated, the object being to have the back teeth cut furrows in the ridges made by the front teeth.

If sand was fed at the center of the first rabble, it was gradually pushed outwards until the last teeth of the second rabble started raking it into the second zone of the furnace, which was formed by the second and third rabbles. The second rabble raked the sand inwards and the third rabble

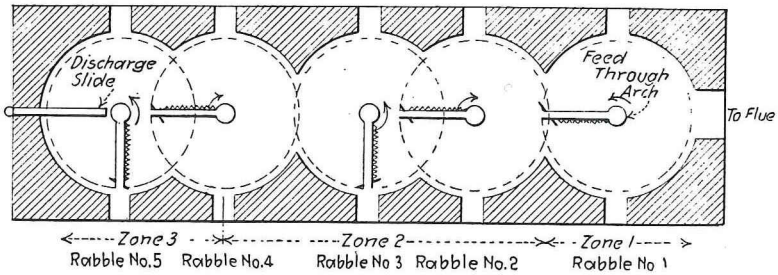

FIG. 1.—STRAIGHT-LINE ONE-HEARTH MERTON FURNACE.

raked it outwards again; no material entered the third zone, which is formed by the fourth and fifth rabbles, until it had traveled nearly the whole surface of the second zone. It was remarkable how well the Merton principle of zone-rabbling worked, and the speed of the driving machinery was so regulated that the material traveled in 8 hr. from the feed to the discharge end. This was supposed to be long enough for good roasting and chloridizing. All rabbles were provided with water cooling. No attempt was made to chloridize continuously as it was thought that better results could be obtained by intermittent work. The five spindles were driven through bevel gears from one shaft, which was cut between the third and fourth spindle, a jaw clutch being placed at this point. This arrangement allowed the independent operation of the fourth and fifth spindles, while the first three were stopped.

The furnace was charged near the center of the first spindle through a drop hole in the arch and the roasted ore was discharged through a radial slot under the last rabble. This slot could be opened and closed by a sheet-iron slide operated from the outside of the furnace.

The operation of the furnace was as follows: After heating the furnace by burning taquia fuel and oil on the hearth at the last four rabbles, ore was fed at the first rabble; after some time the ore would be spread all

through the furnace. As soon as it appeared to be sufficiently roasted at the last two rabbles, the clutch was thrown out (releasing the first three rabbles) and the necessary amount of salt was shoveled in through the working doors at the fourth and fifth rabbles. After chloridizing for about 20 to 30 min., the discharge slide was opened and the chloridized charge drawn off. After closing the discharge slide, all five spindles were again put into operation and a charge of raw ore was fed at the first spindle. The idea of stopping the first three rabbles during chloridizing was to prevent ore from the second zone, which was not roasted enough, from entering the third zone and spoiling chloridizing.

All the raw ore was not fed at one time for this would cool off the furnace too much; one half was fed and the remainder about ½ hr. later, after the first half had begun to ignite.

If the ore, during roasting, had behaved in the same way as the sand with which the movement was studied, the furnace would have worked admirably. But as soon as the ore becomes hot, it flows easily in the furnace, so that, instead of being nearly 8 hr. on its way between feed and discharge, it required less than ½ hr. for raw ore to appear at the last rabbles; therefore, raw ore and nearly roasted ore were constantly mixed; and to obtain a properly roasted charge in the third zone, part of the ore had to remain much longer in the furnace than was necessary and had to be over-roasted in order to roast the raw ore that had just been charged. This not only caused high silver losses through volatilization of silver from the over-roasted ore but decreased the capacity of the furnace until it would not keep its temperature through the combustion of heat of the ore alone, and after drawing off a charge, a small amount of taquia fuel had to be burnt on the hearth of the third zone. The losses of silver were nearly as high as in the McDougall furnace, and the furnace could be considered as an absolute failure. But its operation showed that chloridizing was more rapid and better than in the hand-rabbled furnaces, and that the consumption of salt could be reduced to about 60 per cent. This is to be attributed to the rapid and thorough mixing afforded by overlapping rabbles. The furnace was operated during several months in this way and many plans were tried to improve the results. The speed of the rabbles was varied from ½ to 6 r.p.m., and the rabble teeth were arranged in several ways, but always the ore moved too freely in the furnace and could not be kept in the zone where it belonged according to its state of oxidation. Also considerable ore moved backwards in the furnace, although this should have been impossible on account of the disposition of the rabble teeth, and particles that had been in the third zone were occasionally brought back to the first rabble.

