Iron Smelting in Vinland

Converting archaeological evidence to a practical method.

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Abstract:

The excavations at L'Anse aux Meadows Newfoundland uncovered remains interpreted by the original excavation team as a 'Furnace Hut' containing an iron smelting furnace. The remains are fragmentary, and at best only represent the last stages of a complex physical sequence. What might this furnace have looked like, and exactly how might the smelting process have been undertaken by the Norse, 1000 years ago? As well as considering furnace remains from Norway and Iceland, practical experience derived from a long series of experimental iron smelts will be considered.

Introduction : L'Anse aux Meadows

L'Anse aux Meadows National Historic Site of Canada (LAM) lies at the very top tip of Newfoundland's Great Northern Peninsula. From the site, the coast of Labrador is visible across the Straight of Belle Isle. Labrador itself then leans from there back to the north west, reaching as far north as the southern tip of Greenland. Helge and Anna Stine Ingstad came to the then isolated fishing village in 1960, guided by clues from the Sagas. Local head man George Decker would take them over to what the locals called "the Indian Mounds". (1) The long speculated about site of 'Leif's Houses' had been found. Over the following decades, from 1961 to 1968 under Anna Stine Ingstad and in 1973 - 1976 under Dr Birgitta Wallace, the full extent of the Norse presence at this outpost in Vinland was uncovered. (2)

The Norse occupation site lies at the bottom of the deep curve of Epaves Bay. The ancient shore line forms a terrace runing roughly south to north, extending back about 60 meters from the water's edge and then dropping into a low lying peat bog. Black Duck Brook bends around the occupation area, and cuts a channel across the terrace. Three main house complexes were built by the Norse, starting at the brook and extending for about 100 metres towards the north. On the slightly elevated southern bank of the brook were found the remains of what what has been described as "the Smithy" and a charcoal kiln. (3) Investigation of this small structure indicated the presence of a bloomery iron smelting furnace. As such it marks the first iron production in the New World.

That the overall site is Norse in origin, and dated to the Viking Age, has long been established. H. Ingstad had utilized details of geography contained in the Vinland Sagas to help him discover this evidence of the Norse in the New World. (4) Wallace has been even more specific, stating that the building remains at L'Anse aux Meadows are the "Straumsfjørðr" of the Sagas, site of Leif's Houses. (5) Radiocarbon dating of 148 radiocarbon samples ranges from 990 to 1050 AD, suggesting 1014 AD as the most likely occupation date. (6) This agrees with a date of 1000 AD for Lief Eirksson's first voyage to Vinland, calculated by Magnus Magnusson based on descriptions from the Vinland Sagas. (7)

The Archaeological Evidence

Any former iron smelting site presents a special problem for archaeologists. The process of converting iron rich ore into a working iron bar requires a complex series of steps. Each separate function is most likely to be undertaken by heavily modifying the previous equipment set up. Unfortunately for the archaeologist, the evidence of those important earlier stages is certain to be blurred, if not totally obliterated, by later steps. It will be the very last part of the whole process which alone remain as evidence. This is especially the situation with a single ore to object sequence as is most likely to have been the case at Straumsfjørðr.
The intended products, be it either simple compacted blooms or finished currency bars, are intrinsically valuable, so are unlikely to be found at the actual smelting location. If the intention was for a single smelting cycle, the furnace need not be built to be overly durable, and the smelting process itself may result in significant damage to the structure. Such a furnace certainly will not survive the weathering of much more than a dozen, and certainly not hundreds, of years. Conversely, the waste product from smelting, a glassy slag, is extremely durable, and is often all that remains. Few excavating archaeologist have much understanding of the practical workings of the small direct bloomery furnace, so understandably, their field notes often present a confused picture.

The structure 'Hut site J', at LAM was dug into the southern bank of Black Duck Brook, roughly 1.5 meters above the current water level of the stream. It had a width of 290 cm and depth of 320 cm. (8). In use the building had a loose sand floor. There were likely low walls to level out the slope of the bank, supporting a roof of some kind, leaving the side towards the brook open. (9)

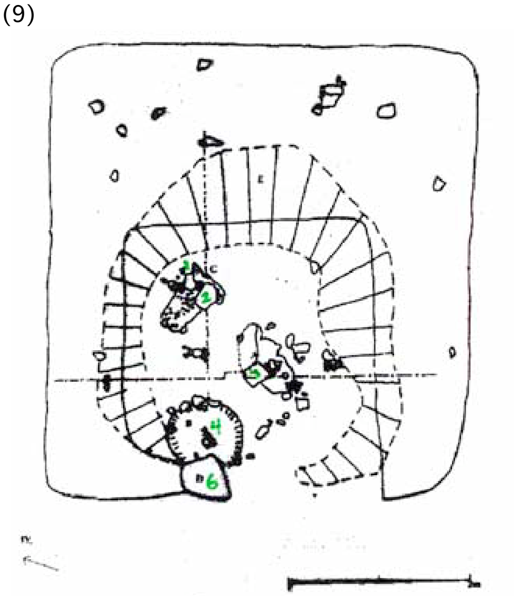

Figure 1 : Plan of the excavated Furnace Hut at L'Anse aux Meadows
Original drawing by Birgitta Wallace. (10)

Inside the structure, Kristjan Eldjarn describes the following two groupings in the published report on the excavations. To the front, at the north west, was “a fairly round, saucer shaped hollow ... the diameter ...70 cm, and its maximum depth 40 cm. ... there was a large stone of irregular shape, although the side facing the hollow - 45 cm high - is fairly vertical. The maximum dimension of this stone is about 50 cm.” (11)

In the rough centre was found the remains of a hearth. This was 30 x 60 cm in a rough oval, set with the long axis pointed to the open side of the building. To one end removing the charcoal exposed “a shallow depression ... quite distinct, and 8 cm deep. ... A layer of white, clay like substance ... extending in a fairly thin layer ... inwards along the floor”. Importantly to the discussion of iron smelting “... the highest concentration of slag was found in front of ... the fire patch - behind these, charcoal predominated.” (12)

Eldjarn also describes the following debris related to iron smelting process:

- a “great deal of slag, mostly fairly small pieces, but some as large as a hen’s egg or still a little larger”
- pieces of of bog iron ore
- “ lumps of white, clay like material, some of them apparently glazed on one side”
- a “large number of fairly thin iron scales ... which are probably forge scales.” (13)

The stone found along one side of the central hearth, described by Eldjarn as the “earth fast stone”, is not considered here to be involved in the smelting process. (14)

What is missing from the archaeology of LAM are two important pieces.

