GT6X (GregTech 6 eXtended)

Boris (AKA Altadoon)'s ideas for a minecraft 1.7.10 meta-mod

Introduction

While playing GT6U and the TFR modpack, I have come to the conclusion that it has some good ideas in it that were executed a bit hastily and sometimes in an unbalanced or weird way compared to the philosophy and standards of “vanilla” GT6 as made by GregoriusT. Another issue that GT6U has is the fact that it is a fork and updating your GT6 version requires an extensive rebase of the code. During a discussion with Bear989 while shooting my base tour, he said that it would be nice if “unorthodox features” from GT6U could be in an extension rather than a fork.

Such features, including but not limited to more complicated oil processing recipes and machines (desulfurization, cracking towers, additional types of plastic), portable gas turbines, more large multiblock versions of normal machines, and overhauls in the fusion reactor are usually subject to opinion. Some people like some of these features, while others do not. Some features are just plain improvements that could be added as pull requests to the normal GT6 codebase so that everyone can enjoy them. But certain features are interesting to some while for others they are a chore. Think for instance about more complex chemical process chains inspired by real life industrial processes, which make setting them up take way more time and thought. For some people it can be rewarding to have finally made a large setup of different machines, but for others this might as well be simplified into just a few recipes, and it does not add to the enjoyment of the game.

This kind of opinionated features better fit within an extension than in the base mod. Not only the wishes of players are of concern here; also the opinion of Greg matters since if it does not fit within his vision of what his mod should look like, it should not be in there.

Since some people might like only certain features of such an extension while others do not, and to make the life of modpack makers more easy, all of these features should be configurable separately. Config files could be used to turn certain features on or off, depending on the tastes or modpack needs.

I expect to have little time myself, working as a software engineer four days a week, and having many other things in my life, planned and unplanned. Only on some evenings or off-days that are relatively quiet does it occur that I have quite a few hours and energy to spare to work on a nice little hobby project like this. For this reason I want to work on those little features one by one, starting with the one I think is the most simple (only requiring the modification and addition of some recipes, materials and oregen config) so I can learn the GT6 and minecraft APIs step by step.

Once I have a better understanding of that API I could actually start accepting PRs and add more ideas from myself or from other people’s suggestions, but for now expect me to take my time. Also expect the possibility that during this process I find out I just don’t have enough time to actually make enough progress on coding to make it fun for myself - it is a hobby project after all, for fun.

Next up is a list of features and rough ideas that I might want to add to this mod. The order of listing is the currently most likely order of implementation, because as I said I will add simpler features first since I am still learning the API. It and anything in this document might change in the future.

Advanced platinum group chemistry

Some of the more rare platinum group elements (Ir, Os) are used in many end-game tier recipes. Somewhere during the time where most GT6 players have the need for lots of platinum for in high-tier circuits, and have enough resources to build an Aqua Regia processing chain, they will start to electrolyze Chloroplatinic acid for extra platinum, while building up tons of Platinum Group Sludge.

Then, when making the best Diesel Engines, Building a fusion reactor or matter fabricator in the endgame, they can use this Sludge and just put it in a centrifuge to separate it. In my opinion, this is a bit trivial.

Also, in real life, separating these elements is a complex task with many chemical reactions taking place that take advantage of the small difference between them in chemical properties, also see https://en.wikipedia.org/wiki/Platinum_group#/media/File:PtMetalExtraction_II.jpg and https://pdfslide.net/documents/a-review-of-methods-of-separation-of-the-platinum-group-metals-through-their.html?page=6

Don’t worry, these diagrams are way too large even for my tastes. But the basic principle is interesting. Every element gets separated from the rest by a different technique, and as such I envision a processing chain which has about one key recipe for retrieving that specific element, and some recipes for reprocessing catalysts.

The chemical reaction chains might look as described in this section. It was heavily inspired by Team Moeg’s TFR, with the notable differences that some reactions have been simplified, the Aqua Regia and other chemicals not part of the ore or end products can be recycled, and it replaces the default GT6 Platinum processing line instead of giving an addition for TFR specific ores.

The input is Purified Pt-group ores/Pentlandite/Chalcopyrite.
In a bath of aqua regia, these ores will produce refined nickel/copper sulphide (if those ores were used), some Platinum Group Residue tiny refined ores with the formula $(Ru,Rh,Ir,Os)_n$, NO to recycle into new Aqua Regia, and a Platinum-Palladium Acidic solution.

Aqua Regia dissolution/precipitation of Pt, Pd

- Step 1: filter out non-Pt group metals and separate Pd/Pt from the rest (Bath)
    - $Pt + 4\ (HNO_3)(HCl)_4 \rightarrow H_2PtCl_6 + 10HCl + 4\ H_2O + 4\ NO_2$
    - $Pd + 2\ (HNO_3)(HCl)_4 \rightarrow PdCl_2 + 6\ HCl + 2\ H_2O + 2\ NO_2$
    - $3\ NO_2 + H_2O \rightarrow 2\ HNO_3 + NO$
- Equal weight simplified reaction:
    - $Pt + Pd + 2\ (HNO_3)(HCl)_4 \rightarrow PdCl_2(aq) + H_2PtCl_6(aq) + 4\ H_2O(l) + 2\ NO(g)$
- Braggite ratio[1]:
    - $5\ Pt + 2\ Pd + 24\ (HNO_3)(HCl)_4 \rightarrow 2\ PdCl_2(aq) + 5\ H_2PtCl_6(aq) + 62\ HCl + 24\ H_2O(l) + 24\ NO_2(g)$ ($\rightarrow 16\ HNO_3 + 8\ NO \rightarrow 8\ AR - 2\ HCl + 24-8=16\ H_2O$)
    - Net: $5\ Pt + 2\ Pd + 8(HNO_3)(HCl)_4 \rightarrow 2\ PdCl_2(aq) + 5\ H_2PtCl_6(aq) -2\ HCl + 16\ H_2O + 8\ NO$ (borrow the 2 HCL from the next reaction)
- Platinum rich variant (native Pt ore = +~1.5 Pt content):
    - $4\ Pt + Pd + 18\ (HNO_3)(HCl)_4 \rightarrow PdCl_2(aq) + 4\ H_2PtCl_6(aq) + 46\ HCl + 18\ H_2O + 18\ NO_2\ (g)$ ($\rightarrow 12\ HNO_3 + 6\ NO \rightarrow 12\ AR -2\ HCl + 18-6=12\ H_2O$)
    - Net: $4\ Pt + Pd + 6(HNO_3)(HCl)_4 \rightarrow PdCl_2(aq) + 4\ H_2PtCl_6(aq) -2\ HCl + 12\ H_2O + 6\ NO$ (borrow the 2 HCL from the next reaction)
- Palladium rich variant
    - $Pt + 4\ Pd + 12\ (HNO_3)(HCl)_4 \rightarrow 4\ PdCl_2(aq) + H_2PtCl_6(aq) + 34\ HCl + 12\ H_2O + 12\ NO_2$ ($\rightarrow 8\ HNO_3 + 4\ NO \rightarrow 8\ AR + 2\ HCl + 12-4=8\ H_2O$)
    - Net: $Pt + 4\ Pd + 4(HNO_3)(HCl)_4 \rightarrow 4\ PdCl_2(aq) + H_2PtCl_6(aq) + 2\ HCl + 8\ H_2O + 4\ NO$

Simple version

If too much chemistry and machine building turns you off, but you still don’t like the idea of only some platinum dissolving in Aqua Regia, getting the rest of the PGMs from centrifuging, I suggest a simpler version where you can just electrolyze the platinum-palladium solution:

- Step 2 (electrolyzer)
- $(H_2PtCl_6)_5.(PdCl_2)_2.-2HCl.16H_2O \rightarrow 32\ HCl + 4\ H_2O + 6\ O_2 + 5\ Pt + 2\ Pd$

Next, the residue can be oxidised using ozone (made by putting oxygen in a lightning processor) to osmium-ruthenium tetroxide gas and Iridium-Rhodium oxide salts in a roaster:

- Step 3 (roaster)
- $(Ru,Rh,Ir,Os)\ (s) +4\ O_3 \rightarrow (OsO_4, RuO_4)(g) + (IrO_2, RhO_2)(s)$

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[1] https://en.wikipedia.org/wiki/Braggite#Composition

each of which can be distilled/reacted with hydrogen to recycle the oxygen and get pure metal back:

- Step 4 (distillery)
- (Os, Ru)O_4 -> 2 O_2 + Os + Ru (chanced outputs)
- Step 5 (roasting oven)
- (IrO_2, RhO_2)(s) + 4 H_2(g) -> 4 H_2O(l) + Ir + Rh (chanced outputs)

Complicated version

The complicated version is more realistic and requires you to build a large setup of machines. It has my own preference as it makes getting end-game elements more rewarding, but to each their own taste.

Precipitating Platinum

The solution can be mixed with Ammonium Chloride, made from HCl and Ammonia (made initially from distilling manure, and later industrially from 3 H_2+N_2 with a catalyst of Hematite in a mixer, a simplified Haber process)

- Step 2: separate Pt and Pd (Bath)
- H_2PtCl_6 .$PdCl_2$.4H_2O(aq) + 2 NH_4Cl (s) -> $(NH_4)_2PtCl_6$ (s) + $PdCl_2$(aq).4H_2O.2HCl
- $(H_2PtCl_6)_5$.$(PdCl_2)_2$.-2HCl.16H_2O(aq) + 10 NH_4Cl (s) -> 5 $(NH_4)_2PtCl_6$ (s) + 2 ($PdCl_2$)(aq).8H_2O.4HCl
- $(H_2PtCl_6)_4$.$PdCl_2$.-2HCl.12H_2O(aq) + 8 NH_4Cl (s) -> 4 $(NH_4)_2PtCl_6$ (s) + $PdCl_2$.6HCl.12H_2O
- H_2PtCl_6 .$(PdCl_2)_4$.2HCl.8H_2O(aq) + 2 NH_4Cl (s) -> $(NH_4)_2PtCl_6$ (s) + $(PdCl_2)_4$.4HCl.8H_2O

Next, we need to extract the metal from the solutions.

- Step 3: Extract Platinum from Ammonium hexachloroplatinate salt (distillery to simulate heating the salt and collecting the gas)
- $(NH_4)_2PtCl_6$ -> 2 Cl_2 (g) + 2 NH_4Cl (s) + Pt (s) (chance output)

Precipitating Palladium

The palladium chloride is first converted to tetraamminepalladium chloride salt using ammonia.

- Step 4: precipitate palladium salt from Palladium Dichloride solution (Mixer)
- $PdCl_2$.4H_2O.2HCl + 4 NH_3 (g) -> $Pd(NH_3)_4Cl_2$ (s) + 4 H_2O + 2 HCl

- $(PdCl_2).8H_2O.4HCl + 4\ NH_3 \rightarrow Pd(NH_3)_4Cl_2\ (s) + 8\ H_2O + 4\ HCl$
- $PdCl_2.6HCl.12H_2O + 4\ NH_3\ (g) \rightarrow Pd(NH_3)_4Cl_2\ (s) + 12\ H_2O + 6\ HCl$
- $(PdCl_2)_4.4HCl.8H_2O + 16\ NH_3\ (g) \rightarrow 4\ Pd(NH_3)_4Cl_2\ (s) + 8\ H_2O + 4\ HCl$

Again, the precipitated salt can be thermolysed:

- Step 5: Extract palladium from the salt (distillery)
- $Pd(NH_3)_4Cl_2 \rightarrow 4\ NH_3(g) + Cl_2\ (g) + Pd(s)$ (chance output)

Solid Pt and Pd here will be some chanced amount of tiny refined ores.
NH_4Cl can be distilled back into HCl and ammonia. The HCl can be recycled back into Aqua Regia together with the other HCl, NO, and O_2 which is made by reacting the chlorine gas with the water. Good luck with the spaghetti pipes!

Note that this process can be made before electrolyzers or cryo distillation towers are available using sulfuric acid + salt/saltpetre, and a bunch of mixers. Which is useful if you don’t have a native platinum deposit, as electrolyzers themselves require platinum. The platinum group residue can be stored for later use as you will need electrolyzers to process the vitriol, ozone and hydrogen needed in later steps. You still need a lot of manual work since you don’t have filters at that point, so it might be worth it to find native platinum ore first and build an electrolyzer for aluminium.

Rhodium separation

The first step in getting the rare Pt-group metals is to separate the Rhodium. For this you will need potassium pyrosulfate, which is made from heating potassium bisulfate in a distillery:

- Step 6a: Get potassium pyrosulfate (dryer)
- $2\ KHSO_4 \rightarrow K_2S_2O_7\ (l)$ + distilled water

- Step 6b: Dissolve rhodium in molten potassium pyrosulfate (bath).
- $2\ (Ru,Rh,Ir,Os)_n + 6\ K_2S_2O_7\ (l) \rightarrow Rh_2(SO_4)_3.6\ K_2SO_4\ (l) + 3\ SO_2\ (g) + 2\ (Ru,Ir,Os)_n\ (s)$[2]

- Step 6c: Dissolve Rhodium/Potassium Sulfate in water and filter out potassium sulfate (mixer)
- $Rh_2(SO_4)_3.6\ K_2SO_4\ (aq) + nH_2O \rightarrow Rh_2(SO_4)_3(aq) + 6\ K_2SO_4(aq)$

- Step 7a: precipitate rhodium using zinc, forming white vitriol and metallic Rhodium (bath)
- $Rh_2(SO_4)_3\ (aq) + 3\ Zn\ (s) \rightarrow 3\ ZnSO_4\ (aq) + 2\ Rh\ (s)$

White vitriol can be electrolyzed with water (default GT6 recipe) to yield Zn, sulfuric acid and oxygen. Potassium sulphate can be mixed with sulfuric acid to get potassium bisulfate:

- Step 7b: Get back potassium bisulfate (mixer)

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[2] https://www.mdpi.com/2075-4701/10/4/485/htm

- K_2SO_4 + H_2SO_4 -> 2 $KHSO_4$

Using a normal sulfuric acid setup, the sulphur dioxide can be reacted with the oxygen from the white vitriol electrolyzer to get SO_3, the water from the dryer to get H_2SO_4, enough to recycle the $K_2S_2O_7$.

