Phase 3 – 2021 : Experiments with Sod Built Iron Smelting Furnaces, based on Hals, Iceland

ABSTRACT :

Phase 3 marks the continuation of a long series of individual bloomery iron smelts, practical investigations arising from **Kevin P. Smith**'s archaeological work at the Viking Age 'industrial' production site at Hals, Iceland. (1) This paper describes the process and results of the 2021 furnace build, used for two experiments, the first June 20, the second September 4. Primary work was undertaken by Darrell Markewitz, with considerable assistance of members of the Dark Ages Re-creation Company, most significantly **Neil Peterson** and **Rey Cogswell**.

INTO PHASE THREE :

Rather than repeat earlier work here, readers are directed to two comprehensive papers prepared earlier in 2021 :

> - '*Now with 70% Less Clay! Experiments with Viking Age Icelandic Turf Walled Iron Smelting Furnaces*' co-authored with Kevin Smith and Neil Peterson. An overview was presented at the EAC12 conference (March 2021) : https://youtu.be/7Ltz5NG2BP0 Publication of the full paper is pending in the EXARC Journal.

This paper gives a revised overview of the archaeology at Hals, and details the initial eight experiments in this series, from 2007 through 2016.

> - '*Into Phase Three – Continuing Experiments with Iron Smelting, based on Hals, Iceland.*' Published on line, August 15, 2021 : http://www.warehamforge.ca/ironsmelting/phase3/phase3.html

This paper describes our current interpretation of the evidence at Hals, compared against 20 years of iron smelting experience. It includes considerable detail on the furnace build and overall objectives of the intended Phase 3 experimental series.

The earlier work in this series had started by attempting to physically test a furnace design and operating methods originally suggested by Smith. (2) The experiments in Phase 1 tested a number of individual elements of furnace build, and also possible operations sequences. Over the same period, considerable working experience had been accumulated with the general 'best functional' layout of small direct process bloomery furnaces, as well as testing of a number of differing historic types. (3) Phase 2 brought together the individual elements into builds using local grass sod as the main structural component.

Important to the progression into Phase 3 was a re-evaluation of the potential archaeological evidence, based on the earlier tests, and importantly viewing the original field report through the lens of (considerable) accumulated direct experience (4). A number of important elements were considered for testing :

- Use of a simulated clay mixture, based on analysis of Icelandic samples from the Hals area. (5) (Considered primary test one)

- Overall construction consisting of a thin (4.5 cm) clay liner, supported by a cone of cut and stacked grass sods. The timber framing and earth fill originally proposed by Smith was considered not required (and more a complication than an advantage).

- Furnace designed with a base level arch allowing for bottom extraction of the resulting bloom. The tuyere point would be above this arch, so allowing a single 'slot' into the conical sod structure.

- Repeated use of the same furnace structure, hopefully with only minimal repairs being required between firings. (Considered primary test two)

