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The reverberatory furnace for ore smelting: an experiment on a South American innovation

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Abstract

Research in both South America and Europe in a diachronic perspective allowed to bring together a series of examples relating to the use of a reverberatory furnace for smelting non-ferrous ores. Although the invention of this process may have occurred in multiple places, the main region of innovation is incontestably the Andes. To approach this dynamic process of innovation, we decided to study this using an experimental approach. Over 6 years and 14 tests, a total of 165 hours of firings were conducted on the experimental platform at Melle, France. The tests carried out with galena (PbS) allowed us to understand the operating mode and the possible yields of this type of furnace. By analogy, this provides information for the better identification of archaeological remains.

Key-words

Lead and silver metallurgy, reverberatory furnace, know-how, efficiency, analogy approach

Introduction

The use of a reverberant roof is a common practice in the cooking of food and pottery, in the production of glass and in the melting of metal alloys. This technique is used very early in history, perhaps as soon as the furnaces appear. However, a reverberant roof is not a reverberation furnace. In the metallurgical field, this designation precisely defines a furnace where there is a separation between the production of heat, its use and the evacuation of gases. A reverberatory furnace consists of three separate spaces connected by windows: a fire chamber, a melting chamber and a chimney. The draught induced by the chimney ensures the circulation of the flame from the fireplace through the melting chamber. Therefore, there is no contact between the material to be melted and the fuel, unlike in wind and shaft furnaces. There is a field in the art of firing where the use of this type of furnace was slow to become established before then becoming predominant: the smelting of ores.

The case of the reverberatory furnace for smelting of non-ferrous ores poses a problem in both historiographical and technical terms. According to German, English and French authors (Schlüter, 1753; Tylecote, 1992; Brûlé, 1994), this mode of production appeared at the end of the 17th century in England before spreading to the rest of Europe. However, referring to the Treaty of Biringuccio (Biringuccio, 1540), it seems clear that such a system was already functional in the mid-16th century. In the same period, in 1557, metallurgists working at Rocca San Silvestro in Tuscany were familiar with the reverberatory furnace for smelting ore (forno del reverbero) although it does not seem to have been widely used (Farinelli, 66 and 230, 2017).

In the Andes, precise descriptions of this type of reverberatory furnace and its mode of operation appear as early as 1618 in the Oruro mine (Cobo, 1653) and around 1626 in Lípez (Barba, 1640). Significantly, because these references show a well-defined technical language, it can be inferred that such technology would date back at least to the last decades of the sixteenth and early seventeenth centuries. It is also relevant that for Alonso Barba, one of the most experienced experts of his time, these reverberatory furnaces, whose use he points out was then widespread in the regions of Chichas

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and Lípez (Barba, 1640, 138), represented something novel. Similarly, Fernando de Montesinos (1638: 278-279) implied some years later that these same furnaces, already widely used "throughout Peru", were the result of local innovation. Likewise, a colonial document from 1635 (AGI, Lima, 331), shows us drawings of a model of a reverberatory furnace and another of a roasting furnace. The text that accompanies these drawings refers not only to the fact that this model of reverberatory furnace is used in "all" Peru, but that its knowledge was "secret", that is, unknown to the Spaniards. The author of this document, whose name is still unknown, claims a prize for revealing this secret. While we have archival evidence of the existence of the reverberatory furnace in Europe (Farinelli, 2017), the Southern Andean region provides much archaeological evidence in addition to historical records. The oldest of these dating back to the Middle Horizon (500-900 AD) was uncovered at a metallurgical site near the Uyuni Salt Flat (Letchman et al., 2010; Cruz, Téreygeol, 2014). Later, during the Colonial Period (second half of the 16th century - 18th century), these furnaces were very successful and widely found in southern Bolivia and north-western Argentina (Angiorama, Becerra, 2017, Cruz, Téreygeol 2020). Our investigations both in Europe and South America suggest that it is possible that we may be see an Andean particularism whose influence on European metallurgy remains to be demonstrated. Precedents exist, as has been shown for the Xabecas furnaces for the sublimation of mercury. It is also important to take into account that the main experts on colonial metallurgy in the Andes, among them Barba, Lorenzo de Mendoza, Francisco Moreno and Carlos Corzo, were repatriated to Spain by the Crown at the beginning of the 17th century to apply their knowledge and experience acquired in the "New World" in Spanish mines (e.g. Rio Tinto and Plasencia).

To discuss this type of furnace, its use in different geographical areas and its chronology from the 16th century to the end of the 19th century, it appears essential to understand how it works, to identify the knowledge created by it, and to comprehend the product and waste obtained by its use. Starting from this perspective, we follow the approach proposed by F. Sigaut to: "understand through experience, and above all understand these techniques for themselves, before using them to prove something else" (Sigaut, 1991, p. 78.).