Iridium separation

There are several ways to separate the last elements, and one such way (similar to the method in TFR) is to dissolve the residue in a sodium peroxide solution[3], oxidising it further to $(Ru, Os)O_4$ and IrO_2, and chlorinating with ammonium chloride to $(NH_4)_3RuCl_6$, finally making it into metal with hydrogen. This is a long reaction chain, and also to me it was not really clear how it worked exactly.

Another way I came across was oxidation using Ozone under high temperature, yielding $(Ru,Os)O_4$ gas at temperatures around 403K, leaving behind solid IrO_2, and afterwards reducing it. This method appears to be easier to implement in the game in a simplified manner. Ozone can be made by passing oxygen through a so-called corona discharge[4] which in-game is represented by a lightning processor.

- Step 7: oxidise everything using ozone under high temperature (roasting oven),
- 3 $(Ru,Ir,Os)_n$ (s) + 10 O_3 -> 6 $(Ru, Os)O_4$ (g) + 3 IrO_2 (s)

- Step 8: reduce Iridium oxide with hydrogen and heat (roasting oven)
- IrO_2(s) + 2 H_2(g) -> Ir(s) + 2 H_2O

Ruthenium and Osmium separation

Ruthenium tetroxide is separated from Osmium tetroxide by dissolving it in hydrochloric acid to form chlororuthenic acid.

- Step 9: separate ruthenium tetroxide from osmium tetroxide using hydrochloric acid (mixer)
- $(Ru,Os)O_4$ + 6 HCl -> H_2RuCl_6(aq) + 2 H_2O + O_2 + OsO_4(s)

- Step 10: neutralise chlororuthenic acid using ammonium chloride to ammonium hexachlororuthenate (bath)
- H_2RuCl_6(aq) + 2 NH_4Cl -> $(NH_4)_2RuCl_6$(s) + 2 HCl

- Step 11: heat the ammonium hexachlororuthenate in presence of hydrogen (roasting oven)
- $(NH_4)_2RuCl_6$(s) + 2 H_2 -> 2 NH_4Cl(s) + 4 HCl + Ru(s)

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[3] industrial separation of iridium and osmium, p.1173, https://books.google.nl/books?id=_to_DQAAQBAJ

[4] https://www.oxidationtech.com/ozone/ozone-production.html

Finally, we can reduce the Osmium tetroxide using hydrogen:

- Step 12: reduce osmium with hydrogen (roasting oven)
- $OsO_4(s) + 4 H_2 \rightarrow 4 H_2O + Os(s)$

The water, together with the water from step 8 and 9, can be electrolyzed to oxygen (needed for the ozone in step 7) and hydrogen (needed in step 8, 11 and 12).

Uses of PGMs

When playing TFR I found that making a similar setup to separate PGMs was a lot of work with little reward. Of course it was optional and centrifuging platinum group sludge was better because the largest source was vanilla GT6 ores from meteorite mining, but another thing which annoyed me was the fact that aside from Platinum, Iridium, and Osmium the other metals were mostly useless.

In reality, aside from jewelry, the PGMs have various uses:

- Pt is used as catalyst in diesel engines, in electronics,and as catalyst in industrial processes.
- Pd is used as catalyst in gasoline engines
- Rh is also used in smaller amounts in engines just because it is more expensive
- Ru is used in electronics

With this mod, I intend to each give them a specific use.

Combustion engines

In GT6, there is no difference between diesel- and gasoline engines, and both petrol and diesel (as are most other liquid fuels) are burned in a diesel engine.
I would like to add this distinction to the game. Diesel engines now only run on Diesel or Biodiesel (made from mixing seed oil or other plant oils with ethanol or methanol and a catalyst of NaOH or KOH). Petrol engines run on Petrol, LPG (propane/butane) or Ethanol (or E85 biofuel, a mixture of 85% ethanol and 15% petrol, which I will introduce a mixer recipe for, and which gives a higher efficiency due to a better octane rating). Kerosine and Fuel Oil can be burned in a Gas Turbine together with most gas fuels.

Also, the minecraft environment has been polluted with people burning petroleum all the time. The government has passed a law that requires those engines to have a Catalytic Converter in their exhaust. Three types of it exist: a Palladium catalytic converter, a platinum one and a rhodium one. A catalytic converter can be crafted using a hammer and saw from a small stainless steel pipe and a metal mesh (a new component) made from Pt, Pd, or Rh. The mesh is made by combining 16 fine wires of the relevant metal in a loom with the correct selector tag. A couple meshes made from other materials will also be an ingredient of all sifters.

The diesel engine is now made using a platinum catalytic converter instead of its bottom small pipe in the recipe.
The petrol engine is made similarly with a palladium CC, except replacing the small gear with a nickel rod (representing the spark plug) and the big gear with a normal axis.
The gas turbine has each of its electric parts (battery, motor, circuit) replaced with a Rhodium CC.

Now, the working of the engines is also different. Diesel engines require a startup time similar to Steam Turbines, beginning at 0% efficiency and running up to 100% eventually. When at 100%, they give more RU/t than petrol engines, which start up immediately for convenience's sake. This gives them different uses, where petrol engines are more useful for powering RU consuming machines that need to be turned on and off frequently, while diesel engines are more useful for other applications such as electricity production and long running machines.

The materials used in different tiers of engines have also been changed to reflect some materials that are used in real life for combustion and jet engines, as well as to provide a use for some more rare materials such as cobalt, nickel, molybdenum, ruthenium and rhenium which otherwise have limited uses.

These materials are:

- Bronze and Arsenic Bronzes are kept unchanged from GT6
- Steel has been replaced with Cast Iron, a malleable type of iron with a lower carbon content than pig iron but higher than steel and which is IRL used for engine blocks.
- Invar has been replaced with Alusil, a light high-performance alloy of aluminium and silicon with some copper, also IRL in use for engine blocks
- Titanium has been replaced with Hastelloy, a high-nickel alloy somewhat similar to Ultimet but with different ratios, which is used in some high-performance engines such as in spacefare.
- Tungstensteel has been replaced with Ti-6Al-4V[5], a Titanium-Aluminium-Vanadium alloy used in place of pure titanium in jet engines.
- Iridium has been replaced with a simplified 5th generation TMS superalloy[6], in-game called TMS-196 after the one described in the linked article.

Electronics

Ruthenium will be a part of high tier circuit boards. This will be discussed in a later chapter about electronics.

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[5] https://en.wikipedia.org/wiki/Ti-6Al-4V
[6] https://www.tms.org/superalloys/10.7449/2008/Superalloys_2008_131_138.pdf

Some changes to simple machines

Thermolysis Oven

Some reactions, such as thermal decomposition and all endothermic combination reactions are not covered by any GT6 machine. Examples are the creation of quicklime from calcium carbonate, the thermal dissociation of ammonium chloride, and thermolysis of some other compounds.
In my opinion it is interesting to add some more realism there as it is a bit frustrating if you know such reactions happen usually under heat instead of with electricity, but you are not that far into the game yet and feel discouraged to progress into the electric age to get your oxygen for roasting or basic oxygen steelmaking purposes.

I propose the Thermolysis Oven which does just this. It has the same faces as the Roasting Oven (heat bottom, items left->right, fluids back->top) but is used for other processes. It should have the same slots as the Electrolyzer but with a different kind of progress bar in the GUI. The machine tiers are similar to other heat-based machines (steel - invar - titanium - tungstensteel) and the looks similar to the dryer, roasting oven and furnace.

Certain recipes can be moved there:

- Decomposition of NH_4Cl into ammonia and HCl
- Calcite -> quicklime + CO_2 (same for other carbonates like Malachite, Smithsonite,..)
- Sodium bicarbonate → sodium carbonate + water + carbon dioxide
- 8 Limonite -> 5 Hematite + 3 H_2O
- HgO (produced from roasting Cinnabar) -> Hg + O[7]
- IrO_2 -> Ir + O_2 (might cost more HU then roasting with H + electrolysis of water, but easier to set up)
- Osmium Tetroxide -> Os + $2O_2$
- NH_4PtCl_6 -> 2 NH_4Cl + Pt + 4 Cl
- $(NH_3)_4PdCl_2$ -> 4 NH_3 + Pd +2 Cl

Vertical Mixer

One thing that bothers me is that chaining mixers (e.g. for sulfuric acid production) is a recipe for spaghetti pipes. Because I will be adding more of those chains, I propose a mixer that is identical to the original except that it takes energy from the back, processes items from left to right and fluids from top to bottom. This will make your setups a bit less of a pain.

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[7] See the bottom part of https://en.wikipedia.org/wiki/Reactivity_series

Oil Refining

Another main feature of the mod focuses on realistic, complex and rewarding oil refining. Other mods such as gt5u or gt6u had expanded oil refining, which could be interesting, except that a lot of oil products were essentially useless. Hereby I present my view on what oil refining should look like.

Distillation of crude oil and gas

Oil distillation

First of all, I wondered what the difference between petrol and naphtha is, same for gas oil vs fuel oil, and if it made sense to add them at all. According to Wikipedia:

***Petroleum naphtha** is an intermediate hydrocarbon liquid stream derived from the refining of crude oil[1][2][3] with CAS-no 64742-48-9.[4] It is most usually desulfurized and then catalytically reformed, which rearranges or restructures the hydrocarbon molecules in the naphtha as well as breaking some of the molecules into smaller molecules to produce a high-octane component of gasoline (or petrol).*

So naphtha is the stream from the crude oil distillation, while petrol is a specific mixture with a high octane rating often produced by catalytic cracking.

Gas oil and Fuel oil appear to be synonyms, though the word gas oil is also used to refer to turning oil fractions into gases during fractional distillation. No sense in adding Gas Oil as a separate liquid.

So for the normal distillation tower processing of crude oil, I will change the recipe so it gives Naphtha instead of Petrol. Petrol will be a refined fuel produced from catalytic cracking (more on cracking later) which is more efficient in certain combustion engines. Naphtha can be burnt as usual but in an engine it has lower efficiency than petrol, which is made in a different way.

In addition, petroleum coke is removed from the recipe as this usually forms from steam cracking, not from crude oil distillation, which produces just asphalt as a solid.

Natural gas processing

In real life, natural gas is also often distilled as it consists of many hydrocarbons. Some heavier hydrocarbons as well, which can be turned into alkenes for plastics, which could be useful when there is no oil source found nearby. It is also a source of nitrogen and helium.

For this reason, I will add a cryo distillation tower recipe (gas distillation uses temperatures around -20 to -100 celsius):

100L Natural Gas => (light to heavy, top to bottom)

1L Helium
2L Nitrogen
100L Methane
5L Ethane
2L Propane
2L Butane
2L Naphtha

Creosote/Coal Tar distillation

Another oil that contains useful organics is Creosote. In reality, wood tar (from wood pyrolysis) and coal tar (from coking) often have different compositions, but in our case we will just stick with one type of creosote in both cases.
Aside from fuel and wood treating, they are often distilled to obtain Polycyclic Aromatic Hydrocarbons (PAHs) such as Naphthalene and Anthracene, as well as single-ringed aromatics such as benzene and phenol.
The latter two can be used as a phenol source in addition to the Cumene Process which produces a surplus of Acetone (see Epoxy Production).
The PAHs are also used in some applications, mostly for making dyes (Coal Tar dyes/Anthraquinone dyes and Azo dyes). Another use of Naphthalene is in the production of DNQ, an important constituent of Novolak-DNQ Photoresists.

Synthetic Dyes

Some of the most basic of these dyes and their precursors include (simplified reactions, isomers are not taken into account for simplicity):

- Anthraquinone Sulfonic Acid (anthraquinone + H_2SO_4)
- Aminoanthraquinone (Anthraquinone Sulfonic Acid + Ammonia)
- Indanthrone blue (reaction of aminoanthraquinone with oxygen and a catalyst of KOH)
- Alizarin red (Anthraquinone Sulfonic Acid + 2 NaOH, forming Na_2SO_3)
- Quinizarine Green (aminoanthraquinone + 4-chlorophenol)
- Aniline (Nitrobenzene + H_2 or Phenol + Ammonia)
- Benzenediazonium Chloride (Aniline + HNO_3 + HCl, forms water)
- Solvent Yellow 1 or 7 (Benzenediazonium Chloride + Aniline or Phenol + NaOH, forms salt water)
    - https://en.wikipedia.org/wiki/Category:Azo_dyes
- Indigo (from Aniline and Formaldehyde via N-Phenylglycine)
- Bleach (white dye) - H_2O_2
- Organol Brown[8] from Benzenediazonium Chloride and 1-Naphthol
- Sulfur Black from 2,4-dinitrophenol and Sodium sulfide
- Maybe Acid Orange 20 (Sulfanilic acid + HNO_2 + HCl -> Benzenediazonium Chloride Sulfonic Acid + 1-Naphthol -> Orange I (Acid Orange 20)

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[8] https://en.wikipedia.org/wiki/Azo_coupling#Examples_of_azo_C-coupling_reactions

Cracking and Desulfurisation

In gt5u/gt6u, sulfurous hydrocarbons were added which needed to be processed with hydrogen in chemical reactors/mixers/fuel cleaners.
IRL, depending on the cracking method used, this might be unnecessary because the cracking process also desulfurises the fuel.

In addition, I found cracking a bit lackluster in GT6, where some oil fractions required steam cracking and others catalytic cracking, and both were used mainly to produce ethylene and propylene.