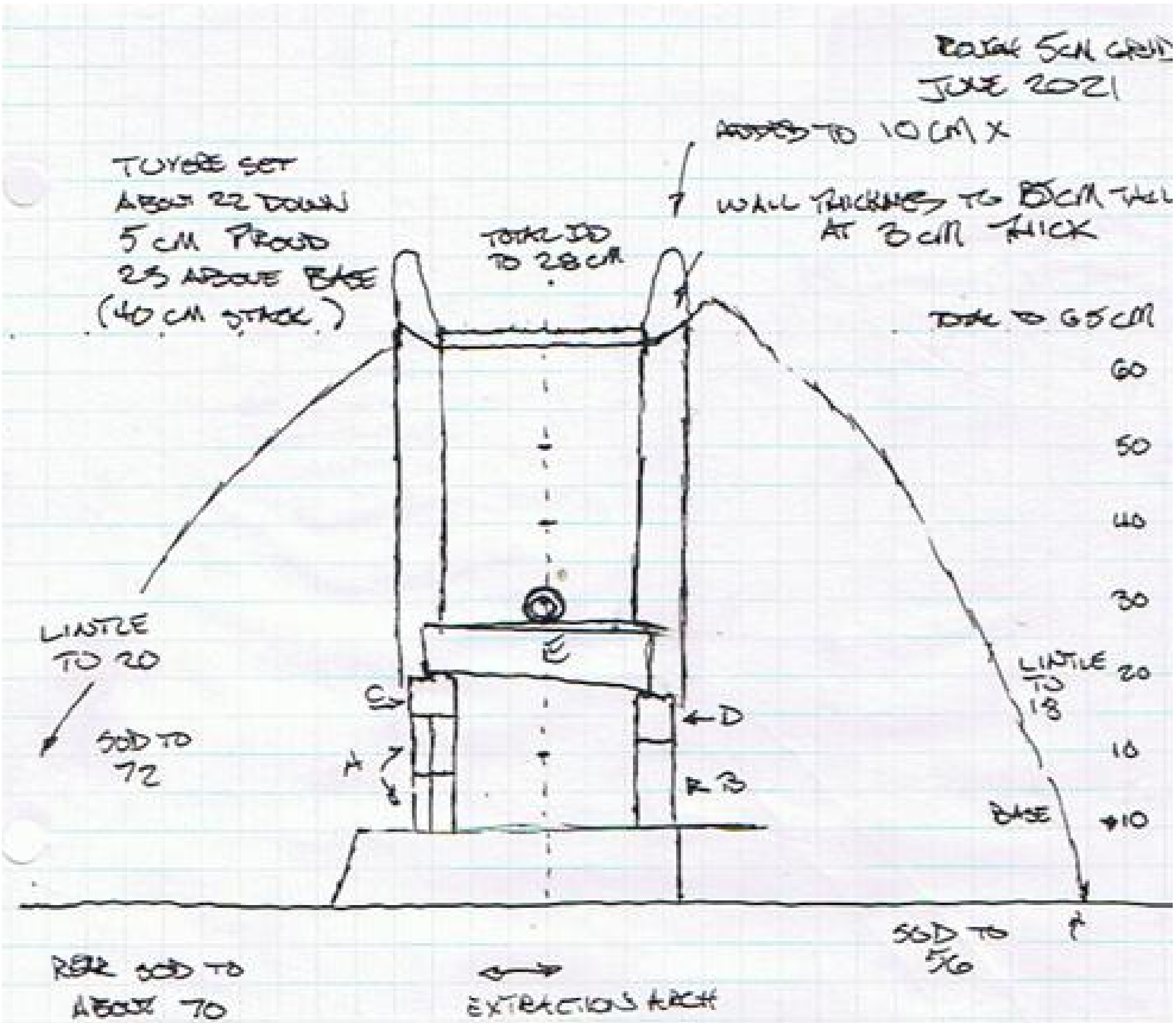
- Assessing the effects of weathering to the furnace structure over time, the gap between smelt A and smelt B intended to be about 4 months (over a Summer), between smelt B and smelt C intended to be over a full Winter (about 8 months). (Considered primary test 3)

Recommendations for the simulated Icelandic clay were given by team member **Marcus Burnaham**, based on a sample provided by **Michelle Hayeur-Smith.** The chemistry was compared to commercially available components, used in the preparation of potter's glazes. The exact mixture was :

Bentonite	22.7 kg
Mullite Grog	2.3 kg
Talc (Amal C-98)	6.8 kg
Wollastonite	7.7 kg
Black Iron Oxide	5.0 kg

The dry powders were mechanically blended using a small cement mixer, then this combined with roughly equal amounts by volume of local (granite based) sand and dry shredded horse manure (an additive mixture proved effective over many past uses).

Furnace Description :



Roughly scaled drawing of the furnace before June firing (square = 5 cm).

The full details of the build process are covered in ‘*Into Phase Three*’.

- Wall Thickness : 4.5 cm
- Interior Diameter : 28 cm
- Total Shaft Height : 70 + cm (extended from first build at 60 cm)
- Grass Sod Exterior : 5 layers stacked, average diameter at 60 cm, height at 65 cm

- Extraction Arch : stone framed, cut through full liner at 23 cm wide by 20 cm tall
- Tapping Port : 6 cm wide by 8 cm tall
- Tuyere : forged copper, set 5 cm proud of interior, 22 degrees down angle, placed above extraction arch
- Stack Height (above tuyere) : 50 cm
- Base Depth : 29 cm above hard base, charcoal fines layer adjusts depth below tuyere to 15 cm

Furnace with air system in place, at first addition of charcoal.

Both smelts would share the following aspects :

- Air Supply : high capacity electric blower
- Ore : standard Fe_2O_3 analog, at roughly 53 % Fe content
- Charcoal : oak, broken to .5 – 2.5 cm pieces
- Addition of a quantity of previously collected and broken tap slag before ore charges

A fairly standard sequence was undertaken both times. A period of pre-heat with wood splits was followed by filling the furnace with rough charcoal. As the interior fully ignited, this was changed to graded fuel. Charcoal is measured using a standard 'bucket' (roughly 2 kg, later one 'bucket full' is weighed to calculate the total amount consumed), further broken into about 500 gms per addition. Air volume was adjusted to set what was considered a suitable burn rate. Slag charges were added first, to quickly establish a working slag bowl system, followed by first charges of ore. Slag and ore is pre-measured by weight, and those amounts added evenly through each of the quarter charcoal bucket units. As the reaction progressed, individual ore charges were increased, and slag was tapped as required to ensure the air blast remained clear. Once all available ore was added, additional charcoal was added to ensure all the reduced ore was deposited onto the bloom, then the volume of charcoal allowed to burn down to close to the tuyere level. At this point the bottom arch was opened and the bloom mass extracted. This was then hammered through a single 'heat' cycle to knock off clinging slag and partially compress the bloom. Final weight was taken afterwards. (A)

Smelt A – June : *For details see appendix A*

Darrell Markewitz was smelt master, with Neil Peterson as lead hand and record keeping, Rey Cogswell as primary assistant.