The archaeological evidence

From 2003 to 2014, a combined team from CONICET (Consejo Nacional de Investigaciones Científicas y Técnicas) and CNRS (Centre National de la Recherche Scientifique) conducted a series of surveys in the department of Potosi in Bolivia, gathering evidence of the use of reverberatory furnaces for the smelting of ores. Among these, the furnaces of Vila Punku Cueva (21°37'51.6" S, 66°26'45.5" W) at an altitude of 4328 m in the mining district of Santa-Isabel are noteworthy for their exceptional conservation due to their position in rock shelters in an isolated valley. The historical context of the Santa Isabel mine as well as the ceramic shards discovered in the immediate surroundings of this workplace are from the Colonial Period, most probably dating to the second half of the 17th century. Here, we will focus on one of the two furnaces located in Vila Punku Cueva. (fig. 1)

Figure 1, Reverberatory furnaces for ore smelting (Santa Isabel, Bolivia)

The excellent state of conservation of this structure observed permitted a precise survey. The only uncertainty is the height of the chimney. The furnace has a length of 3.6m and a width of 2.3m. It is placed directly on the ground surface and consists of three spaces interconnected by small windows (46 cm wide, 15 cm high). The first space is the firebox. It has two compartments: the firebox chamber itself and an ash pit open to the outside, that also provides ventilation for the unit. Stone lintels are placed at the interface of the two compartments to hold the logs introduced laterally through a small opening of 20 x 10 cm. The second space is the smelting chamber. It is positionned under a dome, 2.3 m in diameter with a roof height of 110 cm. The roof is pierced by a top opening of 40 cm in diameter.

Lateral to the axis of the chambers, there is a door equipped at the base with a tap hole of 4 cm in diameter. There are 3 windows facing the door and a fourth one above it. The floor is flat and glazed over its entire surface. It has a deliberate and significant 20° inclination towards the tap hole. As for the chimney, it has a preserved height of 130 cm and a truncated cone shape with a base of 1 m internal diameter. The chimney is connected to the smelting chamber via a small window.(fig. 2)

Figure 2, Drawing integrating both the archaeological and experimental structures

The experiment

A similar furnace was recreated at the experimental platform in Melle, France (Téreygeol, 2011 and see https://www.mines-argent.com/paleo-metallurgie.html). Although the geometry of the furnace was fully respected (fig.2), it was not reasonable to organise a reproduction on a scale of 1:1, for two essential reasons: the mass of materials (clay, stones) to be used would be around 2 tons and above all, the capacity of the original furnace would require gathering nearly 300 kg of galena to carry out a single test. The existence of furnaces with similar architecture, but of smaller dimensions, found in many places in the regions of Lipez and Chichas attest to the functionality of the structure on a reduced scale. The overall dimensions of the furnace were therefore reduced to 2.5 m length and 1.3 m width, a reduction of one-third of the original. The furnace required 448 kg of powdered chamot, 112 kg of dry powdered clay and almost 200 kg of stone. The small quantity of clay (less than 15% by mass) should not be surprising. It corresponds well to the observations made in the field, which showed a very heavily degreased clay used mainly as a binder for the stones.

The experimental work presented here was carried out between 2010 and 2014 with a total of 165 hours of heating in 14 controlled tests. The first step consisted of drying the structure. Next came the first tests of heating without ore to assess the draught, the rise of temperature and the fuel calibration. Once this data was acquired, we started tests to evaluate the heterogeneity of the work conditions in the smelting chamber. At this stage, the first smelting tests were carried out. Finally, we tested the continuous smelting of the ore with successive refills, the data are summarized in figure 3. Thermal graphs of most representative experiments are given in the annex.

Figure 3, synoptic table of experiments

The ore used was a commercial galena. It is pure, very weakly argentiferous and comes from a Moroccan mine. The fuel was simple firewood purchased locally. Logs 50 cm long and 10 cm diameter were split into quarters. The smelting chamber was equipped with a series of 6 K thermocouples and the recordings were made in 20 minutes intervals.

Drying and first trials (tests STI 1 to 5)

The first heating (ST1) aimed at drying the structure because 200 litres of water were needed for the construction. It allowed us to familiarize ourselves with the furnace, to learn how to fire the logs and ensure the best possible draught. A cover was placed over the top opening. The heating process lasted 15 hours. For this preliminary phase, temperature control was limited to a single temperature sensor. After 13h, the furnace reached 750 °C, and when the fuel supply was stopped the temperature rose to 900 °C. The absence of a charge in the furnace induced a limited circulation of the flame, which moved through the smelting chamber from one opening to the other by the most direct path.

A second test (STI2) was carried out by filling the smelting chamber with some ceramic elements to force the flame to circulate longer in the chamber. It is at this time that we equipped the furnace with a

set of 6 thermocouples arranged as shown in figure 4. During the phase of temperature rise (from T100 to 300), the temperature difference between the coldest part (probe 6, door area) and the hottest temperature (probe 5, then probe 10, see figure 2 for location) was about 150°C. This thermal gradient led us to consider the arrangement of the ore in the hearth. A uniform layout does not seem appropriate; rather a stockpile at the top of the inclined base of the hearth, which is located opposite the door. At full operational capacity, the furnace showed a temperature difference between the different measurements on the order of 50 to 100°C. This thermal heterogeneity was sufficient to achieve a complete reaction of the ore regardless of its location in the hearth. It was arbitrarily stopped after 7 hours of heating. In this furnace model, the height of the chimney was restored at the minimum that was observed in its abandoned state at Vila Cueva Punku. For the following tests, we lengthened the chimney duct by about 50 cm to reach 110 cm.