If the furnace had been longer, the ore would have taken more time in traveling from one end to the other, and if it had been possible to experiment with a furnace of fifteen to twenty spindles, the difficulty might

have been overcome altogether. But the erection of such a machine, without the certainty that commercial results would be obtained, was more than the company could afford. Further, although such a furnace might do satisfactory work, the mixture of raw ore with partly and entirely roasted ore would always occur in the first part of the furnace. The ore flows most easily when it has just been ignited; toward the finish of roasting it hardly flows at all, and behaves more or less like cold material. This mixing would always cause over-roasting of part of the ore, causing undue silver losses through volatilization.

Modified Form of Straight-line Furnace

Later, the hearth was divided into three sections and the rabbles of adjoining sections were so spaced that a 6-in. (15-cm.) space was left between the sections that was untouched by the rabbles. A vertical cast-iron sliding door was so arranged between the sections of the hearth

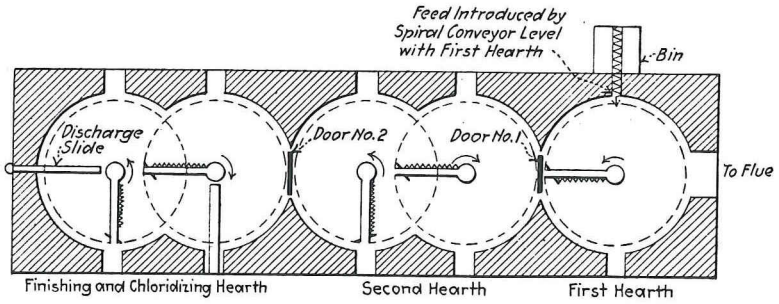

Fig. 2.—Modified form of Merton furnace.

that the ore could not pass from one section to the next if the door was lowered, but the door was low enough to let the gases pass freely between it and the arch. In order to facilitate the movement of ore from one section to the other the hearth was stepped 6 in. between each section, the lowest part being the section where the ore was chloridized and discharged. Instead of feeding the ore through the arch, it was planned to introduce it at the center of the first section, or hearth, by a screw conveyor laid in a channel under the hearth and covered by an iron plate. This arrangement, however, had to be altered because the conveyor could not push the heavy ore up the incline at the end of the channel. The conveyor was therefore raised above the level of the rabble and the ore fed at the periphery of the first hearth. This method of feeding was not satisfactory because on the first hearth, which has only one rabble, the ore should be moved from the center to the periphery, whence it is discharged to the second hearth. Therefore the furnace attendant occasionally had to push the ore to the center in order to make it spread more evenly on the hearth surface. In a later design of furnace this trouble has been overcome. This furnace is shown in Fig. 2.

As soon as the furnace got up to its proper temperature, it proved to be a success; it remained hot without the addition of fuel, roasting was uniformly good, and after slight trouble in the beginning, the doors could be operated quite easily. Chloridizing was excellent, and losses of silver through dusting and volatilizing were even smaller than in the hand-rabbled reverberatory furnaces. This was first proved by the higher silver content of the product of this furnace, compared with the roasted ore from the hand-furnaces, when both are fed with the same ore. Later, when a lixiviation tank was charged with ore roasted by the new furnace, it was found that the percolation was not as good as usual, which, of course, had to be attributed to a smaller loss of fine ore during roasting. Dust losses in the hand-rabbled furnaces must be considerably larger than in the mechanically rabbled, for the furnacemen generally rabble by making small heaps of ore in one corner of the hearth and then spreading these heaps with a violent push or jerk, which lifts small clouds of dust; but in the mechanically rabbled furnace no dust is caused by rabbling or moving the ore through the furnace.