First, there should be a large and relatively solid slag block, which would have formed in, and normally filled, the bottom 25% or so of the furnace. Recovery of this block would have indicated the overall diameter of the furnace. Its shape would have also helped to determine if the final bloom was pulled up through the interior of the furnace (top extraction) or drawn out at the bottom via an enlarged tap arch.

Second, other than the slight features found in the centre of the Furnace Hut discussed above, there were no substantial remains that would indicate the structure of the bloomery furnace itself.

Calculations of Slag and Yields

A closer consideration of the slag found in building J is important to an assessment of LAM as a possible iron smelting site. A detailed examination of a number of samples was made by Anna Rosenqvist. Of specific interest are the samples LaM 303 and LaM 283 (slag) and LaM 293 (bog ore). In her conclusions Rosenqvist states “... that it is highly probable that iron production should have been attempted during an early period on the site... even though the bloomery itself has not been found ...” (15) Wallace, referring to a very detailed study of samples from LAM undertaken by Henry Unglick and John Stewart, states “The total weight of the slag collected was about 10 kg. It was assumed another 5 kg remained uncollected in and around the furnace hut ... Of that {recovered} 85.5 % was derived from the smelting process.” (16) The total amount of smelting slag is roughly calculated at 13.6 kg (10 kg x 85.5 % + 5 kg).

It is important to have some idea of the relative effectiveness of the smelting process. Analysis of the bog iron ore found in the Furnace Hut (LaM 293) shows it had an iron content of some 60 % (Fe2O3 of 69.8 %) which should be considered a nicely rich ore. (17) Wallace states of the smelt "... only one fifth became workable iron." (18) According to a method demonstrated by Arne Espelund, one can calculate yield by comparing other trace elements present in both ore and slag. (19) The manganese (as oxide) present should move straight from ore to slag, so dividing ore MnO by the slag Mn0 can give the yield as a percentage. Using the data recorded by Rosenqvist of the manganese present (shown in the table below) suggests the smelt yield was in the range of 23%.

| Sample | slag 303 | slag 283 | slag 284 | average | ore 327 | yield ? |
|---|---|---|---|---|---|---|
| Fe2O3 | 75.4 | 75.4 | 80.6 | 77.1 | 69.8 | |
| MnO | 3.3 | 2.1 | 1.1 | 2.2 | 0.5 | 23 |

Table 1 - Using manganese to estimate yield at LAM (20)

Applying the calculated yield to determine metal produced (slag % over slag amount equals yield % over bloom amount) gives a weight of 4.0 kg for the raw bloom at LAM. Total furnace input (ore) should equal total output (slag + bloom) , meaning approximately 17 to 18 kg of ore would have been used in the smelt. Care should be taken with all these numbers, for estimates are being drawn from approximations. It should be remembered as well that the raw bloom weight is certain to be reduced, perhaps considerably, in the process of consolidating that bloom to a finished working bar.

Who Were the Iron Makers?

The Greenlanders on the Vinland voyages had only been resident on their new farms at most for 15 or 20 years, having come direct from Iceland. Leif himself was born in Iceland, although his father, Eirik, had emigrated from Norway as a young man. (21) Not only the Sagas, but archaeological evidence such as the study of jasper fire starters at LAM by Kevin Smith, suggest some travelers to Vinland may have come straight from Iceland. (22) At the time that Eirik the Red's Greenland colony was established (about 985), Iceland itself had only been settled for 115 years. (23) It is only recently that Icelanders are shifting from the traditional view that their country was settled by people almost exclusively from Norway. Thus the Norse who traveled to Vinland would have been part of a cultural tradition springing from Iceland. That tradition was itself relatively fresh, and so would draw heavily from older roots in the Norse world, primarily from Norway.

The nature of the Vinland expeditions, and the cycle of life in Vinland at Straumsfjørðr, is critical to placing the iron smelt in its place within a circle of activities. It is important to understand the site at LAM was clearly never intended to be a true self supporting colony. Wallace uses the term 'gateway' : "A gateway is a base situated at the edge of a large hinterland where resources ... are collected in several locations. The goods assembled are brought back to the gateway for later transportation to the home country." (24) This is thus an outpost station, primarily a secure base from which to mount further explorations into the unknown and to safely over winter.

Part of the primary activity there would be assessing the possible resources available throughout this new land. Iron is a core material to the Norse, a people with a well known, and well earned, reputation for skill at its working. The scarcity of wood in Greenland would mean that the smelting of iron in the developing colony would be virtually impossible, for smelting iron ore requires huge volumes of charcoal. Iron would remain one of the primary imported necessities to Greenland throughout the history of the Norse settlements there. (25) That the site at Straumsfjørðr held plentiful amounts of bog iron ore would have been immediately apparent to the Norse. The act of stripping off the many blocks of turf used to construct the buildings needed to over winter could have exposed this material. This was the case during the modern archaeological investigations at LAM. (26) During a 2001 research workshop for Parks Canada, it was still easy to uncover quantities of bog iron ore along the edges of Black Duck Brook at any number of locations while moving upstream from the archaeological site.

The other essential raw material for iron smelting, timber to convert to charcoal, was also close to hand in Vinland. In 1000 AD, the forests of black spruce and white birch would be much the same as they are today. (27) That the Norse were well aware of, and in fact made use of, this particular fuel resource is proven by the remains of the charcoal kiln.

