
Steelmaking on Mars
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Steel is Good

- Arguably the most useful material on Earth:
  - Cheap
  - Strong
  - Lightweight
  - Recyclable
  - Versatile

- The basic material for sustained development in modern industrial society.
- Used for everything from pins to bridges. Cars, ships, planes, cutlery, pots & pans, tools, fasteners, beams, pipe, wire, reinforcement bars, machinery, fences, buildings, appliances, furniture, etc., etc.
- ISRU: Locally-produced steel on Mars a key component of self-sufficient colony. Enables maintenance and expansion.




What is Steel, Anyway?

- Modern definition is “any iron alloy that can be plastically formed”, e.g. rolled, pounded.
- Except for a few new alloys, steel contains 0.05 - 2.1% carbon.
- Small amounts of impurities such as sulphur, phosphorous, nitrogen, etc.
- Some silicon.
- Alloying elements are often added to enhance properties, e.g. chromium and nickel in stainless steel. Others: vanadium, magnesium, tungsten, etc.
- Most common is <u>mild carbon steel</u>, i.e. Fe with 0.05 - 0.26% C.

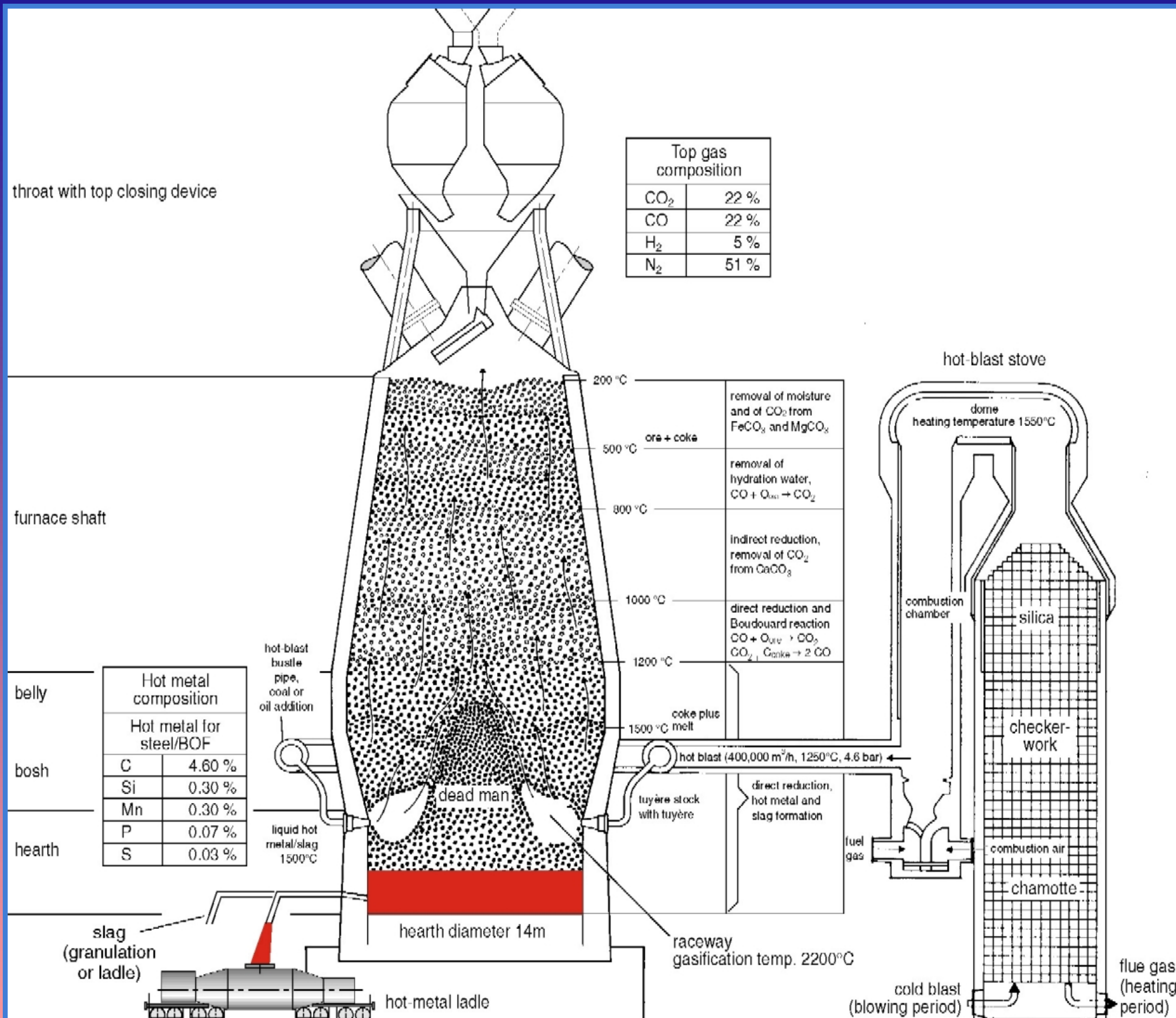
Quick Review: Steelmaking on Earth

- Modern steelmaking plants fully integrated, basic materials input, finished product output.
- Two main streams:
  - <u>Ore-to-steel</u>: blast furnace & basic oxygen furnace (BOF)
  - <u>Scrap-to-steel</u>: electric arc furnace (EAF)
- An iron ore process will be needed on Mars first. (Scrap stream comes later.)

