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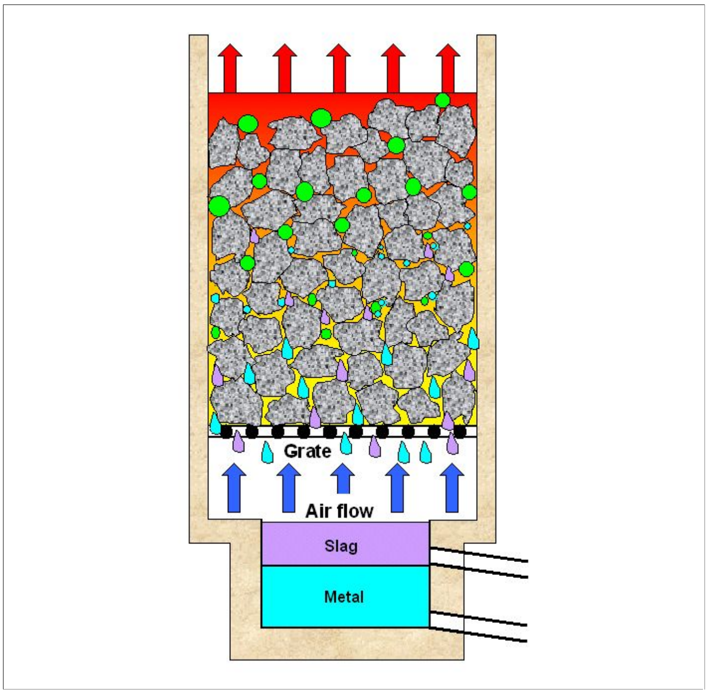
Smelting Science

3. Smelter Technology

Some Basics

From the preceding module it is easy to come up with the design of an ideal furnace-kind of smelter. Just add ore (green globules) and possibly some flux (not shown) to the charcoal bed shown before, and provide for a "bowl" below the charcoal / ore bed that collects the liquid metal and the slag as shown:



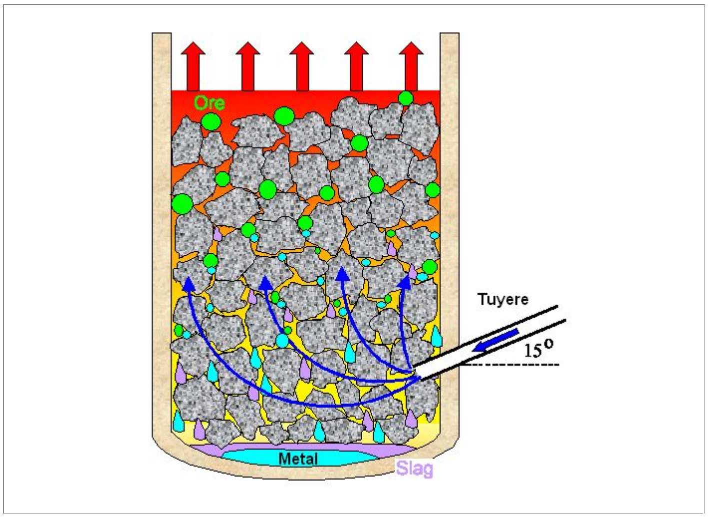
Schematics of an "ideal" smelter

The ore (green globules) gets reduced in the carbon monoxide-rich zone, some layers of charcoal lumps above the burning part on the **grate**. The metal produced moves down with the burden and eventually liquefies, and so does the slag. The liquid stuff trickles down, moving much faster than the solid burden and collects at the bottom.
Since liquid metal always has a higher density than liquid slag, the slag sits atop of the metal, like oil sits atop of water.

Unfortunately, it isn't so easy for several reasons:

- No suitable material for the grate existed in antiquity. The material would need to be mechanically and chemically stable at extremely high temperatures and in a very reactive environment. Even nowadays you would be hard pressed to find something affordable. Find one and you get rich.
- How would you produce the uniform airflow? In a rain of hot liquid stuff?
- Why should the slag and the liquid metal stay molten down there? It might not be particularly hot there.