The people who traveled to Vinland would have been drawn from the Greenlanders most certainly, and has been mentioned earlier with Smith's research, also quite likely included a good number of Icelanders. The Greenlanders would have been essentially rural dwellers, that is to say farmers, and this is likely the case for the Icelanders as well. There should be no doubt these men should be considered 'smart tool using farmers', but it is quite unlikely these men were experienced iron smelting masters.

Physical Traditions

In trying to get some understanding of how the iron furnace at Vinland might have been constructed, and how it would have been expected to operate, a quick overview of the possible smelter types is helpful. The types discussed will be confined to the working traditions of the people involved, which is to say Iceland and Norway. Generally all these furnaces can be described as functioning as a 'Short Shaft' type, with internal diameters (ID) ranging from 25 - 60 cm and with walls 60 - 80 cm tall. (28) They have a forced air draft, provided by some hand bellows arrangement. There is a tuyere or air pipe to introduce this air into the furnace, ideally located about 15 -20 cm above the furnace base. A full charge of charcoal fuel, carefully sized, provides the energy, reactive gases and surface for the reduction chemistry. Once up to working temperature, previously roasted ore and additional charcoal is added in a continuous cycle. Extraction of the resulting bloom may be through a hole made at the bottom of the furnace along one side wall, or quite often through the top of the furnace. Slag control may be passive, by means of a lower 'room' or pit; active, by providing for a tap arch; or even 'automatic', by self tapping through cracks in the furnace walls.

In most cases, excavated furnaces from the Viking Age are parts of larger iron smelting complexes, which is to say they were used by people who repeatedly smelted iron as their primary activity. This certainly effects the nature of the construction, as it becomes worth the investment in time, materials and labour to construct robust furnaces if you are expecting to use them over and over. Often these high production furnaces are dug back into earth banks for additional support. Such 'industrial' furnaces often tend to be larger, in the range of 40 - 60 cm ID. (29) As might be expected, such thick and heavy constructions are also more liable to survive the forces of time. These high production sites are also marked by huge piles of cast off slag, ranging from complete bottom bowls through to fist sized chunks.

The suggested location of the furnace at LAM is in the middle of the building's floor. For that reason, only free standing structures will be considered. Since any smelting furnace needs to be highly heat resistant, the two most likely building materials are clay or stone, or some combination of the two. The furnaces illustrated below illustrate what are being considered here as the four basic possibilities for how the iron smelting furnace at Straumsfjørðr may have been constructed:

1) A clay cylinder that is free standing
2) A clay cylinder inside a ring of supporting stone slabs
3) A stone slab box with clay only sealing the corners
4) A series of smaller stones mortared together with loose clay into a cylinder

1) Freestanding Clay

Figure 2 : Furnace at Lodenice, Bohemia - 'Late Romano-Barbarian' (30)

Note that this furnace has a widened lower arch, suggesting bottom extraction, and also is partially earth banked. Height is indicated at 80 cm, which suggests an ID of 20 cm with wall thickness about 7 - 8 cm.

Through the building and firing of a large number of free standing clay furnaces, is has been demonstrated that with wall thickness of at least 7 - 8 cm, such are able to withstand the rigors of the smelting process while being completely free standing. (31)

Past experience has shown that any pure clay furnace is certain to suffer extensive cracking. This is primarily due to water within the thick material expanding as it flashes to steam as the walls are first heated. Careful drying and slow heating can reduce this effect to a certain extent. Even still, with any clay thickness over about 3 - 4 cm serious cracking, or even explosive spalling, is certain to occur. Past experiments have shown the ideal way to combat this effect is to include some organic material in the mixture. Chopped straw has been found to be ideal. The clay debris recovered at LAM however do not indicate any organic materials have been added to the clay that was used in construction. Sand was added to the clay, which has been suggested to have been included as a way to 'temper' the mixture. (32) The sand acts to reduce the effect of differential expansion between the hot inner and much cooler outer walls of the furnace which can be a problem during the course of the smelt itself. The cracks which form during drying, if not too large or open, can have one advantage. In past experiments such cracks allowed the furnace to self tap excess slag in the later stages of the smelting process, producing an 'incontinent' furnace. (33) This effect is likely to result in distinctive tap slags, tending to long thin runnels, irregularly spaced around the furnace. (This in comparison to the larger plate shapes seen from the use of slag tapping through a pre-constructed arch.)

2) Clay with Stone Support

Furnace at Erlandgard, Norway. (34)
Figure 3: A relatively thin walled clay cylinder with stones supporting.

This basic construction is seen at a number of documented Viking Age iron production sites in Norway . (35) The main advantage of clay cylinder inside stone slabs is that the stones provide support for the clay structure. By packing the gaps between the stones and the clay with earth or sand (or as been discovered is most effective, a sand / ash mix) the effects of large cracks are minimized. One added advantage to the packing material is that it also will prevent hot gasses, the working chemistry of the reduction process, from escaping.

The clay cylinder that forms the core of the furnace can be significantly reduced in thickness, as the surrounding stones and packing material physically support the structure. The clay walls thus are serving as a containing refractory layer only, so only need to be thick enough to withstand the erosion effects of the high smelting temperatures. Past tests have shown straight clay walls as thin as 5 cm can easily withstand a single smelt sequence, if heavily supported in this manner. (36)

It should be noted that most of the stones used for this type of construction are very unlikely to show anything but the most minimal heat effects. Even with the same slabs used repeatedly over a number of past experiments, it would be difficult to distinguish even the most heavily heat effected from those stones used to ring a simple wood cooking fire.

The furnaces excavated by Kevin Smith at Hals in Iceland could be considered a variation on this type. (37) These should be at least mentioned, as they represent a working tradition that would be well known to the Norse voyaging to Vinland. The construction at Hals is in the form of a large conical pile of grass sods, into which a cylindrical hole has been cut down into the centre. The inner surface of this cylinder has a thin layer of volcanic marl applied. The marl is more like a sticky mud than a true clay. In these furnaces, the pile of sods is providing the structure, the marl is basically a fire proof inner layer. The construction method results in a quite massive furnace, in the range of two metres square by over a metre tall. There are no indications of a separate structure of this kind at LAM, and such would certainly not fit inside the Furnace Hut.