Iron Ore → Steel
The Blast Furnace

- Ore refined in a ***blast furnace***. Vertical chamber made from refractory bricks, designed for temperatures up to 2200°C.
- 4 ingredients:
  - *1. Iron ore*, in the form of lump ore, pellets and/or sinter. Ore is received as *lump ore* or *fine ore*. Fines must first to be agglomerated into larger particles, either pellets or sinter.
  - *2. Coke:* mostly solid carbon, formed from coal that has been treated to remove impurities.
  - *3. Flux:* usually limestone ($CaCO_3$), magnesite ($MgCO_3$), dolomite ($CaMg(CO_3)_2$) or some combination of these.
  - *4. Oxygen*.
- Ore, coke and flux are "charged" (added) into the top of the furnace. Oxygen blasted into the bottom.

The Blast Furnace



Iron Ore → Steel Reducing the Iron Oxide

- Coke burns, maintaining high T:

$$2C + O_2 = 2CO$$

- CO reduces about 75% of the iron ore (nominally hematite):

$$Fe_2O_3 + 3CO = 2Fe + 3CO_2$$

- The rest is reduced by C:

$$Fe_2O_3 + 3C = 2Fe + 3CO$$

- Some C also dissolves in the Fe:

$$3Fe + C = Fe_3C$$

Iron Ore → Steel
Flux and Slag

- Flux is used to dissolve impurities, mostly silica (SiO_2)
- Limestone decomposes to quicklime in the heat of the furnace:

$$CaCO_3 = CaO + CO_2$$

- Quicklime combines with silica to form calcium silicate *slag*:

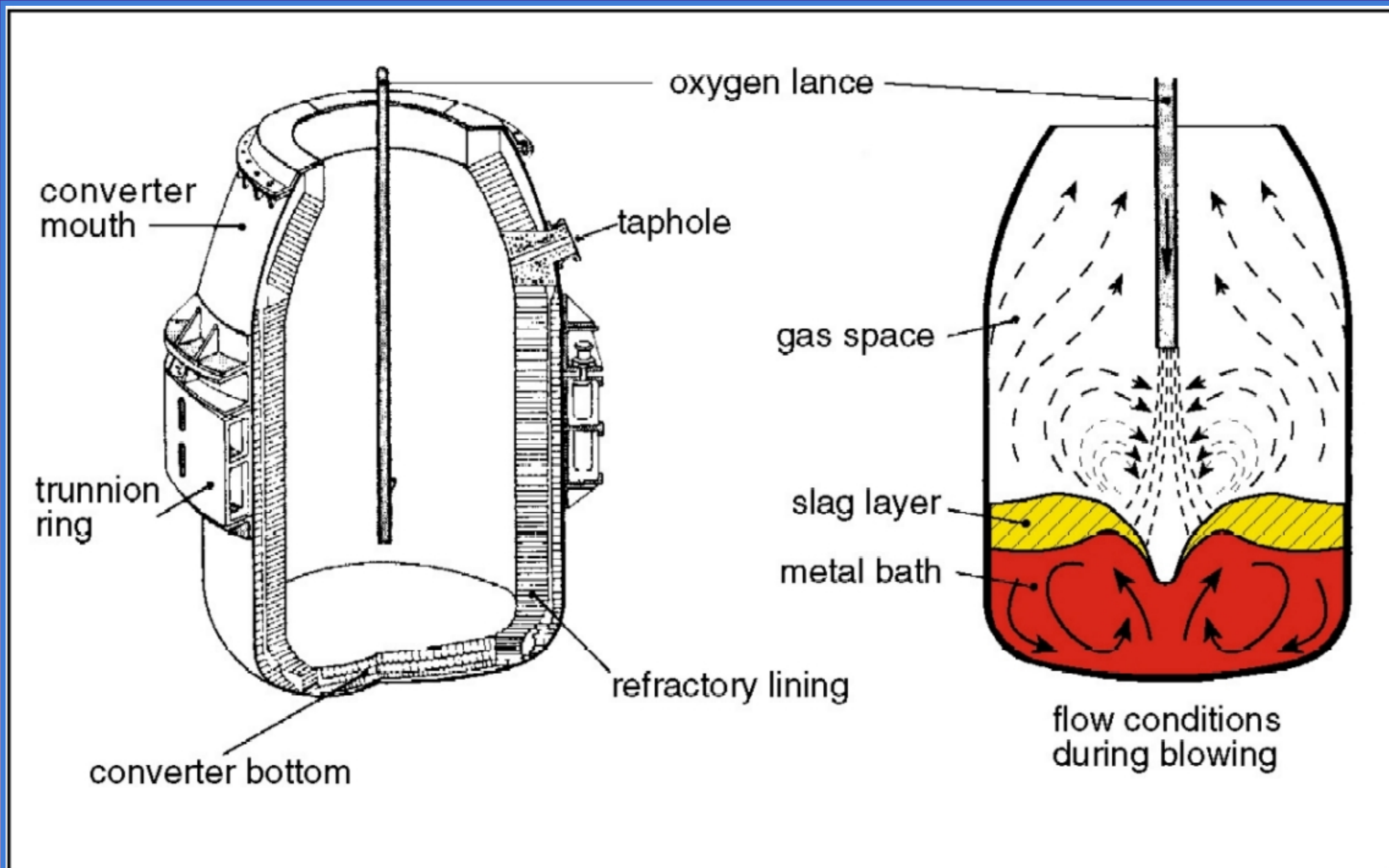
$$CaO + SiO_2 = CaSiO_3$$

- Slag is lighter than the molten metal, floats on the surface and can be poured off.
- Different fluxes can be used to remove different impurities.

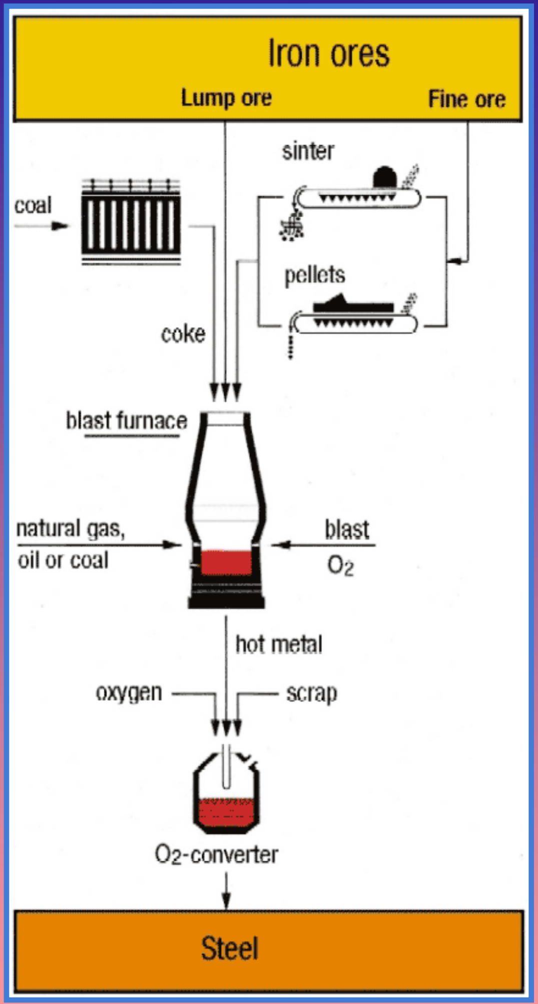
Iron Ore → Steel
The Basic Oxygen Furnace

- The resulting hot metal has too much carbon, up to 7%.
- C removed in a BOF. Oxygen blown into the molten metal, oxidising C to CO_2 gas.
- Will still have too much silicon, sulphur, and phosphorous.
- Flux again used to remove impurities, slag formed and removed.
- Process controlled by computers, and continued until carbon and other elements reduced to desired levels.

The Basic Oxygen Furnace



Iron Ore → Steel Final Product



- Alloying metals may then be added, and the steel is continuous cast into strands for cutting and rolling into product.

Steelmaking on Mars

- Challenges:
  - No coal or natural gas (we think).
  - Concentrated deposits of carbonates?
  - Very little gaseous O_2.
- However, basic materials are available:
  - Iron everywhere.
  - Carbon in air (CO_2).
- Hence, just need new techniques.
- 5 alternatives examined:
  - Carbon Method
  - Carbon Monoxide Method
  - Methane Method
  - Hydrogen Method
  - Carbonyl Method

Carbon Method

- Simplistic approach: manufacture same ingredients, and use same equipment.
- Solid C can be manufactured from Martian air via the Bosch reaction:

$$CO_2 + 2H_2 = C + 2H_2O$$

- Not ideal. Requires an iron, cobalt or nickel catalyst, which would have to be mechanically cleaned to isolate solid carbon. (Inefficient, slow, problematic)
- H_2 for above reaction, plus O_2 for coke burning and BOF, can easily be produced by electrolysis of water:

$$2H_2O = 2H_2 + O_2$$

Electrolysis a well-developed technology that will probably already be in industrial-scale use on Mars.