The **standard smelter** in "advanced" antiquity (that could produce, for example, the Colossus of Rhodes around 285 BC from maybe 15 tons of bronze and 9 tons of iron) thus was built differently. Here is one (simplified and schematic) example:



Schematics of a real smelter

The essential new part is the **tuyere**. It must meet several conditions:

- **1.** *Right size and shape*
  The size (inner diameter) of the furnace smelter needs to be matched to the kind of airflow you must provide (expressed as space velocity and air velocity, see below) . The diameter of the tuyere then must be matched to the airflow needed and to the kind of power / pressure you can provide at its entrance. Do you blow with lung power? Use bellows? Powered by human(s) or machines?
  The length of the tuyere is important. Together with the orifice, it accounts for most of the air flow resistance. The cross-section usually is circular but might be different (e.g. semi-circular) on occasion, changing the air flow pattern through the charcoal bed somewhat.
  A new parameter that now becomes important is the **air velocity** or momentum at the exit of your tuyere. It determines how far the air is "pushed " into the charcoal bed and how, exactly, the blue "flow lines" above look like. For a given *space* velocity, tuyeres with a small inner diameter must deliver higher *air* velocities, and that demands higher pressure in the "blower".
- **2.** *Entry geometry*
  Your tuyere must protrude somewhat into the charcoal bed. Not too much (inhibiting air flow on the tuyere side) and not too little (preventing the air from getting to the other side). The "angle of attack" is important. According to sophisticated modern calculations, 15° is about right - and that's what one often finds in ancient smelters, where experience and evolution taught that value.
  The tuyere should be placed low so it can supply air to all the lower layers of the charcoal. But not so low that it can be reached by the molten slag pool that is building up. If the tuyere gets clogged up by slag, it's all over
- **3.** *Connections*
  You must connect the tuyere with the air source and you must lead it through the walls of the furnace. This should be completely airtight because otherwise your air supply will be leaky and sub-optimal. This is not as easy to do as it appears, nor was that necessity always appreciated. Leaky air supplies were common, endangering the proper operation of the smelter and adding an element of uncertainty.
- **4.** *Tuyere material*
  One or two lump sizes behind the tuyere is the hottest zone of the smelter. The tuyere must be able to take the heat and should not get "fluxed". That means it should not contribute to the formation of slag and slowly dissolve in the process. What is going to happen depends, of course, on temperature and the kind of chemistry provided for by the fluxes added. Also note that the temperature is not constant and might on occasion overshoot, endangering the tuyere.
- **5.** *How many tuyeres?*
  In principle, several tuyeres properly placed are almost always better than just one tuyere. The air flow gets more symmetrical and the mechanical work needed to supply the required air goes down. In reality, however, only one tuyere was used in most of the rather mall smelters throughout antiquity. The reason seems to be that making tuyeres is not that easy, and hooking up several tuyeres to the air source without leaks is rather difficult. So if you can get away with just one tuyere, that's what you do.
  In order to compensate for the basic asymmetry of the set-up, you might take care to position charcoal and ore also asymmetrically - more on the side opposite to the tuyere.

Pieces of antique tuyeres

Source: Photographed in the Heraklion or Istanbul museum, resp.

- Did you already experience your epiphany? Here it is

Smelting is far more difficult than you imagined!

- If you want to smelt some metal, it is just not good enough to set some mixture of ore and charcoal on fire, blowing some air on it. In other words:

Chances of accidentally smelting some metal in a campfire or pottery kiln are very small!
But not zero.

- And we haven't looked at the ore and flux supply yet! That will add a few more complications.
  What we learned with respect to the charcoal makes rather clear that the *average size of your ore pieces* should also be just right. Your ore should be reactive, i.e. have a large (internal) surface and that means some kind of porosity or microcracks. You might achieve that by **roasting** it, i.e. heating it in air at medium temperatures for a while. That will also drive out the sulfur if you have sulfide ores and produce oxides. If you don't do that, it will automatically take place to some extent in your smelter as soon as the ore reaches the medium hot regions but that can upset the balance of what is going on.
- If you don't have very clean ore but also some "**gangue**", the minerals your ore is embedded in, chances are that some **slag** will form. You don't need much gangue for that to happen because the lining of your furnace and the tuyere might also participate in slag formation. Slag, as we will see, is actually good or even necessary for successful smelting, and you may help to produce it by adding some "**flux**", i.e. materials that help in producing the right amount of the right kind of slag.
  The question now is: in what proportion should you mix charcoal, ore and flux? If we forget the flux for a moment, the weight ratio of charcoal to ore determines the temperature you will reach for a given air supply. The higher this ratio, i.e. the more charcoal you use for the same amount of ore, the hotter your furnace will be. That is *not* good! Temperatures too high will not only be expensive because you use more charcoal than necessary, they might also