The third test (STI3) lasted more than 12 hours with the same goals. Sensor 10 was brought to the highest temperatures (+/- 1100°c). Sensor 5, located at the top of the dome, and sensor 9 were exposed to high temperatures, which seemed in line with those observed directly after leaving the fireplace. Sensors 7 and 8 gave a very similar pattern, while one was in the dome and the other at the base of the hearth. Finally, sensor 6 provided the minimum temperature reached throughout the heating process. This was located against the casting door. The thermal gradient as shown is not focused on the center of heating space, but on the window that connects the fireplace to the dome. Very encouragingly, the thermal amplitude in the chamber is reduced by half between the beginning and the end of the experiment, being limited to 70°C. During the heating process, we opened the vents, which gave the furnace a much greater draught and limited the gas backflow to the fire chamber. Although the furnace was cold and humid, there was no problem reaching the 900°C level.

Progressing cautiously, we decided to conduct a 4th experiment (STI4) to better understand the role of openings drilled in the dome. Their function remains difficult to explain even though this configuration has been observed on many occasions in the field. At the time of heating, the cover of the dome was in position, but not hermetically sealed. The openings were plugged. The test lasted just under 10 hours. Around the 7th hour, the furnace reached the operational phase and the flames began to come out through the chimney. The opening of one and then two vents did not seem to lead to any particular change in the atmosphere of the furnace. However, when all the openings were clear, the furnace changed to an oxidizing atmosphere.

For the 5th test (STI 5), we chose to arrange five scorifiers crosses filled with millimetre-grained galena (fig. 4). The objective was to check whether the reduction of the galena took place for all the containers or only for some of them. The heating lasted a little more more than 8 hours. Initially, the temperature rose rapidly (600°C at T120). When an average temperature of 900°C was reached (around T400), this level was maintained until the end of the operation. When the scorifiers were removed, it appeared that the galena had smelted at all locations. The scorifiers were cut for macroscopic examination. In each one, a mass of lead had formed. By cross-referencing the data on the slagging, the temperature records and previous experiences (Mercier, Téreygeol, 2016), it appears possible that the correct conditions were reached on the entire hearth level. The galena smelted, desulphurised and turned into litharge. The atmosphere had been reductive enough to allow the formation of a lead nodule found in each scorifier. But the operation stopped prematurely and the transformation remained incomplete, hence the systematic presence of lead oxide baths. At this point in the procedure, it seemed that the reverberatory furnace was capable of receiving a real charge of ore.

Figure 4, Distribution of the scorifiers during test STI-5

Single-load and casting tests (tests STI 6 to 8)

For this first test with ore (STI6, see figure 5), we used 30 kg of galena with heterogeneous grains (centimetric to pluri-centimetric) arranged vertically towards the opening at the top of the dome. During the temperature rise, the galena was pulverized. An oxidizing atmosphere seems to have been prevalent from T60 to T220, and the transition to the reduction phase took place without any particular intervention. Sensors 6 and 7 showed the lowest temperatures. The final result of this operation was a viscous slag mixed with lead-bearing elements and galena. Metallic lead was well constituted: 400 g could be gathered while there was also a non-negligible quantity of lead nodules in the slag. Obviously, we stopped the experiment too early. A bath was forming associating all the states of transformation of the galena. It is also possible that during this experiment we did not sufficiently drive the furnace to reach the temperatures necessary for the transformation for a sufficient period of time.

Figure 5, Running furnace during test STI – 6

The STI-7 test was conducted over 10 hours with another 30 kg of ore placed under the three openings. After nearly 10 hours of heating and casting, we recovered 1.8 kg of lead. The yield calculated on the basis of the lead available in one kilogram of galena (870 g) is 6.9%. Of course, this is not enough to prove a successful test. The slag recovered weighs 8.8 kg. 2/3 of the material put into the furnace was missing. Some of it was of course lost in the fumes, but most of it had attached to the furnace hearth level.

The STI 8 experiment was conducted 4 days later for almost 6 hours. Benefiting from the thermal inertia and drying of the previous heating, the fire was much less erratic. Galena desulphurization started before the second hour of heating. Then, all sensors showed temperatures systematically higher than 800°C from 3 hours of heating. The furnace itself decided the end of the experiment since at T350 a stream of liquid lead managed to flow out of the furnace without us opening the tap hole. The evidence of a lead bath in the furnace being given, we opened this small tap hole through which 3 kg of liquid lead escaped. Then we opened the slag outlet hole. We obtained a nice vitreous slag flow. The lead yield was 11.5%. (Figure 6)

Figure 6, Running lead then slag from test STI- 8

Multiple loads and castings (tests STI 9 to 12 and 14)

The STI 9 test was conducted over 12 hours, using 90 kg of galena to allow for galena refills after casting. A first load of 30 kg was placed under the vents. We observed a later start of desulphurization of the ore (at T220 instead of T110 previously). Considering the results, the moment when this desulphurization started (more exactly, the moment when the operator was mainly aware of the scent) is not crucial. At T520, we tried a pouring process. Lead then flowed for more than 45 seconds, filling the entire foreheart until it slightly overflowed. No slag flowed out. Immediately, 30 kg of galena were added through the three vents, cooling the furnace. 40 minutes later, another attempt at pouring took place. Only a few fine lead threads ran out. The door was opened wider, which brought about a large slag flow. The opening was closed again and the furnace recharged with ore (30 kg). 40 minutes later, a pour was attempted again. Fine threads of lead flowed out, then, once the door was opened, we observed a thin slag flow. This one was much colder than the first one. The operation was then stopped. The next day, when we opened the smelting chamber, we found the third load of ore intact.