Obtaining Carbonate Flux

- According to current research:
  - Mars surface dust about 2-5% carbonates, uniformly spread across Mars, not in concentrated deposits as expected if Mars was once wet.
  - However: carbonate dust could be erosion products, spread by wind. Carbonate rock layers may exist, hidden below the dust.
  - Not yet known exactly what carbonates, but magnesite ($MgCO_3$) fits thermal emission data (from TES) best.
- There may be methods to concentrate flux from dust, or there may be cheaper alternatives.

Carbon Monoxide Method

- CO primary reducing agent in ore-to-steel process and easier to make than C.
- Bypass burning of coke.
- Make CO with Reverse Water Gas Shift (RWGS)

$$CO_2 + H_2 = CO + H_2O$$

  Endothermic, requires iron-chrome catalyst.
- Direct reduction of atmospheric CO_2 also an option, but harder to do industrially.

Carbon Monoxide Method: *Energy*

- Coke-burning reaction maintained high temperatures required (above Fe melting point).
  - Need to provide this energy some other way, e.g. use graphite electrodes as in an EAF.
- Resulting reduced iron will not contain dissolved carbon, which will still need to be added. May still require manufacture of solid carbon (although considerably less).

Fe might be Ok

- Iron will be suitable for many applications on Mars:
  - Reduced loads in 0.38g.
  - Much lower wind loads in 0.8kPa atmo.
  - Can always make thicker beams if required.
- Sometimes Fe might even be better.
  - Mars very cold. Fe remains ductile at lower temperatures than steel, which becomes brittle in extreme cold.

Methane Method

- **Direct Reduction:** On Earth, uses natural gas (methane) instead of coal.
- Iron produced called DRI (*Direct Reduced Iron*). Usually combined with scrap in electric arc furnaces.
- DR furnace operates at lower temperature – Fe not melted.
- Normally, high-grade ore is used because impurities are not removed.
- DRI contains 1% - 3.5% carbon.

Direct Reduction Chemistry

- Methane partially oxidised to form reducing gases:

$$2CH_4 + O_2 = 2CO + 4H_2$$

- Reduction of iron oxide:

$$Fe_2O_3 + 3CO = 2Fe + 3CO_2$$
$$Fe_2O_3 + 3H_2 = 2Fe + 3H_2O$$

- Reactants reformed into more reducing gas:

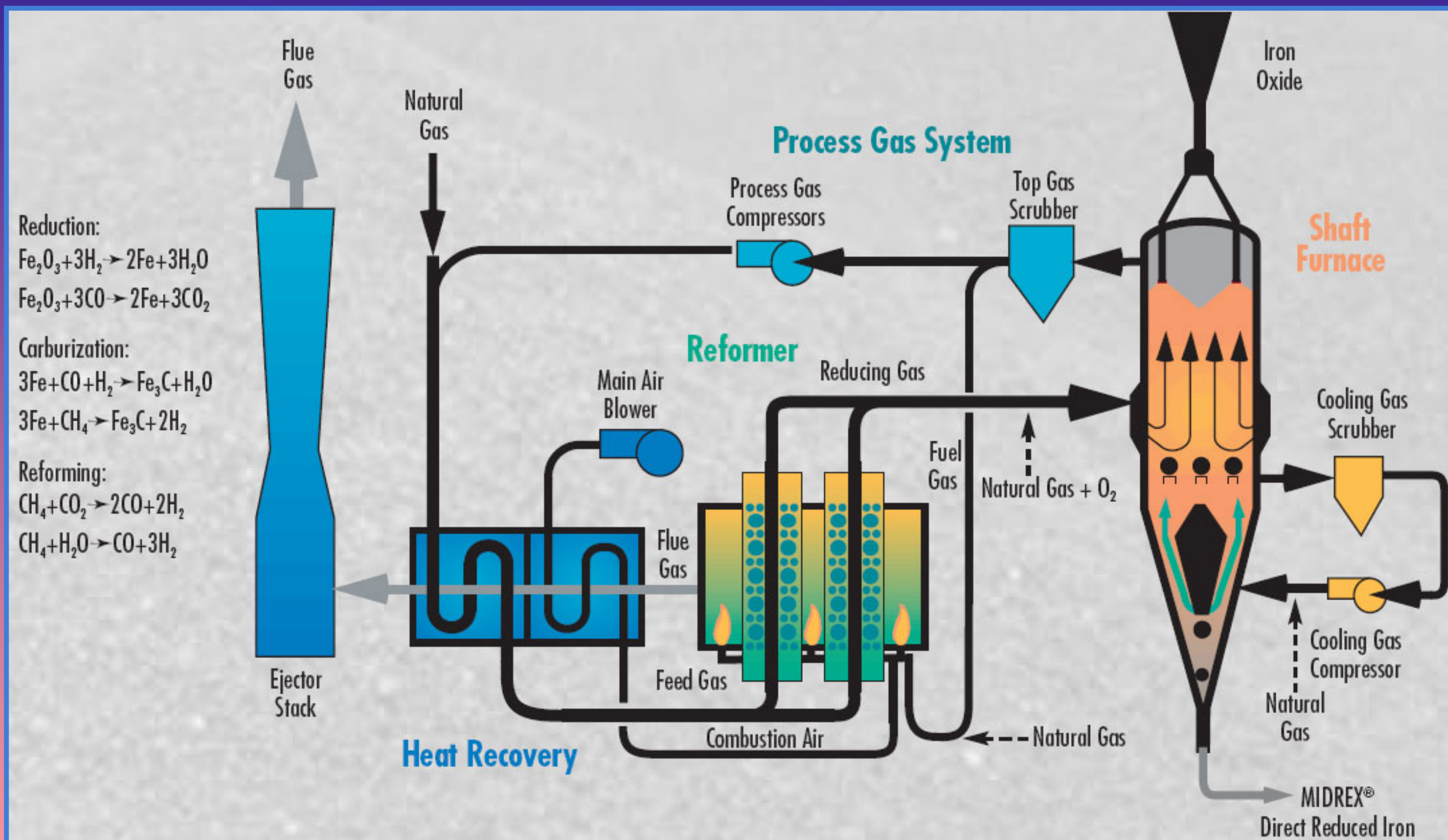
$$CH_4 + CO_2 = 2CO + 2H_2$$
$$CH_4 + H_2O = CO + 3H_2$$