In this mod I try to make it more useful. Nitro fuel will be abolished (sorry turbo lovers, adding glycerine to fuel only makes it go boom) and fuel oil will be burnable only in burning boxes and gas turbines. Same for kerosine, though I will add a recipe for galacticraft/AR rocket fuel combining kerosine and oxygen. Diesel and Petrol will be the way to go instead, yielding the highest turbine gains.

IRL, there are three main forms of cracking:

- Steam cracking, used mostly to produce unsaturated hydrocarbons such as ethene, propene, and aromatics,
- Catalytic cracking, used to produce high-octane petrol,
- Hydrocracking, used to convert heavy fuel oils into diesel and kerosine and to remove sulfur.

In game, these could be represented the following way:

Steam cracking

Steam cracking can be used on Ethane, Propane, Butane, and low-sulfur Naphtha to produce olefins as well as Petroleum Coke. Special uses are for Steam Reforming of Methane and coal gasification.

ethane -> ethene, methane, petcoke (can use distillery instead of tower)
propane -> propene, ethene, methane, petcoke
butane -> butene, butadiene, propene, ethene, methane, petcoke
naphtha -> steam-cracked naphtha (a single mixture liquid), petcoke
Methane/Natural Gas -> Syngas
Coal Dust -> Syngas + Fly Ash (contains Germanium)

Steam-cracked naphtha can be distilled in a distillation tower to yield methane and a bit of all the primary olefins: ethene, propene, benzene, toluene, butadiene, butene and methane.

These olefins have the following uses:

Primary olefins

Ethene - plastics
Propene - plastics
Butene - mixed together with butane and a catalyst of alumina or zeolite to produce petrol (actually (iso-)octane, but here we just call it petrol because it is a main constituent).
Butadiene - mixed together with Styrene and a catalyst of Potassium Persulfate to produce rubber. Hydrocracked to butane, propane, ethane, methane.
Benzene - mixed with propene to make cumene, mixed with ethane and a catalyst of zeolite to make Styrene, or with ethylene to make ethylbenzene
Toluene - used for TNT by nitration with nitric and sulfuric acid (recipe similar to glycerol -> glyceryl), mixed with methanol and a catalyst of zeolite to make Styrene, hydrocracking to benzene and methane.
Isoprene - used for rubber

Secondary olefins
Ethylbenzene - can be steam-cracked using a hematite catalyst to make Styrene and hydrogen.
Styrene - mixed with butadiene for rubber. Polymerized to polystyrene. One polystyrene dust can be extruded with a block mold to produce 9 blocks (!) of styrofoam. This is not very durable but a very cheap building material which can be broken in one hit.
Cumene - mixed with oxygen to produce phenol and aceton
Phenol, Aceton - mixed to create Bisphenol A
Bisphenol A - component of Epoxy

Hydrocracking

Hydrocracking is done in the same device as used for steam cracking, which is renamed “thermal reformer” instead of “steam cracker”.
It is used to turn heavier fractions into saturated lighter ones while desulfurizing in one go. If already desulfurized, no H_2S is produced.

Heavy fuel -> low-sulfur diesel + H_2S
Diesel -> low-sulfur kerosine + H_2S
Kerosine -> low-sulfur naphtha + H_2S
Naphtha -> butane + propane + ethane + methane + H_2S
Butane -> propane + ethane + methane
Butene/Butadiene -> butane + propane + ethane + methane
Propane -> ethane + methane
Ethane -> methane

The primary uses of hydrocracking are for making diesel/kerosine if you need those, and for cracking rest products such as ethane into methane so you can feed everything into your gas turbine or syngas plant without needing a separate one for each of them.

Catalytic cracking

Mainly used to convert low-sulfur heavier fuels into Petrol. If you use petrol engines as your main power source this should be the way to go.

Heavy fuel/Diesel/Kerosine/Naphtha -> Petrol + butene + propene + ethene + petcoke. (petrol is the main component).

Uses

Syngas

Syngas can be used to produce Direct-Reduced Iron (see chapter 4) or in the Fischer-Tropsch process[9] to produce synthetic oil.

It can also be distilled into CO and Hydrogen so you can convert natural gas/methane into Hydrogen if you don't have electrolyzers yet.

Syngas can be combined with a Ruthenium catalyst in a new HU requiring Heat Reactor to produce Synthetic Oil, a variant of Heavy Oil that distills into its low-sulphur constituents in a distillation tower.

Syngas can also be made by mixing CO and Hydrogen in a mixer. This means it is possible to produce oil and gas from coal, biomass (through methane), H_2 (from electrolysis) and CO made from charcoal. In other words: oil products will be renewable if using a tree or crop farm for biomass or charcoal, even without an available source of natural gas or oil.

I realize that this could lead to loophole exploits, so the methane used to produce synoil should always be more than the amount of methane that could be recovered by hydro-cracking the synoil multiple times.

Synthetic rubber

As described earlier, rubber can be made as styrene-butadiene or polyisoprene.

Phenol Formaldehyde Resin

PF is made by combining Phenol and Formaldehyde. Formaldehyde is made by mixing Methanol and Oxygen. Methanol is made by reacting hydrogen and carbon monoxide under a catalyst of Copper and Zinc Oxide. PF is used for med-tier circuit board plastics.

Epoxy

Epoxy can be made from BPA+epichlorohydrin+NaOH (also yields salt water). ECH can be made in these steps:

- allyl chloride (propylene + chlorine) or glycerol (from biomass) + HCl -> dichloropropanol
- Dichloropropanol + NaOH -> ECH

A catalyst of Phosphoric acid is required, obtained using:

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[9] https://en.wikipedia.org/wiki/Fischer%E2%80%93Tropsch_process

$Ca_3(PO_4)_2 + 3\ H_2SO_4 \rightarrow 3\ CaSO_4 + 2\ H_3PO_4$

Next, the BPA produced in the cumene process can be combined with the ECH and 1L of phosphoric acid to make Epoxy dust, which can be low-heat extruded into parts.
Epoxy will be a requirement for tier-3 and up circuit boards, a bit similar to gt6u.

Polyvinyl Chloride

PVC will be the main pipe material. The recipe for plastic pipes will be removed! Instead, you can make the dark grey pipes from PVC which is made by the polymerisation of Vinyl Chloride.
Because it has a specific and wide use, vinyl chloride production is made more easy by just requiring chlorine and ethene, or chlorine and ethane, in the second case yielding more HCL in addition. HCL can be mixed with oxygen to yield back Cl_2 and water (deacon process).

Polytetrafluoroethylene

PTFE can be made to make relatively cheap but good capacity acid-proof pipes.
It is made from chloroform with the following reaction chain:
$CH_4 + 3\ Cl_2 \rightarrow CHCl_3 + 3\ HCl$
$CHCl_3 + 2\ HF \rightarrow CHClF_2 + 2\ HCl$
$2\ CHClF_2 \rightarrow C_2F_4 + 2\ HCl$
$C_2F_4 + TiCl_4 \rightarrow PTFE$
The HCl can be recycled in the deacon process described above.
An option is to make PTFE a requirement for tier 2 and up-mixers instead of stainless steel, which would be needed for some of the advanced recipes, such as for epoxy.

Metallurgy

Return of the Blast Furnace and Electric Arc Furnace

Ferrous Metallurgy

For me, making steel from Wrought Iron in a crucible, which was made by heating up Iron, was a disappointment. In the real world, none of these descriptions are accurate. I understand that maybe Wrought Iron should have been named Pig Iron, and Greg wants to keep things for backwards compatibility, I do not care to keep that legacy, and will make things proper again.

Iron and Steel

So what are we talking about here? What are the real life meanings of all these kinds of Iron?

- Pig Iron, or Raw Iron, is made in a Blast Furnace. It has a very high carbon content (3.5-4.5%) and contains other impurities and therefore is really brittle and not really useful to work with.
- Steel is an alloy of Iron and Carbon, and has a lower carbon content than Pig Iron, which varies widely depending on the steel type (0.002 - 2.14%). It is made by blowing air through Pig Iron (Crucible Steel/ Bessemer Process Steel), or more efficiently by blowing pure oxygen through the Pig Iron (Basic Oxygen Process).
- Sponge Iron/Direct Reduced Iron is made in a bloomery or Direct Reduction Furnace. It can be made with lower temperatures and using reducing gases not limited to CO. It does contain more impurities.
- Wrought Iron is historically made by hammering the Sponge Iron from Bloomeries, which did not get hot enough to melt the iron completely but hot enough to reduce the oxides. It contains a lot of slag which needs to be hammered out while it is hot. This working is why it’s called wrought iron. Wrought iron is a type of steel that contains relatively little carbon (< 0.1%), where most normal steels are around 0.2%. Nowadays, a similar carbon content can be reached by adding a bit of Iron Oxide to molten Pig Iron, releasing CO_2.
- Stainless Steel is steel containing medium amounts of carbon (around 0.1%), as well as chromium and some other alloying elements, such as nickel, manganese, molybdenum, silicon, and phosphorus. Since there are many types of Stainless Steel, I found there to be no reason to change the original GT6 formula of $Fe_6CrMnNi$, even though IRL the alloy usually contains more chromium, making it closer to Fe_6Cr_2Ni. But, Mn is still a component but is more commonly added in larger quantities to other steels. I do not want to add a separate manganese steel since there are no uses for it at the moment, and as such I will keep it in the stainless steel recipe to still have a use for manganese.
  Also, Stainless steel contains carbon which needs to be decarburized, and as such I will have it be made from Pig Iron, requiring air/oxygen to be blown just like with carbon steel.

In the game, I assume the following molecular formulas for simplicity:
Pig Iron: Fe_5C
Steel: $Fe_{100}C$ (assuming carbon content of ~0.2% by weight)
Wrought Iron/Vanilla Iron: Fe
DRI: $(Fe_5C)_8(Fe_2SiO_4)_5$ - every 10 moles of iron inside ore gives 8 moles of metallic iron + 1 mole of ferrous slag)
Stainless Steel: $(Fe_6CrMnNi)_{20}C$ - smaller carbon content (molar) than normal steel.

As for conversions, I assume 1 unit of Pig Iron or Cementite can be converted to 1 unit of wrought iron or steel, not counting the carbon units separately. This means those high carbon steels are more compact, and converting them to low carbon steels increases the amount of units of the end product.

Gangue and Slag

As for gangue/slag (also see the Blast Furnace), a blast furnace produces about 20%-35% slag compared to pig iron from the gangue inside iron ore. Now let's simplify and say the slag consists of 20% $CaSiO_3$ (116u) and other constituents are negligible. That means for 10 moles of Fe (56*10=560u) there will be roughly 1 mole of $CaSiO_3$ in the product, in other words 5 moles of Fe_2O_3 contains about 1 mole of SiO_2.
Let's assume the same molar ratio for other oxide ores: for 10 moles of metal (Ni, Co, Sn, …) there will be roughly 1 mole of SiO_2 present in the ore (but it might get rounded down to get better numbers in the equations).
Secondary steelmaking produces a different kind of slag more rich in FeO and CaO, the CaO coming from flux which is used to maintain basicity, the FeO coming from oxidising some of the iron during the conversion to steel.

Specialty steels

Some high-end non-fantasy (tool) materials in GT6 include tungstensteel, titanium-gold, and HSS. Unfortunately, HSS, which is a type of steel in real life used for cutting tools and the like as it can keep an edge and does not wear too much, in the game it is not so useful as its durability is not better than tungstensteel (its primary ingredient) and it's more of a hassle to make since it requires more other ingredients.
In real life, HSS also comes in different types. HSS-T1 contains 18% tungsten by weight. The formula would be close to $(Fe_{20}C)_4W_6Cr_4V$. It is used mostly interchangeably with HSS-M grades which contain more Mo instead of W, and is often preferred because of Mo being cheaper and its lower weight. The most common HSS-M grade is M2, containing 0,85% C, 6% W, 5% Mo, 4% Cr, and 2% V (83,25% Fe). This means 1 kg of HSS-M would contain 15 mol Fe, 0.3 mol W, 0.5 mol Mo, 0.8 mol Cr, 0.4 mol V, and 0,7 mol C. In other words, a formula of $Fe_{150}W_3Mo_5Cr_8V_4C_7$, further simplified down to $(Fe_{20}C)_2WMoCr_2V$, and it could be made from a 3:1 ratio of Iron:Pig Iron or a 4:1 ratio of steel:pig iron (in game: 30 units of iron, 10 units of pig iron, 2 Cr, and 1 of the rest) in the EAF.

Primary Steelmaking

Bloomery

Before blast furnace technology, making wrought iron required a lot of manual labour.
This I want to represent in-game by adding (Iron) Bloom to the game, similar to TerraFirmaCraft. Recipes for Iron (e.g. Hematite + Coke) in the crucible will produce Sponge Iron/bloom instead, the scrap of which can be hammered to produce Wrought Iron. No flux is used other than the iron oxide itself, causing the slag to contain Fayalite (Fe_2SiO_4), with the following simplified reactions (which occur alongside the carbothermic reduction of iron oxides):

$Fe_2O_3 + SiO_2 + C \rightarrow Fe_2SiO_4 + CO$
$Fe_3O_4 + SiO_2 + C \rightarrow Fe + Fe_2SiO_4 + CO_2$

The overall reaction will be something like:

$5\ Fe_2O_3 + SiO_2 + O_2 + 12C \rightarrow 8/5\ Fe_5C + Fe_2SiO_4 + 5\ CO + 5\ CO_2$

Blast Furnace

To make stronger Steel with high carbon content, you will need a blast furnace. A blast furnace uses Coke both as a fuel and as a reducing agent, and therefore it should not be a HU-requiring machine. Only a bit of KU will be needed to blow the air through. As such it will function a bit like the Burner Mixer, which needs to be fed kinetic energy and then ignited using flint and steel or similar.