3) Stone Slab

Figure 4 : Furnace from Skeie, Norway. (38)
Showing rectangular shape in stone slab construction. Note that this furnace is earth banked.

It is of course possible to use flat stone slabs for the structure of a furnace. The suggestion has been made that the furnace at LAM would be a free standing 'box' with the gaps in the corners and around the tuyere sealed with clay. (39) Although at first glance this would appear a simple construction, in fact this method relies on first being able to find the correct sizes and shapes of a suitably heat resistant type of stone. Second there must be the correct skills in the hands of those building the furnace, especially if it is to be free standing (as opposed to earth banked as in the example from Skeie, Norway shown in Figure 4). Effective dry stone building is certainly a skill unto itself.

In a series of experimental iron furnaces in 2001, 2002, then again in 2007, the stone slab construction method was tested. (40) Although the stone used was at type of schist found in Ontario, and thus likely to differ from the stone available at LAM, some general observations can be made.

First, it was found that it is difficult to effectively seal the gaps between individual stones. In practical experience it was found that as the clay used for this purpose dries, it shrinks or cracks away from these seams. This effect is greatly exaggerated with the temperatures inside a working furnace. In an earth banked construction, the surrounding soil both keeps the cracked clay from falling way, and limits the loss of reduction gases. In a free standing structure, 'plugging the gaps' becomes a major problem.

Second, it was found that there can be very significant erosion of the stones themselves at the front of the furnace around the tuyere. In the October 2007 test, which ran over a complete smelt sequence of just over four hours, the stone slab just above the tuyere had been reduced from 4 cm to only 1 cm in thickness. In addition, slag also attaches, often quite heavily, to those stone surfaces. These effects are considered significant, for no such heat damaged or slag bearing stone slabs were reported to have been found in the excavations at LAM.

Third, it has been observed that even with high volume air sources, a rectangular furnace does not function as efficiently as one with a circular cross section. The air leaving the tuyere will travel in a fan shape, also moving upwards as it approaches the rear of an ideal furnace. (41) In a box shaped furnace, this results in a D shaped burning pattern, the flat of the D centred on the tuyere. This distribution leaves the two rear-most corners of the furnace cold and unignited. The net effect has been found to be a reduction of the overall performance of the furnace, with any ore accumulating in those corners not correctly involved in the reduction chemistry.

4) Clay Mortared Stone

Figure 5 : Furnace 2 from Sunnanäng, Sweden (42)
Heavy walls showing smaller stones held together by clay.

In this construction method, stones of various random sizes and shapes are bound together with clay. Most historic furnaces of this type have very thick walls, and the stones used vary considerably in size. The result is that the proportion of stone to clay also varies. Stones may be completely encased in the clay, or the clay may appear more like a mortar between stones which will have inner surfaces exposed to the full heat of the furnace. The historic samples all show quite massive construction, suggestive of a more 'industrial' smelting undertaking.

To date, no attempt has been made by this research team to utilize this construction method. Although using a quantity of stone within the clay walls is certain to speed up construction, a number of potential problems are likely to arise. First, the clay serving as mortar is certainly going to shrink and crack as it dries, creating serious gaps in the furnace wall. These may both create structural problems, and void reactive gases from the interior. A critical factor in the effectiveness of this method lies with the stones themselves. If a location lacked stone as slabs, but had suitable heat resistant stones as rounded pieces, perhaps this method might be employed. Depending on the size of the stones, and the thickness of the desired walls, the volume of clay required might actually prove to be more than that required for a simple Freestanding Clay construction. In terms of the physical remains, it would be expected to see much the same effects on the stones of high temperatures (melting and erosion) plus slag adhesion seen with Stone Slab construction.

## The Iron Smelt At Straumsfjørðr

The confined area of the Furnace Hut at LAM requires that any furnace built within it would be of relatively light construction, for the simple reason that space needs to remain for the workers themselves. So it is not surprising there is no evidence of a massive construction. This fact alone eliminates Clay Mortared Stone as a possible construction type. Stone Slab construction creates a rectangular footprint. Further, no large stone slabs were uncovered which have attached slag or show exposure to extremely high temperatures, signs which are both distinctive and durable. If the remains inside the Furnace Hut are in fact those of a iron smelter base, the circular shape present indicates the furnace was not Stone Slab construction. The two remaining methods, Freestanding Clay or Clay with Stone Support are thus the only methods which fit the situation and archaeology at LAM. The pieces of clay smelter walls found, which as discussed have had no organic materials added, certainly suggest a less sophisticated approach to furnace construction. Because of the extra advantages of the Clay with Stone Support construction method, it is this method which is suggested as the one used at Straumsfjørðr.

The remains of the hearth in the centre of the Furnace Hut are being interpreted here to be primarily those of a forging operation, with the rectangular 'earth fast stone' serving as an anvil. At this point in the sequence of ore to object, most of the remains of the actual smelting operation would have been removed and discarded. Likely all that remains would be a small part of the lowest wall section of the original smelter. Retaining a 'C' shaped enclosure of clay would greatly improve the efficiency of the forging fire, both to concentrate temperature and prevent the spreading out of the charcoal fuel.