produce inferior results. You might, for example, get iron-rich copper (not good) in copper smelting, or cast-iron (very bad) in iron / steel smelting. Temperatures too low are of course not good either. You want your temperature, and thus your mix, to be *just right*!
Considering that the density of charcoal might vary quite a bit, a fixed relation of ore to charcoal *by volume*, as always done in antiquity, leads to a varying relation *by weight*, which is not good. In more modern times this became clear and the ingredients were weighted before mixing. On old times, you just never varied the type of charcoal you used.

Running Your Smelter at the Right Temperature

- You have a well-build smelter, the right mix of charcoal, ore and flux, a slave, your wife or kids to man the bellows, and a sufficient supply of beer and pretzels. How do you do your smelting now?
  - Typically, you first fill the smelter with pure charcoal and set it on fire. You blow air in to make a good fire and keep doing that for a while. The idea is to get everything up to temperature and that needs a certain amount of initial energy that you must supply by burning charcoal. Since your charcoal disappears almost completely by reacting to carbon dioxide (CO_2) or monoxide (CO), the burden moves down and you must replenish it from the top. It might be hot up there, with poisonous gases coming out, so be a bit careful about adding the fuel.
  - When your smelter is "at temperature" and ready for work, you start to feed it the well-prepared charcoal / ore / flux mixture, the **burden** or charge. It also sinks down with a certain speed. The time it takes for newly added fuel /ore to reach the reaction zone is called "**residence time**", and this is an important parameter. It must not be too short because the reactions necessary to produce the metal take some time, and it shouldn't be too long because that decreases throughput and makes the operation uneconomical. An experienced smelter operator knows how fast the burden should sink down, and can take correcting actions if there are deviations.
- The metal produced from the ore in a solid-state process higher up in the smelter might eventually melt farther down in the hot regions. Being liquid it will trickle down, collect at the bottom of the typically bowl-shaped hearth, and form a pool of liquid metal. If you produce liquid slag - and with the advanced smelter described here you certainly will - it also trickles down and collects *on top* of the liquid metal since its density is smaller.
  Now an interesting question should come up: How is the burden, the whole stack of charcoal, ore and flux, **mechanically supported** with those liquids down there? Wouldn't it just plunge into the liquids? Interestingly, most sources remain vague on this point - in words and in schematic drawings!
  - It is a tricky questions and there is no universal answer. Your furnace design might have made the bottom part a bit slanted so that the liquids collect in the lowest corner and the fuel / ore stack rests mostly on the lining. Then we need to consider that the burden consists mostly of very light-weight charcoal, so the whole thing just swims on the heavy liquids like a big piece of styrofoam on water.
    Quite often, the diameter of your furnace narrows somewhat at the bottom, providing some mechanical support at the edges (by friction) for the fuel / ore stack. This picture gives an impression of how that might work.
    Whatever you do to keep the liquids nicely separated from the solids above, you must do it in such a way that the temperature down there is still high enough to keep the slag molten with a good fluidity (meaning low viscosity) and your metal not only molten but somewhat **superheated**, i.e. at a temperature well above the melting point lest it solidifies right away at tapping. Some energy must flow into the soups down there and for that you have radiation from the hot zone above and the energy the superheated liquid metal and the hot slag bring along as they drip into the pools.
- Now we reached the point where the role of temperature in *efficient* smelting can be discussed in some detail. I'm emphasizing "efficient" because early smelting for the first 1 500 years or so was *not* efficient but a mess and quite different from what I describe here. Anyway, there is a simple rule:

Temperature control is everything!

