I'll Huff and I'll Puff…

Observations on Air Delivery in Bloomery Iron Furnaces

How it Works

Puzzle of Historic Air

When Data doesn't fit Hypothesis

Darrell Markewitz

The Wareham Forge

Forward Into the Past 23 - 2013

How it Works

The Direct Process
Bloomery Furnace

African Furnace

Tall = Natural Draft

Sauder & Williams

Refractory with Blower

Chemistry is STANDARD

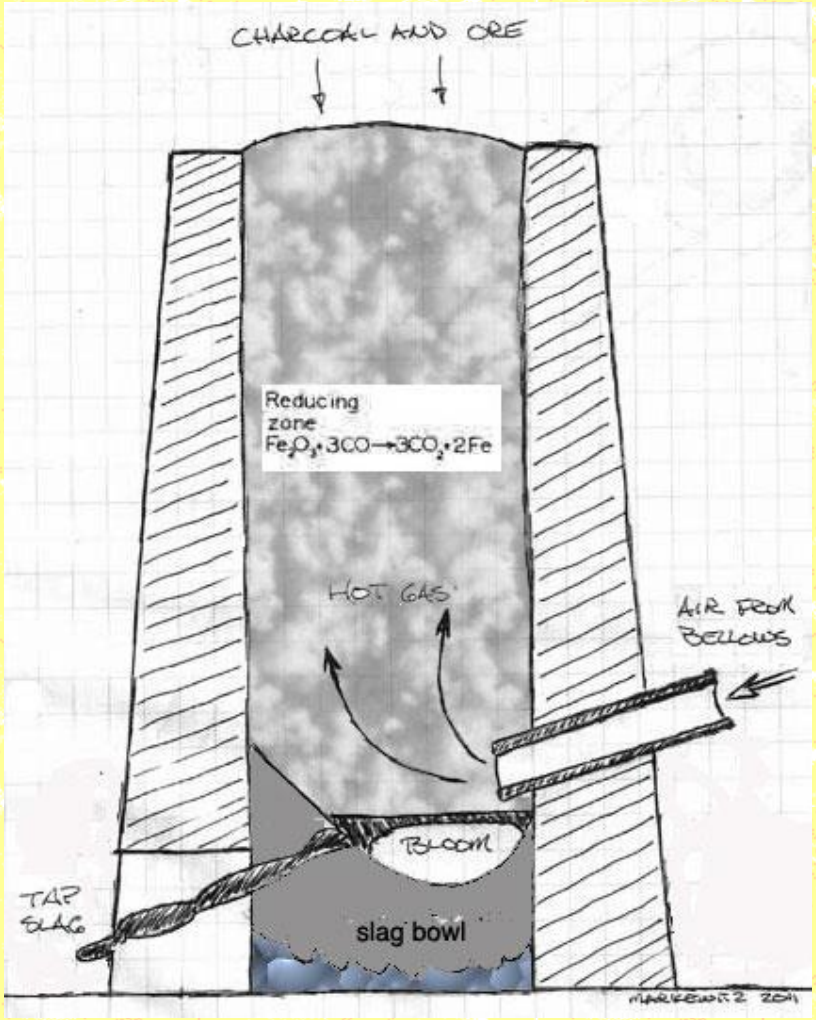
- **Fire Proof Container**
- **Burning Charcoal**
- **Iron Oxide Ore**

Reduced to Metallic Iron

How it Works

The Direct Process

Bloomery Furnace



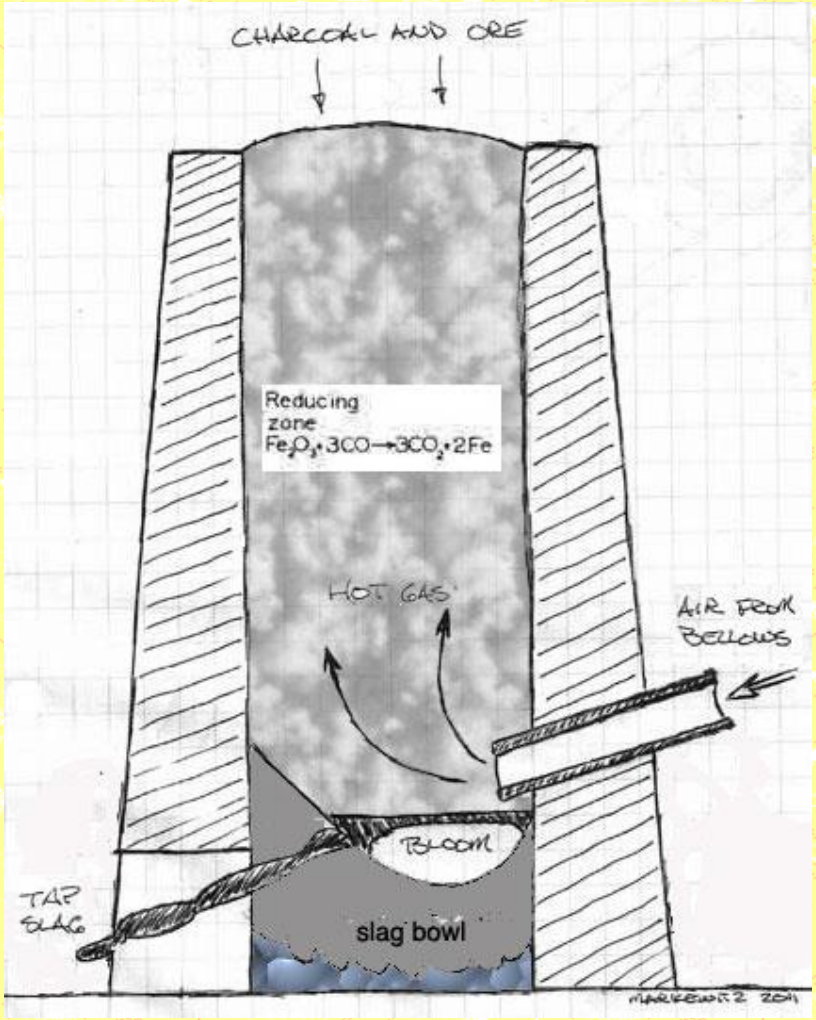
Physical Mechanism Messier!

- **Burning charcoal produces heat & C0**

How it Works

The Direct Process

Bloomery Furnace



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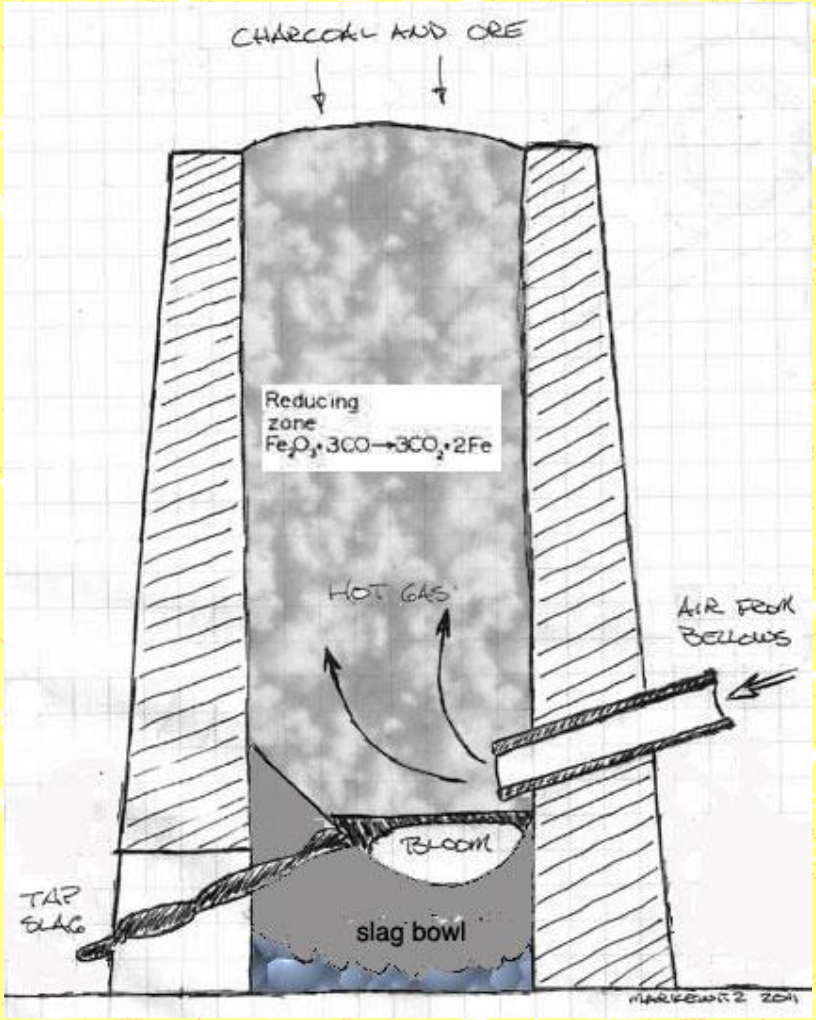
How it Works

The Direct Process

Bloomery Furnace



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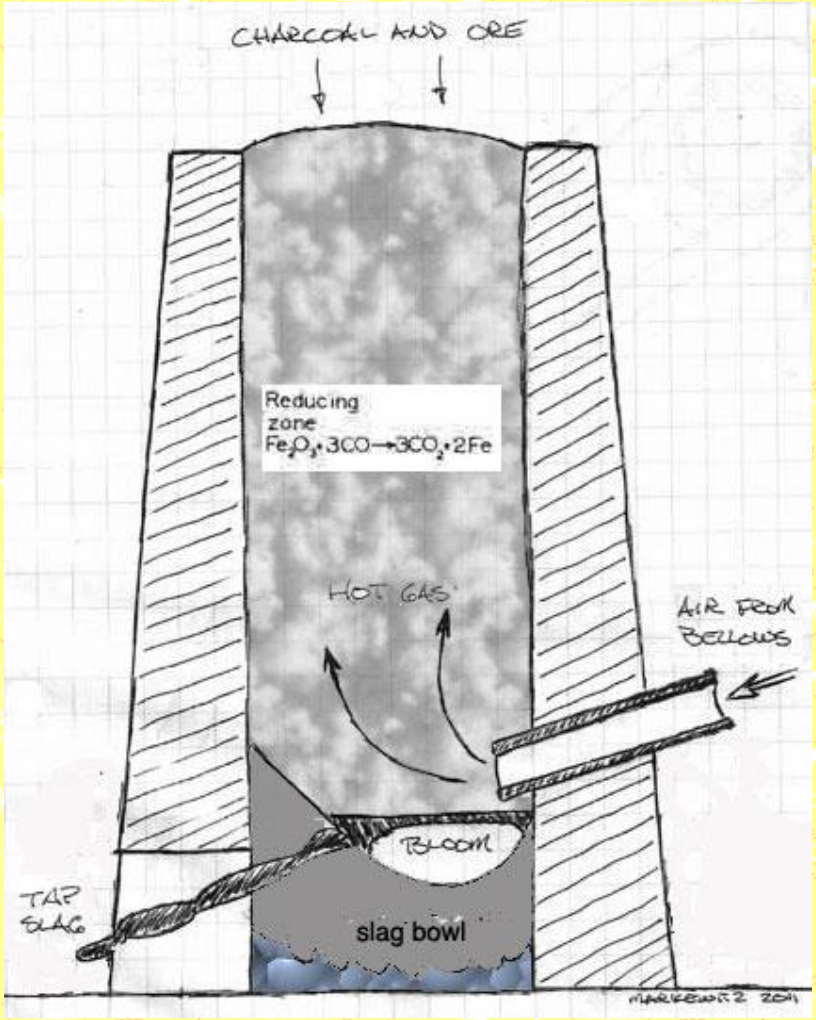
- **CO removes oxygen, forms CO2**