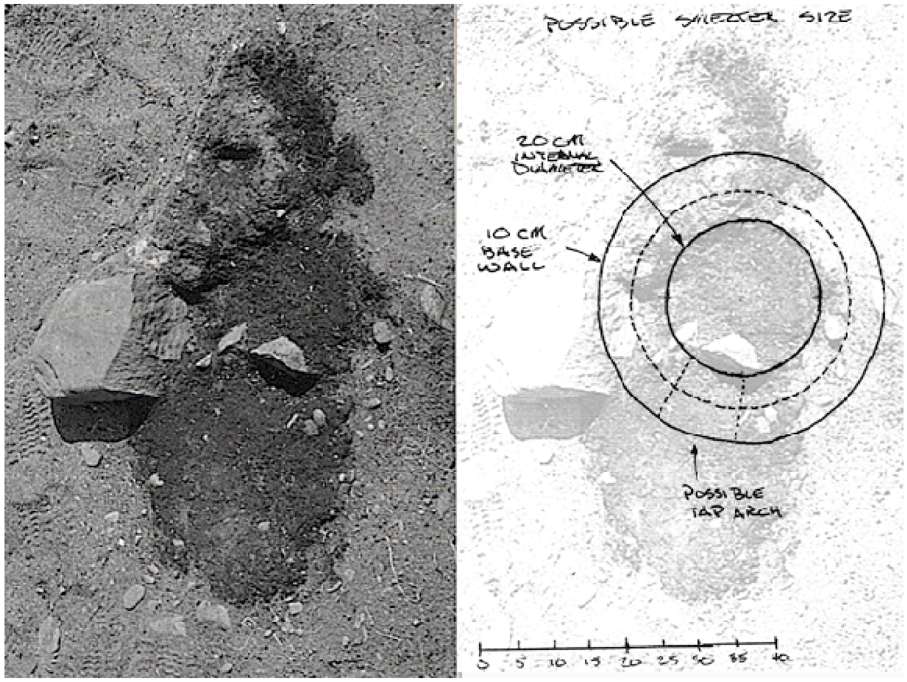


Figure 6 : Possible furnace structure at L'Anse aux Meadows.
Right : Original image from Eldjarn
Left :  Overlaid with a possible furnace structure.
The scale indicated is drafted from the recorded dimensions of the stone to the left side. (43)

The central bowl shaped depression of the hearth uncovered at LAM, measured at 8 cm deep, could easily be the type of feature often found when a solid slag bowl mass has been removed when cleaning out a smelter base once it is cold. On the image, there is a clear concentration of fine charcoal creating the circular pattern of this bowl.  The inner circle as shown in Figure 6 indicates a 20 cm internal diameter line.  Around this circle the texture of the material changes, with a ring of clay being found. As has been discussed, the fragments of clay walls uncovered varied from 2 - 10 cm. These pieces will represent primarily the inner sections of partially through to completely sintered furnace wall, glazed with slag on what would have been the inner surface. Using a minimum effective clay wall thickness of 5 cm, the second ring indicates a 30 cm diameter. The largest circle shown, at 40 cm, would account for walls at 10 cm thick, as indicated by the samples uncovered. In actual construction, it is most likely for the clay walls to have been thicker at the base and narrow as they proceed upwards. This is primarily a natural effect of building such a tall clay cylinder by hand. As succeeding layers of material are added, there is always some downwards pressure exerted by even the most careful workers, which tends to slump the height of the walls and expand the thickness at the base. (44)

There is no specific evidence remaining of any stone slabs which might have served to support this inner clay cylinder. As has been discussed, there would not be expected to be any heat damage to such slabs, so identifying them if the smelter had been broken down and cleared away after use would likely be impossible. The same situation exists for any sand or other simple packing material which might have been placed between the clay cylinder and the irregular shape of the stone 'box' supporting it. Eldjarn does mention that the cultural layer was of much the same sand as made up the undisturbed layer below, only slightly trodden down to indicate a loose floor level and containing pieces of charcoal. (45) This is what is observed when the stones are pulled away to clear a used smelter, spilling the packing material.

Figure 7 : Comparison - Debris from Vinland 2 Experiment, October 2009 (46)
The flat stone on the left was positioned after the smelt specifically to mimic the image above from LAM. Before the smelt, a layer of charcoal fines had been laid to aid in distinguishing the debris created. For that reason, it is the lighter material seen, primarily packing from between the clay and stone slabs, which is important. The tap arch was located at roughly the 5 o'clock position.

The location and size of a possible tap arch is much more speculative. As was discussed, the excavation report noted the major concentration of slag pieces was found at the front of the hearth base. The shape of the debris field at LAM suggests that there was a specific tap arch, and it was located directly at the front of the furnace, closest to the open door of the building. This is certainly the most practical location for such, as any hot slag would drain away downhill and out the open side, reducing the hazard of burns to the workers inside the generally confined space. The relatively short apron of charcoal and slag to the front also suggests any running slag was carefully controlled. In fact there were no large sized runnels of tap slag found certainly suggests that any hot slag was simply scooped up and tossed the short distance directly into Black Duck Brook. Hot slag hitting those icy waters would certainly shatter, leaving little to be found after so many centuries of spring floodwaters. That pieces of hot slag would have been quickly scooped up and tossed outside such a confined working area is hardly surprising. (The experimental team does just this as a matter of course during their own smelts.) The fact that the slag debris are relatively concentrated to one area also suggests that the furnace was not self tapping. If that had been the case, the cracks from which slag flowed would certainly be more randomly located around the furnace perimeter, as would be any slag remains.

Key to determining the position of the tuyere is first considering the other major surface feature uncovered in the excavation (marked 'B' on the site plan seen in Figure 1). This is the large 'saucer shaped hollow' located at roughly the 7 o'clock position to the smelter, with only about 40 cm separating them. Wallace initially suggested this feature marks the location of a wooden tub of water, a slack tub. (47) Although having a supply of water close to hand has proven extremely important during experimental iron smelts, such a tub is normally a low, wide shape that would sit on top of the ground surface. As has been described, this pit actually extends 40 cm below ground level. The only practical reason such a pit would be required for a slack tub would be if a full sized barrel was used. By digging a barrel in for some of its total height, it would be possible to not modify an existing barrel (i.e. - cutting it in half) if it was only required for a short time at the smelter. This all may be somewhat unlikely, as this scenario also presumes there was no other wooden tub (like a washing tub) available for short term use. There is no requirement hold such a large volume of water (a complete 'barrel full') close to hand, with the brook mere steps away from the front of the Furnace Hut. From a strictly functional perspective, locating a half buried water barrel so close to the front of the smelter actually places it in an very awkward position.

In later descriptions,  Wallace has suggested that this pit may be a "roasted bog ore supply pit". (48) With only 18 - 20 kg of ore required for the smelt, only a normal water bucket or two would be required to hold this material. Not only is the existing feature certainly much larger than is required for this purpose, it would place a large and very unstable hole right in the middle of the main working area close to the smelter.