- Carburisation reactions:

$$3Fe + CO + H_2 = Fe_3C + H_2O$$
$$3Fe + CH_4 = Fe_3C + 2H_2$$

- Reactions occur at lower temperatures – less energy required.

Direct Reduction



Methane Manufacture

- Use well-described and experimentally verified processes (In-Situ Propellant Production).
- Sabatier reaction:

$$CO_2 + H_2 = CH_4 + H_2O$$

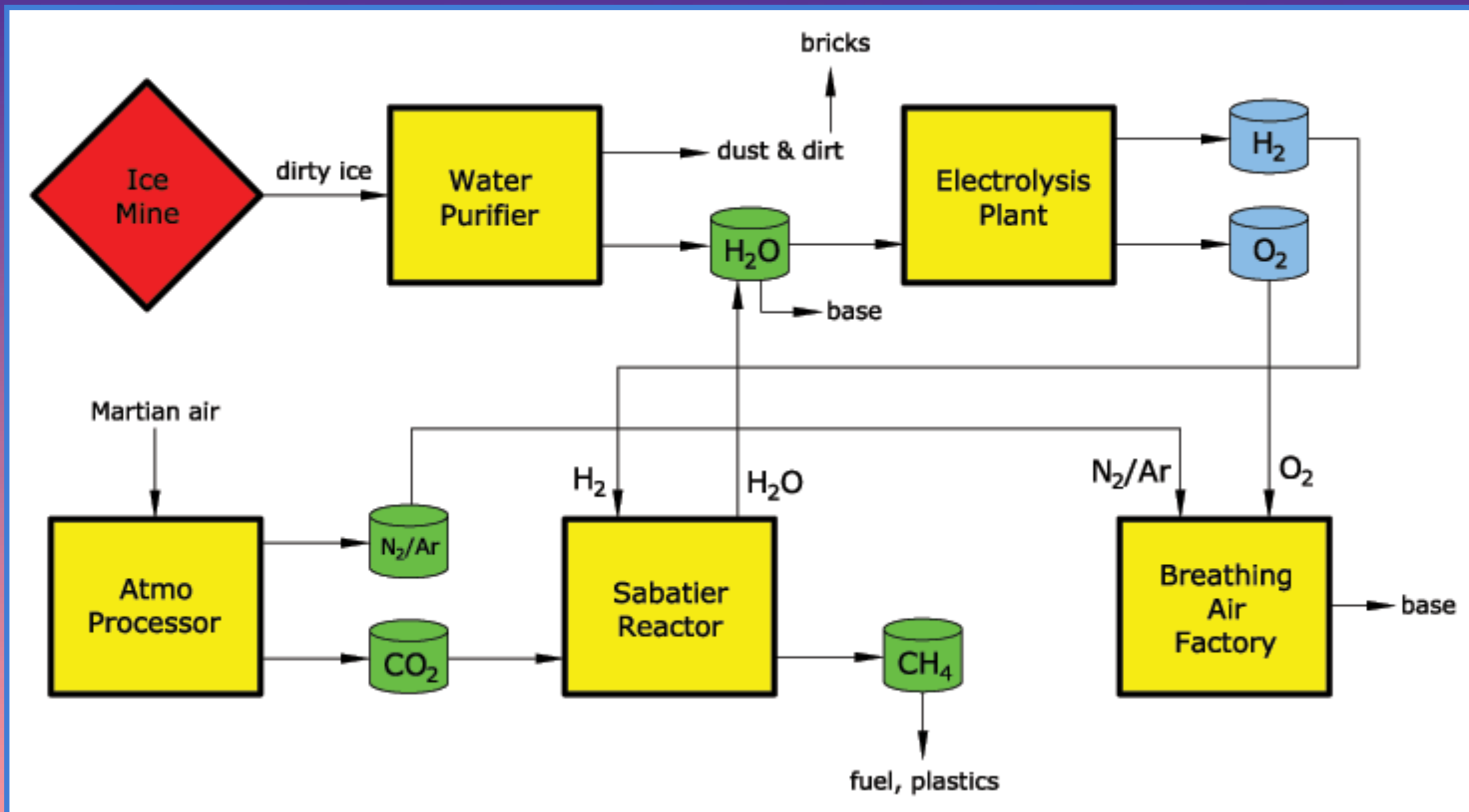
- Cheap & easy. Probably will already be in industrial-scale use on Mars for rover and rocket fuel, plastics and hydrocarbons, and maybe even as a greenhouse gas.
- H_2 & O_2 produced from electrolysis.