How it Works

The Direct Process

Bloomery Furnace



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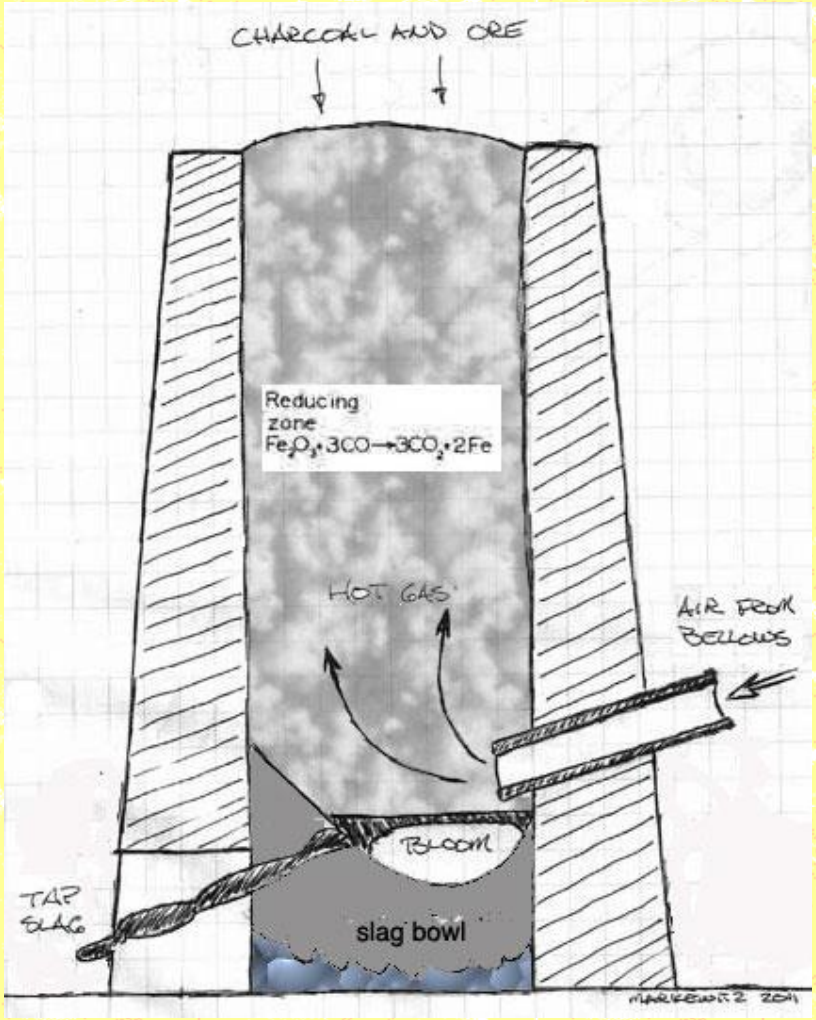
- **Metallic iron particles, fall and sinter**

How it Works

The Direct Process

Bloomery Furnace



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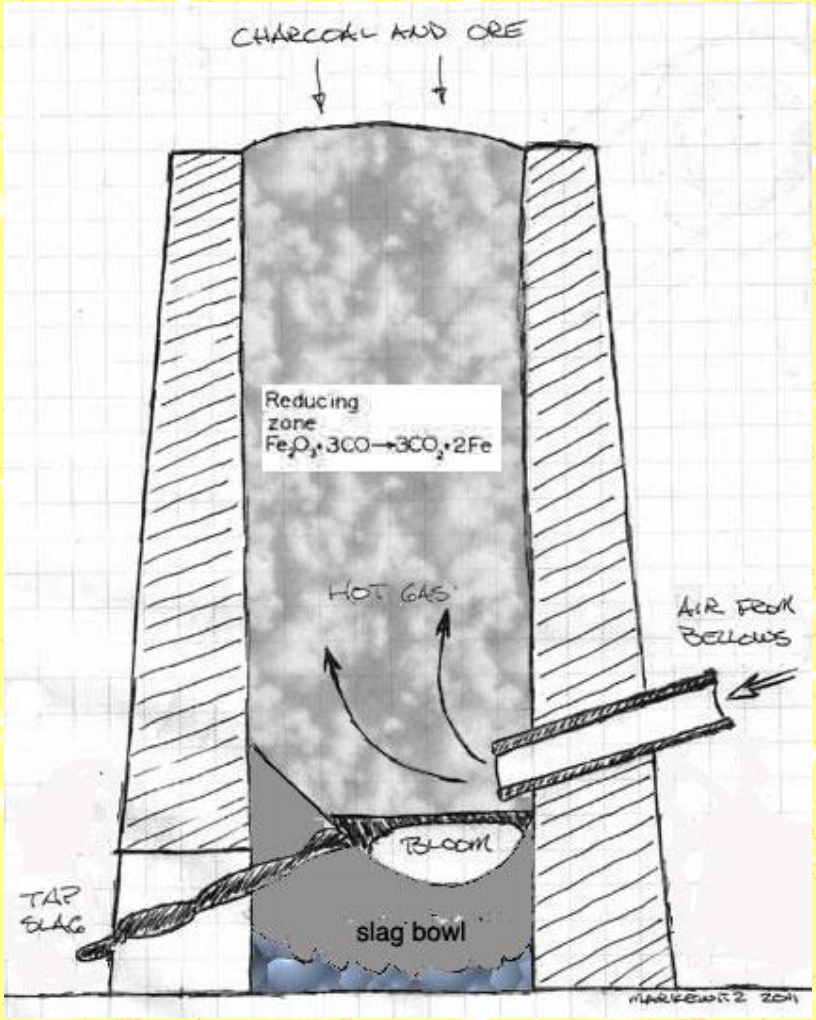
- **Silica from ore & walls forms glass slag**

How it Works

The Direct Process

Bloomery Furnace



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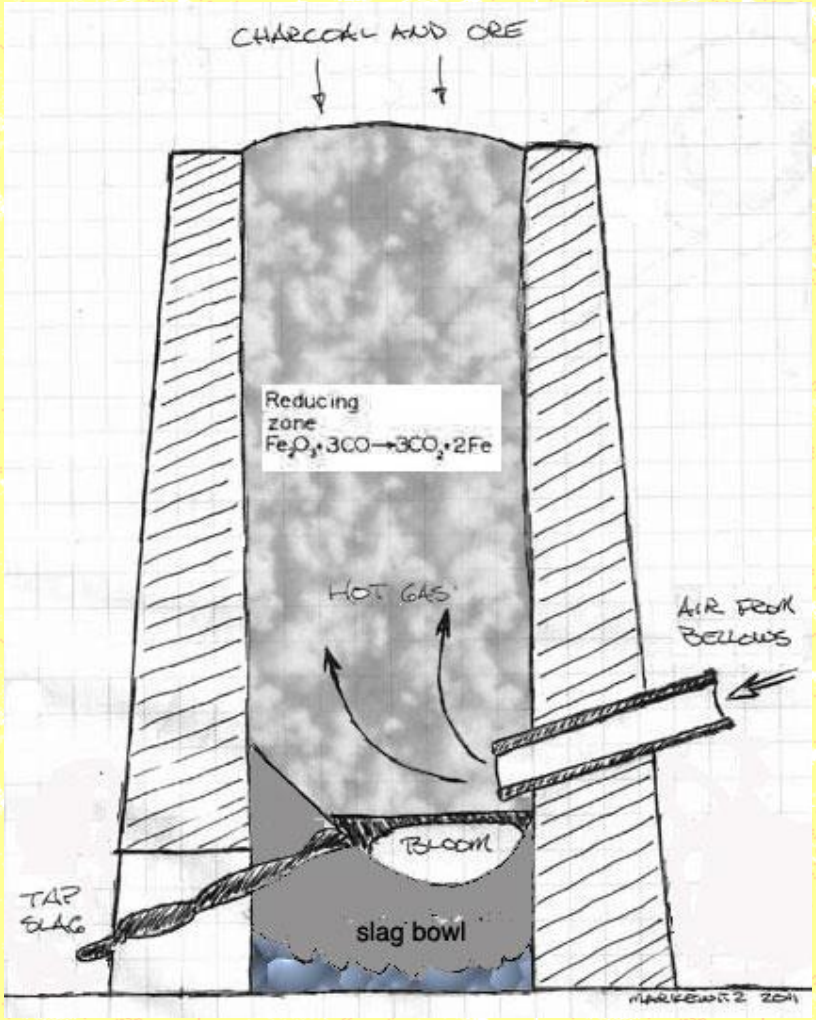
- **Bowl forms , solid at bottom, liquid inside**

How it Works

The Direct Process

Bloomery Furnace



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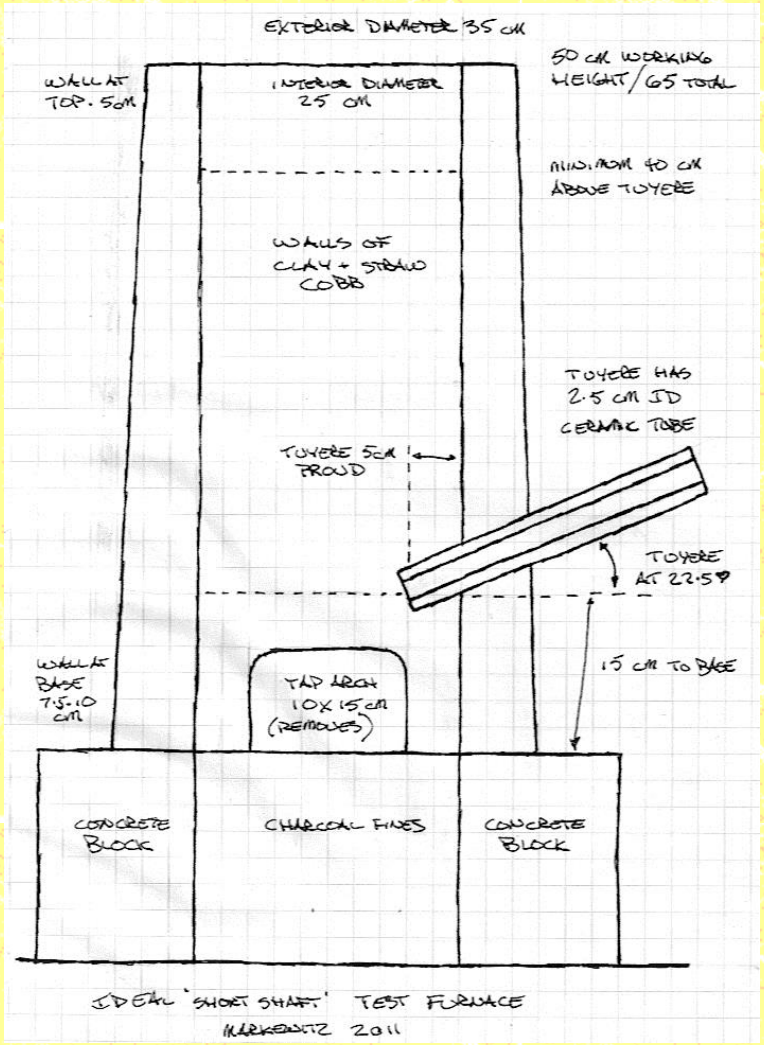
- Bowl forms , solid at bottom, liquid inside
- **Iron bloom collects inside this slag bowl**

How it Works

The Direct Process

Bloomery Furnace



Not so EASY!