The clue to understanding the purpose of this pit may lie with the large stone that was found just in front of it (marked 'D' on Figure 1). The pit may mark the mounting location for a large wooden stub, something certainly required for consolidation of the iron bloom. It is important that such a working surface be close to the smelter or later forge, to limit the loss of heat when the mass is removed from the fire as much as possible. It is important that this surface remain stable as it is pounded upon. The easiest way to accomplish this is to bury a good length of the timber into the ground. The timber required would need to be wide enough to totally support the large stone, so in the range of 40 - 50 cm in diameter. Later removal of such a stub could easily leave a ground feature like the one uncovered.

During the extraction and consolidation phase, it is critical that there be a clear path to move from smelter to stub, and for there to be enough room for several workers to gather around it. One person will be holding the bloom with oversized tongs, and ideally there are two people striking the metal surface with two handed sledge hammers. It is certain that the bloom will require a number of heating and working cycles to compact it, so during this phase the bellows must remain in action.

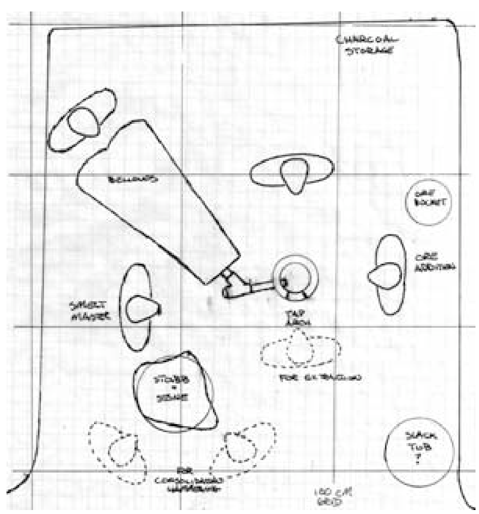


Figure 8: A possible working layout for the Furnace Hut at LAM.

The outline and positions of the archaeological components taken from Wallace's drawing (figure 1).

In practice, it has been found that the most convenient location for a tap arch is roughly 45 to 90 degrees to one side of the position of the tuyere. The location of the tuyere must have been further influenced by the space requirements of the bellows and bellows operator.

It has become clear over the progress of over 40 experimental smelts, plus the direct observation of at least as many more, that the key to producing a dense, lens shaped iron bloom is the application of high air volumes. Although it certainly is possible to create some iron in a furnace with lower air delivery, the iron mass is certain to be both smaller and quite lacy in structure. Such iron is difficult both to extract from the slag mass and considerably more difficult to consolidate into usable working bars. Significant losses in yields should be expected at both those stages in the overall production. This is an important consideration, as the size of bellows required for effective smelter operations is considerably larger than that required for a basic blacksmith's forge. A smelting bellows thus represents a specialized piece of 'semi industrial' equipment, and as such it is not likely to be on hand at an outpost station like Straumsfjørðr.

Sauder & Williams have offered the rough rule of thumb of providing 1.2 to 1.5 litres of air per minute for each square centimetre of cross sectional area at tuyere level. (49) Known artifact blooms from the Viking Age represent masses that have had varying amounts of primary consolidation applied to them. (50) Still, it is certain from those samples that it was desirable to produce dense blooms, so the application of high air volumes historically is indicated.

Considerable work by the experimental team has gone into producing correctly functioning Norse styled bellows for iron smelting, balancing the limited archaeological evidence and the practical requirements.

With the estimated size of the Vinland smelter at 20 cm ID, the required air volumes can be calculated to fall between 380 to 570 litres per minute. Experience has shown comfortable operating rate for most operators is roughly one stroke per second. Taken together, the approximate size of a Norse double bag bellows that produces the desired air volumes can be estimated. (51) Such a bellows requires a footprint in the range of 110 cm long and 70 cm wide. The operator requires at least an additional 50 cm of depth to stand and work in.

The nozzle of the bellows would not be attached directly to the face of the furnace. Experience has shown the advantages of using a Y shaped coupler to join the bellows nozzle to the mounted tuyere. Making such a fitting out of leather effectively creates a flexible coupling, reducing the effects of vibration from the operation of the bellows from reaching the tuyere. By dampening the leather with water, heat effects back up from the furnace can be reduced.

There is no evidence remaining at LAM to suggest what material the tuyere may have been made of. A clay tube or a forged iron pipe are both possibilities. The tuyere, regardless of the material of which it is constructed, needs to remain firmly embedded into the brittle clay wall of the furnace. The remaining branch of the leather Y can be aligned to permit a straight line down into the tuyere. Plugging this branch with a simple wooden plug which can be removed allows access down through the tuyere. This allows obstructions to be cleared from the tuyere, most especially solidified slag deposits. This is a common problem during the later stages of even a well managed smelt.

Given that the position of the smelter base inside the Furnace Hut is slightly to one side of center, the most functional arrangement is to place the tuyere to the wider side, running more or less parallel to the line of the open front wall. This in turn places the bellows in a diagonal line, running roughly from the center of the structure back into the rear corner.

This would position the smelt master working between the bellows and the mounted stub when managing the tuyere, and just in front of the tap arch when controlling slag levels. This arrangement leaves room along the rear wall of the structure for bulk charcoal storage. About 30 - 40 kg fuel that would be expected to be consumed during the progress of the smelt (a pile roughly 100 x 100 x 50 cm).

Besides the bellows, there are a number of other specialized tools that have been found necessary for the operation of a small bloomery furnace. At the barest minimum, there would have to be a pair of tongs large enough to lift and hold the bloom, plus at least one sledge hammer with enough head weight to effectively impact on this mass. It would be to hard manage the smelt without a long, ideally round cross section, rod. This would be used to clear obstructions down the tuyere, and to poke holes as required in the side of the slag bowl to drain excessive slag through the tap arch. This rod could easily be taken from any blacksmith's 'open stock', as its diameter would be in the same range of that required to forge ship's rivets. One last important tool would be a heavy combination bloom hook and slag chisel. This tool could be forged from a standard Norse currency bar with few changes, then fitted to a longer wooden handle. A number of other tools like rakes and shovels would certainly have been made of wood, and so are so are simple to make and could be considered almost disposable.