The material balance is debatable, but merits discussion. During this test, 8.5 kg of metallic lead and a 21 kg vitreous slag were collected. This slag was analysed by LA-ICP-MS. The glass holds 70 % mass lead (i.e. 14.7 kg of lead). A total of 23.2 kg of lead was removed from the furnace. The graph of the temperature curves also seems to prove that our precipitation had fixed the successive additions of galena. The 2nd and 3rd series of lead casting came from the first charge. So, only the first 30 kilograms of galena (i.e. 26.1 kg of lead) seemed to participate in the production of lead. We therefore had a maximum loss of 2.9 kg. The lead metal yield of this first charge is of the order of 28%. If it were otherwise, we would have had a more important formation of slag. We understand the function of the four vents. The three opposite the door are used to recharge the furnace during heating. The fourth one, above the door, allows us to see at which level the bath is located in order to choose the moment of casting. It would therefore only play a controlling role.

A further year separated the STI 9 and 10 experiments. For this new attempt, we considered that the 3rd un-smelted charge from the previous experiment was sufficient. No fresh galena was added at the beginning. The temperature rose quickly. When reaching 750°C (T180), white smoke appeared accompanied by the smell of sulphur (SO2 release). The roasting process began and lasted nearly 3 hours. Then, the temperature stabilized between 900 and 1000 °C. At T540, a casting was carried out consisting solely of lead. Following this, a load of 30 kg of galena was added. This resulted in a sudden drop in temperature at sensor 7, to 675°C. The top of the dome as well as the door area were practically unaffected in terms of temperature change. At T645, a new casting was attempted. This time, after a slight lead outflow, slag ran out of the furnace for 10 minutes. The operation was then stopped. The successive lead and slag flows were easy to separate. We could therefore cold assess the yield of each casting. The first casting came only from the 30 kg stock in the furnace before firing. There was only lead for a mass of 12 kg. The yield reached 46% taking into account only the lead available in the galena (87% or 26.1 kg of lead for 30 kg of ore). The following charge led to an almost exclusive casting of slag. For this experiment, the roasting phase lasted 3 hours. And the lead casting took place 3 hours after the end of the roasting process. It is difficult to assess whether this duration can be reduced. The only information we have on the durations relates to our own previous ore tests in a muffle furnace (Mercier, Téreygeol, 2016): the roasting process then lasted 30 to 40 minutes while the reduction phase did not exceed 10 minutes. We did not note any variation in time for 10 to 30 g testings, but we were working with a 30 kg load in the current test. In the previous case, the $T_{Roasting}/T_{Reduction}$ ratio was 4 (Mercier, Téreygeol, 2016). It was 1 with the reverberatory furnace. It would seem that the ore mass has a positive influence on the reduction of the roasting time and thus the total smelting time.

The STI 11 test was carried out a few days after the previous one. The protocol was evolving: the ore was introduced once the furnace reached smelting temperature. The additions of ore were made at regular intervals in quantities of 2.5 kg. This was a fundamental change to see if it was possible to work the non-ferrous metal sulfide melt (matte) in a single smelting process. In fact, at smelting temperature, the galena liquefied and formed a bath of lead sulphide that had to be desulphurised. The temperature of the furnace rose quickly to reach the temperature range necessary for smelting the ore.

We have not attempted to maintain this since the ore was not yet in the furnace. When the sensor 7, usually the coldest along with sensor 6, reached 900°C, we started the ore feed. Directly afterwards, sensor 6 lowered and then stabilized at about 750°C. This sensor was located at the door. The linearity of the temperature measurement after T240 indicated that the thermocouple was caught in a bath, which was confirmed by the third casting. The presence of a bath already formed before the introduction of the ore led us to try an opening at T322, when only 2 ore charges were introduced (at T315 and 320). The lead flowed out. We recharged twice more before attempting a second pour. This one was much less significant, so we left more time for the process to continue. After 20 charges of galena and when the furnace showed good thermal regularity, we first open the tap hole, then the small door. A very small amount of lead flowed out while an impressive mass of vitreous slag escaped from the furnace for 10 minutes. In this slag glass, lead prills could be seen percolating at times. At the end of the operation, we collected a total mass of 21 kg in the forehearth (figure 7). It was composed of three different layers: at the bottom, a 6 kg lead mass, above a matte (10 kg), all covered with a vitreous slag (5 kg). It should be especially noted that the pouring of the 6 kg of lead occurred during the first opening of the furnace when only 5 kg of galena had been put into the furnace! This lead therefore comes from a remaining charge from previous operations. Thus, the operation did not really result in the production of metal. This shows the importance of working with a used furnace. It provided a situation much closer to the metallurgist's experience. They knew how to take advantage of the residual matter in their furnace to facilitate subsequent smelts.

Figure 7, lead, matte and slag from test- 11 (scale: 20 cm)

Clearly, the procedure chosen was still not completely appropriate. The introduction of galena while the furnace was in a temperature range above 1000°C led to the melting of the galena, but not to the smelting. To reach this temperature, the furnace was in the reducing phase and sulphur could not be released efficiently. Here we observed a change in the system of production compared to a shaft furnace, in which we are looking for these temperature ranges. But, in that case the ore is in contact with the charcoal and can be reduced.