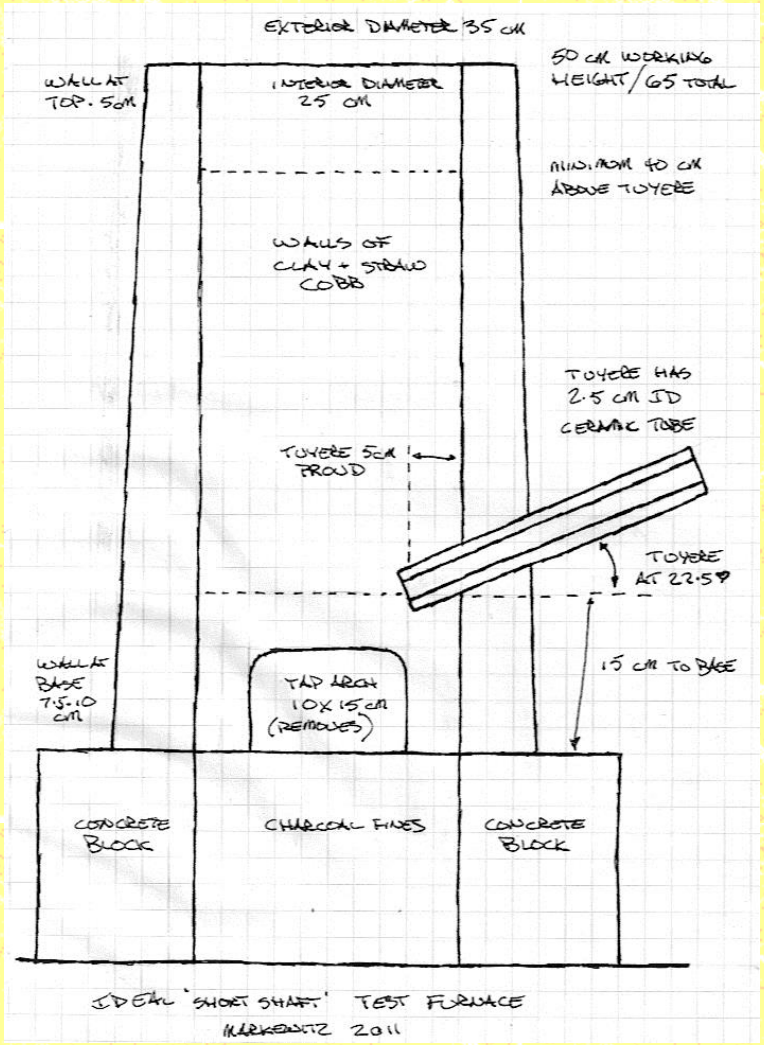
For any given Ore…

- **General shape & construction of furnace**

How it Works

The Direct Process

Bloomery Furnace



Not so EASY!

For any given Ore…

- General shape & construction of furnace
- **Combination of ore & charcoal size**

How it Works

The Direct Process

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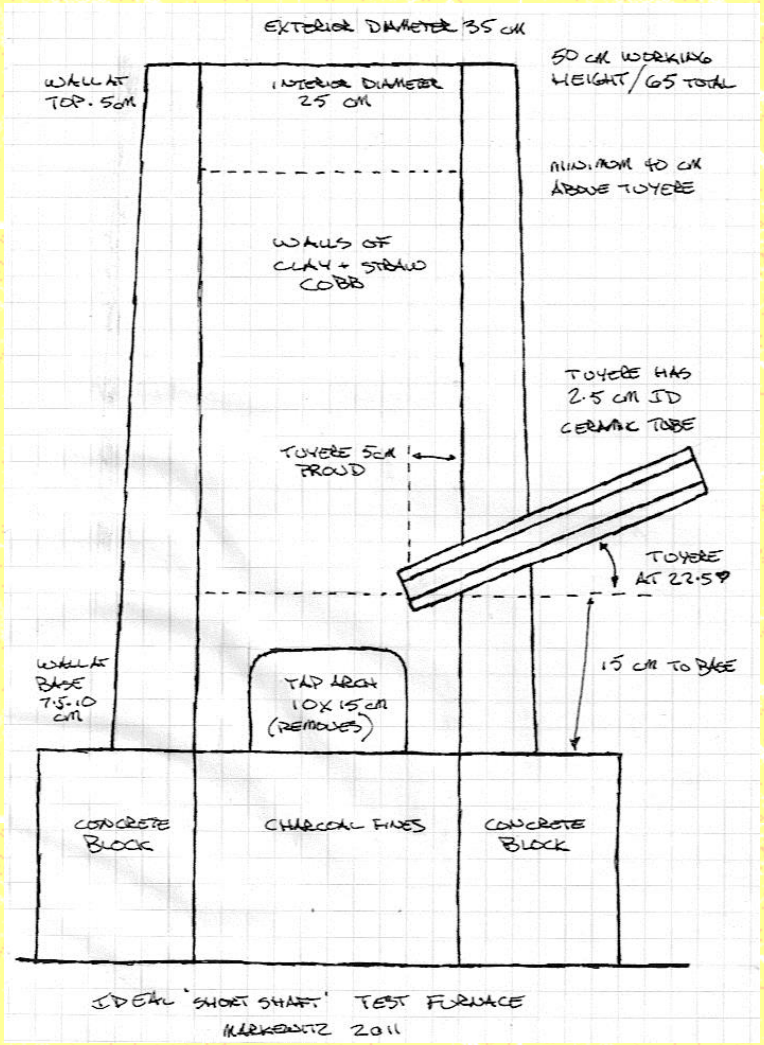

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- General shape & construction of furnace
- Combination of ore & charcoal size
- **Height of reaction column**

How it Works

The Direct Process

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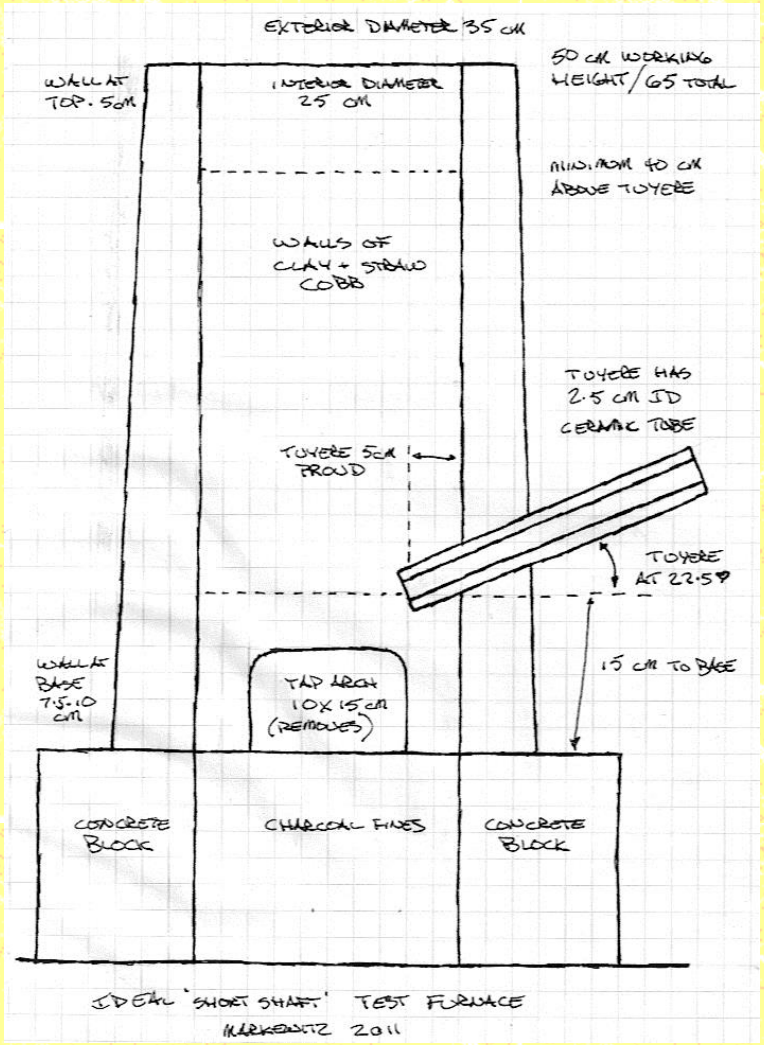


Not so EASY!

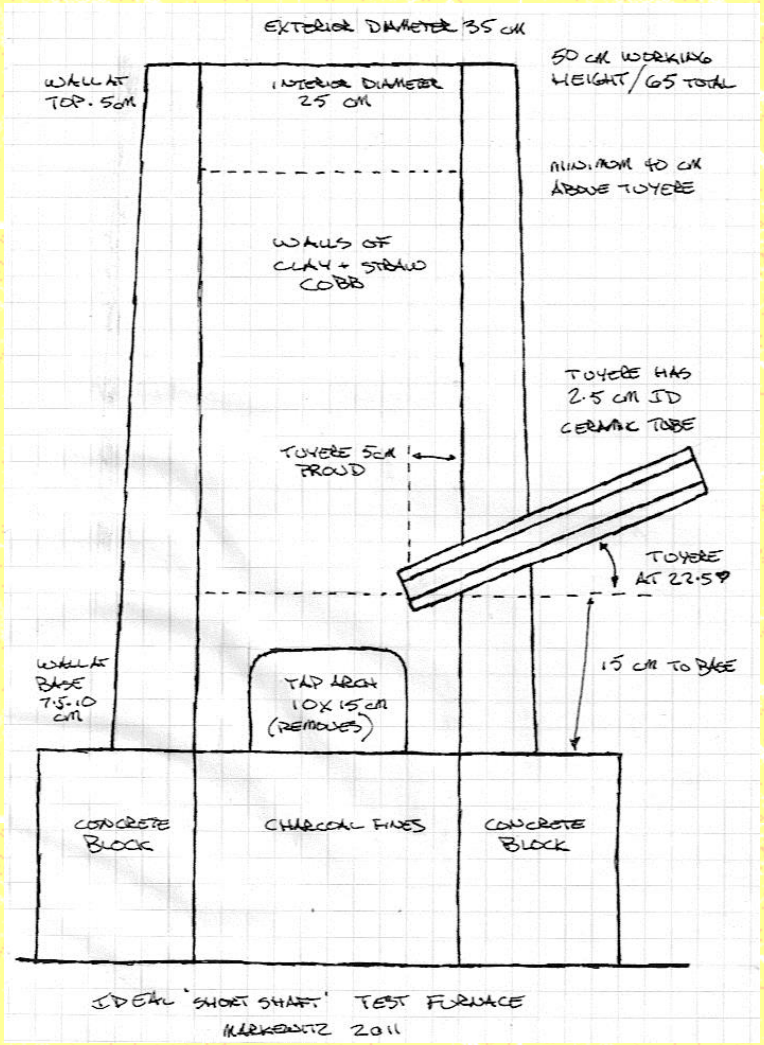
For any given Ore…

- General shape & construction of furnace
- Combination of ore & charcoal size
- Height of reaction column
- **Volume / Pressure (!) air**