The operation of the furnace is as follows: After bringing the second and third hearths up to as high a temperature as possible by burning fuel upon them, 700 kg. of ore is fed to the first hearth. If it fails to ignite, some sulfur and oil are introduced through the working door until roasting begins. As soon as the ore has begun to burn in the first hearth, the sliding door to the second hearth is opened, and a certain amount of ore is passed to the second hearth. Every revolution of the rabble pushes a small quantity of ore through the discharge opening to the lower hearth; and as the ore slides and does not fall there is no dusting whatsoever. It is absolutely necessary for the ore on the first hearth to be ignited, because if it is cold it does not flow and moves so slowly that it is practically impossible to transfer a charge of ore to the second hearth. Raw ore is gradually fed to the furnace and, after ignition, is passed farther down on the second and third hearths until there is a full charge of ore on every hearth. From this stage the operation must be carried on carefully and systematically. When the ore on the last hearth is ready to be chloridized, the damper is closed, the necessary quantity of salt is shoveled in at the two working doors, and the charge is chloridized in about 15 min. The discharge slides and the damper are then opened and the chloridized ore is discharged in another 15 min. After closing the slides, door No. 2 is opened and a charge of half-roasted ore is transferred from hearth No. 2 to No. 3, which requires 35 min. Door No. 2 is then closed and door No. 1 opened so that freshly ignited ore from the first hearth is charged on the second; about 25 min. are needed for this operation. Door No. 1 is then closed and the cycle of operations is completed by starting the feeder and introducing raw ore on the first hearth.

Under the conditions described, the capacity of this furnace, which

has hearths of 10 ft. (3 m.) inside diameter, is about 4 tons per 24 hr., when roasting an ore with 30 to 35 per cent. sulfur. The lowest sulfur content at which the furnace can be operated without fuel is 24 per cent., and on such ore the capacity increases to 5.5 tons. The rabbles make 2.2 r.p.m.; if operated at 5 r.p.m. the capacity of the furnace is increased about 20 per cent., but frequent breakage of gears and bearings showed that the construction is not strong enough for the higher speed. Power consumption is 1.8 hp. at 2.2. r.p.m. and 2.6 hp. when running at 5 r.p.m. The operation is simple and easy. All that the work requires is a little attention to the progress of roasting and regulation of draft. The damper is always open just enough to prevent smoke coming out of the two working doors on the third hearth, which are the only openings through which the furnace draws air. A cycle of operations requires no attention but the opening and closing of a few slides and doors, and starting the feeder, which draws its charge from a small bin placed by the side of the furnace. After raw ore is fed on the first hearth, there is nothing for the attendant to do until the charge on the third hearth is ready for chloridizing, which generally takes several hours. Bolivian boys quickly learn to do this work well, and one good man can easily attend to a battery of four furnaces.

Efficiency of Modified Straight-line Furnace

In this furnace 85 sq. ft. (7.8 sq. m.) of hearth area are required to roast and chloridize 1 metric ton of ore with over 30 per cent. sulfur; in the McDougall furnace 58 sq. ft. of hearth are required, but 10 sq. ft. per ton are necessary to chloridize the product in a reverberatory, so that the capacity of the new furnace per square foot of hearth area is 20 per cent. less. If, on the other hand, the modified Merton furnace were built with step bearings to support the spindles from below, instead of suspending them from the framework above, it would be feasible to drive the rabbles at 5 r.p.m. and to obtain a capacity of 5 tons per 24 hr., which would be 1 ton per 68 sq. ft., or exactly the same as the combination of McDougall and hand-reverberatory. But, even if the capacity were considerably lower the quality of work done is so much superior that loss of capacity is not a great objection.

The intermittent system of working, of course, means a certain loss of capacity. The furnace is working at full capacity only when there is a charge of ore on every hearth; therefore, counting from the moment when a charge has been chloridized, it is working on two charges instead of three during 85 min., which is detailed as follows:

	Minutes
Discharging	15
Passing ore from hearth No. 2 to No. 3	35
Passing ore from hearth No. 1 to No. 2	25
Feeding raw ore to hearth No. 1	10
Total	85

One-third of this time, or 28 min., must be considered as lost, since there are only two charges of ore in the furnace; as the time required for one complete cycle is 4 hr., nearly 12 per cent. of the capacity is lost. The difference in time needed to pass a charge of ore from hearth No. 2 to hearth No. 3 and that required to pass it from No. 1 to No. 2 is due to the fact that freshly ignited ore flows more easily than half-roasted ore. Further, the difference in level between hearth No. 2 and hearth No. 3 is 3 in. (7 cm.) less than the height of the rabble teeth. When the ore is being chloridized it piles up in front of the rabbles so that it is pushed against the communication with hearth No. 2, where it is apt to form incrustations which prevent the half-roasted ore from passing freely when the door is raised. These incrustations have to be removed every 24 hr. For this reason the fall between hearth No. 2 and hearth No. 3 should be at least equal to the height of the rabble teeth.