The STI 12 procedure was carried out in 2014. The operation started with the heating of the smelting chamber prior to the deposition of the ore. A first lead pour occurred less than two hours after the start of the experiment before any ore was introduced. The furnace was then in production conditions closest to reality: a used device with a presence of remaining lead to help to reduce the charges. This obviously renders the question of yields very difficult. The desulphurization of the charge put into the furnace started after 4 hours. It would be effective for 5 hours. As the furnace reached a temperature plateau at 1000 °C, the tap channel was opened. It let out 8 kg of lead. Once the temperature was brought back below 750°C, we added a new charge of 30 kg of small-calibre galena. Desulphurisation was almost immediate, while the temperature rose faster than we would have liked. Two and a half hours later, the temperature peaked again around 1000 °C. A second emptying started with a lead metal pouring followed quickly by a slag glass. We then made sure to lower the temperature more sharply (700 °C) before proceeding to a new galena load (in the form of blocks). Signs of desulphurisation appeared later, once the 800-850°C threshold was reached. The reduction continued with a regular rise in temperature over 3 hours. Then, another consequent lead casting followed by a slag casting was carried out. The test was stopped at the end of this fourth run. This allowed the furnace to run continuously. Lead production was realised. Only a too short a time period between the two smelts explained the poor yield. Unsurprisingly, the use of small grains of ore was preferable to the use of blocks. For the same mass, a fine grain size ensures more contact surface. By contrast, there is no advantage in using powders that tend to agglomerate.

We then heated the furnace to "clean up" it. No galena was introduced. The operation (STI 13) took place between 9h and 17h30 with a maximum rise to 1080°C on sensor 9. A casting of 11kg of lead was carried out, showing how much the hearth was impregnated with ore and how difficult it can be to evaluate the efficiency of an experimental furnace.

The last test (STI 14) was carried out in 2015. It aimed at validating the cyclic running of this furnace as well as our ability to correctly manage the temperature so as to alternate the roasting and reaction phases over a long period of time. The experiment was conducted for more than 28 hours with 90 kg of ore. For the first 8 hours, the operation consisted of raising the furnace temperature. During this increase, temperatures varied by about 100 degrees from one point of the furnace to another. Sensor 6 was a special case. The sensor was mired in the hearth level of the furnace, which has thickened considerably because of the accumulation of slag from previous tests. As the temperature rose, it followed the same course, but with a differential of 400°C. More than 15 hours after the start of the experiment, we were able to remove it and restore it to a position equivalent to that in the previous tests. At that point, the temperature indications then joined with the other 5 sensors. The table (fig. 3) summarizes this later test delivering 21.4 kg of lead in 5 castings. The efficiency of the operation was around 26%.

Discussion

With the results of the 10 tests carried out with galena, totalling more than 116 heating hours, we can propose a model of operation of this type of furnace. According to contemporaneous historical data, this type of furnace operated via the roasting and reaction method (Schnabel, 1896, 259-261). During a single heating, the desulphurization of the ore was induced at a temperature range around 750°C while the atmosphere was oxidizing, following by an increase in temperature by changing to a reducing atmosphere around 950-1050°C. However, the reaction was complex, leading to reversible formations of lead, lead oxide, lead sulphate and lead sulphide.

The mode of operation seems to be as follows (figure 8). Before heating, the ore is deposited in the upper part of the hearth level at the base of the three openings. A hazelnut size ore appears to be the best granulometry. The temperature increase is directly linked to the ambient humidity level. In this experiment, a minimum time of 2 hours is necessary to obtain the temperature range required for roasting. This stage is characterised by the appearance of white smoke and a distinct smell of sulphur dioxide. This roasting phase is maintained for at least two hours. The fire is then enhanced by changing the type of fuel: the logs are replaced by small sticks of wood that burn more quickly and give off a flame. Two more hours are needed to reach a 250°C increase and bring the smelting chamber to 1000°C. A first lead pouring can take place at this time. At the same time, the lead reacts with the clay on the walls, causing the vitrification of the furnace walls and the formation of a vitreous slag. The temperature is maintained in the range of 1000 °C for almost 3 hours, which allows for the production of lead. This first cycle concluded the majority of our tests. During our last test, we tried to reproduce the cycle. After a first lead pouring, we lowered the temperature to return to the range corresponding to the roasting. Galena was added at the beginning of the temperature drop. The cycle was reproduced, leading to a new lead pour. The same sequence was repeated four more times before the experiment was stopped. It is here that the metallurgist's knowledge matters most. Indeed, the first cycle is relatively simple to manage, but its reproduction while the combustion structure is hot, is a far more delicate process. It is necessary to be able to maintain the smelting chamber at a low temperature allowing for desulphurisation, without the galena melting as soon as it is introduced. The formation of a matte in this process must be avoided, as it affects the entire charge and can no longer be picked up when it has accumulated against the door. We have shown that the reverberatory furnace works efficiently during the roasting and reaction phases, delivering at each pour an argentiferous lead which does not require any reprocessing before refining. The slag is easily evacuated without disturbing the lead pouring. It covers the metal and can easily be removed once cold.

Figure 8, standard sequence of smelting in a reverberatory furnace

It is always delicate to come up with an idea of the yield. In our tests, it seems to be around 25-30% of the mass of lead available. The rest of the metal is lost in the fumes for a lesser part and during the reactions with the furnace walls, participating in the formation of the slag.