- Preheat Phase : 60 minutes
- Air Volume : 800 Litres/minute (estimated, via gate markings)
- Total Slag Added : 5 kg
- Total Ore Added : 25.5 kg
- Charcoal 'Bucket' : 1.8 kg
- Primary Sequence (over ore additions) : 295 minutes
- Primary Charcoal Burn Rate : (average) 8.7 minutes / kg
- Ore Rate : (average) 11.6 minutes / kg

This smelt overall ran as was expected. The one modifying aspect was the use of a slightly lower air volume, set intentionally to closer mimimic what was more like amounts possible through the use of human powered bellows systems. This substantially increased the burn rate (where something closer to 4 – 5 minutes per kilogram might be considered more ideal). The most obvious impact of this was that the slag bowl initially developed too high and potentially too close to the front (tuyere side) of the furnace. This necessitated an early tap to prevent 'drowning' the air blast. Shortly into the addition of ore charges, some of the lower charcoal fines were scrapped out, allowing tapped slag to flow below the bottom of the existing bowl. This distributing of hot slag has been found to soften the bottom of a slag bowl, allowing it to slump downwards, in effect lowering the entire complex so as to leave more space for the growing slag 'lake' and also more room for the developing bloom. Over the course of the entire smelt, the furnace would self tap a number of times, a total of 7.9 kg tap slag would be recovered.

- Final Bloom Weight : 8.9 kg
- Yield : 35%

Another impact of the lower air rate was the resulting bloom mass was larger overall, but with a noticeably less dense 'spongy' texture, visibly with considerable slag still included. It is fully expected that although the nature of this bloom has resulted in a high yield number (especially for a smelt of this ore amount), there will be a considerably higher loss of weight at the bloom into bar phase.

It proved easy enough to break the front part of the interior slag bowl clear, making it possible to pull out the larger mass of bloom and clinging slag during extraction. The size of this mass did result in also pulling off the lintel stone, which in turn caused the sod strips being supported by this stone to also fall away. The line of breakage to the interior liner was slightly above the original cut for the extraction arch, running along just at the lower edge of the tuyere point.

During the extraction, the pieces of broken sod and any hot slag were shovelled up and discarded to one side, primarily to keep the working area clear. The lintel block was shifted slightly forward, and was retained in place, serving as a fulcrum for the long bar used to lever the bloom mass free. The overall extraction process created a triangular shaped spray of small slag fragments and partially burned charcoal, leading away from the front of the furnace. The portions of the slag bowl remaining inside the furnace were a C shape, pointed towards the extraction arch, with a clear depression marking the location of the removed bloom. All these features were considered relevant, as the exposed remains of the last furnace fired at Hals (number VII), showed much the same kind of ground features.


Furnace just after extraction – June experiment.