Methane Method: *Advantages*

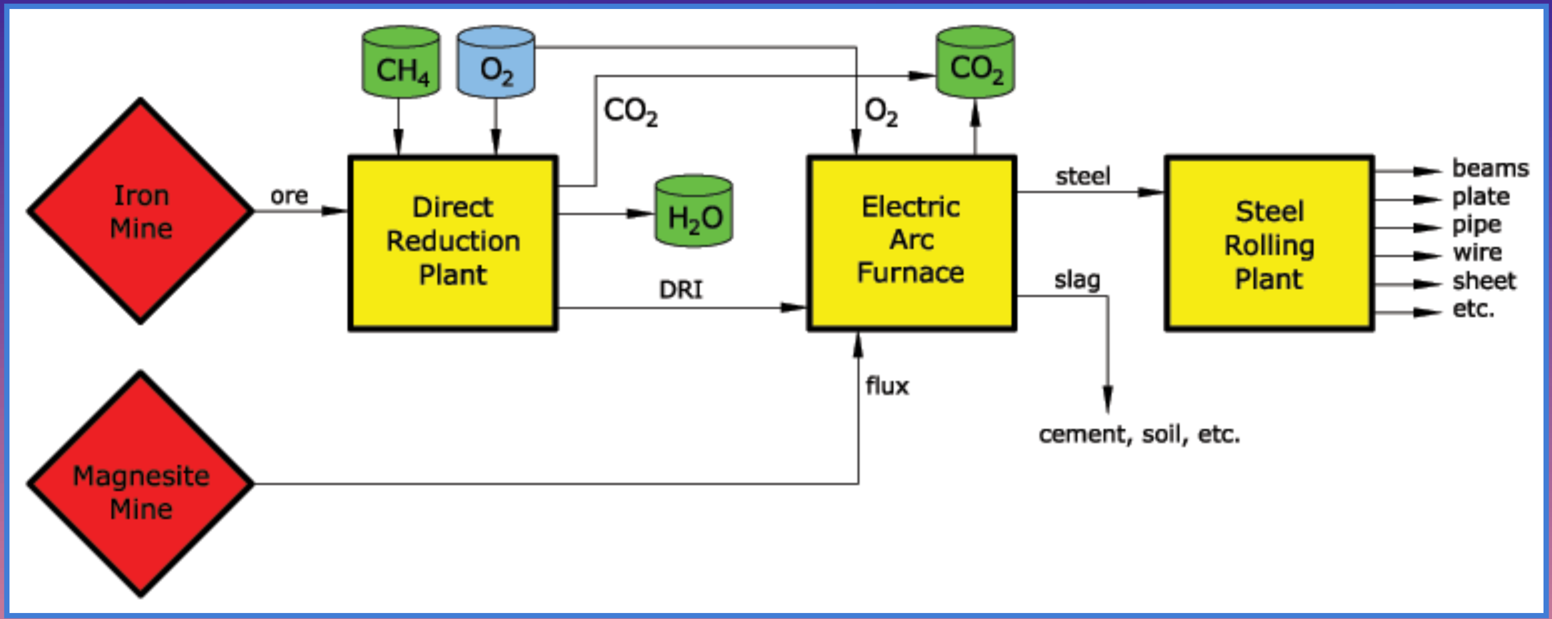
- Does not require manufacture of solid C.
- Methane factory already part of base, may be available in abundance.
- Uses well-developed and understood technology & equipment.
- DR methods also exist that use fluidised beds to reduce fine ore. Eliminates the need for sintering or pelletising.

Materials Flow: the Basics

- These elements already part of Mars base:



Methane Method:
Flow Diagram



- Emphasis on recycling. Reuse offgas. Slag used as cement substitute, or to enrich soil, as on Earth.