How it Works

The Direct Process

Bloomery Furnace



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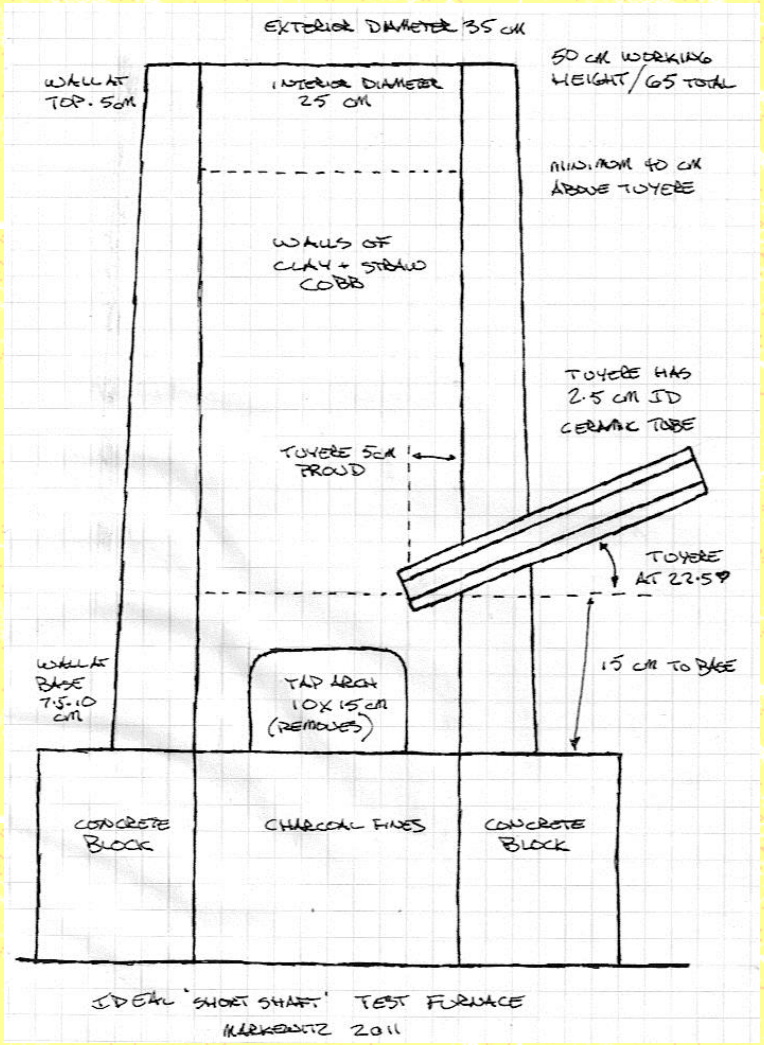
For any given Ore…

- General shape & construction of furnace
- Combination of ore & charcoal size
- Height of reaction column
- Volume / Pressure (!) air
- **Arrangement of tuyere**

How it Works

The Direct Process

Bloomery Furnace



Not so EASY!

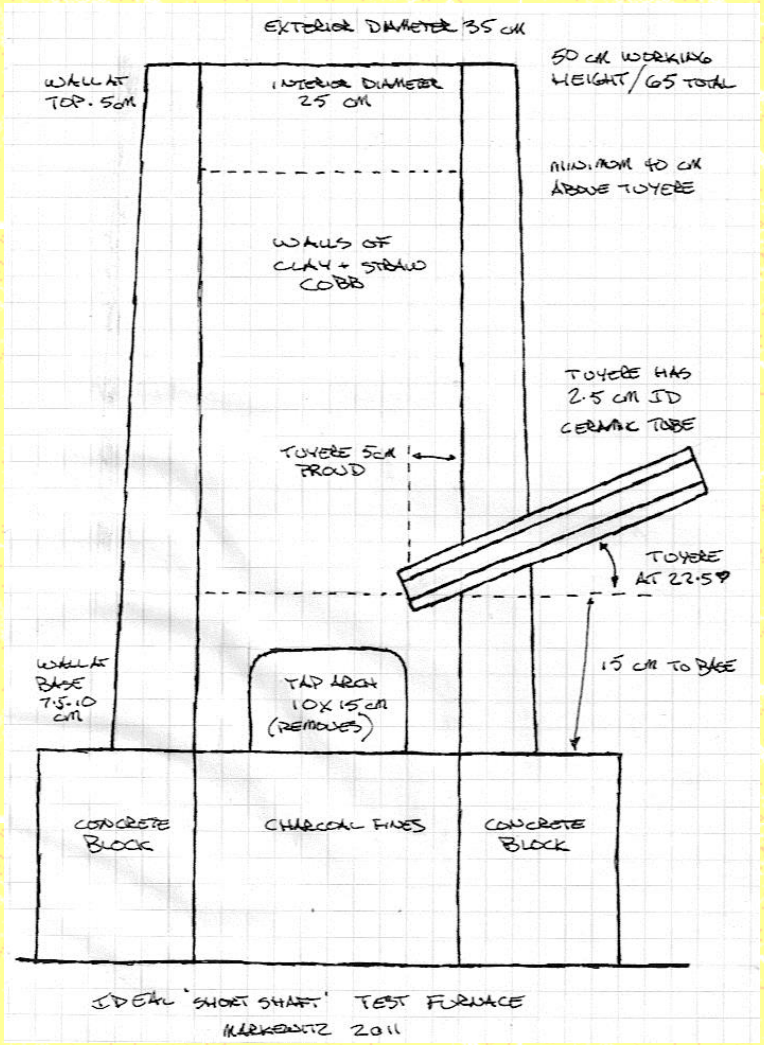
For any given Ore…

- General shape & construction of furnace
- Combination of ore & charcoal size
- Height of reaction column
- Volume / Pressure (!) air
- Arrangement of tuyere
- **Ideal temperature range**

How it Works

The Direct Process

Bloomery Furnace



Not so EASY!

For any given Ore…

- General shape & construction of furnace
- Combination of ore & charcoal size
- Height of reaction column
- Volume / Pressure (!) air
- Arrangement of tuyere
- Ideal temperature range
- **Ideal addition rate for ore & fuel**

How it Works

The Direct Process

Bloomery Furnace

Ore Varies!

- **Fe00H / Fe2O3 / Fe3O4**

How it Works

The Direct Process

Bloomery Furnace

Ore Varies!

- Fe00H / Fe2O3 / Fe3O4
- **Fe Content**

How it Works

The Direct Process

Bloomery Furnace

Ore Varies!

- Fe00H / Fe2O3 / Fe3O4
- Fe Content
- **Density / Porosity**

How it Works

The Direct Process

Bloomery Furnace

Ore Varies!

- Fe00H / Fe2O3 / Fe3O4
- Fe Content
- Density / Porosity
- **Particle Size**

Historically - Sites chosen for ORE

Historic Prototypes

Norse / Viking Age
Short Shaft Furnace

Lodience, Bohemia

Earlangard, Norway

Designed for Bog Ore

- **Clay / Stone**

Historic Prototypes

Norse / Viking Age
Short Shaft Furnace

Lodience, Bohemia

Earlangard, Norway

Designed for Bog Ore

- Clay / Stone
- **ID : 30 - 50 cm**

Historic Prototypes

Norse / Viking Age
Short Shaft Furnace

Lodience, Bohemia

Earlangard, Norway

Designed for Bog Ore

- Clay / Stone
- ID : 30 - 50 cm
- **Height : 60 cm (?)**

Historic Prototypes

Norse / Viking Age
Short Shaft Furnace

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Earlangard, Norway

Designed for Bog Ore

- Clay / Stone
- ID : 30 - 50 cm
- Height : 60 cm (?)
- **Inset Tuyere @ 2.5 cm**

Historic Prototypes

Norse / Viking Age
Short Shaft Furnace

Lodience, Bohemia

Earlangard, Norway

Designed for Bog Ore

- Clay / Stone
- ID : 30 - 50 cm
- Height : 60 cm (?)
- Inset Tuyere @ 2.5 cm
- **Bottom Extraction (?)**

Remains Fragmentary = MUCH WAG

Historic Prototypes

Bloom Production

Very Few Artifacts!

- **Full Blooms**

Historic Prototypes

Bloom Production

Very Few Artifacts!

- Full Blooms
- **5 - 10 kg range**

Historic Prototypes

Bloom Production

Very Few Artifacts!

- Full Blooms
- 5 - 10 kg range
- **Partially compacted**

Historic Prototypes

Bloom Production

Very Few Artifacts!

- Full Blooms
- 5 - 10 kg range
- Partially compacted
- **Edge Cut**

Historic Prototypes

Bloom Production

Very Few Artifacts!

- Full Blooms
- 5 - 10 kg range
- Partially compacted
- Edge Cut

Very Dense

(5 - 6 gm/cc*)

Historic Prototypes ?

High Volume Air

Sauder & Williams

Proven System

1.2 - 1.5 l/m/cm2

(580 - 1270 l/m)

Historic Prototypes ?

High Volume Air

Sauder & Williams

Proven System

1.2 - 1.5 l/m/cm2

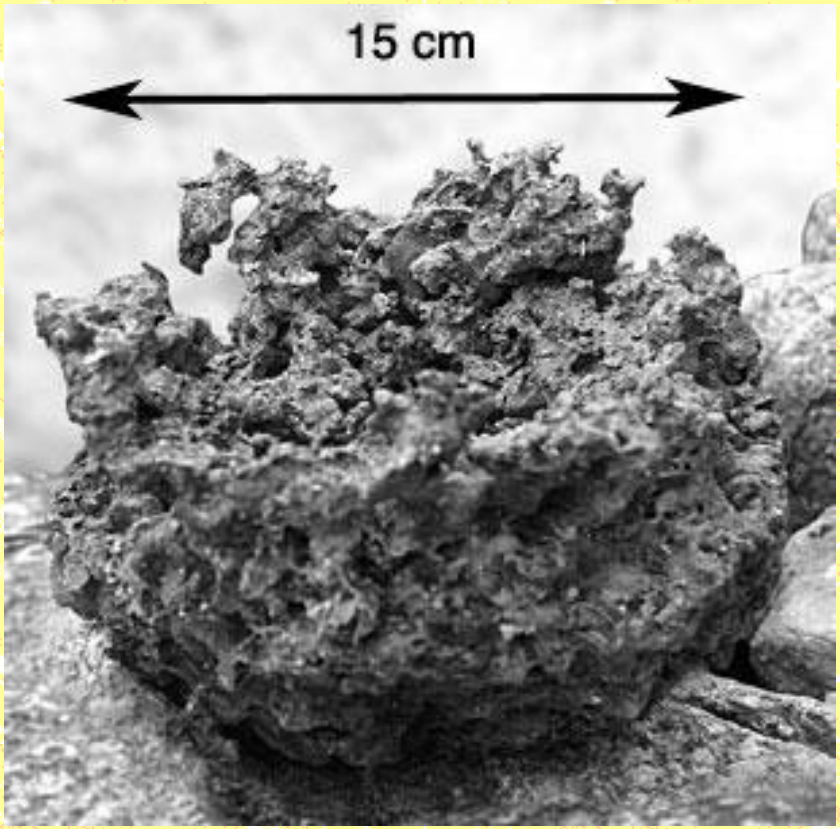
(580 - 1270 l/m)

Problems :

- **Using electric blowers**
- **What is historic air?**

Historic Prototypes ?