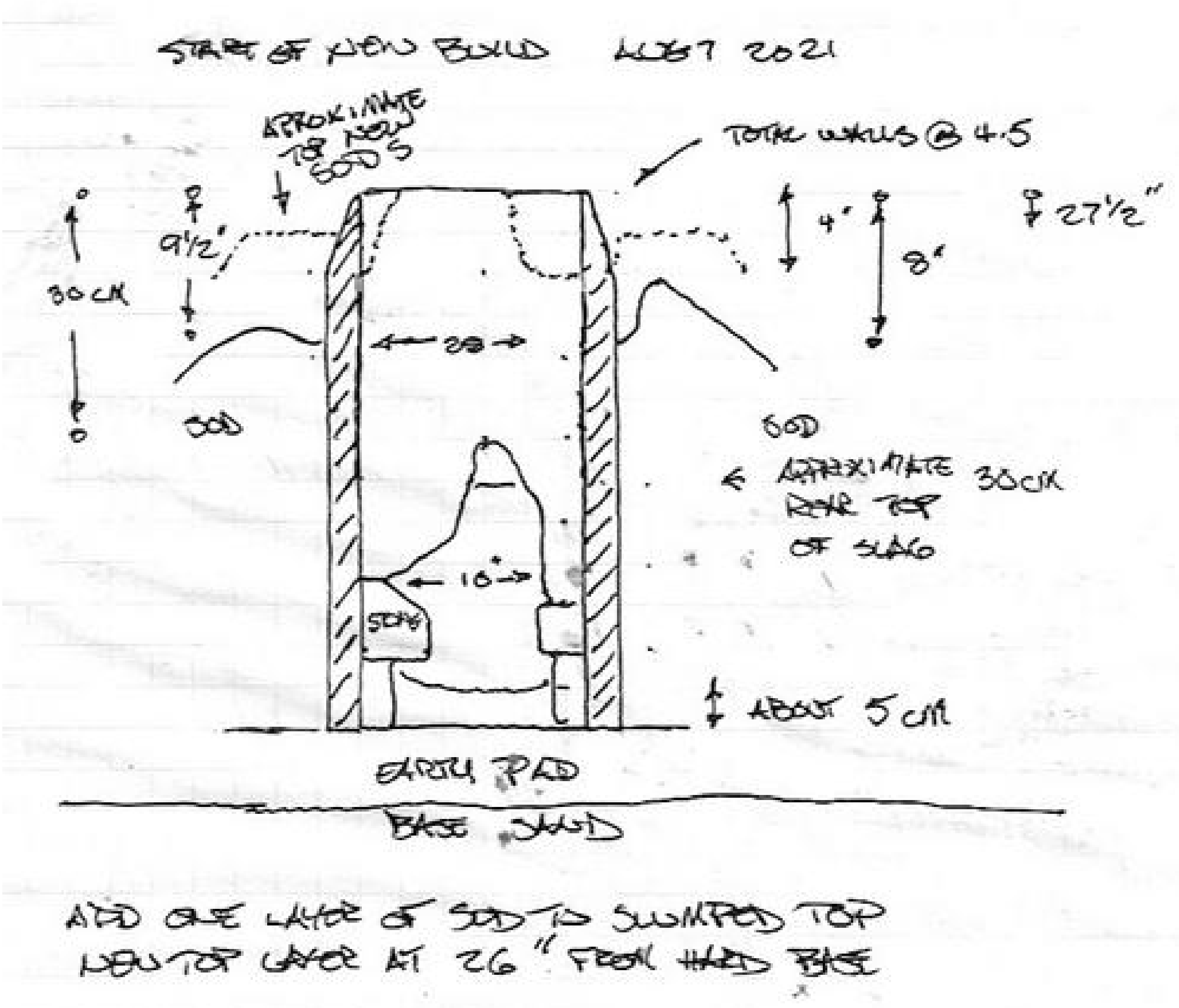
Inside the furnace itself, there was considerable erosion of the clay liner, following the expected oval pattern centred around the tuyere. At some places (especially close to and above the tuyere) the wall thickness had been reduced from the starting 4.5 cm to as little as an estimated 1 cm thick, all now heavily slag coated. The Icelandic clay mix did survive a full smelting cycle, but with more erosion damage than was the case with the standard EPK clay base normally used. This depth of erosion suggested that if the wall thickness had been much less than the 4.5 cm used, failure due to melting through the walls would certainly have occurred. On examining the overall damage to the furnace structure as it slowly cooled, it was felt that it would prove fairly easy to repair the lower sections that had broken away, and layer fresh clay onto the eroded areas inside.

The following morning however – this was discovered :

Likely in the early dawn hours, a roughly 20 cm long snapping turtle had crawled into the still warm furnace! (A) This resulted in additional damage to the front of the furnace. (In the image above the red line shows approximately the lower line of the furnace wall at the end of the smelt. The larger piece seen lying to the right of the turtle was the section broken free.)

The portions of slag bowl remaining after extraction were left in place. A metal cover was placed over the top opening of the furnace liner, but otherwise the sod structure was left exposed to natural weathering over the summer months, with the original intent to return for the normally scheduled early October smelt event.

Rebuild of the Furnace :



Top edge of the furnace liner, above the tuyere – condition after 5 weeks.