Hydrogen Method

- All previous methods require hydrogen to produce the reducing agent.
- Cheaper/simpler to just use the hydrogen:

$$Fe_2O_3 + 3H_2 = 2Fe + 3H_2O$$

- Same problem as CO - resulting metal contains no dissolved carbon.
- Good method for making iron/DRI.

Hydrogen Method: *Add Carbon from CO_2*

- **Key concept:** Add carbon using the Bosch reaction inside the furnace:

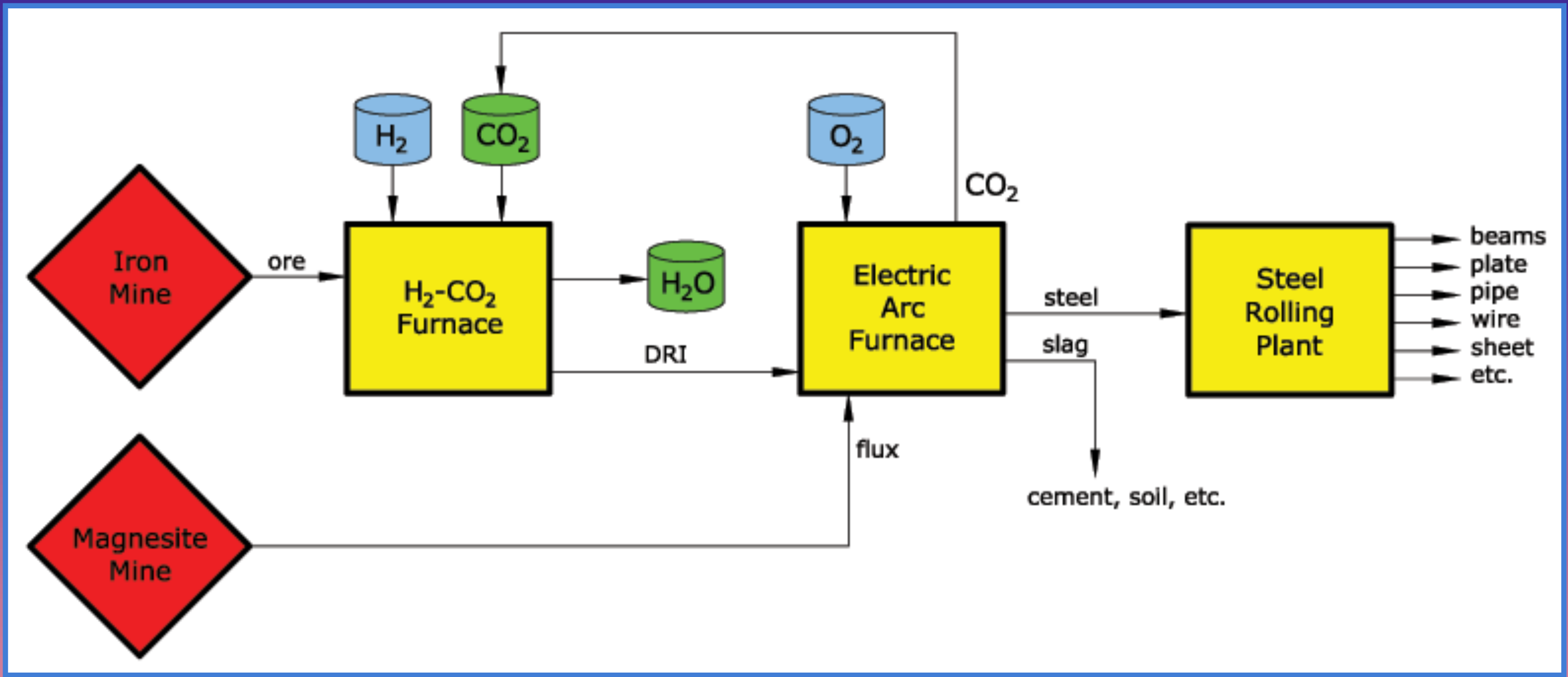
$$CO_2 + 2H_2 = C + 2H_2O$$

- Reaction is accelerated by an iron catalyst – furnace is full of iron.
- On Mars, both H_2 and CO_2 very cheap (compared with previous alternatives C, CO, CH_4).
- Other advantages:
  - Solid carbon does not need to be made separately.
  - Bosch reaction exothermic, and can maintain furnace temperatures, i.e. lower energy costs.
  - Computers can adjust H_2-CO_2 mixture to precisely control the amount of dissolved carbon.

Hydrogen Method: *Implementation*

- Reaction temperatures: Bosch reaction occurs at 450°C-600°C, whereas iron melts at 1538°C. Need to melt iron to remove impurities via flux/slag technique.
- Hence, plant with two components:
  - Low-T furnace to reduce iron oxides and add carbon using H_2 and CO_2. Produces DRI.
  - High-T furnace using oxygen and flux to remove impurities and control steel chemistry. Use an EAF.
  - Overall process very similar to DR → steel.
- Untested technology – would need to verify, build and fine-tune plant on Earth before sending to Mars.

