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1 **The reverberatory furnace for ore smelting: an experiment on a South** 2 **American innovation**

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8

9 Abstract

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

18 Key-words

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

20 Introduction

21

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

32 The case of the reverberatory furnace for smelting of non-ferrous ores poses a problem in both
33 historiographical and technical terms. According to German, English and French authors (Schlüter,
34 1753; Tylecote, 1992; Brûlé, 1994), this mode of production appeared at the end of the 17th century in
35 England before spreading to the rest of Europe. However, referring to the Treaty of Biringuccio
36 (Biringuccio, 1540), it seems clear that such a system was already functional in the mid-16th century.
37 In the same period, in 1557, metallurgists working at Rocca San Silvestro in Tuscany were familiar
38 with the reverberatory furnace for smelting ore (forno del reverbero) although it does not seem to have
39 been widely used (Farinelli, 66 and 230, 2017).

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

46 and Lipez (Barba, 1640, 138), represented something novel. Similarly, Fernando de Montesinos
47 (1638: 278-279) implied some years later that these same furnaces, already widely used "throughout
48 Peru", were the result of local innovation. Likewise, a colonial document from 1635 (AGI, Lima,
49 331), shows us drawings of a model of a reverberatory furnace and another of a roasting furnace. The
50 text that accompanies these drawings refers not only to the fact that this model of reverberatory
51 furnace is used in "all" Peru, but that its knowledge was "secret", that is, unknown to the Spaniards.
52 The author of this document, whose name is still unknown, claims a prize for revealing this secret.
53 While we have archival evidence of the existence of the reverberatory furnace in Europe (Farinelli,
54 2017), the Southern Andean region provides much archaeological evidence in addition to historical
55 records. The oldest of these dating back to the Middle Horizon (500-900 AD) was uncovered at a
56 metallurgical site near the Uyuni Salt Flat (Letchman et al., 2010; Cruz, Téreygeol, 2014). Later,
57 during the Colonial Period (second half of the 16th century - 18th century), these furnaces were very
58 successful and widely found in southern Bolivia and north-western Argentina (Angiorama, Becerra,
59 2017, Cruz, Téreygeol 2020). Our investigations both in Europe and South America suggest that it is
60 possible that we may be see an Andean particularism whose influence on European metallurgy
61 remains to be demonstrated. Precedents exist, as has been shown for the Xabecas furnaces for the
62 sublimation of mercury. It is also important to take into account that the main experts on colonial
63 metallurgy in the Andes, among them Barba, Lorenzo de Mendoza, Francisco Moreno and Carlos
64 Corzo, were repatriated to Spain by the Crown at the beginning of the 17th century to apply their
65 knowledge and experience acquired in the "New World" in Spanish mines (e.g. Rio Tinto and
66 Plasencia).

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

73 The archaeological evidence

74

75 From 2003 to 2014, a combined team from CONICET (Consejo Nacional de Investigaciones
76 Científicas y Técnicas) and CNRS (Centre National de la Recherche Scientifique) conducted a series
77 of surveys in the department of Potosi in Bolivia, gathering evidence of the use of reverberatory
78 furnaces for the smelting of ores. Among these, the furnaces of Vila Punku Cueva (21°37'51.6" S,
79 66°26'45.5" W) at an altitude of 4328 m in the mining district of Santa-Isabel are noteworthy for their
80 exceptional conservation due to their position in rock shelters in an isolated valley. The historical
81 context of the Santa Isabel mine as well as the ceramic shards discovered in the immediate
82 surroundings of this workplace are from the Colonial Period, most probably dating to the second half
83 of the 17th century. Here, we will focus on one of the two furnaces located in Vila Punku Cueva. (fig.
84 1)

85

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

87

88 The excellent state of conservation of this structure observed permitted a precise survey. The only
89 uncertainty is the height of the chimney. The furnace has a length of 3.6m and a width of 2.3m. It is
90 placed directly on the ground surface and consists of three spaces interconnected by small windows
91 (46 cm wide, 15 cm high). The first space is the firebox. It has two compartments: the firebox chamber
92 itself and an ash pit open to the outside, that also provides ventilation for the unit. Stone lintels are
93 placed at the interface of the two compartments to hold the logs introduced laterally through a small
94 opening of 20 x 10 cm. The second space is the smelting chamber. It is positioned under a dome, 2.3
95 m in diameter with a roof height of 110 cm. The roof is pierced by a top opening of 40 cm in diameter.

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

101

102 Figure 2, Drawing integrating both the archaeological and experimental structures

103 The experiment

104

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

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

124

125

126 Figure 3, synoptic table of experiments

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

131 Drying and first trials (tests STI 1 to 5)

132

133 The first heating (ST1) aimed at drying the structure because 200 litres of water were needed for the
134 construction. It allowed us to familiarize ourselves with the furnace, to learn how to fire the logs and
135 ensure the best possible draught. A cover was placed over the top opening. The heating process lasted
136 15 hours. For this preliminary phase, temperature control was limited to a single temperature sensor.
137 After 13h, the furnace reached 750 °C, and when the fuel supply was stopped the temperature rose to
138 900 °C. The absence of a charge in the furnace induced a limited circulation of the flame, which
139 moved through the smelting chamber from one opening to the other by the most direct path.