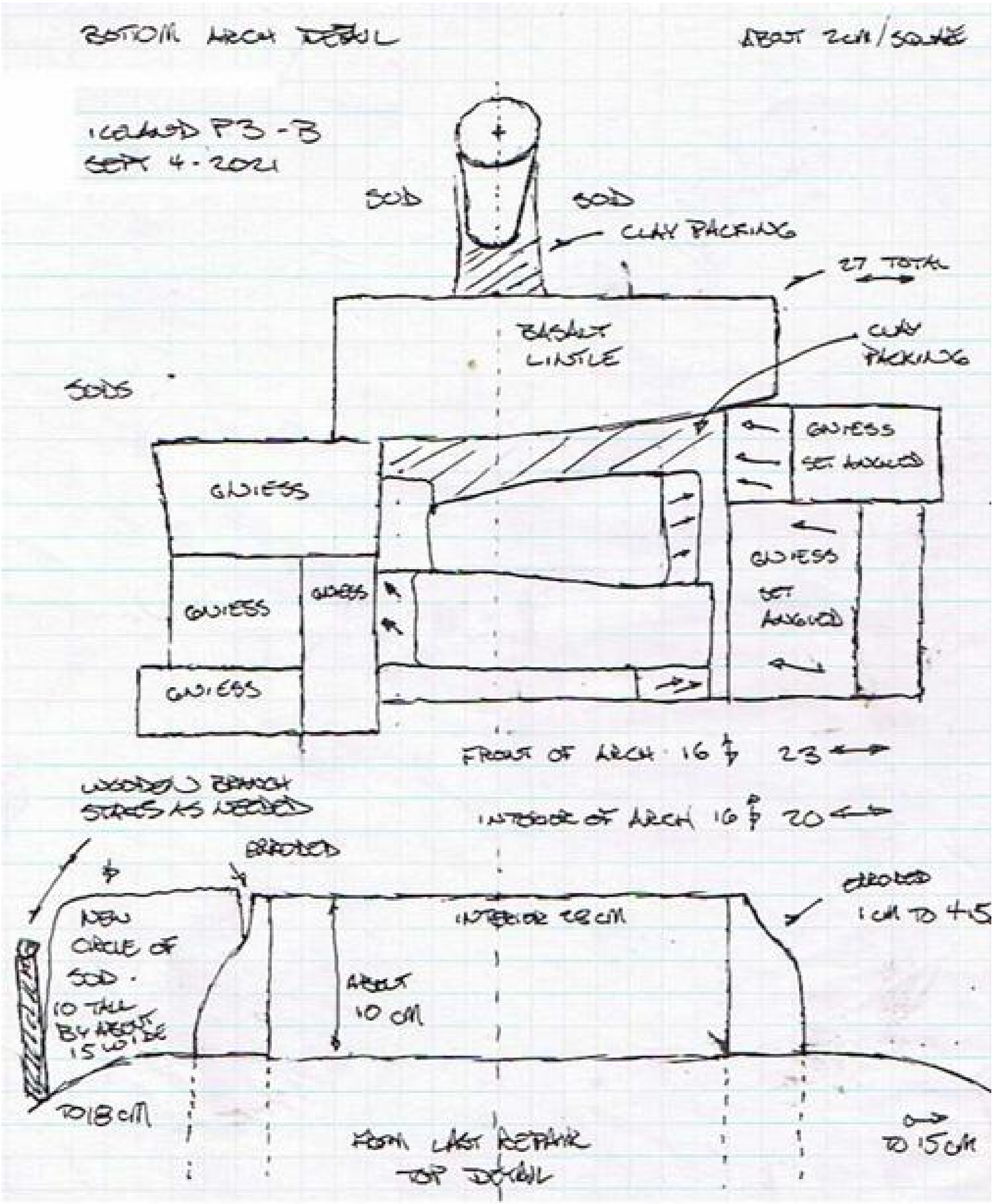
The temperature gradient that is produced by the firing of a smelting furnace has been seen to effect clay composition walls in varying ways, which results in variation in damage effects, as a furnace is exposed to weather over time. (6) There had been an unusual amount of rain over early Summer at Wareham (a period where normally there had been little, if any, rain in past years). The fracture line seen above (image taken July 17) marks the division between the sintered interior and the 'baked mud' exterior heat effects. By early August, the outer portions had broken free along this line. There had also been considerable slumping of the sod structure, again due to the exposure to rain. With concern that the existing furnace might suffer too much damage to be easily repaired for re-use, it was decided to move the scheduled second experiment forward to the later part of August. Repairs were undertaken the week of August 9 to 13.

The slag bowl remaining was removed, with any lumps of slag still adhering to the inner walls broken free. The interior was cleaned down to the original starting hard base (dirt) level.

View down the interior, after slag clinging to walls and remaining lower bowl was removed. Extraction arch to the top of this image.

In the image above, the considerable heat erosion of the clay liner is clear. The smooth circular surface at the bottom indicates the starting surface, protected by the base layer of charcoal fines. The heat effects are concentrated to the central portion of the shaft, the hottest part of the interior during firing. The upper portions (although somewhat distorted here by perspective) are again seen to be relatively free from any damage. This erosion was both more extensive and considerably deeper than had been seen in previous clay walled furnaces. This was clearly the result of the significantly lower melting point of the simulated Icelandic clay body.