Hydrogen Method:
Flow Diagram



- All input gases cheap, on Mars.
- Recycle offgas, slag.

Carbonyl Method

- Usually used in nickel refining, or to produce high-purity iron.
- Main benefit – straight from ore to iron.
  - **DOES NOT REQUIRE FLUX**, i.e. very useful if concentrated carbonate deposits not found.
- 1. Iron oxides reduced (e.g. using H_2).
- 2. Pressurize reduced iron with CO gas.
- 3. Fe combines with CO to form iron pentacarbonyl gas, $Fe(CO)_5$. Piped to deposition chamber.
- 4. Exposing carbonyl gas to hot surface causes Fe to be deposited and CO gas released (can be used to directly produce iron beams, pipes, plate, sheet, vessels, etc.).
- 5. CO recycled back to first chamber.

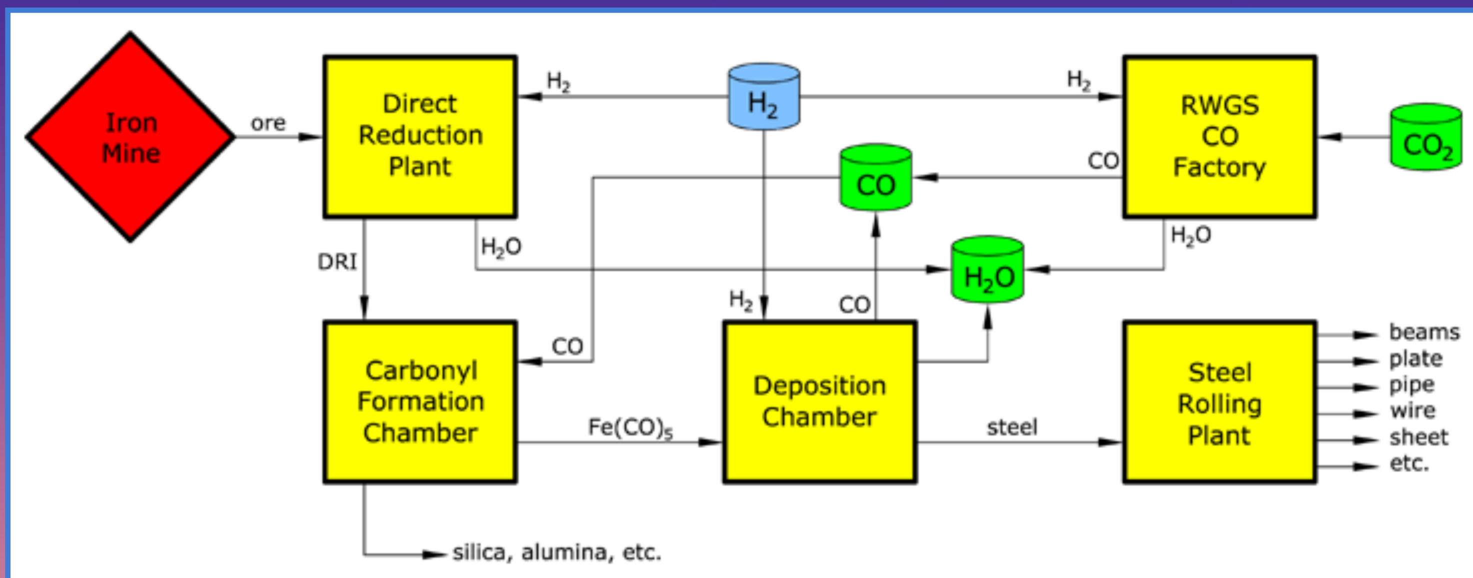
Carbonyl Method:
Adding Carbon from CO

- Can add carbon via similar process as described in Hydrogen Method , but use CO instead of CO_2:

$$CO + H_2 = C + H_2O$$

- Sensors/computer adjust H_2 input to control concentrations of dissolved C. May be more precise than using CO_2 as in H method, because impurities removed first.
- Deposit iron and carbon at the same time – <u>straight from ore to steel without melting!</u>

Carbonyl Method:
Flow Diagram



- Note absence of magnesite mine.

Conclusions

- Steel can be made on Mars from local ingredients, various options.
- Concentrated carbonate deposits will be valuable – must search for them beneath Martian dust.
- Methane Method has merit.
  - Uses well-understood and developed technology: Direct Reduction.
  - Methane probably manufactured in large quantities anyway.
- Hydrogen Method attractive due to low cost of ingredients. Method and equipment needs to be verified and tested.
- Carbonyl Method could be best. Effective for pure Fe, does not require flux. Need to verify processes for adding carbon.