For such operations, a flux such as Calcite is used to get rid of Silica impurities, according to the reaction:
$CaCO_3 + SiO_2 \rightarrow CaSiO_3 + CO_2$
The $CaSiO_3$ will be in the form of Slag, which in case of Iron Smelting will come out in molten form, but in case of other metals such as tin, which requires less heat, will be in solid phase and can be scraped off the molten metal.
In the end, you get simplified equations such as:
$5\ Fe_2O_3 + 14\ C + O + CaCO_3 + SiO_2 \rightarrow 2\ Fe_5C + CaSiO_3 + 6\ CO + 6\ CO_2$
$10\ Fe_3O_4 + 35\ C + O_2 + 3\ CaCO_3 + 3\ SiO_2 \rightarrow 6\ Fe_5C + 3\ CaSiO_3 + 16\ CO + 16\ CO_2$
$10\ FeO.OH + 14\ C + O + CaCO_3 + SiO_2 \rightarrow 2\ Fe_5C + CaSiO_3 + 6\ CO + 6\ CO_2 + 5\ H_2O$
Alongside the burning of coke ($x\ C + y\ O \rightarrow z\ CO/CO_2$)

The CO_2 and CO will be mixed with the remaining nitrogen in the air, forming a blast furnace offgas usually containing about 20-25% CO, 20-25% CO_2, 50% N_2, and 5% H_2.
The gas can be burnt as low-caloric gas in a gas burning box, or cryo-distilled to give the constituents.

One important part to improve the efficiency of the BF is to preheat the blast. This happens in a tall tower called a Cowper Stove where the air is stored in preheated spaces in the inside of checker bricks. It is often heated using the hot exhaust gas from the blast furnace.

DRI

Direct-Reduced iron (DRI) is similar to sponge iron produced from a bloomery in terms of carbon and slag content (the flux used is the iron oxide itself, which combines with silica inside the ore to form Fayalite), except it is produced using reducing gases (such as H_2 and CO). This is usually done in a vertical shaft furnace, where the ores sink down and gases float up due to gravity, similar to the blast furnace, except no air is used. This is done both to reduce CO_2 emissions and to reduce coal usage if methane (or green hydrogen) is readily available. Also, the temperature used is lower (similar to Bloomery temperatures) as the iron is not smelted. This does mean smelting is needed in the second step, which is carried out in an Electric Arc Furnace (EAF), described in the next section. At that stage the slag is also separated from the iron.

The following simplified reactions are used (remember that DRI was assumed to have an approximate molecular formula of $(Fe_5C)_8(Fe_2SiO_4)_5$):

$25\ Fe_2O_3 + 5\ SiO_2 + 8\ CO + 73\ H_2 \rightarrow (Fe_5C)_8(Fe_2SiO_4)_5 + 73\ H_2O$
$50\ Fe_3O_4 + 15\ SiO_2 + 24\ CO + 254\ H_2 \rightarrow 3\ (Fe_5C)_8(Fe_2SiO_4)_5 + 254\ H_2O$
$50\ FeO + 5\ SiO_2 + 8\ CO + 48\ H_2 \rightarrow (Fe_5C)_8(Fe_2SiO_4)_5 + 48\ H_2O$

If you want to utilize the syngas produced from steam reforming of methane ($CH_4 + H_2O \rightarrow CO + 3\ H_2$), with a $CO{:}H_2$ ratio of 1:3:
$100\ Fe_2O_3 + 20\ SiO_2 + 81\ CO + 243\ H_2 \rightarrow 4\ (Fe_5C)_8(Fe_2SiO_4)_5 + 243\ H_2O + 49\ CO_2$
$200\ Fe_3O_4 + 60\ SiO_2 + 218\ CO + 654\ H_2 \rightarrow 12\ (Fe_5C)_8(Fe_2SiO_4)_5 + 654\ H_2O + 122\ CO_2$
$50\ FeO + 5\ SiO_2 + 14\ CO + 42\ H_2 \rightarrow (Fe_5C)_8(Fe_2SiO_4)_5 + 42\ H_2O + 6\ CO_2$

If you want to utilize gasified coal ($C + H_2O \rightarrow CO + H_2$) with a $CO{:}H_2$ ratio of 1:1:
$50\ Fe_2O_3 + 10\ SiO_2 + 81\ CO + 81\ H_2 \rightarrow 2\ (Fe_5C)_8(Fe_2SiO_4)_5 + 81\ H_2O + 65\ CO_2$
$100\ Fe_3O_4 + 30\ SiO_2 + 218\ CO + 218\ H_2 \rightarrow 6\ (Fe_5C)_8(Fe_2SiO_4)_5 + 218\ H_2O + 170\ CO_2$
$50\ FeO + 5\ SiO_2 + 28\ CO + 28\ H_2 \rightarrow (Fe_5C)_8(Fe_2SiO_4)_5 + 28\ H_2O + 20\ CO_2$

If you want to use CO from coal only, just use a blast furnace or bloomery/crucible. (In reality, a rotary kiln or some other furnace is used, for more info lookup the Corex process).

DRI is in practice often turned into steel by smelting it in an EAF together with scrap (some mixture of iron/steel and iron oxides). In-game this will be achieved by smelting with wrought iron/iron dust. This also releases the slag which will float on top of the molten steel.

Iron Carbide Process

Another route is via Iron Carbide or Cementite (Fe_3C), which is produced by reducing iron oxides using Hydrogen and Methane. This forms little CO_2. The temperature needed for this is even lower. The cementite can be further reduced with scrap or oxygen to produce steel. The cementite still contains slag, and hence the formula of the impure cementite produced in this process is written down as $(Fe_3C)_8(Fe_2SiO_4)_3$.

The reactions are:
$15\ Fe_2O_3 + 3\ SiO_2 + 8\ CH_4 + 23\ H_2 \rightarrow (Fe_3C)_8(Fe_2SiO_4)_3 + 39\ H_2O$
$10\ Fe_3O_4 + 3\ SiO_2 + 8\ CH_4 + 18\ H_2 \rightarrow (Fe_3C)_8(Fe_2SiO_4)_3 + 34\ H_2O$
$30\ FeO + 3\ SiO_2 + 8\ CH_4 + 8\ H_2 \rightarrow (Fe_3C)_8(Fe_2SiO_4)_3 + 24\ H_2O$

Secondary Steelmaking

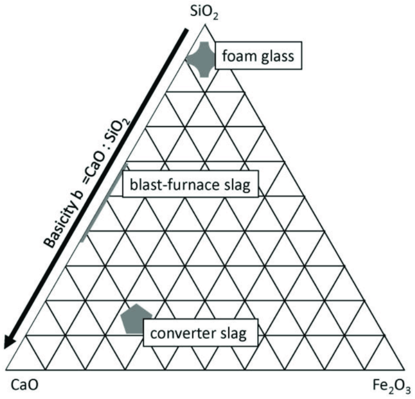
Crucible Steel/Bessemer Process

The oldest industrial steelmaking process is the Bessemer Process, where hot air is blown into a converter/ladle, decreasing the content of carbon and other impurities in the iron, converting it to steel.
In-game this will be done by just hooking a good old engine onto your crucible, putting some hot pig iron in (you can transfer molten pig iron from a blast furnace so you do not have to heat the crucible that much), and adding some lime (for the basic bessemer process).

Basic Oxygen Process

An improved version of the basic Bessemer process is the Basic Oxygen Process (BOP), in which pure oxygen and lime are added. This process produces better steel with less nitrogen impurities and finely-tuned carbon content.

The oxygen causes carbon, some iron and other elements to oxidise and form a slag. This slag mainly consists of CaO and FeO with some P_2O_5, MnO_2 and SiO_2) and will float on top. IRL, the slag is not recyclable economically, but since this is GT6x we want to both recycle everything and provide some insights about the composition of such compounds.
About 10-15% of the converter output consists of slag[10]. The main constituents are CaO, FeO and SiO_2 with a FeO content of 15-25%, and MgO content of 8-10%.



In this diagram you can see that this example converter slag has about 60% CaO, 25% iron oxides, and 15% SiO_2. Let's in our case assume 20% FeO and 5% P_2O_5, as well as 10% MgO substituting for CaO. MnO_2 often comes from the addition of manganese into the steel, which we don't do for simplicity.

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[10] https://onlinelibrary.wiley.com/doi/full/10.1002/srin.202100167

An issue is the amount of heat generated by the process. It can destroy the furnace (also called a basic oxygen converter, similar to the bessemer converter) if it gets too hot. For this reason, 25-30% scrap is often added.
Also, the FeO mixes with the MgO of the refractory walls, just as in the EAF (see next section), making the wall dissolve and melt. For this reason, the flux used is usually quicklime with some magnesia or burnt dolomite, which contains some more MgO.

So if the steel itself does not contain significant amounts of CaO and MgO, we could have a slag consisting of 50% CaO, 10% MgO, 20% FeO, 5% P_2O_5, and 15% SiO_2 (which combines with CaO to form $CaSiO_3$) by weight. This slag is assumed to be 12,5% (⅛) of the output, the rest being steel.

Calculations to get the equation approximately right

This section is not interesting. Please skip to the next. I just keep it here so if I find a mistake somewhere later someone can spot it in all these notes more easily.

Now CaO weighs about 1,4 times as much as MgO, FeO about 2,5 times, P_2O_5 about 3,5 times, and SiO_2 about 1,5 times.
So for every mole of MgO, we would have this rough estimate:
5/1,4 = 3,57 mol CaO
2/2,5 = 0.8 mol FeO
0,5/3,5 = 0,14 mol P_2O_5
1,5/1,5 = 1 mol SiO_2
That adds up to 1+3,57+0.8+0,14+1=6,5
Or, 1 mol of slag contains 0.15 mol MgO and SiO_2, 0,55 mol CaO, 0,12 mol FeO and 0,02 mol P_2O_5.
The SiO_2 combines with some of the CaO (0,15 mol) to form 0,15 mol $CaSiO_3$, leaving behind 0,4 mol CaO.

Let’s use those ratios for centrifuging molten slag into its components (a very energy intensive process so it is not done in practice, but we can manage with a 512RU/t centrifuge if we want since in GT6, energy can often be cheaper than materials, especially in end-game).
Then, the unit equivalent of 1 mol converter slag contains 0.3 units MgO, 0.75 units $CaSiO_3$, 0.8 units CaO, 0.24 units FeO, and 0.14 units P_2O_5. That adds up to 2.23 units of slag.
So, 1 unit of slag centrifuges to 0.13 units MgO, 0.34 units wollastonite, 0.36 units CaO, 0.11 units FeO, and 0.06 units P_2O_5.

The MgO+CaO comes from the flux, so 0,7 mol flux is needed for 1 mol slag.

As for the steel, 25% of 12,5% (3,125%) of the mass is FeO while 87,5% is Fe. That means for every g of steel produced, 0.0357 g FeO is produced, so for every mol of steel we have 0.0357 / (56+16) * 56 = 0.028 mol FeO. That FeO is part of 0,027/0,12=0,23 mol slag for every mol steel. That is roughly a 1:4 ratio (check: 0,25*0,12=0,03) of slag:steel. And we need 1,03 mol of pig iron for that, since 0.028 mol of that iron goes into the slag.
Or, for every 36 units of pig iron, 1 goes into 8 units of slag, and produces 35 steel.

The pig iron contains 7.2 units of carbon, and the steel contains 0,35 units, so 6,85 units of oxygen is needed to burn the carbon, plus (8*0,12=0,96) for the FeO, totalling 7,81 units.

Example equation for just iron, carbon and oxygen:
$144\ Fe_5C + 78½\ O_2 \rightarrow 7\ Fe_{100}C + 20\ FeO + 137\ CO$

Also, 25-30% scrap steel is used, so that could be exactly 2 $Fe_{100}C$ added to the mix. If slag is used for cooling, it will be solid on the left side of the equation and molten on the right side. If (wrought) iron (we disregard its carbon content) is used instead of steel scrap, we have:
$144\ Fe_5C + 200\ Fe + 77½\ O_2 \rightarrow 9\ Fe_{100}C + 20\ FeO + 135\ CO$

Parallel to this equation we have the flux + gangue -> slag:
$96.25\ CaO + 26.25\ MgO$ (122.5 flux) + 26.25 Si (gangue) + $26\ O_2 \rightarrow 26{,}25\ CaSiO_3 + 70\ CaO + 26{,}25\ MgO + 3.5\ P_2O_5$

Leaving us the total equation:
$144\ Fe_5C + 104.5\ O_2 + 26{,}25\ Si$ + flux($96.25\ CaO + 26.25\ MgO$) -> $7\ Fe_{100}C + 137\ CO$ + slag($70\ CaO + 26{,}25\ CaSiO_3 + 26{,}25\ MgO + 3{,}5\ P_2O_5 + 20\ FeO$) (and extra slag or steel as coolant on both sides, solid to the left and molten on the right)
$144\ Fe_5C + 200\ Fe + 103.5\ O_2$ + gangue + flux -> $9\ Fe_{100}C + 135\ CO$ + slag

If HBI is used instead of scrap or slag for cooling, we get more slag in the end, and require more flux so the ratio of the slag remains roughly the same - yes it means bonus P_2O_5. We also get more FeO but we act as if that reacts with the carbon in the HBI.:
$144\ Fe_5C + 5\ (Fe_5C)_8(Fe_2SiO_4)_5 + 27.5\ Si$ + flux($192.5\ CaO + 52.5\ MgO$) + $102.35\ O_2 \rightarrow 9.3\ Fe_{100}C + 159.7\ CO$ + slag ($140\ CaO + 52.5\ CaSiO_3 + 52.5\ MgO + 7\ P_2O_5 + 40\ FeO$)

On the left, we have 144+25=169 C, 720+200+50 Fe, and 100 O.
On the right, we have 940 Fe so 30 more need to be in the steel.
We have 169-9.3 = 159.7 C that need an O to form CO, and we will need 105 O for the Si and 40 for the FeO. 159.7+105+40-100=204.7 O needs to be added.