The practice of smelting ores in the reverberatory furnace has allowed us to characterize the function of the different openings: the three vents at the top of the hearth are used for recharging. Their aperture during heating favours the creation of an oxidising atmosphere and the drop in temperature. The fourth opening above the door makes it possible to visually control the bath level, which dictates the moment of pouring. Finally, the top opening is useful during the phases of refurbishment and reloading of the cold furnace

Except for human endurance, there is no limit in the duration of an operation. It can enchain the roasting and reaction cycles after each emptying of the smelting chamber. At the end of our series of experiments series, we chose to cut the reverberatory furnace. This allowed us to provide additional information useful for understanding the procedure, but also to better identify the archaeological structures. The traces from the experimental heat were not directly comparable to those archaeologically observed for the simple reason that we did not use the same materials. However, some common features can be highlighted. In the smelting chamber, the glaze and the beginnings of melting of the walls concern the totality of the surfaces. The lead-bearing products have particularly interacted with the hearth level to the point of consuming it in the part under the three openings through which the ore is introduced. If the fire chamber shows only traces of conventional heating, the gases escaping through the chimney led to the vitrification of the walls, which in the experimental case and in archaeological cases (for several furnaces identified a posteriori in Bolivia) took on a green colour at the base and honey colour in the upper part. In the case of the archaeological reverberatory furnace used for cupellation, the chimney bears only the traces of the heating without any real chemical interaction between the gases and the lining. This detail makes it possible to identify and discern the function of a furnace with certainty when only the base of the chimney remains (figure 9).

Figure 9, Comparison of chimney between experimental furnace (left) and Bolivian archaeological ones (right up, Santa Isabel ; right down Tholampa)

Conclusion

This set of experiments, conducted between 2010 to 2015, allowed us to understand the construction and functioning of this type of furnace. As far as our yields may be trusted, they reflect historical data on modern reverberatory furnaces, and show that around to 25 to 30% of available lead was produced (Prost, 1924, 346). Thus, we highlight the efficiency of these first kinds of smelting furnaces, the use of which became more widespread in the XIXth century. Beyond the discovery of the required know-how for the operation of these furnaces, our experiments also prove how interesting it is to work step by step, taking the time to build the experimental process as part of the research. Far from being time consuming, this process avoids errors and the waste of time, energy and provisions. These experiments provide data that can easily be transposed to fieldwork and help in the recognition of furnace remains. Now, a new sequence of experiments have begun in Argentina that explore other ways of setting up the furnace and allow for an analysis of their use in a natural *habitus*, specifically taking into account local atmospheric conditions.

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Figure 8, standard sequence of smelting in a reverberatory furnace

Figure 9, Comparison of chimney between experimental furnace (left) and Bolivian archaeological ones (right up, Santa Isabel ; right down Tholampa)