To conduct the smelt itself, a bare minimum of two people would be required at the smelter, at least one with enough understanding of the process to supervise it. Along with keeping control of the work of all the others, this 'smelt master' would have to understand the various warning signs indicating problems with the mechanisms of the smelt. When correcting problems, action must be undertaken in mere minutes, especially in any situations involving possible blockage of the air blast. The second worker's primary responsibility would be maintaining the correct additions of charcoal and ore. In practice it has been found that having a third worker greatly improves the flow of the smelt, especially when problems arise (as they are almost sure to on any smelt). During the consolidation phase, the optimum is three workers, one holding the bloom and two working sledges. In addition, there needs to be a number of essentially unskilled workers to operate the bellows. With one stroke required each second over the course of four to five hours, in modern experiments it has been found that switching operators every 10 minutes, using a total of at least three individuals, gives the best performance.

## Judging the Effectiveness of the Norse Smelt

At Straumsfjørðr, the Norse were blessed with not only easy access to suitable quantities of primary bog iron ore, but with an ore of significantly high iron content. This should be considered a 'lucky accident', as it is likely the Norse just gathered up the pebble like pieces of ore exposed when they worked to cut turf slabs when constructing the many buildings on site.

| Smelt | Ore | Fe Available | Bloom | Yield |
|---|---|---|---|---|
| Norse | natural bog | 68% | 4 kg (EE) | 23 % (E) |
| Vinland 1 | DD-2 analog | 64% | 4.9 kg | 33% |
| Vinland 2 | DD-2A analog | 61% | 5.6 kg | 27% |
| Vinland 3 | DD-2 analog | 64% | 2.9 kg | 16% |

Table 2 - Comparing Smelt Yields
Note that Vinland 1 & 2 had much higher air volumes, delivered by an electric blower.
Vinland 3 used a reconstructed Norse type bellows.

The smelt by the Norse at Straumsfjørðr was a particularly small one. If the evidence has been correctly interpreted here, the furnace had only a 20 cm ID. Although furnaces with this diameter have been operated successfully for a number of past experiments, there can be a problem with heat loss through the walls in furnaces so small. Generally a furnace has a fairly high 'energy budget', but a smaller furnace will have a much higher proportion of surface area loss to internal ignition volume. Perhaps more importantly, the developing bloom itself will be constrained by the walls of a small furnace. Available diameter, along with the amount of space available between the base and the position of the tuyere, are factors which effect potential bloom size.

Direct experience has shown that in smelters of this type and size (short shaft, 20 - 30 ID), a minimum of 8 kg ore is generally required to establish the required conditions inside the smelter to permit the starting formation of an iron bloom. Once enough charcoal has been burned to heat the furnace system, the first ore added creates the basic slag bowl structure in the bottom of the furnace. This bowl then serves like a heat mirror, increasing the overall efficiency of the working furnace. Without a liquid slag pool to encase the developing bloom mass, the direct air blast from the tuyere would simply eat the bloom away.

In operation, the raw efficiency of any smelting event increases significantly if the process, once established, is allowed to run longer with larger amounts of ore applied. Yields as high as 40 - 50 %, or even higher, can be achieved in very large quantity smelts (ore amounts in the range of 50 kg). The simple truth is that a small smelt like that at Straumsfjørðr, employing 15 - 20 kg of ore, requires only slightly less work, fuel, and elapsed time than one with double that ore amount. Such a higher ore volume smelt might easily result in three times the bloom yield.

Normally if a correct dense bloom is produced in a smelt, an experienced worker can easily extract this mass while it is hot, leaving the classic  cylindrical planno - concave slag bowl mass behind as an extremely durable remnant. This method, despite the difficulty in reaching down inside the furnace, with internal temperatures in the range of 1200 C, has many secondary advantages. (54) Extracting the bloom while hot allows an initial consolidation hammering to be undertaken when the iron is at its highest temperature, thus producing the greatest effects.  It does however, take some experience to locate and effectively extract the hot bloom from the encasing slag bowl. Another advantage of hot extraction is that the layer of lacy iron and slag surrounding even a dense bloom can be quickly compressed and welded into the mass on that first hammering step, increasing effective yield. Even using the smelter as a giant forge, it always proves more difficult to bring the mass up again to an effective working temperature (ideally in the range of 1000 - 1100 C).

Although care must certainly be taken when drawing conclusions from evidence that is missing, the lack of a single slag block may indicate it was smashed apart intentionally. It certainly is much easier to break apart a cold furnace, then break up the slag mass to locate and separate the iron produced, especially if the bloom is small and not very compact.  If this was the case, this would certainly explain why the slag pieces found are so small. Such a method suggests less skill on the part of the workers. Balanced against ease of recovery, it then requires a significant effort to take a cold bloom mass, even one at the smaller 4 kg size estimated for the Norse smelt, and re-heat it up to the required temperatures for consolidation. A specialized forge set up is required for working with such a large mass. The amount of charcoal required to convert a raw bloom into a working bar may prove in the same order as that required for the initial smelting itself.

An Emergency Smelt at Straumsfjørðr?

Birgitta Wallace has linked the recovery of a large number of damaged ship rivets outside Hall F, evidence of a major repair to one of the smaller boats, directly to the production of iron : "This smithing was probably not a planned event but prompted by an accident with one of the ship's boats : the many discarded boat nails found in the F-G complex indicate that replacements were needed. ... The iron master was not particularly skilled ... only one-fifth became workable iron, little more than 3 to 5 kg, sufficient for the making of about 100 to 200 nails..." (55)
For a number of reasons, it is suggested here that the repair of the boat and the smelting of iron are two completely separate events in the cycle of activities at Straumsfjørðr, and might easily have occurred on entirely separate expeditions.