Low Volume Air

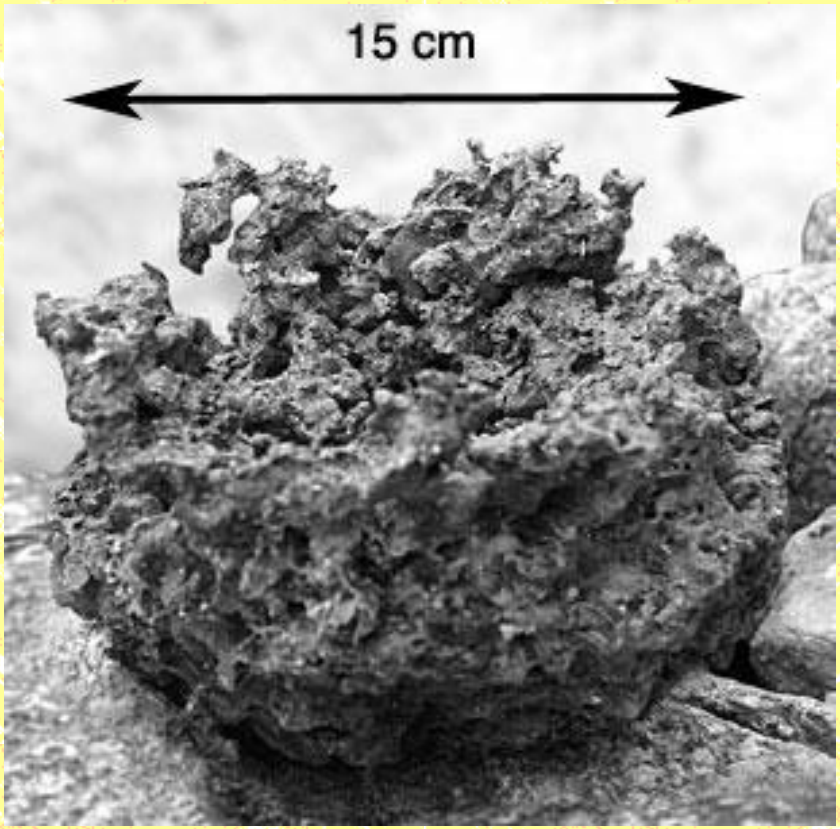


Bloom from Margi, Africa

Passive or Small Bellows

Historic Prototypes ?

Low Volume Air



Bloom from Margi, Africa

Passive or Small Bellows

Problems :

- **Lacy consistency**
- **Reduced Yields**

Historic Prototypes

Viking Age References?

Hylestad, Norway

- **Twin chambers**
- **Three lame construction**
- **Chamber 4 - 5 x hand width**
- **Tube from each chamber**
- **Chambers empty alternately**

No (?) Surviving Artifacts !

Historic Prototypes

Viking Age References?

Hylestad, Norway

- Twin chambers
- Three lame construction
- Chamber 4 - 5 x hand width
- Tube from each chamber
- Chambers empty alternately

Problems :

- **Artistic rendering**
- **Wood carving**
- **Impossible position**

No (?) Surviving Artifacts !

Historic Prototypes

Viking Age References?

Ramsund, Sweden

- **Twin chambers**
- **Width to length**
- **Proportion of inlet hole**

No (?) Surviving Artifacts !

Historic Prototypes

Viking Age References?

Ramsund, Sweden

- Twin chambers
- Width to length
- Proportion of inlet hole

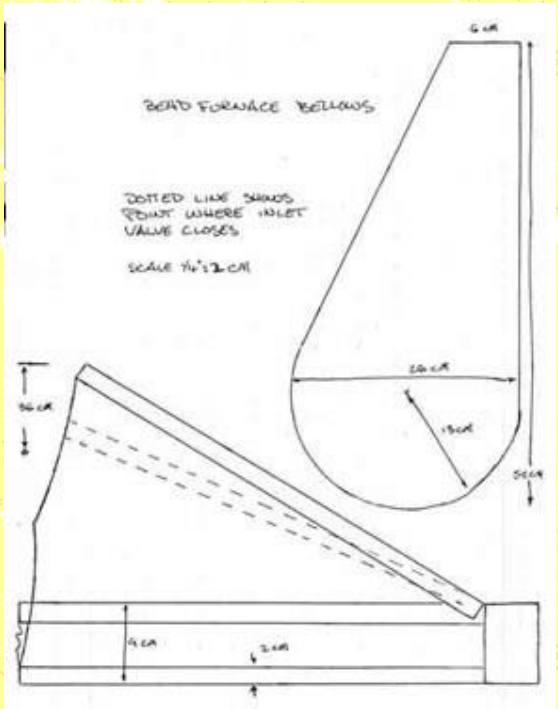
Problems :

- **Simple outline**
- **Stone carving**
- **No scale**

No (?) Surviving Artifacts !

Historic Prototypes

Viking Age Replicas ?



Bellows Reconstruction

Sand Table Forge

Smelting Furnace

Problem : 120 - 130 litres / minute

BLACKSMITH'S Equipment!

Historic Prototypes

‘Historical’ Replicas ?

Nissen - Ribe, Denmark

Staffordshire, England

Olesen - Heltborg, Denmark

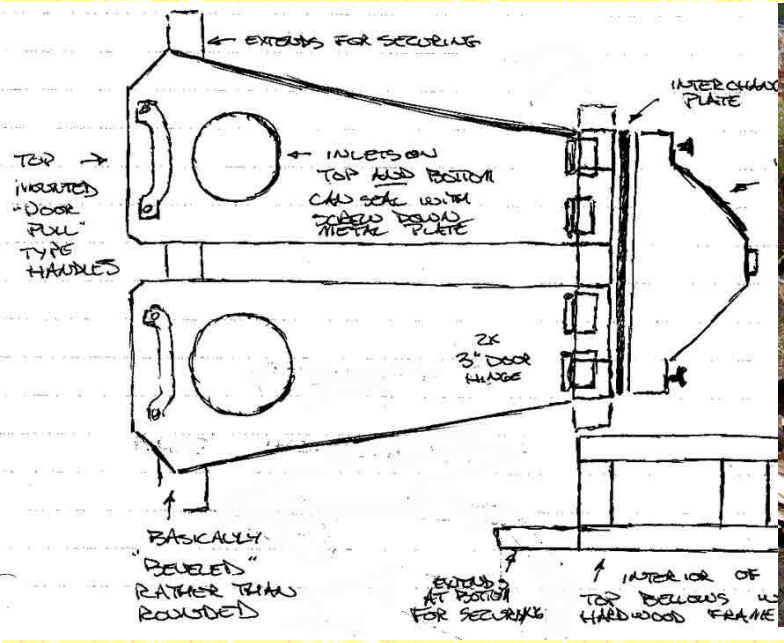
Double to Triple X Measurements

Eight to Twenty Seven X Volumes

Function or Evidence ?

Historic Prototypes

‘Historical’ Replicas ?



Smelter Test Bellows **DARC - Canada, 2009** **Green - USA, 2013**

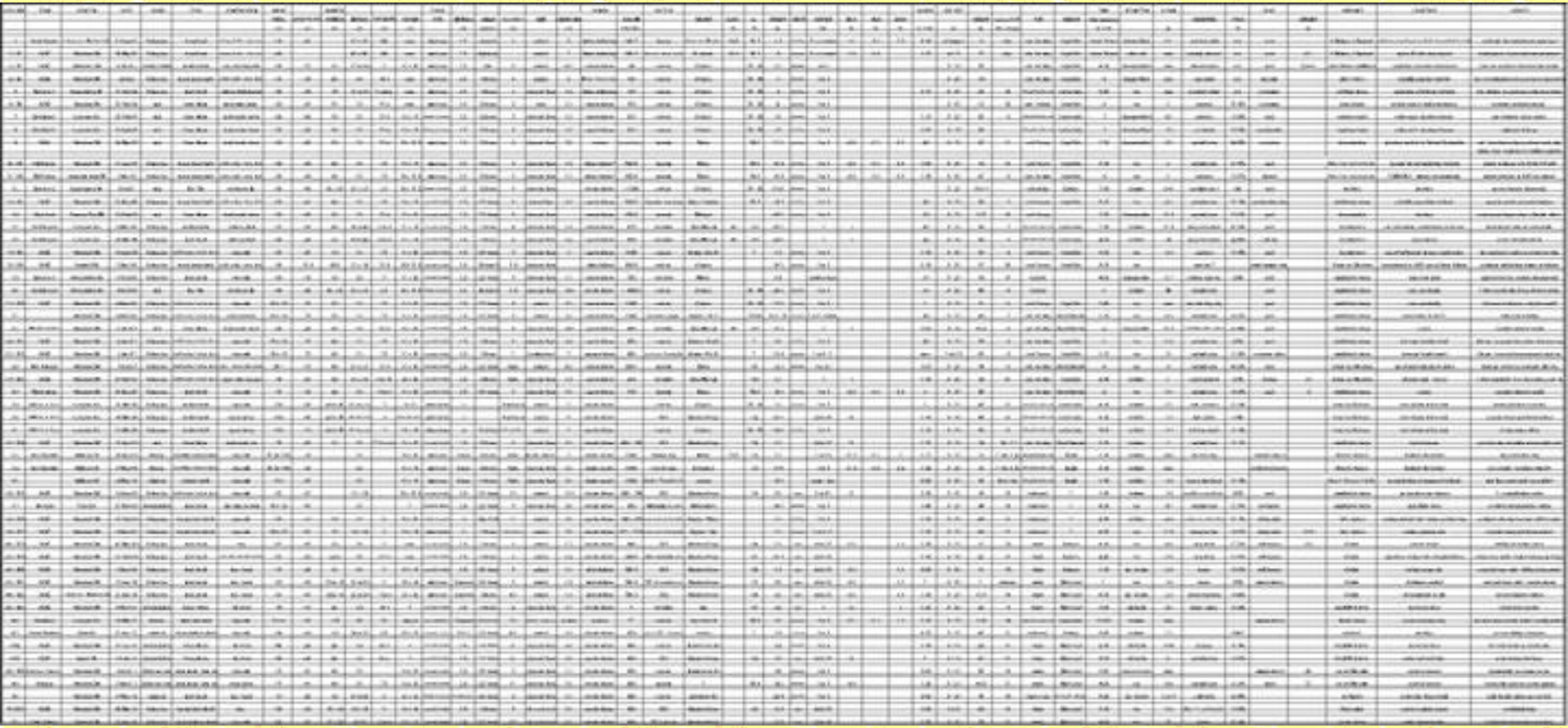
Theoretical Delivery = 750 l/m

Measured Delivery = 350 l/m

Function or Evidence ?