  - The first thing to realize is that there is not just one, but three or even four *different* **temperatures** that are crucial for **proper smelting**:

- **1.** *Temperatures for carbon monoxide production*
  Carbon monoxide is produced a few layers of properly sized charcoal lumps above the "fire" that produces CO_2 and heat. That is a few charcoal lumps above the tuyere. Note once more that the average lump size of your charcoal sort of defines the length scale in your smelter.
  In the upper layers the carbon dioxide produced by the "burning" charcoals meets hot charcoals that can't burn properly because there is not enough oxygen. carbon monoxide (CO) is now produced according to the reaction
  $\mathbf{CO_2 + C \Leftrightarrow 2\,CO}$, but *only* if the carbon is hot enough, like 1 000 °C (1 832 °F), the hotter the better.

- This reaction actually *consumes energy* and thus cools its surroundings somewhat. That means that you should have at least 1 200 ^{o}C (2 192 ^{o}F) close to the tuyere, the hottest part in your furnace. If your temperature there is lower, carbon monoxide production goes down. In this case you must either supply less ore or accept that not all the ore will get reduced. Whatever - your smelting now is more inefficient.

2. *Temperature for ore reduction*

Your oxide ores, always something like **$\mathrm{Me_yO}$** (Me = some metal atom) reacts with CO according to **$\mathrm{Me_yO + CO \Rightarrow y\ Me + CO_2}$**. This reaction will occur at some temperature that is specific for the ore in question and might be rather low, e.g. 400 ^{o}C (752 ^{o}F) for some iron ores. Of course, the reduction reaction will proceed faster if it is hotter. But at some still rather low temperature all your ore will become reduced - and higher temperatures then are just a waste of money. If you don't have oxide ores but, for example, sulfite ores, things can get really tricky; the link supplies examples.

What that means is that the reduction process for many ores starts already high up in the stack where the temperature is rather low. Trivial - but with an interesting consequence:

Pretty much all metal ores get reduced in the solid state!

- You can't melt your metal before you have it. And you do not typically reduce *molten ore* into molten metal either! When your ore melts - something not likely but possible, see point 5 - chances are that it reacts with whatever is around or trickles down too fast through the CO bearing zone to become reduced. Reduction typically starts already at medium temperatures in the carbon monoxide rich zone way above the really hot zone.
  The solid-state reduction process gets more efficient if there is a lot of surface where it can happen. In other words, your ore pieces should be small (but not so small that they increase air flow resistance too much) and "porous", for example full of microcracks. This calls for a suitable pre-treatment of your ore like "crushing".

Crushing (silver) ore

Source: Part of an altar picture in the St. Anne Church in Annaberg-Buchholz / Germany form 1521.

- It is time now to look at an important if somewhat difficult diagram, the gain Δ**G** in "free enthalpy" if this or that compound is formed as a function of temperature. "Free enthalpy" is just a fancy word for energy. The diagram is shown in its own module and will make clear which ores you can reduce with *carbon* in an advanced antique smelter, and which ones you cannot. Even more, it shows the minimum temperature needed for the reduction process *and* what determines that temperature.

Advanced Link

Smelting Energy

3. *Temperatures for metal melting*

You have produced some metal by a solid state reaction at rather low temperatures rather high up in the stack. These little solid metal pieces move down with the speed the burden moves, getting hotter all the while. Eventually they will reach the very hot zone where the charcoals burn - and get oxidized again!
???? That would defy the purpose of smelting! Nevertheless, here you have a major problem of smelting. You can solve it in two basic ways:

1. If your metal melts already in the CO rich reduction zone, it can trickle down to the very bottom of the smelter so fast that only parts of it get reoxidized. That's where a low melting point is helpful. Melting takes some energy, i.e., uses up heat, and thus cools its environment, but that is a minor effect.
2. If you produce liquid slag above the oxidizing zone, it can sweep small liquid *and* solid metal particles with it as it trickles down, protecting them from getting fully oxidized

Of course, you can also combine the two points - having liquid slag and liquid metal - for best results.

One more point to note: your drop of metal entering the pool of molten metal must have a temperature well above the melting point since it must transport heat into that "dark corner" lest the pool solidifies. The pool also needs to be kept a a temperature above the melting point because otherwise it would solidify too soon during handling. You thus need temperatures considerably higher than the melting point in the hottest part of your furnace just to keep the temperature "down there" where it should be. You can't smelt copper, for example, by producing only a bit more then 1 084 ^{o}C (1 983 ^{o}F) in the burning zone.