Next a new extraction arch was created, with the framing build up using the same stone blocks and lintel stone as before. One change was that the arch space was filled with a number of smaller flat pieces of stone (gneiss), which extended to form the lower front wall into the interior of the furnace. Gaps between the stones were filled with the clay mixture (remaining from the batch mixed for the original build).



A new set of grass sod strips were cut and placed above the lintel stone, to help define the shape of the (missing) front part of the furnace. New clay mix was applied from the inner side of the furnace, first to re-establish missing portion from the earlier turtle damage. Next, clay was added into the eroded wall, attempting to even the surface out back to the original 4.5 cm thickness and smooth shape.

Interior after patching, larger areas indicated. At the top is seen the straight line of the lintel stone, which will support the tuyere tip when that is installed. The edges of the extraction arch stones are seen below the lintel.

As the supporting grass sods had slumped considerably, an additional layer of sod was added to the top, building up to roughly the same height as the clay liner.

With re-use of Furnace A, most of the layout details remained the same, with these changes :

- Grass Sod Exterior : 6 layers stacked,
- Extraction Arch : stone filled, at 25 cm wide by 18 cm tall
- Tapping Port : none
- Stack Height (above tuyere) : 43 cm
- Base Depth : 30 cm above hard base, charcoal fines layer adjusts depth below tuyere to 16 cm

Smelt B – September : *For details see appendix B*

Neil Peterson was the smelt master, with **Dave Cox** as lead hand, Rey Cogswell undertaking the extraction, Marcus Burnham as primary assistant (Darrell Markewitz supervising).

- Preheat Phase : 87 minutes
- Air Volume : varies, *see description below*
- Total Slag Added : 4.3 kg
- Total Ore Added : 26 kg
- Charcoal 'Bucket' : 1.97 kg (difference due to absorbed water as stored outdoors)
- Primary Sequence (over ore additions) : 156 minutes
- Primary Charcoal Burn Rate : (average) 5.7 minutes / kg
- Ore Rate : (average) 6.0 minutes / kg

A major addition to instrumentation had been made, and employed for this smelt. This was the purchase of an Omega HHF1000 flow meter. (C) This allowed for far more accurate measurements of the actual air volumes being injected into the furnace, over the roughly calibrated 'sliding blast gate' numbers recorded in the past (including for Smelt A). (7) One of the problems with the earlier measurements was that these were the potential <u>total</u> air available from the air equipment, and so did not account for the restrictive effect of the materials inside the furnace stack, certain to vary considerably over time. As this was the first use of this gauge, only infrequent measurements were made :

Time	Event	Plate	Meter	Calculated
10:11	fill rough charcoal	700		
10:15	air increase	(900)		
11:19	full graded charcoal		11.5	865
11:23	air reduced	700	(no record)	550
12:00	air increased	800	8.8	660
12:44	air increased	900	9.6	720

The overall implication of these measurements is that earlier reported air volumes are only significant as they are compared to each other, <u>not</u> an accurate indication of exact volumes. Roughly, these earlier numbers are likely to be 25 % higher than the actual air amounts into the furnace. In working practice, the physical burn rate (consumption of a given amount of charcoal) is used to determine the best functional air volume at any given point.

Again in Smelt B, potential air volumes were reduced towards what was considered possible via human powered bellows systems. Again the first impact of this was to cause the initial slag bowl to form too high, raising the level of liquid slag upwards to where there the air blast was being effected. This was partially corrected by using a metal rod (3/8 inch diameter) to probe vertically, about 1/3 of the furnace diameter from the tuyere. This was forced down through the still fragile bottom of the slag bowl, allowing hot liquid slag to drain down into the charcoal fines layer, a process repeated three times early in the smelt. Significantly, a burning through of the front furnace wall, about 10 cm above the tuyere was observed at roughly 90 minutes into the primary furnace cycle. This suggested that the lower volume air blast was not fully penetrating into the furnace, but instead washing back against the furnace wall at this location.

Also as with Smelt A, roughly after the addition of the first two ore charges, the extraction arch was opened, in this case by the removal of one of the lower stone pieces filling the arch. Again some of the lower charcoal fines were scraped out, allowing any self tapping slag to flow below and soften the slag bowl, a process that would proceed without any further intervention for the remainder of the smelt.

Although it would be the first time for this task, Rey Cogswell undertook the full extraction process. Lack of experience would result in the extraction to be considerably drawn out, all the while the furnace slowly cooling. The net effect was that the bloom did not easily pull free of the encompassing slag bowl, and a much larger mass than normal had to be removed from the furnace. The raw size of this mass would result in considerably more damage to the lower front of the furnace than was expected. The stones supporting the front of the furnace ended up all being removed. As the strips of sod above the fallen lintel block collapsed, it was obvious there had been a major burn through of the front wall, with fused dirt now attached in a thick band in the area above the tuyere. The entire tuyere and air supply system would pull off, dropping into the fan of hot debris at the front of the furnace.