Experimental Results

Collecting Data

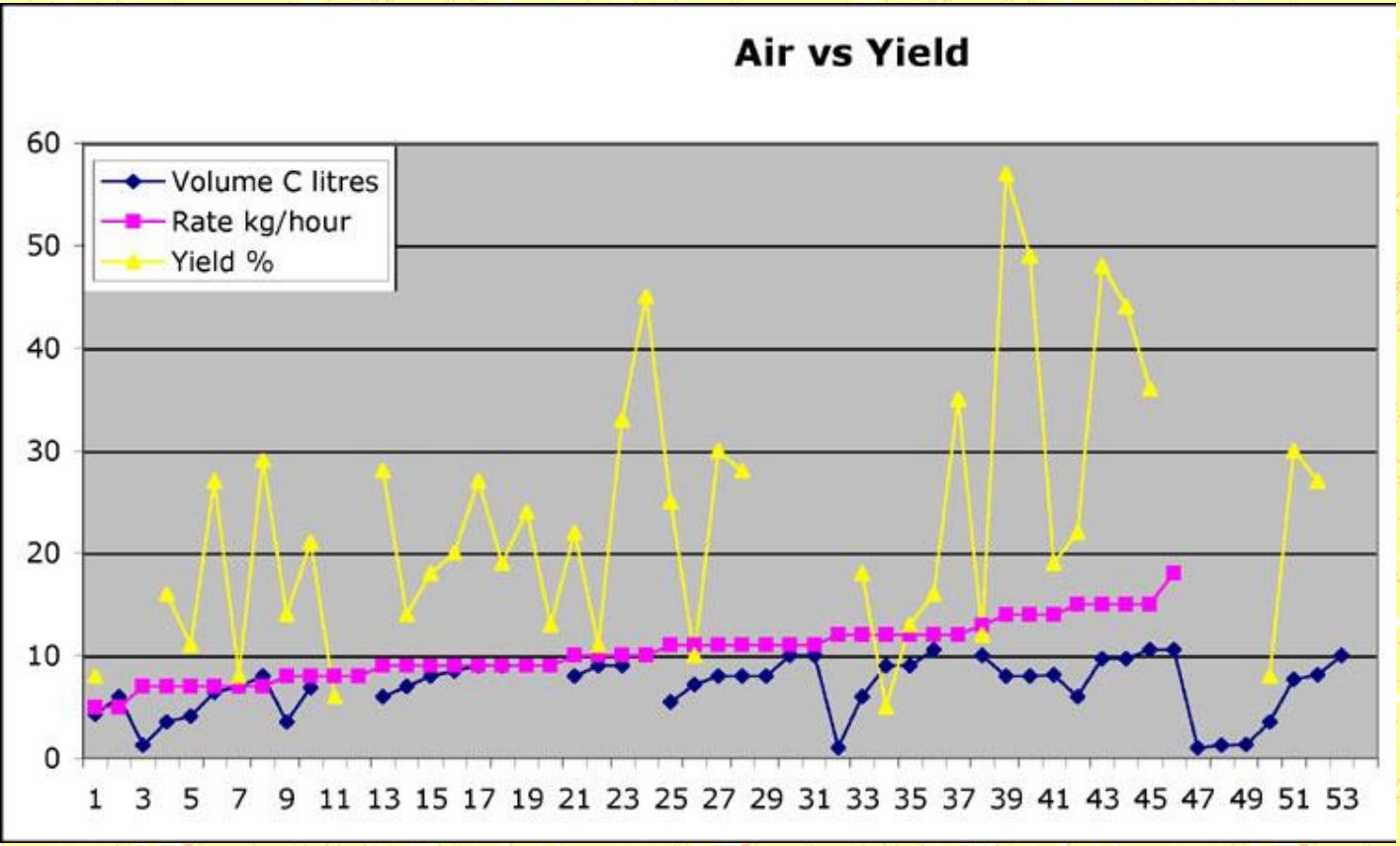


50 + Experiments

48 + Variables

Experimental Results

About the AIR (?)

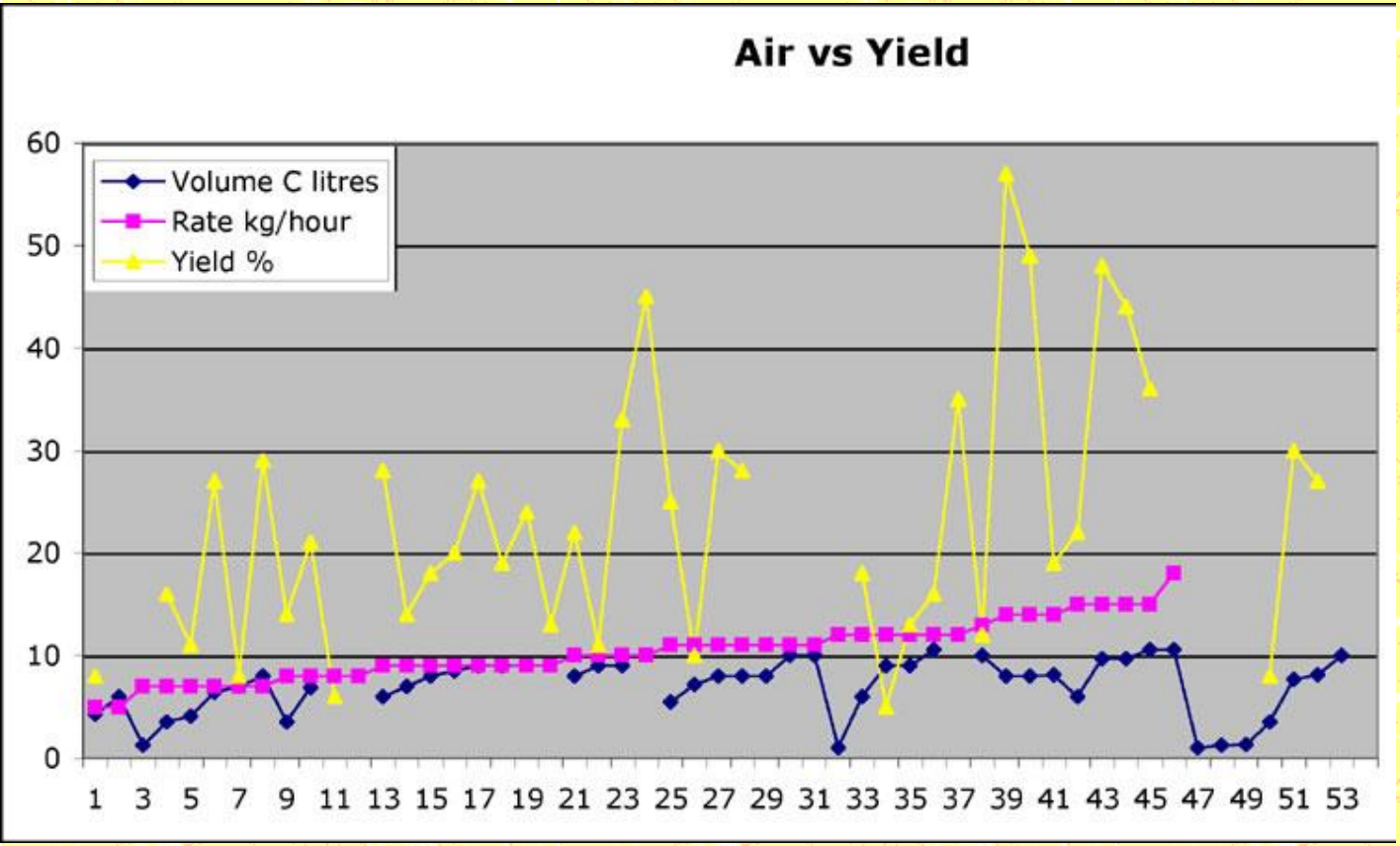


Problem :

Is BURN RATE more important?

Experimental Results

About the AIR (?)



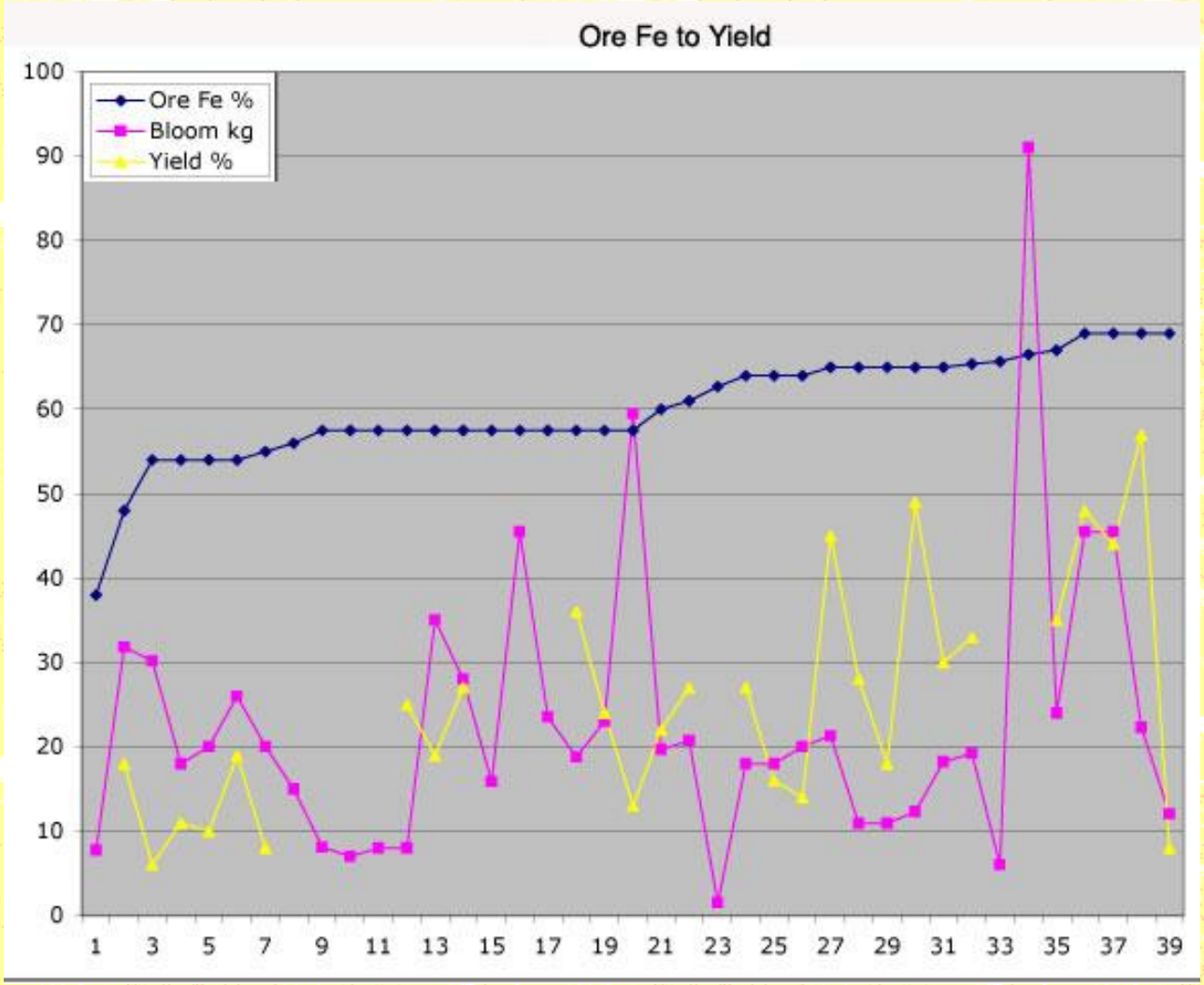
Problem :

Is BURN RATE more important?