Annex /

Plans and sections of archaeological and experimental reverberatory furnaces

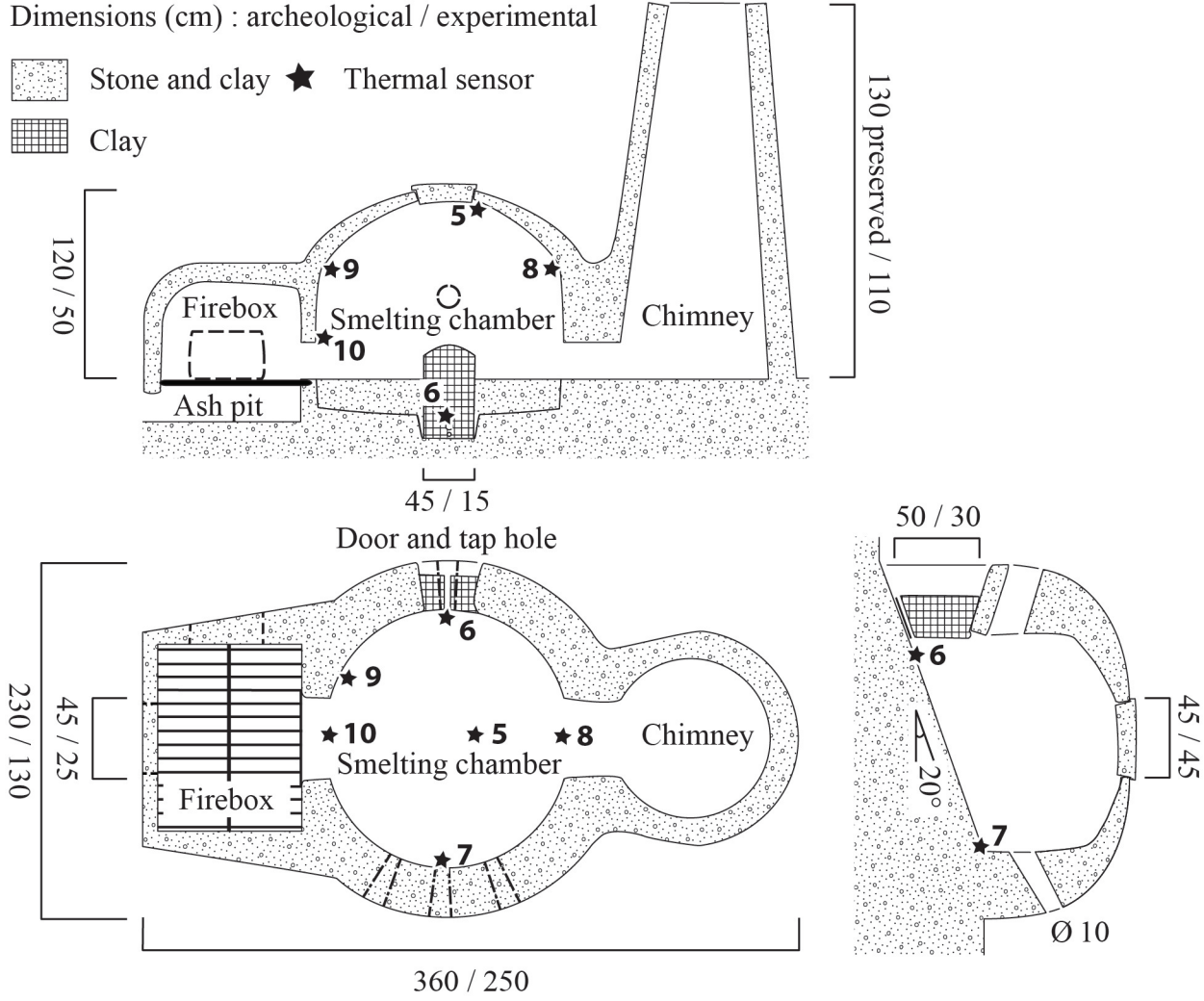
Thermal graph of each experiment

Visual Comparisons between experimental furnace (up) and archaeological ones (down)

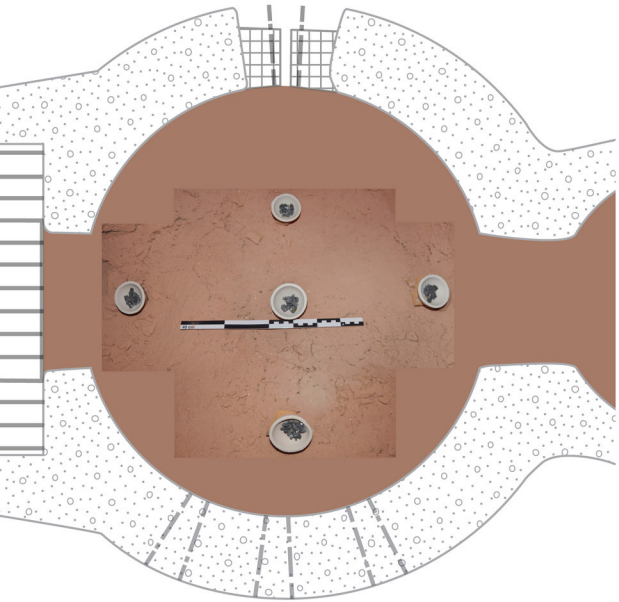
A full furnace (archaeological one from kuli-kuli fundicion)

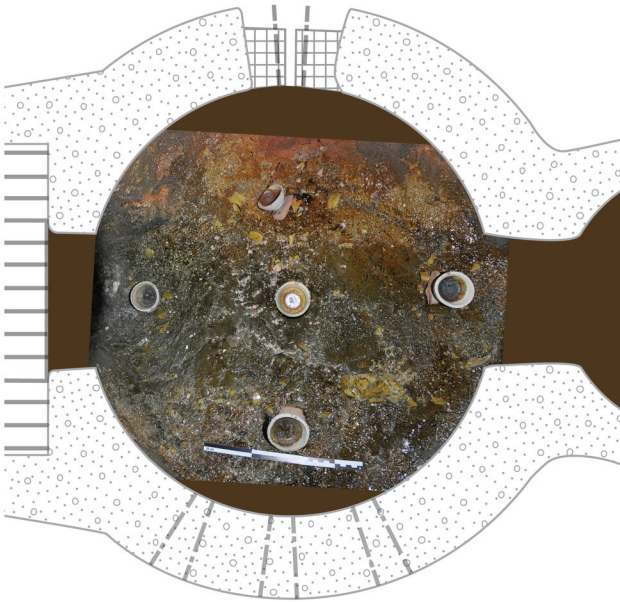
B smelting chamber (archaeological one from Santa Isabel)