This has a nasty factor of 25 in it so let's add one HBI to make it match better:
$144\ Fe_5C + 6\ (Fe_5C)_8(Fe_2SiO_4)_5 + 22.5\ Si$(more in the steel?) + flux($192.5\ CaO + 52.5\ MgO$) + $103.6\ O_2 \rightarrow 9.8\ Fe_{100}C + 182.2\ CO$ + slag ($140\ CaO + 52.5\ CaSiO_3 + 52.5\ MgO + 7\ P_2O_5 + 40\ FeO$)

On the left, we have 144+48=192 C, 720+240+60 Fe, and 120 O.
On the right, we have 980 Fe so 80 more need to be in the steel.
We have 192-9.8 = 182.2 C that need an O to form CO, and we will need 105 O for the Si and 40 for the FeO. 182.2 +105+40-120=207.2 O needs to be added.

That is in moles, now in Units (which are moles times the atom count in each molecule, except some atoms which are not counted such as the carbon in steel/pig iron).
First, let's do it undivided, then divide it to get nice unit ratios and round up.

720 Molten Pig Iron + 200 steel dust + 209 oxygen + 192.5 quicklime + 52.5 magnesia -> 900 molten steel + 274 CO + 381.25 slag (140 CaO + 131.25 $CaSiO_3$ + 52.5 magnesia + 40 wüstite + 17.5 phosporous pentoxide)
720 Molten Pig Iron + 200 Iron + 207 oxygen + 192.5 quicklime + 52.5 magnesia -> 900 molten steel + 270 CO + 381.25 slag (140 CaO + 131.25 $CaSiO_3$ + 52.5 magnesia + 40 wüstite + 17.5 phosporous pentoxide)
720 Molten Pig Iron + 450 HBI + 207.2 oxygen + 385 quicklime + 105 magnesia -> 980 molten steel + 364.4 CO + 762.5 slag (2x(140 CaO + 131.25 $CaSiO_3$ + 52.5 magnesia + 40 wüstite + 17.5 phosporous pentoxide))

Since the molten ones are divisible more easily as 1 unit is 144L, let’s look at the flux to slag ratio. 192.5 CaO : 52.5 MgO : 381.25 slag = 11 : 3 : 21.8 or roughly 1:0.25:2, which is at least a workable ratio. I guess the MgO content does not really matter anyway as long as you don’t get a net gain of it (as with CaO).

If we want the right iron ratios, we get for instance a divisor of 180 to have batches of:
4 molten pig iron + 10 tiny steel/steel scrap + 1.161 oxygen + 1 quicklime + 1 small magnesia -> 5 molten steel + 1.52 CO + 2 slag (same story with Iron but with O/CO ratios adjusted)
With HBI the factor 180 leads to strange amount of HBI ingots (and I prefer to use ingots here since they come right out of the compressor) so we can use a divisor of 90 instead to get:
8 molten pig iron + 5 HBI + 2.302 O + 4 quicklime + 1 MgO -> 10+8/9 molten steel + 4.05 CO + 8 slag

Electric Arc Furnace

The Electric Arc Furnace (EAF) is a tech that was originally designed for scrap recycling. It also allows for smaller-scale secondary steelmaking plants, as the setup is smaller than the traditional BF-BOF steelmaking route. DRI products are frequently fed into an EAF.
The furnace itself is built using refractories such as sintered MgO-C.

It is meant as a high-tech alternative to the crucible. Since it is an electric machine, it can be gated behind some tier of circuits (maybe T3? Have to look where it’s needed). It will be an automatable machine with a builtin monitoring system in the GUI (sensors are needed in the crafting recipe) that checks the temperature and weight. The temperature is configurable in the GUI. The content in units is also displayed in the GUI. Whenever it is turned on,it will heat itself and its contents, consuming electricity, just as with the crucible.
Normal crucible smelting recipes can be carried out in the EAF, as well as some EAF-specific recipes, for instance:

- 5 Pig Iron + 15 iron -> 20 steel
- 3 Cementite + 2 iron -> 5 Pig Iron
- 15 Impure Cementite -> 8 Cementite + 7 Ferrous Slag
- 15 DRI -> 8 Pig Iron + 7 Ferrous Slag

The DRI/Cementite slag can be reacted with lime as well, yielding extra iron output:
$Fe_2SiO_4 + CaO \rightarrow 2 FeO + CaSiO_3$

Total reactions:
3 Fe_2SiO_4 + 8 Fe_3C (3*15 units of Impure Cementite) + 3 CaO -> 3 $CaSiO_3$ + 6 FeO + 8 Fe_3C.

5 Fe_2SiO_4 + 8 Fe_5C (5*15 units of DRI) + 5 CaO -> 5 $CaSiO_3$ + 10 FeO + 8 Fe_5C

To get rid of the FeO:
Fe_5C + FeO -> 6 Fe + CO
Fe_3C + FeO -> 4 Fe + CO
Fe_3C + 2 Fe -> Fe_5C
Fe_5C + 95 Fe -> $Fe_{100}C$

In the case of DRI, there is a shortage of carbon, while in the case of Cementite, there is excess carbon. One way to solve this is to combine the two processes, another is to only use the Cementite process and feed excess iron carbides to the converter, and the final is to use the DRI process, tap off the FeO as slag, and use the Fe as wrought iron or add in some pig iron from the BF.
In reality, carbon content in these processes can be controlled carefully by adding carbon or oxygen to the mix using lances.

Thermite reactions have a special place here. At relatively low temperatures (maybe 600K), reactive metals such as Aluminium can ignite with oxides. At this point, the EAF has reached the reaction temperature and can stop consuming energy (you can control this using a thermometer sensor on the side of the EAF). Now, the reaction takes place, increasing the temperature automatically. This can even be used to heat other metals (scrap) in the furnace! Do watch out to not overheat your furnace, as it will instantly explode when the temperature exceeds around 3000-3500 degrees. Do note that the wall of the furnace will not get that hot, mostly inside the electric arc, which explains why it does not need the walls to be made of tungsten or TaHfC.

Sintering

Sintering is connecting together grains of metal at high temperatures without actually smelting them. This principle is used for example in:

- Welding
- Working metal dusts with high melting points. Metals like tungsten and alloys such as carbides are often produced in this way.
- Creating (Iron) ore sinters for further blast furnace processing. Here, the ore, flux and coke powders are connected together into homogenous chunks which make the blast furnace process more energy-efficient.

Sintering instead of Crucible progression

One of the things that bothered me in GT6 was the crucible progression mechanic. When you made a crucible from some material, it would have a melting point 25% (or 10% for large

crucibles) above that of the material that it was made of (?), allowing you to make higher melting point crucibles in steps by using different materials with slightly higher melting points each time, eventually allowing you to make Tantalum Hafnium Carbide crucibles by smelting the material in a Tungsten crucible.
This all felt as one of the strangest mechanics in the game. If possible I would like to change this heat resistance bonus to +0%, but it would require adding my own crucibles overriding the default ones. It is also a bit against the spirit of the mod as an extension rather than a complete rework, and as such I will leave it as is for now.

Still, an alternative will be added: Sintering refractory and other metals can be done in a Sintering Oven, a closed machine with no exposure to air, leading to corrosion. It simply turns dusts into ingots which can be further processed using cold working.
The metal progression is still a part of the gameplay, but will be reworked in a different manner:

- Some simple metals (and plastics) can be sintered at low temperatures.
- Refractory metals such as W are sintered at temperatures between 2000-3000°C. A clay oven will not handle such high temperatures, but a Tantalum crucible will. As such we can keep the Tantalum -> Tungsten progression the same as with the old crucible progression.
- This will be done using a low heat Sintering Oven and a high heat one, similar to the Extruder Tiers.

Blast Furnace Sinters

Now we have a Blast Furnace and a Sintering Oven, we might as well implement the third use of Sintering: to produce sintered chunks of ore, flux and coke powder. These Sinters have the right structure and porosity to improve efficiency of the Blast furnace, reducing coke use and speeding up the process (requiring both less carbon and air flow/KU).

Non-ferrous metallurgy

Other blast furnace processes

Not only pig iron is made in blast furnaces. All carbothermic reduction processes can be done there, except for Titanium, which is made using the Kroll process which GT6 already implemented. Other processes are the ones for preparing metal from oxides which do not have autoreduction (noble metals) and do not require electrolysis (such as Aluminium or Magnesium)[11]: Mn, Zn, Fe, Co, Ni, Sn, Pb, Sb.

Now some of these metals are early-game metals (Zn, Sn, Pb) and these should be available by smelting in a crucible, though this is less efficient.

Zinc is a bit of a special one, since smelting Zinc in a blast furnace gives Vapour instead of liquid metal. This is mixed with the exhaust gases and can be distilled later to produce liquid

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[11] https://en.wikipedia.org/wiki/Reactivity_series#Table

Zinc and offgas. IRL electrolysis is also used for this reason, as collecting the zinc vapour can be a pain. For this reason electrolysing ZnO should be added.

Roasting

Most of the time, roasting turns sulfides together with oxygen into oxides and SO_2.
I will change some roasting recipes for making oxides instead of pure metal in roasting ovens. For those metals that did not have oxides, the oxides will be added (HgO, PbO, ZnO, Co_3O_4, MoO_3, Sb_2O_3, As_2O_3), and roasting the sulfides should give the oxides now instead of the pure metals (including Sn, Ni, Mn).
Pb, Co, Sn, Ni, Mn, Sb and Zn can be extracted from their oxides in the blast furnace. HgO can be decomposed using thermolysis. For Mo, the temperature required is too high for the blast furnace, and it can be directly reduced using Hydrogen, just as with WO_3.
Sb and As can optionally be reduced from their sulfides using iron instead of the roasting and carbothermic reduction:
$Sb_2S_3 + 3\ Fe \rightarrow 2\ Sb + 3\ FeS$ (same for As instead of Sb)
The iron sulfide can then be further leached into iron sulfate.

Excluded from this are the more noble metals such as copper and silver, which can be roasted to pure metal through autoreduction, e.g.:
$2\ CuS + 3\ O_2$ -> $2\ CuO + 2\ SO_2$
$2\ CuO + CuS$ -> $3\ Cu + SO_2$
Which gives a net reaction of
$CuS + O_2$ -> $Cu + SO_2$
Which I will leave in as a single roasting recipe.

Leaching and Electrolysis

To produce pure metal from some of the above oxides by electrolysis (which are produced from ores or from roasting the sulfides) a leaching step is first required. For example:
$NiO + H_2SO_4$ -> $NiSO_4 + H_2O$
A similar reaction can be made for MnO_2, CoO and so on.
This can be electrolyzed to yield metal, oxygen and sulfuric acid.

Iron (II) sulfide can be leached similarly into green vitriol and H_2S:
$FeS + H_2SO_4 \rightarrow FeSO_4 + H_2S$
Iron sulfate is not electrolyzed but thermolyzed into hematite and sulfur oxides:
$2\ FeSO_4$ -> $Fe_2O_3 + SO_2 + SO_3$

The Bayer Process Revisited

The Bayer process, mainly used for recovering Alumina from Bauxite, is also the stage at which some other metals are recovered that are rarely recovered elsewhere. The most important byproduct for this mod that is not in gt6 (e.g. Titanium) would be Gallium, which is used in electronics. Gallium is also recovered in minor amounts from sulfide ores such as sphalerite and chalcopyrite, as a sulfide. Other metals recovered during the Bayer process are Vanadium[12], and Scandium and Titanium which, together with Iron, aluminium, silicon, sodium and calcium, accumulate in the red mud[13].

Gallium is often retrieved as a byproduct from the NaOH solution recovered from the Bayer Process in the form of Sodium Gallate, which remains in the NaOH solution after the Aluminium Hydroxide crystallisation.
Four processes are used for extracting Ga from the residue[14]:

- Electrolysis using mercury
- Cementation with Al and electrolysis
- Fractional Precipitation using CO_2 and lime
- Liquid-liquid extraction using Kelex 100
- Ion exchange using a chelating resin

The currently most efficient method seems to be ion-exchange. But, together with liquid-liquid extraction, these methods require complex organic chemicals. I believe at this stage in the game, adding another reaction chain is not desirable. The fractional precipitation method uses several stages of lime and CO_2 addition and adds the need to recycle Na_2CO_3 and such chemicals, which also adds to the complexity. This leaves the electrolysis methods, which can be implemented relatively easily in the game.

The mercury method creates a solution of Ga in Hg at the cathode, and an alkali solution containing V at the cathode, which can be filtered and the solution returned to the Bauxite refining process. The Hg-solution can be separated using NaOH, yielding mercury back and sodium gallate ($NaGa(OH)_4$), which can be electrolysed.
$2\ NaGaO_2 + 2\ Na_3VO_4 + x\ Hg + 4\ H_2O \text{ -> } 2\ GaHg_x + 8\ NaOH + V_2O_5 + 1{,}5\ O_2$
$2\ GaHg_x + 2\ NaOH + 3\ H_2O + 1{,}5\ O_2 \text{ -> } 2\ NaGa(OH)_4 + x\ Hg$
$2\ NaGa(OH)_4 \text{ -> } 2\ Ga + 2\ NaOH + 3\ H_2O + 1{,}5\ O_2$

The cementation method uses Al metal to yield more $NaAlO_2$ and Ga, which is fed back into the loop, or it uses an Al-Ga alloy (called Gallama) for a more efficient process:
$NaGaO_2 + Al \text{ -> } NaAlO_2 + Ga$.
For this process to work, the Vanadium first needs to be filtered off, for instance by precipitation of Ammonium Metavanadate using ammonium salts, which react with the sodium orthovanadate:
$Na_3VO_4 + NH_4Cl + H_2O \text{ -> } NH_4VO_3 + 2\ NaOH + NaCl$
To close the loop, the NaCl needs to be re-electrolyzed to make HCl and this needs to be reacted with the ammonia from the metavanadate thermolysis.