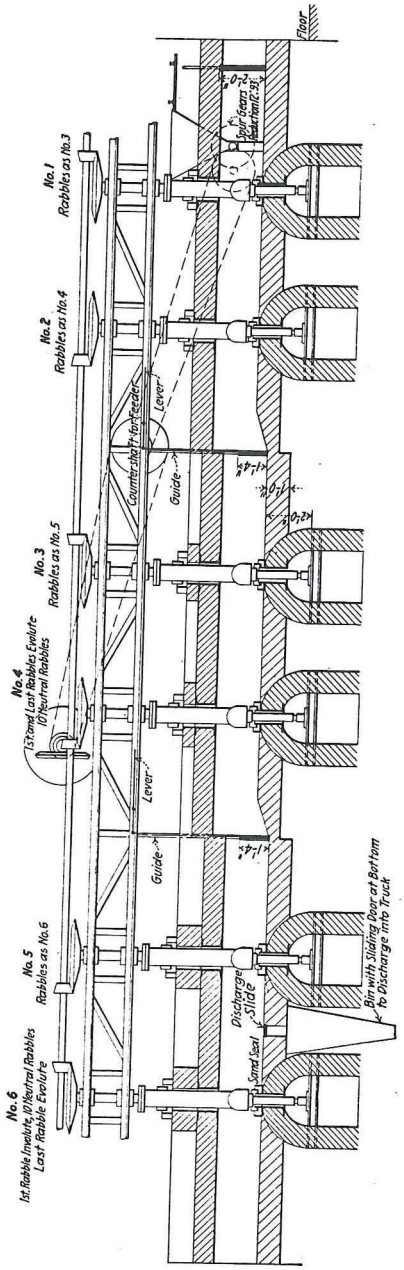

FIG. 3.—CROSS-SECTION THROUGH MODIFIED FURNACE.

In other furnaces of the same type which are now under construction, the spindles are supported on step bearings underneath the hearth, as shown in Fig. 3, and two rabbles are provided for every hearth. The ore is to be fed at the periphery of the first hearth at the first rabble, which has an involute tooth at the end, and will be discharged to the second hearth by the second rabble on the first hearth, which has an evolute tooth at the end. In this way the first hearth will work under much more satisfactory conditions than with only one rabble. The transmission machinery will be so constructed that two speeds are possible, a

slow one, from 4 to 6 r.p.m., to be used during normal operation, and a high one, from 10 to 12 r.p.m., for discharging and moving the ore from one hearth to another. In this way it will be possible to reduce the loss of time perhaps one-half. An attempt will also be made to use two rabbles on every spindle instead of one; this will improve rabbling without increasing the speed.

If a five-spindle furnace running at 5 r.p.m. has a capacity of 5 tons per 24 hr., a six-spindle machine, working under better conditions as far as the first hearth is concerned and equipped with all improvements described, ought to roast at least 6 tons, and probably more. Where larger units are required the furnaces may be built with more hearths, or with hearths of larger diameter. I would prefer the latter, because, if more hearths are used, more time is lost in moving the ore through the furnace. Although the actual time lost is practically the same for a furnace with more hearths, the percentage of time lost is higher on account of the larger charges put through the furnace. For instance, assuming that a five-hearth furnace is working under the same conditions as the present three-hearth furnace, it would have a capacity of about $\frac{5}{3} \times 6 = 10$ charges; this means that every 2.4 hr. a charge is drawn off. The time lost between discharging and feeding is:

	Minutes
Discharging	15
Passing ore to hearth No. 5	35
Passing ore to hearth No. 4	25
Passing ore to hearth No. 3	25
Passing ore to hearth No. 2	25
Feeding ore to hearth No. 1	10
Total	135

During this time the furnace would work on only four charges, so one-fifth of the time, or 27 min., is lost, but as the time needed for a complete cycle is 2.4 hr. the percentage of lost capacity is over 18. Further, if a furnace were built with more than five hearths in succession, more time would be needed to move a charge through it than elapses between two chloridizing operations, which means that the ore could not be fed quickly enough and poor chloridizing would result. All this is changed, of course, if the movement of the ore from one hearth to the other is increased by adopting a higher rabble speed.

If, on the other hand, three-hearth furnaces are used with 15-ft. (4.5-m.) hearths, the charges could be made twice as large, say 1500 kg. It should not take more time to transfer a charge of this weight from one hearth to another than a 700-kg. charge in the 10-ft. furnace, because the opening between the two hearths could be made so much wider, say 6 to 7 ft. Therefore, the percentage of time lost, owing to intermittent work,

should not be more than in the 10-ft. furnace, although this question can only be settled by experimenting with a larger furnace.