Between the extra mass now attached to the upper wall, the removal of the supporting stones, and the force of removing the large bloom encased in additional slag, the entire clay furnace liner would slump outwards, pulling partially clear of the rear sod structure.

Debris at the front of the furnace, after extraction. Note the mass of fuzed dirt, the result of the burn through of the front wall above the tuyere.

- Final Bloom Weight : 8.2 kg
- Yield : 32%

The air rate was set slightly higher than for Smelt A, certainly observed with the higher average burn rate as calculated. Still, the resulting bloom mass was also larger and again with a noticeably less dense 'spongy' texture and containing considerable slag. Again the yield recorded against ore volume is disproportionately high, with excessive losses expected at the later bloom to bar compaction.

One addition to the initial compaction work was the inclusion of a large wooden 'troll hammer', as observed in use by many European teams. This proved quite effective for the initial phases of hammering off the clinging slag 'mother' from the bloom itself.

Marcus Burnham with the 'Troll Hammer', ***Richard Schwitzer*** *with a standard sledge, Dave Cox holding. The slag shows as the darker material still encasing the hot metallic bloom core.*

Weathering :

Primary Test 3 for the Phase 3 series was : " *How does a well designed furnace, on the Hals pattern, endure over time? In this case an overwintering, with a repeat use 12 months after the original construction.* " It was clear however, even at the end of Smelt B, that a significant rebuild of both the inner clay liner and the surrounding sod structure would be required before the existing furnace could be used again.

It was decided instead to leave the furnace remains exposed to weather, basically the start of long term observations of the effects of environmental processes on this specific furnace type. September in Central Ontario saw a huge increase in rainfall over past decades however, clearly accelerating these effects. (D)

Rain erosion, September 24 - compare with post smelt image seen above (pg 16).

Side view, showing slumping of the furnace towards the extraction side (to right).

Photographs of the furnace have been made several times over the month of September, and will be ongoing over coming months. The image above shows the slumping forward of the remaining clay liner, a total of roughly 17 degrees off the original vertical, over the first 20 days since the last firing. Any attempt to re-use this furnace would most certainly require as a first step clearing away the falling dirt, and restoring the line of the liner to vertical. Given the overall fragile condition of the clay, especially along the mass of fused dirt on the front wall, it is considered unlikely that such a re-adjustment would even prove possible.

Conclusions :

Primary Test A : ***The function of simulated clay body, based on the best possible duplication of the material recovered close to Hals.***

Initial heating tests of samples of the simulated Icelandic clay suggested that there might be some problems with melting of this material when subjected to the normal firing temperatures inside a bloomery iron smelting furnace, expected to be as high as 1250 + C. The decision to build the clay walls to a thickness of 4.5 cm was primarily based on experience gained earlier during the Phase 2 experiments. This turned out to be a functional minimum, at least as demonstrated by Smelt A. Through this fairly standard firing sequence, the normal erosion effects that are concentrated around the tuyere had reduced the wall thickness to as little as 1 cm in some spots.

Another expected result of the lower melting point exhibited by this clay body was an increase in slag produced. This proved to be the black (iron rich) and importantly, fluid type. This did require both tapping out and other management processes over the course of the smelt to ensure the air blast through the tuyere was not interrupted.

Used as component of a well understood furnace layout and employing a standard firing process, the simulated Icelandic clay proved quite suitable through single firing.

Primary Test B : *How does this furnace perform with repairs and a second firing?*
It was clear however, that excessive internal erosion had resulted during the first firing. After breading clear the first slag bowl that remained, generally it proved fairly easy to blend new clay on to the inner surfaces, in an attempt to restore the original 4 – 4.5 cm wall thickness. The needed repairs were further complicated by two factors (both beyond the control of the experiment). The first of these was the additional damage done to the middle front wall by the turtle. The second was a two week delay between the undertaking of repairs, and the mounting of Smelt B. (E) Both these factors may have contributed to less than ideal bonding between the existing wall and the repairs applied. This most likely the reason for the burn through failure experienced in Smelt B.
It did prove easily possible to repair a previously used furnace and effectively undertake a second full smelt.

Primary Test C : *How does a well designed furnace, on the Hals pattern, endure over time?*
There was enough accumulated damage to the furnace that it was not considered realistic to be able to repair it so to be able to undertake another firing cycle, so a possible third use has to be considered an open question still. The effects of the additional turtle damage, plus that caused by less experienced hands during extraction in Smelt B, certainly accelerated overall damage to both the clay liner and the surrounding sod structure.