My intention is to make the Ga/V extraction steps optional and allow the residue after Gibbsite crystal growth to be recycled directly into the bauxite reactor. The cementation needs to be done after the crystallisation, so I will employ the electrolysis method instead. The above reactions might be slightly simplified for gameplay ease.

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[12] https://www.sciencedirect.com/science/article/abs/pii/S0892687515000321
[13] https://en.wikipedia.org/wiki/Red_mud
[14] https://www.sciencedirect.com/science/article/abs/pii/S0304386X1200134X?via%3Dihub

The recovery of elements such as In, Ga, Tl, Ge, Cd from Zinc sulfide ores

Another important source of Gallium besides Bauxite is Sphalerite, which is also an important source of other metals such as Indium, Germanium, Thallium and Cadmium. There have been several studies of this, but they all seem to conclude that these elements are present in the slag of pyrometallurgic zinc extraction (using the Blast Furnace), or in a leaching residue during the hydrometallurgic process.

For the leaching, we will make sure an impure form of zinc sulfate (white vitriol) is produced when leaching zinc ores or zinc oxide with sulfuric acid. Cadmium dissolves with the zinc, while In, Ga, and Ge remain in a residue called ZRR (Zinc Refinery Residue)[15].

1. ZnO/Zinc ore + H_2SO_4 -> Zn-Cd leaching solution + ZRR

This leaching solution is then processed using the process described here, treating it with zinc powder to produce a more pure zinc sulfate solution and a cadmium sponge.

2. Zn-Cd leaching solution + Zn -> $ZnSO_4$+ Cd

ZRR is then processed by first roasting it with hydrogen for partial reduction of zinc ferrite ($ZnFe_2O_4$), its main constituent, into ZnO and FeO and water. Then it is leached with sulfuric acid again.[16] This leaves behind a residue containing thallium sulfate, which is electrolyzable.

3. ZRR + H_2SO_4 -> GaGeIn sulfate solution + Tl_2SO_4

Germanium is usually precipitated using tannic acid from tannin (from tree bark).

4. GaGeIn sulfate solution + 2 H_2T -> $GaInSO_4$ (aq) + H_2SO_4 (l) + GeT_2 (s)

Then, it is distilled together with water to yield back the tannic acid and germanium dioxide:

5. GeT_2 + 2 H_2O -> 2 H_2T (aq) + GeO_2 (s)

From the resulting solution, indium precipitates as indium hydroxide and gallium as gallium hydroxide when combined with sodium hydroxide.
According to Wikipedia, Gallium Hydroxide is more acidic and as such better soluble in basic solutions, for example in Sodium Hydroxide solution it yields sodium gallate, which was present in the bayer liquor process and can be electrolyzed, while the indium hydroxide dissolves less rapidly.
Indium Hydroxide can be pyrolyzed into water and indium oxide.

6. GaIn solution + NaOH -> Na_2SO_4 (aq) + $Ga(OH)_3$ (aq) + $In(OH)_3$ (s)

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[15] Extraction of gallium and germanium from zinc refinery residues by pressure acid leaching, Liu et al.

[16] https://repository.mines.edu/bitstream/handle/11124/14248/Kashyap_mines_0052E_12269.pdf?sequence=4&isAllowed=y

The solution is further treated with NaOH:

7. Na_2SO_4 (aq) + $Ga(OH)_3$ (aq) + NaOH -> Na_2SO_4 (aq) + $NaGa(OH)_4$ (s)

Refractory Metals Processing

The refractory metals are elements with high hardness and melting points. Often included on this list are Ti, Zr, Hf, V, Nb, Ta, Cr, Mo, W. They can be considered end-game metals useful in many strong and heat-resistant alloys. Because of their high melting point, they usually cannot easily be extracted by smelting them in a blast furnace. Separating the elements in the group is also very difficult, as many of the metals in the Ti group, V group and Cr group resemble each other chemically. Instead, they are often refined using chains of chemical processes which take advantage of some small differences in reactivity, solubility, or other properties. I will implement most of these into the game, though the Cr and Nb/Ta ones are optionally disabled through the config.

Chromium production

Chromium is usually produced from Chromite. Most of the chromium is used to produce Stainless Steel by smelting Chromite in a blast furnace, which first produces Ferrochromium. This alloy consisting of iron and chromium is then combined with other metals to form Stainless Steel.

Early game, pure chromium is not needed and stainless steel can be produced with ferrochromium.

Pure Chromium however, is produced using aluminothermic reduction of Chromium(III) Oxide. This oxide is separated from the iron inside the chromite by the following reactions:

$4\ FeCr_2O_4\ (s) + 8\ Na_2CO_3\ (s) + 7\ O_2\ (g) \rightarrow 8\ Na_2CrO_4\ (s) + 2\ Fe_2O_3\ (s) + 8\ CO_2\ (g)$
If you take SiO_2 impurities into account (which we did in the blast furnace) you end up with a more complex reaction.
$10\ FeCr_2O_4 + 3\ SiO_2 + 3\ CaCO_3 \rightarrow 3\ CaSiO_3 + \ldots$

But since we can reduce Hematite with a calcite flux, producing slag, half of the SiO_2 is treated as though it is contained within the Hematite (even though in reality, this is the stage where all the slag is separated, yielding a more pure form of Iron(III) oxide):

$4\ FeCr_2O_4\ (s) + 6/5\ SiO_2\ (s) + 4/5\ CaCO_3(s) + 8\ Na_2CO_3\ (s) + 7\ O_2\ (g) \rightarrow 8\ Na_2CrO_4\ (s) + 2\ Fe_2O_3.1/5SiO_2\ (s) + 4/5\ CaSiO_3(s) + (8+4/5)\ CO_2\ (g)$

The Na_2CrO_4 is soluble in water, while the hematite and calcium silicate is not. As such, water is added to the salt mixture to create a solution of sodium chromate, leaving behind slag-rich hematite.

This is usually further reacted with Sulfuric Acid:
$2\ Na_2CrO_4 + H_2SO_4 \rightarrow Na_2Cr_2O_7 + Na_2SO_4 + H_2O$

This produces the undesired Sodium Sulfate, which needs a lot of effort to recycle into Sodium Carbonate using the Leblanc Process[17].

Instead, we can use an alternative route to recycle the CO_2 more easily:
$2\ Na_2CrO_4 + 2\ CO_2 + H_2O \rightarrow Na_2Cr_2O_7 + 2\ NaHCO_3$

The sodium bicarbonate can be thermolyzed to sodium carbonate:
$2\ NaHCO_3 \rightarrow Na_2CO_3 + H_2O + CO_2$
The reason this is not used in practice is because Sodium Bicarbonate is less soluble in water than Sodium Sulfate, leading to a more impure solution. But the whole chain is already complicated enough in my opinion.

Combining the Thermolysis of Sodium Bicarbonate and Evaporation of Sodium Dichromate into one gives the following simplified net reaction:

$Na_2Cr_2O_7$ (aq) + 2 $NaHCO_3$ (aq) +3 H_2O(l) -> $Na_2Cr_2O_7$ (s) + $Na_2CO_3.H_2O$ (aq) + CO_2 (g) +3 H_2O(g)

Finally, the Sodium Dichromate is reduced using carbon to yield back Sodium Carbonate:

$Na_2Cr_2O_7 + 2\ C \rightarrow Cr_2O_3 + Na_2CO_3 + CO$

The mixture of dusts can be separated using water:

Cr_2O_3 (s) + Na_2CO_3 (s) -> Cr_2O_3 (s) + Na_2CO_3 (aq)

Finally, the chromium oxide is reduced using Aluminium:

$Cr_2O_3 + 2\ Al \rightarrow Al_2O_3 + 2\ Cr$

Vanadium production

Vanadium is usually encountered in magnetite deposits, or as the mineral Vanadinite ($Pb_5(VO_4)_3Cl$), rather than as the pure pentoxide, which is an intermediate product in vanadium processing.
I replaced V_2O_5 deposits with Vanadinite ones.
Treating Vanadinite with brine gives lead chlorides and oxides, as well as a solution of sodium metavanadate:
$Pb_5(VO_4)_3Cl$ + 3 NaCl(aq) -> 2 $PbCl_2$ (s) + 3 PbO (S) + $NaVO_3$ (aq)

This solution can be treated with ammonium chloride to give a precipitate of ammonium metavanadate, and the result calcined to give vanadium pentoxide:

$NaVO_3$ (aq) + NH_4Cl (s) -> NaCl (aq) + NH_4VO_3 (s)

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[17] https://en.wikipedia.org/wiki/Leblanc_process

$2\ NH_4VO_3\ (s) \rightarrow 2\ NH_3\ (g) + H_2O(l) + V_2O_5\ (s)$

The pentoxide is used in an aluminothermic reaction:

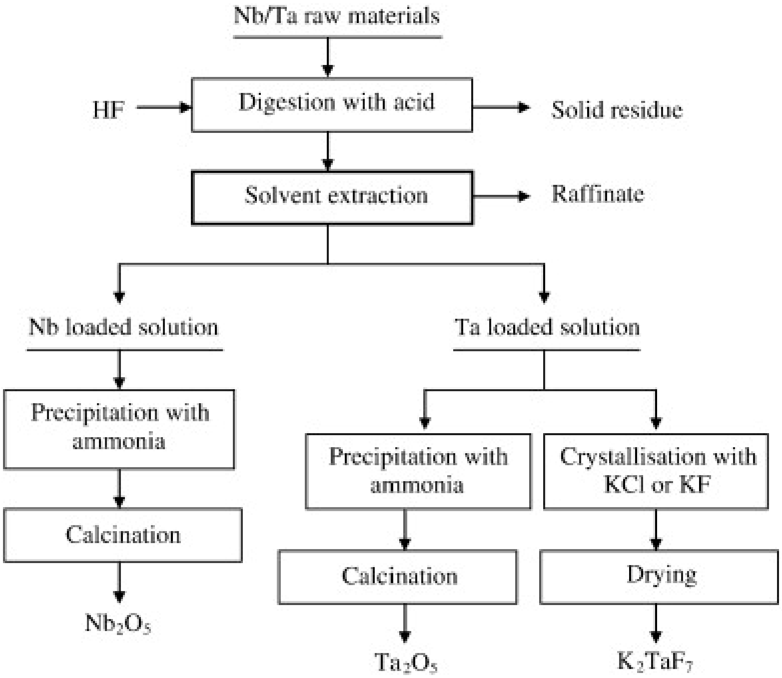
$3\ V_2O_5 + 10\ Al \rightarrow 6\ V + 5\ Al_2O_3$

Niobium-Tantalum Refining and separation

Greg recently added an update where Nb/Ta is found in Coltan ores. The chemical processing in GT6 is quite strange though, if you think about why these reactions, including chemicals such as Potassium heptafluorotantalate are even used. In reality, there are two difficulties with the refining of Coltan:

- Separation of (Nb, Ta) and other metals such as (Fe, Mn)
- Separation of Niobium and Tantalum, which are quite similar.

One such way described at Wikipedia (which Greg also used but poorly) comes from a study by Zhu & Cheng, and can be displayed as the following diagram[18]:



The fluorination is used to turn the tantalum oxides into fluorides, which have better solubility in organic solvents such as methyl isobutyl ketone (MIBK) than other fluorides. Furthermore, the Nb fluoride precipitates more readily as oxides when the pH is increased (by adding alkaline solutions such as ammonia)[19], leaving the Ta in solution. Then after removing the Niobium Pentoxide, the Ta can either be turned into oxides using the same route or turned into Potassium Heptafluorotantalate. Turning pure Ta_2O_5 into that as Greg did, would not make any sense in the real world as the fluoride in the end requires more energy to separate than the oxide, which can be reduced using aluminium or calcium.

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[18] https://www.sciencedirect.com/science/article/abs/pii/S0304386X11000028
[19] https://en.wikipedia.org/wiki/Tantalum_pentoxide

The full reaction chain looks as follows:

1. $2\ (FeMn)(NbTa)_2O_6 + 28\ HF \rightarrow 2\ H_2[TaF_7] + 2\ H_2[NbOF_5] + FeF_2 + MnF_2 + 10\ H_2O$
2. Dissolve the solution into MIBK, yielding one aqueous solution of $FeF_2 + MnF_2 + 10\ H_2O$, as well as an organic solution of $H_2[TaF_7] + H_2[NbOF_5]$, which do not mix well.
3. The aqueous solutions can be dried and the salts electrolyzed or reduced using sodium.
4. The organic solution is mixed with an aqueous solution of ammonia:
    $2\ H_2[NbOF_5] + 10\ NH_3 + 13H_2O \rightarrow Nb_2O_5\ (s) + 10\ NH_4F + 10\ H_2O$
5. The remaining solution is either mixed with ammonia in the same way or with potassium fluoride:

5a. $2\ H_2TaF_7 + 19\ H_2O + 14\ NH_3 \rightarrow Ta_2O_5 + 14\ NH_4F + 14\ H_2O$
5b. $H_2TaF_7 + 2\ KF \rightarrow K_2TaF_7 + 2\ HF$

K_2TaF_7 can be reduced using molten sodium, and the pentoxides using a thermite reaction.

Zirconium and Hafnium

Chemically similar to Titanium, these two elements are often found together. In practice Hafnium is a rare metal occurring in Zircon ($ZrSiO_4$), substituting the Zr atom in about 2-3% of the cases.