4. *Temperature for good slag fluidity*

If you want to make good use of the slag always produced, you should ensure that its **fluidicy** is high. In other words, it should flow like water and not like honey. Fluidicy is just the inverse of *viscosity* and comes in here because the glassy slag does not have a well-defined melting point. It just gets less viscous with increasing temperature, like honey or processed cheese, for example. This calls for high temperatures once more, and I will get to this in more detail soon.

5. - ... *Special temperatures*

Ores have a melting temperature. You may not want to exceed that because liquid ore will trickle down and it may or may not get reduced. Most ores have high melting points so there is no problem but for example "covellite" (simply copper sulfide, CuS), a very rich ore, melts already at 813 ^{o}C (1 495 ^{o}F) and you need to be aware of that.
There is sure to be more but right now I can't remember.

Now you are confused. Sorry. So just try to remember that efficient smelting needs to control the temperature distribution all the way from the very bottom of the furnace where the liquid metal collects, to the very top where it is rather cold. The decisive part is the high temperature region around the tuyere. And no, producing very high temperatures does not take care of all this because you will run into problems if it's too hot.
The question clearly is: "How do I control all these temperatures?"

The answer is straight forward.

1. By paying attention to geometry. The design of your furnace, the size of the lumps of charcoal, ore and flux you feed your furnace with, and in particular the size, length, angle of attack, height of entry, and so on, of your tuyere(s) should be "just right".
2. By packing the "right" relation (preferably by weight) of charcoal, ore and flux into your burden. Here is an example.
3. By producing the right air space velocity in the furnace by blowing the right amount of air through the tuyere(s).
4. By blowing with the right air velocity to optimize airflow through your bed of charcoals.

If your analytical mind, as far as existent, is still with you, it is now apparent that after meeting conditions 1 and 2, the *only* adjustable and thus *controllable* parameter is the tuyere geometry and the air flow through the tuyere. The geometry of the tuyere is fixed by making sure that this happens with the right air velocity. All that remains is how hard you blow into a blow pipe or work your bellows.

Assuming that your bellows can produce the right amount of air, you now must work it just right. Working it too mildly is bad, working it too hard is bad, too.
The fact that pretty much all bellows and blowpipes do not deliver a constant stream of air but only periodic blasts is not so good either. It makes your temperature go up and down with the rhythm of the blast and that can't be good.

Almost There

- Efficient smelting isn't easy - when you have to start from scratch. Let's say you are marooned on this rocky island, with some tools, clothes, etc. but nothing to read but this Hyperscript. After you found ways to supply the absolutely essential necessities of life like beer and girl friend (or a substitute thereof), you now decide to smelt some copper because you found some copper ores.
    - Despite all the good advice in this hyperscript you will find it a very difficult thing to do. You wonder how those ancient cultures could do it; they didn't have any decent literature or insights into the technology after all.
      Yes - but they had the experience of a few thousand years of doing it. Very inefficiently and messily at first, but every now and then more or less accidental "mutations" of the process provided some improvements. Others made it worse. The good process mutations survived and crowded out the old, less efficient ways. I'm talking straight evolution here. It sure works for improving smelting processes and technologies - and nobody needs to understand how and why.
      Just to be on the safe side: You *cannot* improve any technical product or process by evolution. Fool around as long as you and your culture likes, you will not come up with an integrated circuit in millions of years.
      But an evolution of early, inefficient, messy and small-scaled smelting technologies to the advanced antique smelter shown above is entirely possible in the space of a few thousand years.
- It remains to look at a few more topics concerning smelting:

    1. The various ways to supply air. Advantages and limitations.
    2. What limits the size of a smelter? How hot should it get?
    3. The role of slag. Can one smelt without producing slag and why is this not necessarily desirable? How does one optimize slag?
    4. Are there other ways to smelt? How did the often alluded to "messy and inefficient" ancient smelting work? How did smelting develop?
    5. What is different between, for example, copper and iron smelting? Could a well-designed efficient copper smelter also produce iron if charged with iron ore?

    - This will take two more modules. I suggest to get some beer before reading on.