The original outline for Phase 3 called for the furnace to be somewhat covered, at least to prevent rain and eventual snow from falling down the open top, but otherwise exposed over an Ontario winter. Freezing temperatures can be expected at Wareham by later October, snow by mid November, eventually accumulating to a metre or more in depth. The furnace would have been examined, with repairs made as possible, against a potential third firing in mid June.

In light of the damage at the end of Smelt B, coupled with the effects of unusual rainfall over the month of September, it has been decided not to attempt to re-use this furnace. Instead, it will remain in place and be exposed to the natural cycle of weather over an extended period into the future – ideally many years. As it degrades, it is hoped that records of that process may serve to have some value to archaeologists when interpreting ancient smelting furnaces.

One additional observation from the two smelt experiments of Phase 3 lays in the ore into iron results. Both smelts used identical ore analog, ore amounts and charcoal type. Air volumes applied were roughly similar. The overall working sequence both times was also similar, outside the fine detail of needed slag control. The end results where found to be virtually identical as well, with unusually high bloom sizes and yield numbers, with the blooms created of similar quality. This also proves the viability of this reconstruction of the Hals working system, at least for a limited set of firing cycles. **The placement of several furnaces in close proximity at Hals suggests that these also were short use cycle structures, tore clear and re-made as each failed.**

Appendix A : Experimental Data / Smelt A, June 20, 2021

Appendix B : Experimental Data / Smelt B, September 4, 2021

Notes :

A) This is only a brief description of the standard working sequence that has been developed over two decades by this team. A fuller description of the process can be found : Markewitz, D., 2012, ' *"If you don't get any iron ..."- Towards an Effective Method for Small Iron Smelting Furnaces.*', EXARC Journal Issue 2012-1 : https://exarc.net/issue-2012-1/ea/if-you-dont-get-any-iron-towards-effective-method-small-iron-smelting-furnaces

B) The snapping turtle (*Chelydra serpentina)* is native to North America. The smelting area at Wareham is adjacent to a small pond, and a creek runs behind the (rural) property : https://en.wikipedia.org/wiki/Common_snapping_turtle

C) One of the problems effecting all Independent Researchers is access to high quality (priced!) instrumentation : see : https://www.omega.com/en-us/test-inspection/handheld-meters/anemometers/p/HHF1000-Series

D) Records from Environment Canada give the past average rainfall for the area around Wareham for the month of September as 7.7 cm total. In 2021, there was a single one day amount of 5.6 cm. Although exact overall total for September were not available at time of writing, September 2021 certainly had the highest amount of overall rainfall, often as heavy downpours, seen over 30 + years of personal observation.

E) The repair work was undertaken on August 18, with the second firing scheduled on the 20th. On the 19th, project leader Darrell Markewitz would experience an unforeseen medical, which resulted in the effective loss of the left hand for many weeks following. (This also the reason for shifting of roles during Smelt B.)

References :

1) Smith, K.P., 2005, *'Ore, Fire, Hammer, Sickle: Iron Production in Viking Age and Early Medieval Iceland',* AVISTA Studies in the History of Medieval Technology, Science, and Art, Volume 4, USA
Also available as PDF on line :
https://www.academia.edu/191535/Ore_Fire_Hammer_Sickle_Iron_Production_in_Viking_Age_and_Early_Medieval_Iceland

2) Markewitz, D., 2007 '*Working towards an Icelandic Viking Age Smelt - Based on the remains at Hals*'. Published on line (web site) :
http://www.warehamforge.ca/ironsmelting/HALS/index.html

3) Markewitz, D., ongoing from 2001, '*Experimental Iron Smelting*', Web site - documentation of individual tests and experiments :
http://www.warehamforge.ca/ironsmelting/index.html

4) Markewitz, D., with contributions by Neil Peterson and Rey Cogswell, 2021, '*Into Phase Three – Continuing Experiments with Iron Smelting, based on Hals, Iceland.*'

Published on line (web site) :
http://www.warehamforge.ca/ironsmelting/phase3/phase3.html

5) Markewitz, D., 2021, '*Sticking To It – A clay mix for Icelandic Furnaces*'. Published on line (blog posting) : https://warehamforgeblog.blogspot.com/2021/06/sticking-to-it-clay-mix-for-icelandic.html

6) Markewitz, D., 2021, '*Evidence of Absence – Erosion of Furnace Walls*', Published on line (web site) :
http://www.warehamforge.ca/ironsmelting/erosion/erosion2021.html

7) Markewitz, D., 2021, '*Mind the Blast – Correcting Reported Air Volumes*', Published on line (blog posting) :
https://warehamforgeblog.blogspot.com/2021/09/mind-blast.html

October 2021

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