In furnaces of this kind, it is always necessary to have the two rabbles of one hearth overlap as much as possible so that no dead corners are formed. If an ore contains less than 20 per cent. sulfur, it is not likely that the furnace will keep its temperature, so to avoid the use of fuel the hearths may be built superimposed. During chloridizing and passing the ore from one hearth to the lower one, all draft can be shut off; to avoid loss through dusting, but there is always danger of volatilizing silver because oxidation of the ore, when falling through the furnace, is rapid and gives rise to high local temperatures.

Advantages of Intermittent System

Wherever it is important to obtain a uniform roast, the operation should be conducted in furnaces operated on the intermittent system, as described. If anything goes wrong in a continuous furnace, several hours are required to restore proper working conditions, and in the meantime a product that is not suitable for subsequent treatment must be discharged. In addition to roasting for leaching, this system may be useful when roasting for magnetic separation, or for differential roasting of complex sulfide ores preceding flotation.

As regards the performance of the furnaces, the following figures may be of interest.

Hand-rabbled Re verberatory Furnace

		Kilograms, Silver
Feed.....	15,353 kg. with 1038 gm. silver per metric ton contain	15.936
Product..	12,868 kg. with 1187 gm. silver per metric ton contain	15.274
Difference	2,485 kg.	0.662

The loss in weight during roasting was 16.2 per cent.; the loss of silver, 4.16 per cent. Screen tests on feed and product were as follows:

Through Mesh	On Mesh	Feed, Per Cent.	Product, Per Cent.
10	20	14	14
20	40	33	30
40	80	19	20
80	100	6	8
100	150	3	2
150	...	23	25
Tin content.....		2.35	2.74
Sulfur content.....		33.6	2.8
Iron content.....		32.0	39.3
Insoluble inclusive SnO_2.....		26.6	32.8

For chloridizing 4.9 per cent. of salt was used and 2.1 per cent. of fuel was added. The furnace product contained 220 gm. per ton of silver insoluble in water and hyposulfite solution, and lost 6.2 per cent. of its weight by lixiviation, so that 0.938 × 12,868 × 0.00022 = 2.655 kg. of silver were lost in the residue. This gives an extraction of 82.6 per cent. of silver from the roasted ore and a total recovery of 79.15 per cent.

Mechanically Rabbled Reverberatory Furnace

		Kilograms, Silver
Feed.....	26,866 kg. with 1119 gm. silver per metric ton, contain	30.063
Product.....	21,690 kg. with 1365 gm. silver per metric ton, contain	29.606
Difference.....	5,176 kg.	0.457

The loss in weight during roasting was 19.3 per cent.; the loss of silver, 1.52 per cent. Screen tests on feed and product:

Through Mesh	On Mesh	Feed, Per Cent.	Product, Per Cent.
10	20	20	16
20	40	28	27
40	80	18	25
80	100	5	7
100	150	5	8
150		23	25
Tin content.....		2.01	2.38
Sulfur content.....		33.1	3.1
Iron content.....		31.7	38.6
Insoluble inclusive, SnO_2.....		27.8	35.3

Only 3.3 per cent. of salt was used, and no fuel. The residue of the chloridized ore contained 175 gm. silver per ton after leaching, and 4.2 per cent. of weight was lost during leaching, so the insoluble silver lost in tailings was 0.958 × 21,690 × 0.000175 = 3.636 kg., or 12.2 per cent. of the silver in the roasted ore. The total recovery is 86.37 per cent. The larger loss of weight during roasting, compared with the hand-rabbled furnace, is due to the smaller percentage of salt used in the mechanical furnace and to the omission of fuel, which contains 45 to 50 per cent. of ashes. Further, the smaller amount of salt used accounts for less soluble salts and therefore for less loss in weight during lixiviation.

No detailed figures need be given for the McDougall and reverberatory chloridizing plant, as the loss of silver in the McDougall alone is over 30 per cent. The McDougall product is never uniformly chloridized and the insoluble residue of the final product is always above 200 gm. per ton on an ore containing around 800 gm. per ton, so the total loss in this system is well over 40 per cent.