This mineral is refined in a similar way to titanium in the Kroll process, where the oxide is reacted with chlorine and carbon, yielding CO_2 and the metal tetrachloride. In-game, treating Zircon this way yields SiO_2 and an impure tetrachloride consisting of 2% $HfCl_4$ and 98% $ZrCl_4$. This can be distilled into each separate compound, and then treated in a bath with Magnesium or Sodium, just as with $TiCl_4$. Meaning Hafnium will be even harder to obtain than usual! Quite a lot of Zircon needs to be grinded before being able to make a nice top tier burning box. Matter fabricators might be the best solution here…

Tungsten and Molybdenum

Also chemically similar, their ores often occur together, such as in Scheelite-Powellite deposits.
These Molybdenate ores can be treated with hydrochloric acid analogous to tungstate minerals, producing Molybdenic acid, which through heat decomposes into water and molybdenum trioxide.
Molybdenum can also occur in Molybdenite, which is roasted, converting it into MoO_3 as well. The trioxide is reduced in a mixer using hydrogen, again yielding water and pure metal.
As a side note, I now added Lead Chloride, which precipitates when lead-containing tungstates and molybdenates (stolzite, pinalite, wulfenite) are treated with hydrochloric acid.

Semiconductor industry

PCBs

Printed Circuit Boards (PCBs), units used for electronic control, are already present in GT6. I did find the production process kind of dumb and unsatisfying, and as usual with this mod, I will try to implement a more realistic production process.
A PCB consists of at least the following parts:

- A board often made of wood or plastic.
- Circuit wiring (called a Trace), usually made of copper, and in GT6 also made of gold or platinum in higher tiers.
- Electronic components that are soldered onto the board.

These basics I will not change, though the production process will change, and there will be new kinds of electronic components, from simple resistors to complicated Integrated Circuits (ICs).

Board Manufacturing

The raw boards are made from fiber-reinforced polymers. Simple boards used to be made from paper coated in an organic resin such as Phenol Formaldehyde (PF); nowadays, Fibreglass-reinforced Epoxy Resin is used. Tier 1 PCBs will be craftable from wood.
On these raw boards, a copper (or other conducting) layer is laminated, producing a Copper-Clad Laminate (CCL), usually by.electroplating.

Traces

From this copper layer, the traces are made. Traces are put in the right shape using Etching. Where in GT6 a trace was made using 1 unit worth of fine copper wires, in practice it is often done by taking the CCL, putting an etch-resistant mask on it, and using the right etchant to dissolve one part, giving the correct pattern.

I will change the traces to have a content of 0.5 units instead of 1. The original recipe for the copper wiring will remain there, but be inefficient.
Then, another Bath recipe will be added with a plate of the material, an etchant, and a mask, which will produce the trace as well as a solution which contains the other half of the material which is now dissolved.
For copper, the etchant will be a $FeCl_3$ solution, and the result after etching will be a solution of $FeCl_2$ and $CuCl_2$. For gold and platinum, the etchant will be Aqua Regia and the result will be chlorauric acid and chloroplatinic acid, respectively.
The masks can be made from Silicon Carbide, PVC or PTFE.

Components

Some basic components of most PCBs include resistors, transistors, capacitors, and diodes. Diodes have specific functions like AC/DC conversion or LEDs, and will not be part of the general-use PCBs here.

For all these components, they can be through-hole components which must be soldered by hand into holes on the board, or Surface-Mounted Device components which are smaller, costing less resources in total but are harder to produce. They can be soldered both by hand and more easily by machines.

Resistors resist currents and are often made of carbon dust surrounded with ceramic or plastic coatings.

- Through-Hole Resistors are made using a tiny ceramic plate and a small pile of carbon, coke or charcoal dust with two tiny copper or brass wires.
- SMD-resistors from NiCr foils (see Thin Film Resistors) on a tiny plastic plate. (crafting a whole batch of 8/*16/32???*)

Capacitors “hold” charge and can be made from ceramic or more exotic materials like Tantalum.

- Through-Hole Capacitors are made using a tiny piece of paper, a tiny aluminium plate, two tiny copper or brass wires, and a soldering iron on a crafting grid.
- SMD capacitors are made similarly from Ta capacitors, made by sintering together Ta rods with Tantalum Pentoxide, then combining them together with plastic plates and wires (crafting a whole batch of *32*)

Vacuum Tubes are used instead of transistors in tier 1 circuits when semiconductors are not yet available. They are made from tungsten or molybdenum filaments and surrounded by a glass tube.

Transistors use a current to control another current and are the basis of modern computers.

- The first transistors are based on Bipolar Junction Transistors, made using Germanium or Silicon layers with different dopants.
- SMD-transistors are made using Gallium Arsenide FETs made using photolithography, tiny plastic plates, and tiny brass wires in a soldering machine (crafting a whole batch of 64)

Integrated Circuits (ICs) are combinations of components that are “baked” into a single chunk of silicon. They can contain up to a few to billions of transistors. They are produced using photolithography (see later). These ICs will be needed for PCBs of tier 4 and up and represent generic ASICs used in the circtuitry for the machines and other items in GT6(x) requiring them. Alternatively, one could conceive of them as FPGAs that could be programmed for such applications.

Soldering

Soldering should happen with manual crafting using a Soldering Iron (a new tool) that can be (re)filled with soldering alloy at a canning machine or by right clicking a crucible or tap, like lighters or jugs.

Later, when SMD-components become available, these can be soldered onto the PCB using a soldering machine (pick-and-place machine), requiring soldering paste in one of the tanks. Using pure tin or lead for solder just requires twice the amount of solder instead of producing lower tier circuits to encourage players to make Soldering Alloy from tin and antimony just as in vanilla GT6.

SMD-components can be substituted by their Through-Hole counterpart, but the recipe makes more of each and is generally cheaper unless these elements are not available. They are gated behind Ta, Cr and doped GaAs production. Unlocking one of these technologies allows the SMD component to substitute for classic components in manual recipes, but to use the soldering machine for automating soldering requires all three SMD components. At that stage it also allows for the fabrication of smaller PCBs that could not be crafted by hand, which saves on raw materials.

Semiconductors

Many types of semiconductors exist. A few will be added in-game that are used for components.

- Polycrystalline Germanium/Silicon (Poly-Si/Ge) - used for early transistors and cheap solar panels.
- Monocrystalline Silicon (Mono-Si) - used for medium tier solar panels.
- Mono-Si (PMOS) - used for basic ICs such as tier 4 chips
- Mono-Si (NMOS) - used for advanced ICs such as tier 5 chips
- Silicon-Germanium (small traces of Ge, CMOS) - used for high-end ICs such as in tier 6 chips.
- Gallium Arsenide - used for high power FETs, they are used in SMD-transistors soldered separately onto PCBs, as well as LEDs and high-end solar panels.
- Indium Gallium Phosphide, -Arsenide - used for LEDs and high-end solar panels
- Copper indium gallium selenide - used for basic thin-film solar panels (covers)
- Cadmium Telluride - used for advanced thin-film solar panels

Production of polycrystalline semiconductor materials

Polycrystalline Germanium can be made by thermolysis of Germane (GeH_4) (actually by epitaxy, but the main process for turning Germane into Germanium is a pyrolysis process). Using existing GT6 machinery, the easiest production method for Germane is electrolyzing a Germanium cathode in an electrolyte solution (i.e. salt water, although in practice a NaOH solution is used) with an anode of Molybdenum or Cadmium, producing Germane and MoO_3/CdO[20] as a side product.
Germanium itself is often found in zinc leaching residues and coal fly ash, which is processed into GeO_2 and reduced by hydrogen.

Likewise, Polycrystalline Silicon can be produced by the thermolysis of Silane. Silane is made from reacting Magnesium Silicide (can be made by crucible smelting 2 Mg+Si) and HCl:
$Mg_2Si + 4\ HCl \rightarrow SiH_4 + 2\ MgCl_2$ (bath)
$SiH_4 \rightarrow \text{Poly-Si} + 2\ H_{2,}$ (thermolysis oven)

Polycrystalline Gallium Arsenide can be made by treating liquid Gallium with dopant (see later) and Arsenic Gas.[21]

Polycrystalline Silicon-Germanium can be made by thermolysis of a mixture of Germane and Silane.

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[20] https://www.freepatentsonline.com/5158656.html (examples at the end)
[21] https://www.osha.gov/semiconductors/gallium-arsenide/ingot-growing

Polycrystalline materials can be sawed into tiny crystalline plates, but not into normal ones, or wafers.

Production of monocrystalline semiconductors (boules)

Boules now require an actual seed crystal instead of just dust. This can be a tiny crystalline plate, or a chipped gem in case of e.g. sapphire. In case of Si, Ge, or GaAs, this plate can be retrieved from sawing polycrystalline Si/Ge. In this mod, Red Alloy is not used since there are so many more cool realistic semiconductors out there! Also, it’s nice to have an actual use now for some materials such as Gallium, Indium, Phosphor, Boron, ….

Doping

Doping is the addition of certain impurities into a semiconductor material to enhance its properties and is crucial in producing electrical components such as transistors.
Doping can be achieved during several stages. Most common ways are:

- Doping during crystal growth (in the cryst. crucible). This is done by adding the dopant in gaseous form, such as Phosphine/arsine gas or Diborane, causing them to diffuse into the boule.
- Doping the wafers after growth. This can be done using ion implantation or diffusion at specific places in the wafer, selected using photolithography (see next section), protecting the parts of the wafer which should not be doped using e.g. a silicon dioxide layer which is etched away using HF.
    - It can be done using liquids such as $POCl_3$, made from PCl_3+O_2 (PCl_3 is made from P_4 + Cl_2, or trimethyl borate, made from boric acid + methanol.[22]

Phosphine is made from Phosphorus in a NaOH-solution:
$3\ NaOH + P_4 + 3\ H_2O \rightarrow 3\ NaH_2PO_2 + PH_3$
$2\ NaH_2PO_2$ -> $Na_2HPO_4 + PH_3$
$Na_2HPO_4 + NaOH$ -> $Na_3PO_4 + H_2O$ (might be wrong)
Net: $9\ NaOH + 2\ P_4 + 3\ H_2O \rightarrow 3\ Na_3PO_4 + 5\ PH_3$

Thermolysis gives:
$2\ Na_3PO_4$ -> $3\ Na_2O + P_2O_5$

Dopants can be used to create specific semiconductors (P and N-type). They can be used in several ways:

- For through-hole transistors, AKA BJTs, for instance a NPN junction is made by doping a N-doped wafer consecutively with P and N dopants.
- For PMOS, the earliest form of IC production, the substrate is N-type (diffused with P/As during crystal growth), while the channels are P-type (diffused with B on the wafer during the photolithography process)
- For NMOS, the substrate is P-doped, with N-channels.
- For CMOS, we use N-well technology[23], and dope our boule using diborane gas, while adding the other ones using ion implantation during two photolithography steps

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[22] https://www.cityu.edu.hk/phy/appkchu/AP6120/8.PDF
[23] https://www.elprocus.com/the-fabrication-process-of-cmos-transistor/

instead of one. (In reality, many more steps are used, such as for patterning in-between layers, metal layers, etc.)

- For GaAs, Si and either Be or Mg are used as dopants. Si is deposited using silane, Be using MOVPE of dimethyl beryllium, magnesium using magnesocene.

Semiconductors for Solar Panels

Basic solar panels from Monocrystalline Silicon are made from doped silicon wafers. For instance, p-doped wafers can be doped with phosphine to create p-n junctions. But to make silicon solar cells efficient, they are *textured* in order to reduce reflection losses, for example by utilising a pyramidal structure[24]. This could be achieved by laser-cutting the wafers using the Precision Laser Engraver. Afterwards, the other dopant is applied by diffusion from a gaseous source. Other steps that are used here are ignored for simplicity.

For the most advanced solar panels, a Multi-Junction solar panel is simulated with three layers: A bottom layer of Germanium, a middle layer of InGaAs, and a top layer of InGaP. These layers are created using Metalorganic vapour-phase epitaxy (MOVPE) using a Germanium Substrate, and reacting it with Trimethylgallium/-indium as well as Arsine and Phosphine during the respective phases.

Trimethylgallium and -indium are produced the same way from Methyllithium (CH_3Li):
Methanol + HCl -> $CH_3Cl + H_2O$
$2\ Li + CH_3Cl$ -> $CH_3Li + LiCl$
$2\ Ga + 3\ Cl_2$ -> $2\ GaCl_3$
$GaCl_3 + 3\ CH_3Li$ -> $Ga(CH_3)_3 + 3\ LiCl$ (PH_3 is also part of this reaction as a catalyst)
$Ga(CH_3)_3 + PH_3$ -> $GaP + 3\ CH_4$
Same for indium.

Photolithography

Photolithography in semiconductors is the process of selectively protecting certain areas of a wafer from etching or doping using a photoresist, a substance that either hardens or weakens when exposed to light, resisting the etchant or diffusion gas at places that were exposed (or not exposed), while the other areas are washed away using a fluid called a developer. This light comes from a source such as an ultraviolet laser and passes through a photomask in order to create microstructures on chips.

Layer addition

In order to add a layer onto the wafer in a certain pattern, first the material can be deposited onto the wafer using vapours, as is the case for creating interconnections e.g. using aluminium. Part of this layer will be etched away in the right pattern.

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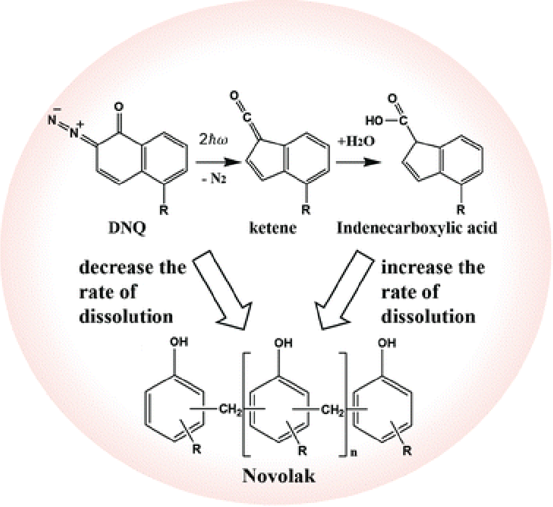
[24] https://sinovoltaics.com/solar-basics/solar-cell-production-from-silicon-wafer-to-cell/

Photoresist

Common photoresist materials include Novolak-DNQ (Phenol-formaldehyde resin with Diazonaphthoquinone), SU-8 (epoxy with Triarylsulfonium hexafluoroantimonate salt) , and some other less-used ones.