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

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

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

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

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

186

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

188

189 [Single-load and casting tests \(tests STI 6 to 8\)](#)

190

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

202
203 Figure 5, Running furnace during test STI – 6
204

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

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



220
221 Figure 6, Running lead then slag from test STI- 8
222

223 Multiple loads and castings (tests STI 9 to 12 and 14)
224

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

237 The material balance is debatable, but merits discussion. During this test, 8.5 kg of metallic lead and a
238 21 kg vitreous slag were collected. This slag was analysed by LA-ICP-MS. The glass holds 70 % mass
239 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
240 temperature curves also seems to prove that our precipitation had fixed the successive additions of
241 galena. The 2nd and 3rd series of lead casting came from the first charge. So, only the first 30
242 kilograms of galena (i.e. 26.1 kg of lead) seemed to participate in the production of lead. We therefore
243 had a maximum loss of 2.9 kg. The lead metal yield of this first charge is of the order of 28%. If it
244 were otherwise, we would have had a more important formation of slag. We understand the function
245 of the four vents. The three opposite the door are used to recharge the furnace during heating. The
246 fourth one, above the door, allows us to see at which level the bath is located in order to choose the
247 moment of casting. It would therefore only play a controlling role.

248 A further year separated the STI 9 and 10 experiments. For this new attempt, we considered that the
249 3rd un-smelted charge from the previous experiment was sufficient. No fresh galena was added at the
250 beginning. The temperature rose quickly. When reaching 750°C (T180), white smoke appeared
251 accompanied by the smell of sulphur (SO₂ release). The roasting process began and lasted nearly 3
252 hours. Then, the temperature stabilized between 900 and 1000 °C. At T540, a casting was carried out
253 consisting solely of lead. Following this, a load of 30 kg of galena was added. This resulted in a
254 sudden drop in temperature at sensor 7, to 675°C. The top of the dome as well as the door area were
255 practically unaffected in terms of temperature change. At T645, a new casting was attempted. This
256 time, after a slight lead outflow, slag ran out of the furnace for 10 minutes. The operation was then
257 stopped. The successive lead and slag flows were easy to separate. We could therefore cold assess the
258 yield of each casting. The first casting came only from the 30 kg stock in the furnace before firing.
259 There was only lead for a mass of 12 kg. The yield reached 46% taking into account only the lead
260 available in the galena (87% or 26.1 kg of lead for 30 kg of ore). The following charge led to an
261 almost exclusive casting of slag. For this experiment, the roasting phase lasted 3 hours. And the lead
262 casting took place 3 hours after the end of the roasting process. It is difficult to assess whether this
263 duration can be reduced. The only information we have on the durations relates to our own previous
264 ore tests in a muffle furnace (Mercier, Téreygeol, 2016): the roasting process then lasted 30 to 40
265 minutes while the reduction phase did not exceed 10 minutes. We did not note any variation in time
266 for 10 to 30 g testings, but we were working with a 30 kg load in the current test. In the previous case,
267 the $T_{\text{Roasting}}/T_{\text{Reduction}}$ ratio was 4 (Mercier, Téreygeol, 2016). It was 1 with the reverberatory furnace. It
268 would seem that the ore mass has a positive influence on the reduction of the roasting time and thus
269 the total smelting time.

270

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

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

296

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

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

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

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

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

339 Discussion

340

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

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

372

373 Figure 8, standard sequence of smelting in a reverberatory furnace

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

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

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

399

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

402 Conclusion

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

415

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424

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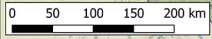