The following figures show that nothing is gained by leaving the ore longer in the furnace in contact with salt. After chloridizing a charge, as usual, for 15 min. a sample was taken, and chloridizing continued for another hour, samples being taken at intervals of 10 min.

Chloridizing Period, Minutes	Silver Content of Charge, Grams Per Ton	Insoluble Silver, Grams Per Ton
15	1160	160
25	1200	150
35	1130	150
45	1270	150
55	1260	140
65	1220	150
75	1230	150

The differences in silver content of the charge are due to imperfect sampling, but it can be assumed that once the silver is chloridized no volatilization takes place even if the finished ore is left too long in the furnace. Chloridizing is improved so little by prolonging the process that it is not worth while doing so.

The following figures give a comparison of the cost of roasting in the three different types of furnaces:

	Hand-rabbled Reverberatory	Mechanically Rabbled Reverberatory	McDougall, with Hand-rabbled Chloridizing
Labor	$2.57	$0.52	$0.92
Salt	1.60	1.38	1.41
Fuel	0.40	....	0.17
Repairs	0.05	0.31	0.40
Power	....	0.89	0.73
	$4.62	$3.10	$3.63

These figures are in Bolivian dollars per metric ton; one Bolivian dollar is equal to about $0.36 United States currency. At the time of writing, the improved Merton furnace had been used for over 20 months, and the only repairing due to normal operation was the replacing of several rabble teeth. Since the charge-roasting system puts a much heavier strain on the rabbles than continuous work, all the original gears had to be changed for heavier ones, and rabble arms and spindles were broken in the beginning through the carelessness of operators, whose cleaning tools were caught by the mechanism, but these are not repairs due to normal causes. The rabbles and spindles do not appear to become corroded by the chloride fumes.

Crushing

Originally, No. 4 Krupp ball mills were used, but they were later replaced by two pairs of 36 by 12-in. (91 by 30-cm.) rolls. The rolls did the work for less than one-third of the cost of the ball mills, but gave a

distinctly coarser product which decreased the furnace capacity considerably. Therefore, a Toncap wire cloth of only 0.85-mm. opening was used on the finishing screen instead of one with 1.2-mm. opening on the ball mills, to obtain a product that was suitable for the furnaces. The first rolls were set with a ¼-in. (6.4-mm.) opening and their product went to a trommel with ⅜-in. (9.5-mm.) openings, the oversize being returned to the coarse rolls and the undersize going to the finishing trommel, which was 42 in. in diameter and 12 ft. long. The last trommel was operated in closed circuit with the finishing roll.

Afterwards, a ring-roll mill was installed to do the work of the fine rolls and a 6 by 8 ft. (1.8 by 2.4 m.) Newaygo screen was used instead of the trommel. Although with this arrangement the product was as fine as that from the ball mills and the capacity higher than from the roll plant, it was not found economical, on account of the high power and steel consumption of the ring-roll mill, which also showed other weak points in its construction after having been used for some time. At the time of writing, the rolls are again used, but with a Newaygo screen instead of the finishing trommel; although the product is not quite as fine as that from either ball mills or ring-roll mill, it is sufficiently fine for the purpose. The cloth on the Newaygo screen, which is a No. 8 with 0.078-in. (1.9-mm.) opening, lasts over two months, and the screw conveyor which distributes the the ore evenly over the screen surface has a life of about 75 days. Power consumption is 11.8 hp.-hr. per ton ground from 2 in. (50-mm.) maximum size to about 1 mm., and steel consumption is 0.38 lb. (0.17 kg.) per ton. The following list gives a comparison of products from the different grinding machines used.

Mesh	Krupp Ball Mill 1.2-mm. Toncap Wire Cloth, Per Cent.	Rolls With 0.85-mm. Trommel, Per Cent.	Rolls With Newaygo Separator, No. 8 Cloth, 1.9-mm. Opening, Per Cent.	Roughing Rolls and Ring-roll Mill With Newaygo Separator No. 6 Cloth, 3.0-mm. Opening, Per Cent.
On 10	3.0	0.0	1.5	4.0
On 20	17.0	19.0	16.0	24.5
On 40	24.0	31.5	19.5	20.0
On 60	8.5	11.0	23.0	5.5
On 80	7.0	10.0	8.0	4.0
On 100	5.0	5.5	5.5	6.5
On 150	3.5	4.5	4.5	9.0
Pass 150	32.0	18.5	22.0	26.5
	100.0	100.0	100.0	100.0