BOLIVIA
Santa Isabel
CHILE
ARGENTINA
0 50 100 150 200 km

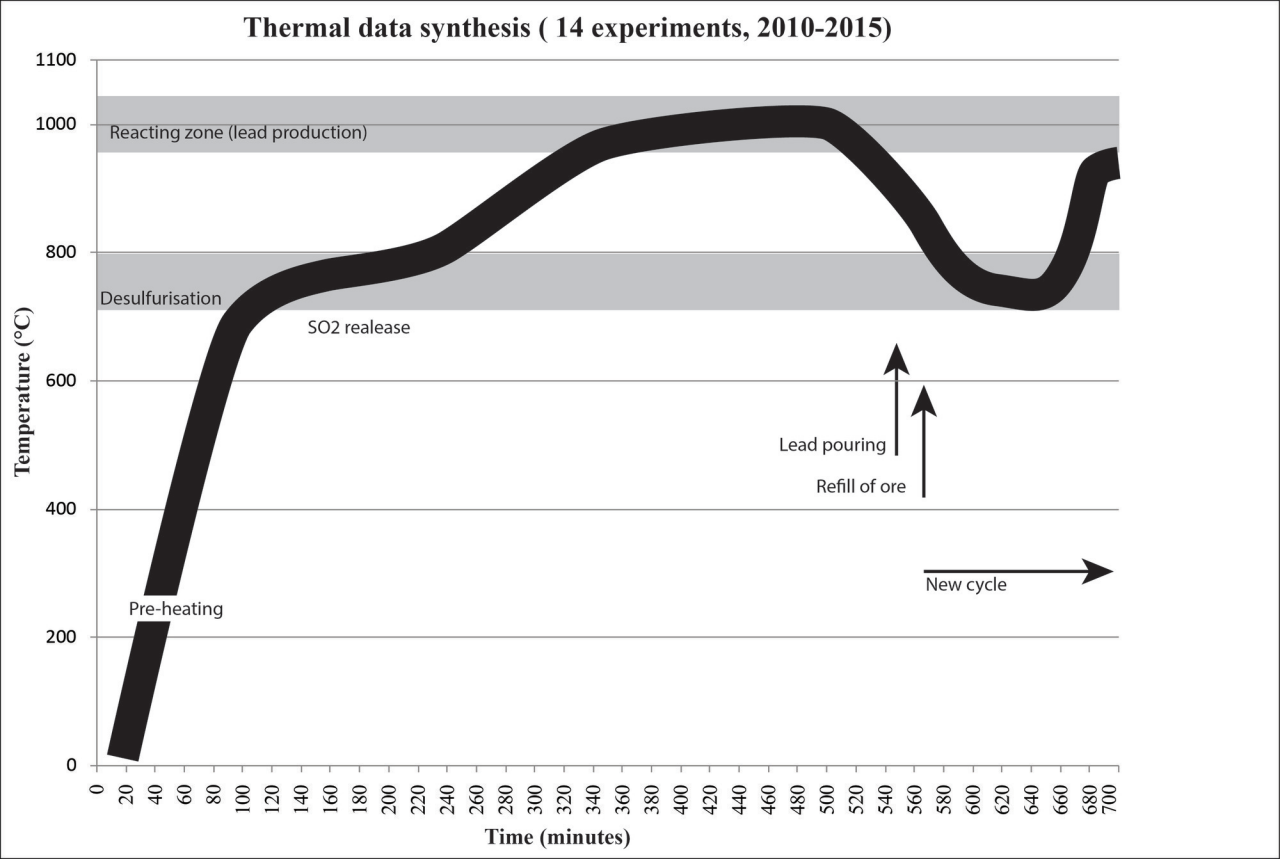

Dimensions (cm) : archeological / experimental
Stone and clay
Thermal sensor
Clay
130 preserved / 110
120 / 50
Firebox
Smelting chamber
Chimney
Ash pit
45 / 15
Door and tap hole
230 / 130
45 / 25
360 / 250
50 / 30
45 / 45
20°
Ø 10

									Production				Yield (Pb)			
	Year	Type	Duration	Galena	Nbr of charges	Avalaible lead	Grain size	Pouring	Per casting	Total metallic lead	Matte	Fluid Slag	Yield / Pouring	Global Yield	Max Range T°c	Aims
STI-1	2010	Test	15 hrs	No											900°c	Drying
STI-2	2010	Test	7 hrs 20 min	No											900°c	Heating
STI-3	2011	Test	12 hrs	No											1050°c	Drying and heating
STI-4	2011	Test	10 hrs	No											900°c	Redox variations
STI-5	2011	Test	8 hrs	0,15 kg	1		Grains								900°c	Redox variations and smelting
STI-6	2011	Smelting	11 hrs 20 min	30 kg	1	26,1	Nuts and blocks	1		0,4kg	no	unrecorded		1,5%	950°c	Smelting
STI-7	2012	Smelting	10 hrs	30 kg	1	26,1	Nuts	1		1,8kg	no	8,8 kg		6,9%	950°c	Smelting
STI-8	2012	Smelting	5 hrs 50 min	30 kg	1	26,1	Nuts	1		3 kg	no	unrecorded		11,5%	950°c	Smelting
STI-13	2014	Purge	8 hrs 30 min	no				1		11 kg	no	unrecorded			1050°c	Showing lead reliquat
STI-9	2012	Smelting	12 hrs	90 kg	3	78,3	Nuts	3	7,5kg /0,5kg /0,5kg	8,5 kg	no	21 kg	28,7%/2%/2%	10,8%	950°c	Multiple smeltings
STI-10	2013	Smelting	12 hrs 30 min	60 kg	2	52,2	Nuts	2	12 kg / 0 kg	12 kg	no	unrecorded	46% / 0%	23%	950°c	Multiple smeltings
STI-11	2013	Smelting	9 hrs 10 min	50 kg	20	43,5	nuts	3	6 kg / 0 kg / 0 kg	6 kg	10 kg	5 kg	139% (!)/ 0%/0%	13,8%	1050°c	No roasting phase
STI-12	2014	Smelting	15 hrs	60 kg	2	52,2	Nuts and blocks	4	2,5kg/8kg/0kg/5kg	15,5 kg	no	34 kg	40%/19,15%	29,7%	950°c	Multiple smeltings
STI-14	2015	Smelting	28 hrs	90 kg	5	78,3	Nuts	5	4,5kg/4,7kg/4,9kg 3,8kg/2,7kg	20,6 kg	5 kg	4kg/6kg/0kg/6kg 20kg	51,7%/27%/28,16% 21,8%/15,5%	26,3%	1000°c	Multiple smeltings





Slag
Matte
Lead
20
cm


Thermal data synthesis (14 experiments, 2010-2015)
Temperature (°C)
Time (minutes)
Reacting zone (lead production)
Desulfurisation
SO2 realease
Pre-heating
Lead pouring
Refill of ore
New cycle
0
200
400
600
800
1000
1100
0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300 320 340 360 380 400 420 440 460 480 500 520 540 560 580 600 620 640 660 680 700