Of course we can never tell just who the people actually were on those Vinland voyages. Leif Eiriksson himself can be considered as a 'professional expedition leader', being an important member of a family into its second generation as explorers of remote regions. The Eiriksson clan had once moved from Norway to Iceland. They later undertook a long exploration voyage to virgin Greenland, then mounted a major colonization effort there. A voyage to Vinland was also a significant effort, one that was mounted a number of times if the saga tales are to be trusted. It is hard to believe that such experienced people would embark on a voyage into the unknown without being prepared for emergency repairs by way of bringing a bag of spare rivets. Although it is reasonable to assume that such expeditions would be equipped with a basic set of blacksmithing tools, it is almost certain such a toolbox would also include a few lengths of working bars as raw material. The making of rivets is a relatively simple process, not requiring any of the specialized skills required to successfully smelt iron, or those needed to convert raw bloom to working bar.

Balanced against the serious nature of boat repairs while at an isolated location has to be a consideration of the raw mass of tools required to undertake a smelt in the first place. As has been discussed, actual iron smelting requires a completely different set of equipment from that used by the blacksmith. It is true that a blacksmith with suitable working bars available could certainly forge up the tools for iron smelting on the spot. Again, if that extra metal stock was on hand, why not convert that straight into the required rivets? The weight of what is considered the most minimal set of tools as used in the Vinland experimental smelts is roughly 4 kg, not including any hammers. Adding a single sledge hammer, like the ones from the Mastermyr tool find, would increase this between 2 - 3.4 kg each, as a single large piece. (54). Sacrificing a single hammer to make sure that the boat holds water well enough to get home again certainly seems a small price to pay!

One critical factor that has been missing in interpretations by others of the original smelt at Vinland by the Norse is a consideration of the process of conversion of the raw bloom to a working bar. Sauder & Williams, working with considerable experience as both smelt masters and with Sauder a professional blacksmith, suggest a conversion of raw bloom to finished working bar at a yield rate of roughly 35 - 40%. (55) Certainly the conversion rate from bloom to bar will vary, dependent on the density of the starting bloom. Using this conversion rate, the Norse at Straumsfjørðr certainly would not have been able to transform their small bloom, estimated at about 3 - 4 kg on extraction, into anything better than about 1.6 kg of working bar ready for the forge. Given the general conditions and likely limited equipment available (and probable low skill levels), even that final working yield may be overly optimistic. This alone suggests that if the smelt was in fact undertaken purely to create the rivets needed for the known boat repair, it could not possibly have provided any more than half the raw material required.

Conclusion - Why Smelt Iron in Vinland?

What would be the expectation of these explorers that they would be able to smelt iron in Vinland? The answer may relate to their starting locations. The general knowledge of basic blacksmithing certainly appears to be quite widely distributed through the Norse of the Viking Age, and it is certainly true that most of those in Vinland were at core independent and highly self reliant farmers. Iron smelting, however, is a separate specialist activity, with skills quite different and more complex that those required by the rural blacksmith. Direct experience is critical, for the conduct of a smelt can easily jump off track, and if not very quickly repaired, the process will freeze to a halt. Iron smelting was not an activity undertaken in Greenland at all, so for at least the Greenlander members of any expedition to Vinland, personal memories of participating in a smelt would be over a decade and a half old.
Assessing the full resources available in his newly discovered lands was critically important to Leif Eiriksson. He obviously intended to paint a glowing picture of his territory - his name 'Vinland' is simple proof of that. Finding bog iron ore so easily, and certainly knowing that producing iron was not going to be possible in Greenland, it is perfectly understandable that Leif would take some effort to test out this valuable resource. However, not only would specialized skills be required to correctly smelt iron, specialized tools would have to be on hand in Vinland as well. It would only be from Iceland that direct experience with iron smelting methods could be provided, and there certainly is direct evidence that Icelanders did travel to Straumsfjørðr.

It must be remembered that the archaeology at L'Anse aux Meadows certainly compresses a number of individual expeditions, each likely separated by several years, into a single layer. From a one thousand year distance, there is no way to directly link evidence of different individual activities which might certainly have originally involved entirely different groups of people. Earlier interpretations of the cycle of work undertaken at Straumsfjørðr had linked the repair of a ship's boat, demonstrated by a concentration of cut rivets outside House F, with the single smelting event. This appears to have been based on a simple correspondence of mass of estimated bloom production to mass of required rivets. To be fair, any information on the quite separate process of consolidating iron bloom direct from the smelter down into working bar for the hands of a blacksmith did not really exist when those earlier reports were published. As the current generation of working iron makers and blacksmiths attempt to re-discover these long lost skills, slowly a better understanding of the potential losses for this aspect of the process are becoming understood. It is clear that even the best quality blooms in the highest skilled hands should be expected to suffer considerable losses during the bloom to bar phase. The linking of the estimated 3 kg bloom produced to a mass of rivets also at 3 kg is thus not the direct correspondence it once was thought to be. Another aspect which was not considered by the original investigators was that iron smelting itself requires a number of specialized and large iron tools, the total of which also represents at least twice the raw mass required for that critical pile of repair rivets. Taken together, all these factors suggest that the event of smelting iron at Straumsfjørðr should be firmly separated from the boat repair activity undertaken there.

On the merely technical side, the archaeology clearly points to at least one iron smelt being undertaken by the Norse at Straumsfjørðr, but so many details are lacking. What evidence remains can be perhaps be best interpreted when viewed in the light of accumulated practical experience with operating similar direct process bloomery furnaces. If the hearth base in House J is in fact the last remains of a furnace, it appears to be quite small, and constructed using the simplest and most 'fail safe' of possible methods. The smelt itself utilized a very small amount of ore, greatly reducing any potential reward in iron bloom size when measured against the raw effort of mounting the smelt in the first place. Despite having a quite pure ore on hand, the relative yield is calculated to be quite low. That no large slag mass was found, but merely smaller pieces, might even suggest that what iron was produced was gathered well after the smelt itself, by breaking up the cold slag bowl. All these aspects taken together might suggest less that optimum technique on the part of the furnace operators.

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Footnotes:

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