BOLIVIA

Santa Isabel

CHILE

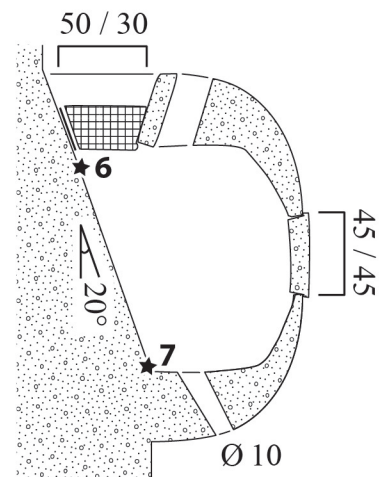
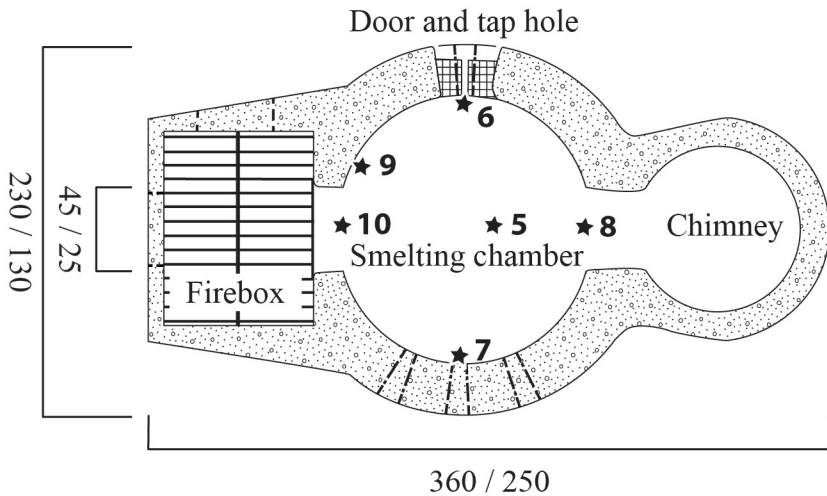
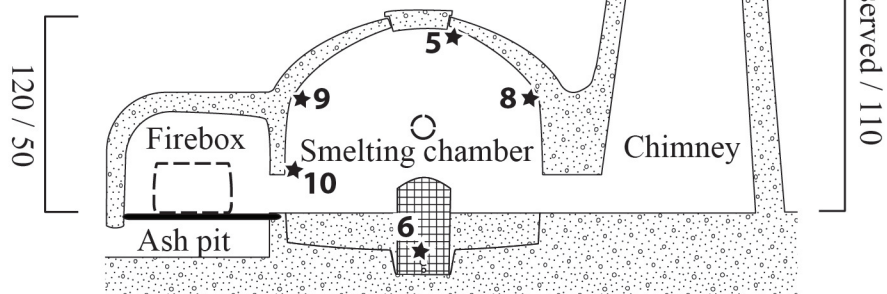
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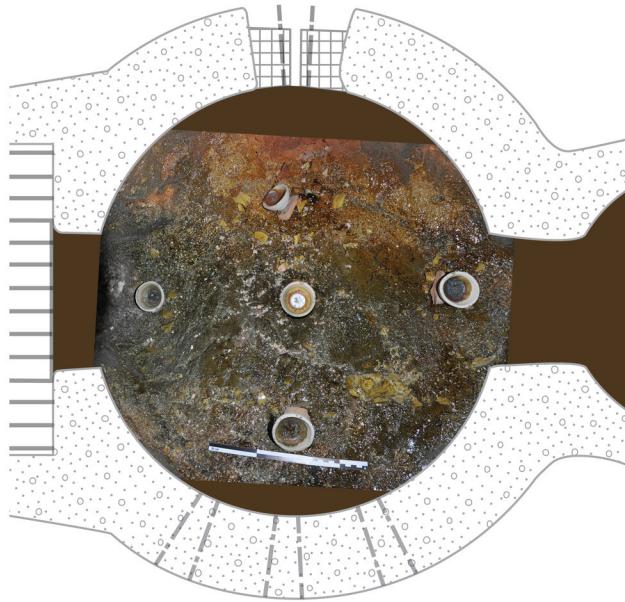
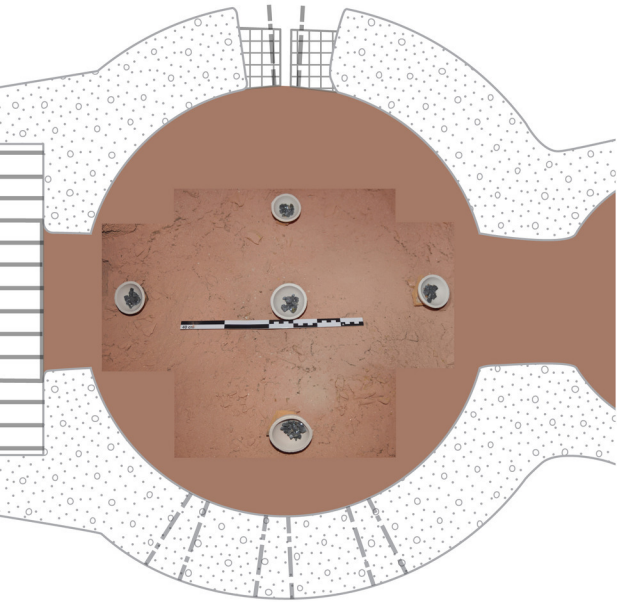
Dimensions (cm) : archeological / experimental

 Stone and clay  Thermal sensor

 Clay



									Production				Yield (Pb)			
	Year	Type	Duration	Galena	Nbr of charges	Available 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



Thermal data synthesis (14 experiments, 2010-2015)