Inconclusive !

Experimental Results

About the ORE (?)



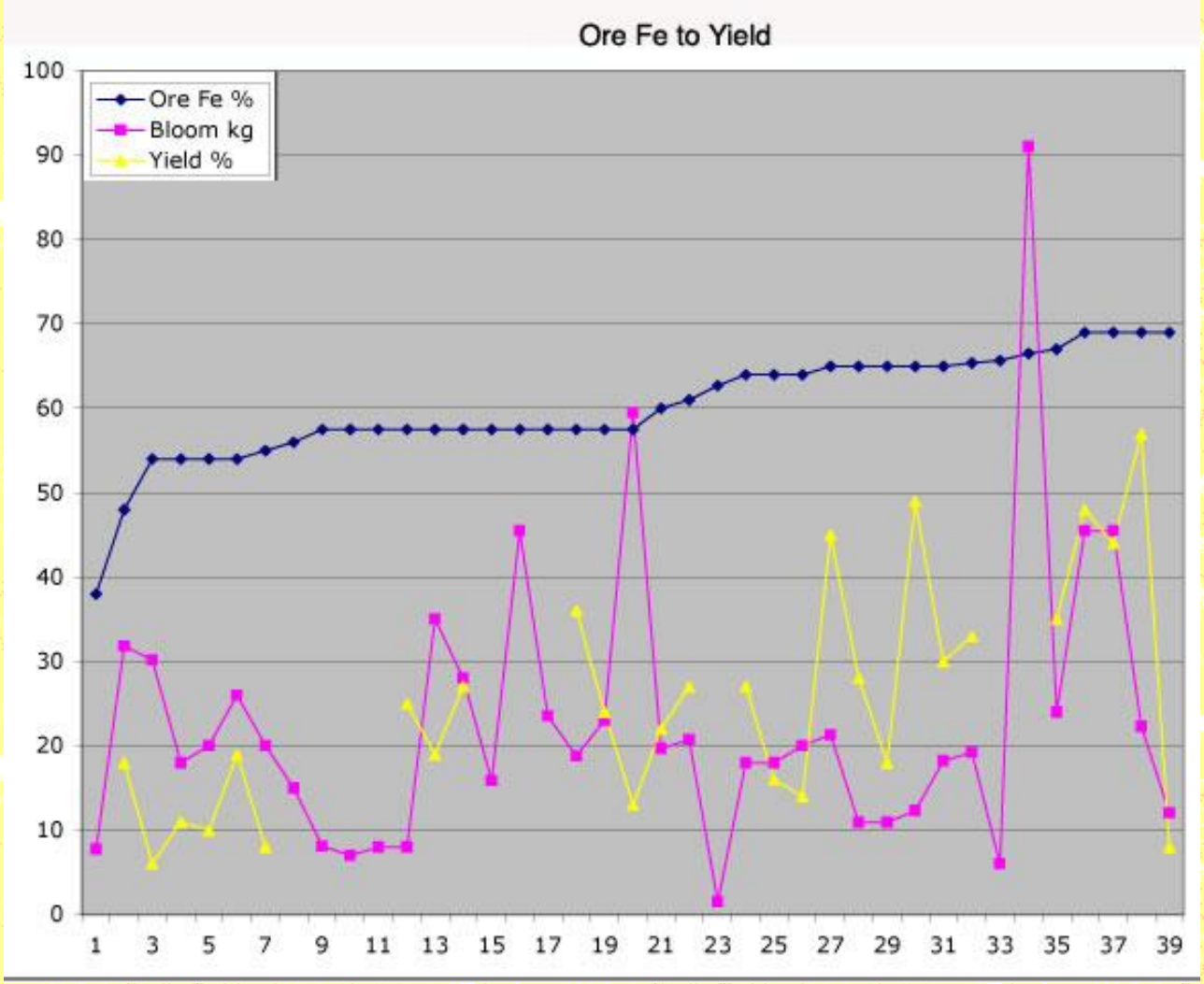
Problem :

Small Fe change

Is <u>type</u> important

Experimental Results

About the ORE (?)



Problem :

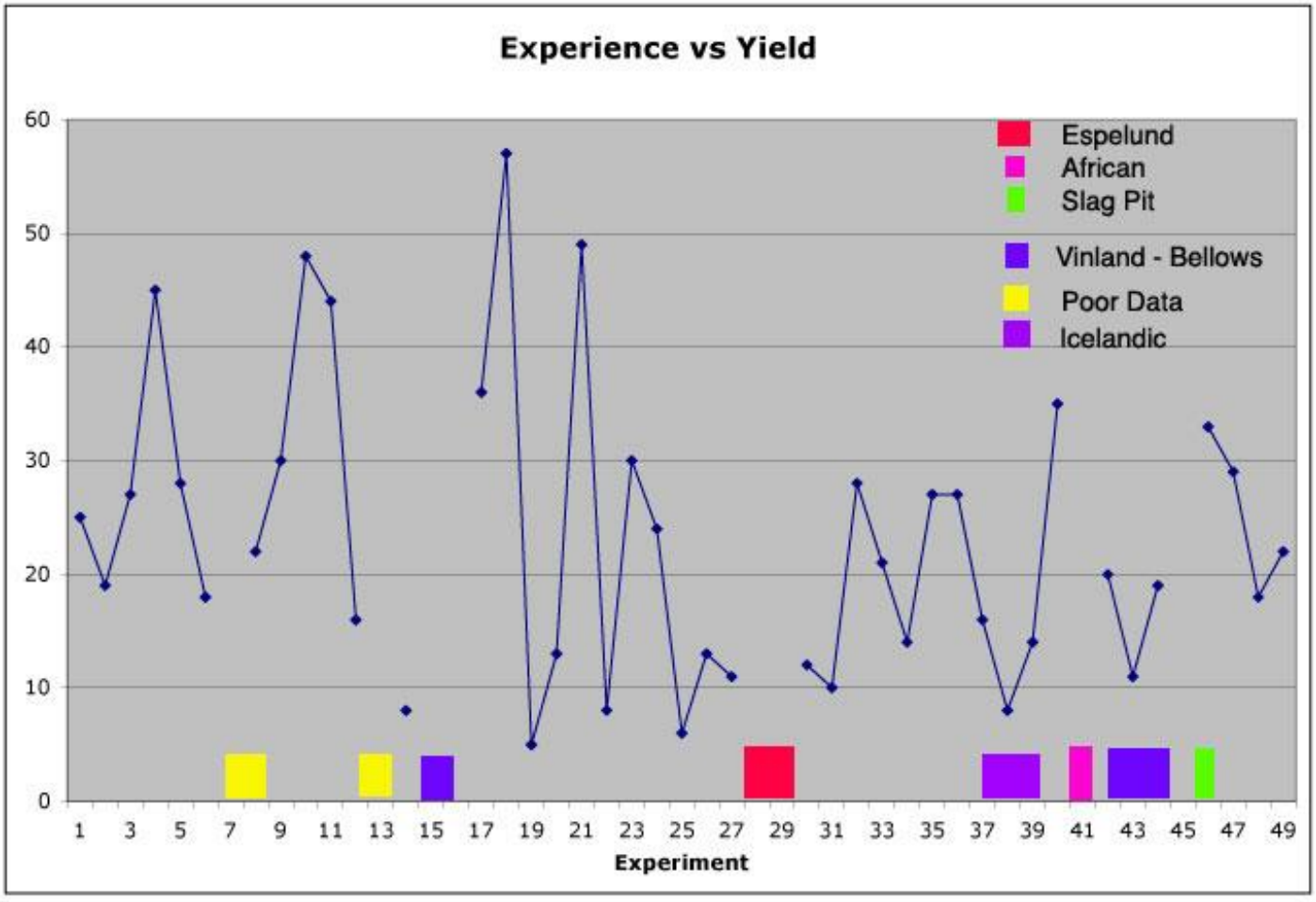
Small Fe change

Is <u>type</u> important

Some direct effect

Experimental Results

Experience Counts (?)

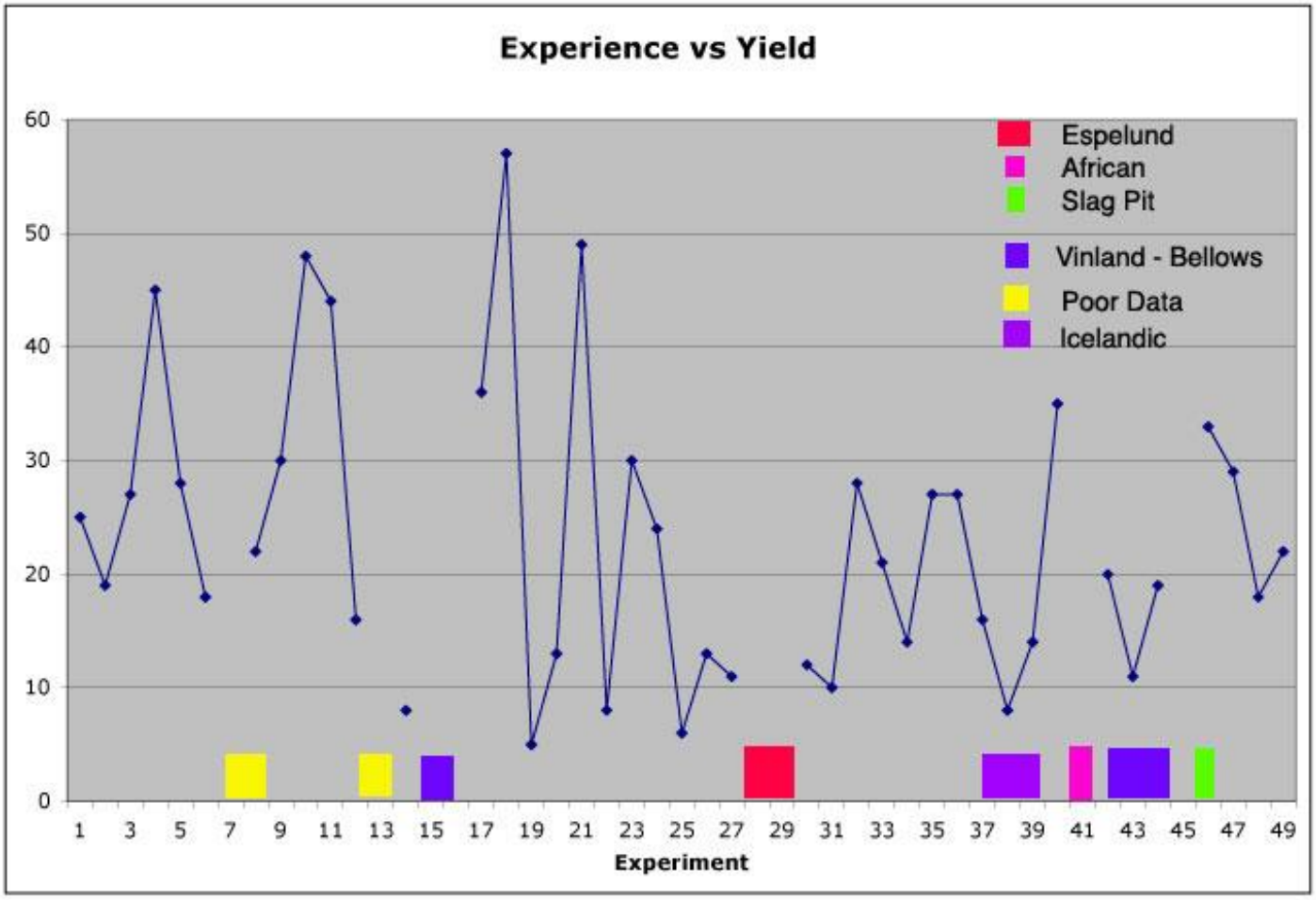


Problem :

Changing Systems

Experimental Results

Experience Counts (?)



Problem :

Changing Systems

Maybe Not !

Experimental Results

Remember the Objective

2006

Oyane Norway

BAR - <u>not</u> BLOOM

Experimental Results

Remember the Objective

EXPERIMENT	VOLUME C litre/min	RATE kg/hour	Fe %	WEIGHT kg	BLOOM kg	YIELD %	DENSITY
36 / D15	*7.2*	11	54	20	1.9	10	4.3
9		10	65.0	21.3	9.5	45	4.4
32 / D14	*4.1*	7	54	18	2	11	4.6
8	8.15		57.5	28	7.5	27	4.7
22	10.6	15	57.5	18.8	6.8	36	5.2
41 / D19	*9*	9	61	20.7	5.6	27	5.5
13/ D7	*6*	15	*60*	19.7	4.3	22	5.6
24 / D11	9	12		20	0.9	5	5.7
D25	9	9	54	26	*5*	19	5.7
38 / D16	*6.85*	8		23	4.9	21	5.9
10 / D5	*6*	9	65.0	10.9	*3*	28	6.3
51 / D27	8	9	48	31.8	5.8	18	6.4
18 / D9	*6*	5		10.5			7.1
40 / D18	6.4	7	64	18	4.9	27	7.7
50	8	7		42.9	12.27	29	8.5
52	8	10		31.8	7.1	22	9.5

Increase in RATE = Improved **DENSITY** ?

Experimental Results

Remember the Objective

EXPERIMENT	VOLUME C litre/min	RATE kg/hour	Fe %	WEIGHT kg	BLOOM kg	YIELD %	DENSITY	to BAR %
13/ D7	*6*	15	*60*	19.7	4.3	22	5.6	48
16	9.7	15	69	45.5	20	44		60
30		8	54	30.2	1.7	6		63
8	8.15		57.5	28	7.5	27	4.7	77
43 / D21	*3.5*		55	20	1.6	8		80
14	*8*	11		45.5	13.5	30		81
49	9	10	65.4	19.2	6.4	33		83

Increase in RATE = Improved Bloom to Bar ?

Experimental Results

Remember the Objective

EXPERIMENT	VOLUME C litre/min	RATE kg/hour	Fe %	WEIGHT kg	BLOOM kg	YIELD %	DENSITY	to BAR %
13/ D7	*6*	15	*60*	19.7	4.3	22	5.6	48
16	9.7	15	69	45.5	20	44		60
30		8	54	30.2	1.7	6		63
8	8.15		57.5	28	7.5	27	4.7	77
43 / D21	*3.5*		55	20	1.6	8		80
14	*8*	11		45.5	13.5	30		81
49	9	10	65.4	19.2	6.4	33		83

Increase in RATE = Improved <u>Bloom to Bar</u> ?

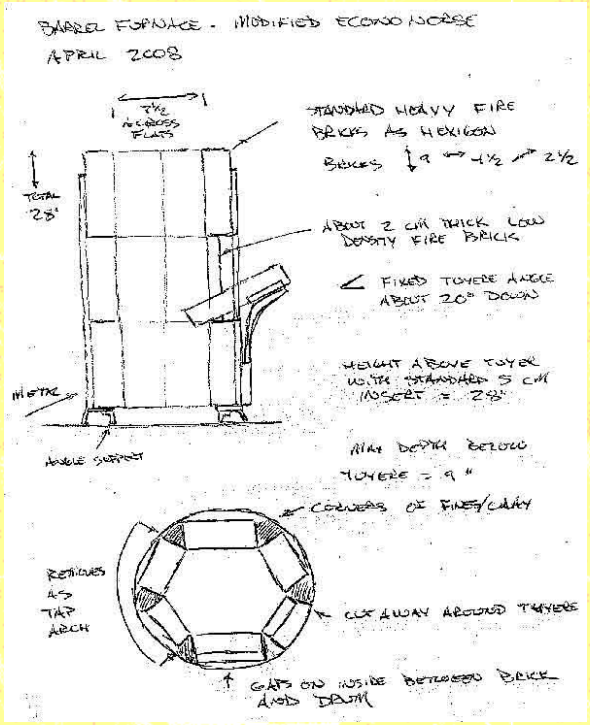
Inconclusive :

Not Enough Data Points

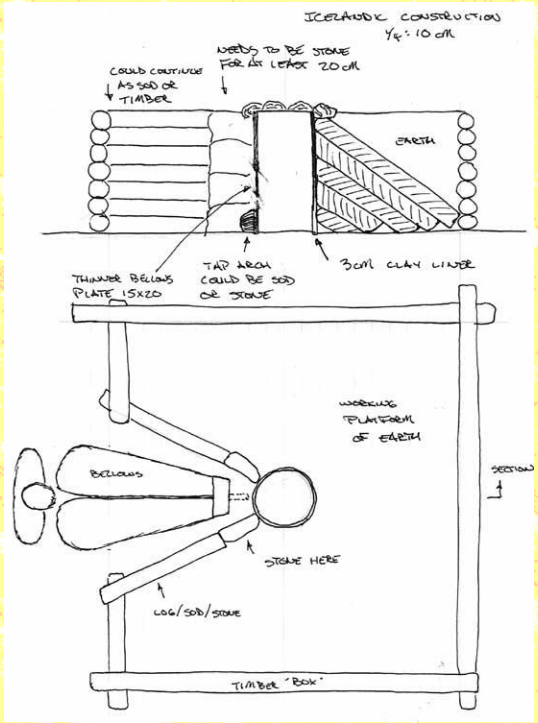
Future Experiments

Limit Variables!

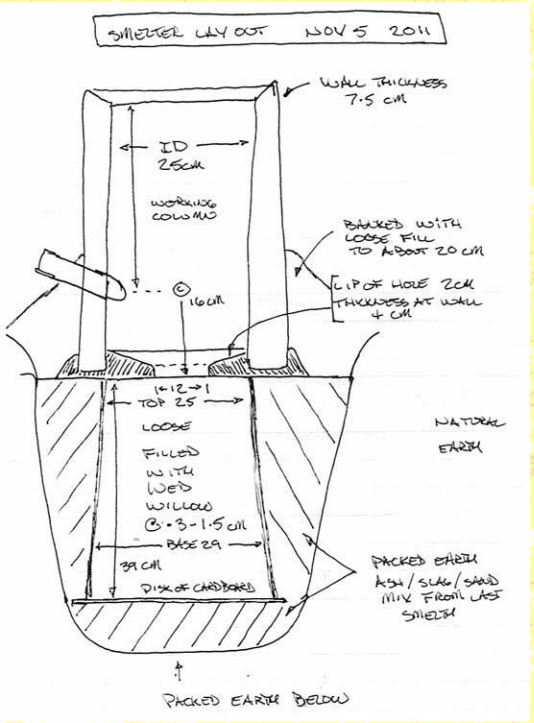
Furnace Design



Econo-Norse



Icelandic



Slag Pit

- **Material**
- **Dimensions**
- **Layout**

Future Experiments

Limit Variables!

Ore

Bratton's Run

Dark Dirt Analog

- **Chemistry**
- **Concentration**
- **Form**

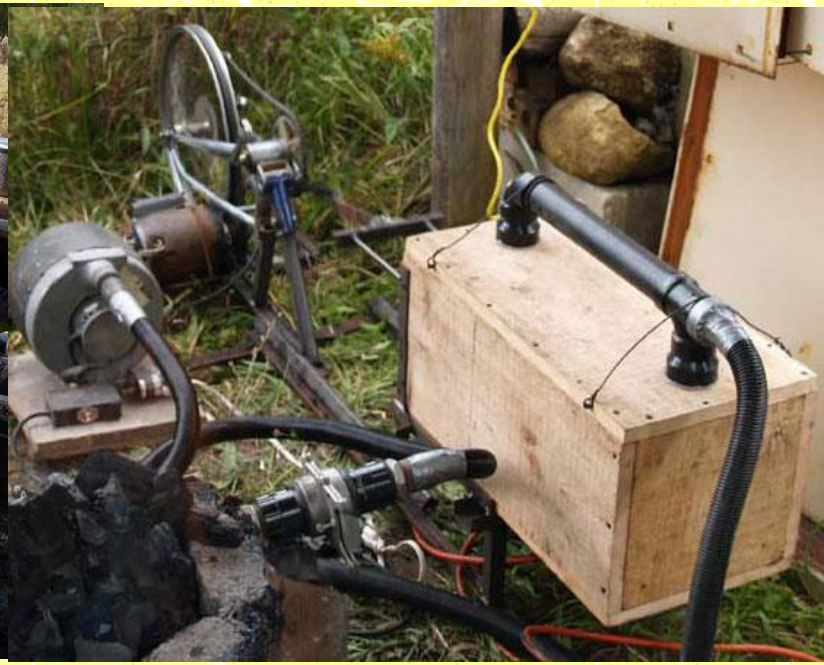
Future Experiments

Limit Variables!

Bellows Design

Ubber-Bellows

Smelt Test Frame



Blower & ‘Franken-bellows’

- **Power**
- **Dimensions**
- **Operation**

Future Experiments

Extend Process

Bloom to Bar

Vinland One - Compacting

Replica Currency Bar

- **Develop Experience**
- **Historic Method**
- **Repeated Experiments**

Further References

The Adventure Continues !

the Wareham Forge

www.warehamforge.ca/ironsmelting

DARC

www.darkcompany.ca/iron