We already have processes for PF or Epoxy resin, only the DNQ is a bit harder to get right, as is the Triarylsulfonium hexafluoroantimonate.
Of the two, I think DNQ is the easiest, as it arises from naphthalene, which is a part of creosote/coal tar.
Do note that instead of pure DNQ, a diazonaphthoquinone sulfonic acid ester is used in reality (denoted by the R-group in the image).

The process of DNQ photo-exposure is shown in the following image:



In reality, DNQ is sometimes produced by diazo transfer of naphthol using ADMC[25], or using Diazotization[26] of aminophenol:

[delet this]

1. Naphthol from Naphthalene
    a. 1. 2 $C_{10}H_8$ (Naphthalene) +HNO_3 -> 1-Nitronaphthalene + H_2O
       2. Nitronaphthalene + 3 H_2 -> Aminonaphthalene
       3. Aminonaphthalene + 2 H_2O + H_2SO_4 -> $(NH_4)_2SO_4$ + Naphthol
    b. 1. Naphthalene + H_2SO_4 -> Naphthalene sulfonic acid + H_2O
       2. Naphthalene sulfonic acid + NaOH -> Naphthol + $NaHSO_3$ (add O to get $NaHSO_4$)
2. Aminonaphthol from Naphthol
    a. 1. Naphthol + HNO_3 -> Nitronaphthol
       2. Nitronaphthol + H_2 -> Aminonaphthol
    b. 1. Naphthol + Benzenediazonium chloride -> benzeneazo-naphthol (Sudan I)
       2. Benzeneazo-naphthol + HCl -> Aminonaphthol + Aniline

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[25] https://www.thieme-connect.com/products/ejournals/abstract/10.1055/s-0030-1258568
[26] https://www.organic-chemistry.org/namedreactions/diazotisation.shtm

3. DNQ from (Amino)naphthol[27]
    a. $C_{10}H_6(OH)(NH_2)$ (2-amino-1-naphthol) + HNO_2 -> DNQ ($C_{10}H_6ON_2$) + 2 H_2O
    b. Naphthol + ADMC -> DNQ + DMC
4. DNQ + PF -> Photoresist

Nitrous acid is made by mixing water and dinitrogen trioxide. N_2O_3 is made by cryo-mixing NO and NO_2.

Triarylsulfonium hexafluoroantimonate is made by something like the following simplified reaction chain:
Benzene + $SOCl_2$ (with $AlCl_3$ catalyst) -> diphenyl sulfoxide[28]
diphenyl sulfoxide + C_6H_5MgCl + Cl-Si$(CH_3)_3$ -> triphenylsulfonium chloride + Cl-MgSi$(CH_3)_3$

$SbF_3 + F_2$ -> SbF_5
$SbF_5 + HF \rightleftharpoons SbF_6^- + H^+$ (fluoroantimonic acid)

triphenylsulfonium chloride + fluoroantimonic acid -> Triarylsulfonium hexafluoroantimonate + HCl
Triarylsulfonium hexafluoroantimonate + epoxy -> Photoresist
(notice that a special type of epoxy, not just the normal BPA+ECH, is used)

Photomasks

A photomask can be made from a glass pane with a chromium plate patterned using maskless lithography, a slow process.

Developers

PF+DNQ photoresist can be developed using TMAH, but since I've had enough complex chemicals, instead I follow this one and use an easier base:
"The photoresist is typically developed using a dilute Sodium or Potassium Carbonate solution. This mildly alkaline solution reacts with the unexposed portion of the "acidic" photoresist, neutralizing its acidity, and making it water soluble"[29].

Layer addition/removal step

The next step after patterning is either a passivation (e.g. SiO_2), an etching, or a diffusion/ion implantation process for producing p-n junctions.

Photoresist removal

The remaining photoresist is dissolved using a solvent such as piranha solution (sulfuric acid + hydrogen peroxide mixture).

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[27] Diazonaphthoquinones: Synthesis, Reactions and Applications
[28] https://patents.google.com/patent/CN110642761A/en
[29] http://rdchem.com/chemical-milling-processes/photoresist-developing.html

Simplifying the IC production process

In-game, having many separate photolithography steps (thermal oxidation, doping, interconnection metal, …) with all of these substeps is quite a few too many.
For this reason, we use the following steps (same for SMD-transistor production, except step 1, 6, 7 which are dropped):

1. Oxidation of wafer (roasting oven)
2. Patterning using LU, photomask and photoresist (using new Photolithography machine)
3. Developing using NaOH/Na_2CO_3 + water (bath)
4. Etching SiO_2 using HF (Bath, Creates $H_2SiF_6 + 2\ H_2O$) or CF_4 Plasma (Ion Bombardment chamber)
5. Additional Doping using diffusion/ion implantation
6. Cleaning using Piranha Etch
7. Aluminium vapour addition to wafer for metallization (Vacuum Chamber)
8. Interconnect etching (e.g. Al is etched using a mixture of Phosphoric and Nitric acid, producing Aluminium Phosphate, water and nitrogen oxide):
    a. $2\ Al + 2\ HNO_3 \rightarrow Al_2O_3 + H_2O + 2\ NO$
    b. $Al_2O_3 + 2\ H_3PO_4 \rightarrow 2\ AlPO_4 + 3\ H_2O$
    c. Net: $2\ Al + 2\ HNO_3 + 2\ H_3PO_4 \rightarrow 2\ AlPO_4 + 4\ H_2O + 2\ NO$
9. Dicing using buzzsaw
10. Bonding & Packaging using the die, fine gold/aluminium wires (bond wires), tiny copper plates (lead frame) and tiny PF resin plates.

ICs and Moore's Law

Moore's law says the amount of transistors on a fixed-size chip (such as an IC or CPU) doubles every two years. We don't have years in gt6 but we doe have chip tiers. In this case, it would mean that with the same amount of silicon, you can make more intricate (higher tier) circuits, and also, at a certain tier of ICs, you can make twice the amount of previous tier circuits from one wafer.

At some points these components become so small that the boards themselves can also be made smaller. I will add Small copper circuit plates at tier 3-4 for this purpose, each size being half as small as the previous, and Tiny Copper/Small gold circuit plates at tier 5-6.

In this way, improving your circuitry production costs time and effort (and more rare materials), but in return you can make better circuits or cheaper simple circuits, saving valuable resources such as copper and gold, instead using smaller amounts of platinum, gallium, phosphor, etc.

The tiers

- Tier 1 basic circuits can be made with electron tubes and wooden boards. They are expensive in raw material cost but relatively easy to make - not many steps should be required. Just a board (plastic or maybe wood) with some copper wiring and some tubes.

- Tier 2 circuits require polycrystalline silicon/germanium to make transistors. The transistors can now also be used instead of the electron tubes, which are more expensive. The boards should be made with at least Phenolic paper boards (paper + PF resin)
- In tier 3 circuits, boards must be made with epoxy and gold traces, and you can start making monocrystalline silicon through Boules. Instead of silicon dust, the Boule recipe requires either a tiny crystalline plate or a seed crystal. For sapphire e.a., the seed crystal is a chipped gem. For Si, Ge and other semiconductors, you make the first seed crystal using polycrystalline silicon/germanium/etc.

- in tier 4, you will need to start with photolithography to produce PMOS ICs.
- in tier 5, we will be using more advanced techniques such as plasma etching and ion implantation to produce NMOS ICs.
- in tier 6, you will need multiple photolithography steps, as well as advanced materials such as Ruthenium.

Computers

GT6 adds another circuit tier: the crystal processor. This is some kind of scifi technobabble that does not really align with my mod because processors can already be made using (semiconductor) crystals.
Instead, I will add different kinds of chips besides the ICs used in basic PCBs, which can be combined together to craft computers.
These computers and computer parts are just items for now, but they are fully integrated and compatible with the OpenComputers mod, adding a new and realistic way of crafting them.
This includes:

- CPUs
- Motherboards
- Memory chips
- Hard disks
- Flash memory (e.g. for SSDs, USB sticks)
- Graphics cards
- Monitors (Cathode Ray Tubes, LCDs)
- Computer casings including fans and PSUs

Besides being able to craft them directly into their OpenComputers couterparts, they can be combined into GT6x computers which are similar to TerraFirmaRescue computers and into processing unit blocks used by Fusion Reactors and Logistics Cores.
Basically all machines that used to use Crystalprocessors are reworked to use these computers now.

Solar panels

For the raw silicon and germanium solar generators in GT6, GT6x will replace them by five different solar panels that each have their own uses:

1. Polycrystalline Silicon solar panels - these will be the cheapest, easiest to make and least efficient. However, they remain relevant throughout the whole game since they can be mass produced easily and combined together into large solar farms.
2. Monocrystalline Silicon solar panels - once you are able to produce Mono-Si, these will be your bread-and-butter solar generators, giving the same power as current GT6 Si panels do. Their largest cost increase compared to poly-Si will be the noble gases used for growing boules which costs a lot of energy fed into your air distillation setup, but after some time that energy cost will be regained.
3. Thin-Film CdTe solar cells - requiring the rarer elements Cadmium and Tellurium, by-products produced from zinc and copper electrolytic refining, respectively. These thin-film cells will be used as energy producing covers instead of blocks, which can be attached to cables, battery boxes or machines to provide a constant current if in sunlight.
4. Thin-film CIGS solar cells, requiring relatively rare elements such as indium, gallium and selenium. In function they are similar to CdTe but require a longer assembly chain and have more output.
5. Multi-junction solar cells, made from GaAs with layers of Ge, InGaAs, InGaP. These will be the most difficult to produce as well as the most efficient, useful mostly when having little space. In real-life they are used mostly in space applications as they are too costly for your daily rooftop solar panel.

Solar Panel production

Silicon solar panels (both Mono-Si and Poly-Si) require the following layers/steps:

- The p-doped silicon substrate, which is just a p-doped crystalline Si plate or poly-Si item;
- The back-contact, essentially an aluminium foil
- An n-doped Si layer created by dopant diffusion of phosphine
- A front contact, essentially a bunch of fine wires
- An antireflectant (AR) coating made from e.g. Silicon Nitride or Titanium Dioxide deposited using Physical Vapour Deposition (in the Vacuum Chamber). Perhaps this step will only be required for the more advanced Mono-Si cells
- Optionally a ULV machine casing

Thin-film CdTe cells have these layers, in order of assembly/epitaxy:

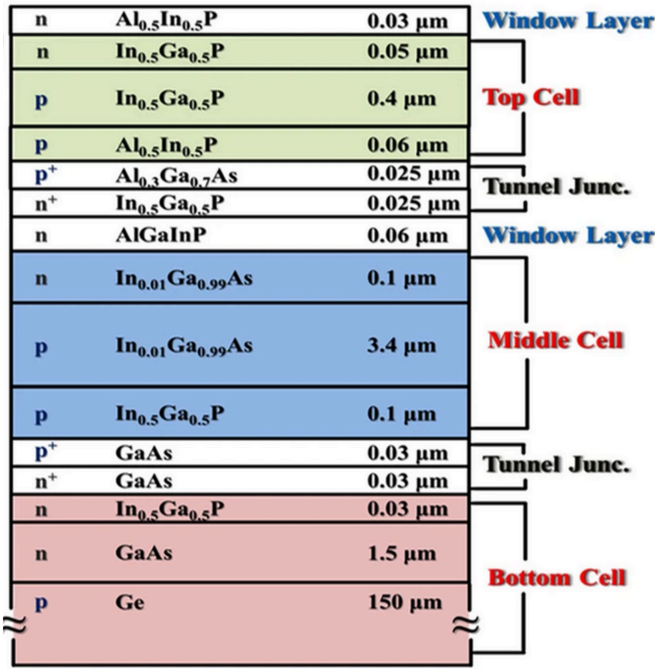
- A glass superstrate
- A SnO_2 TCO front contact patterned using PL
- A thin layer of N-doped CdS (using Ga dopant)
- A bigger layer of P-doped CdTe (using Cu dopant)
- A back contact made of e.g. Al, Au, Ag

For CIGS:

- A glass substrate

- A Molybdenum back contact
- A layer of p-doped CIGS (intrinsically doped due to copper gaps during epitaxy and In/Ga substitution)
- A thin layer of n-doped CdS (Ga dopant)
- An ITO or ZnO:Al TCO front contact

For Multi Junction:
I used this example, slightly simplified:



n	$Al_{0.5}In_{0.5}P$	0.03 µm	Window Layer
n	$In_{0.5}Ga_{0.5}P$	0.05 µm	Top Cell
p	$In_{0.5}Ga_{0.5}P$	0.4 µm	
p	$Al_{0.5}In_{0.5}P$	0.06 µm	
p^+	$Al_{0.3}Ga_{0.7}As$	0.025 µm	Tunnel Junc.
n^+	$In_{0.5}Ga_{0.5}P$	0.025 µm	
n	AlGaInP	0.06 µm	Window Layer
n	$In_{0.01}Ga_{0.99}As$	0.1 µm	Middle Cell
p	$In_{0.01}Ga_{0.99}As$	3.4 µm	
p	$In_{0.5}Ga_{0.5}P$	0.1 µm	
p^+	GaAs	0.03 µm	Tunnel Junc.
n^+	GaAs	0.03 µm	
n	$In_{0.5}Ga_{0.5}P$	0.03 µm	Bottom Cell
n	GaAs	1.5 µm	
p	Ge	150 µm	

I replaced the bottom cell with p-n Ge, the middle cell base/emitter with GaAs, the middle window and tunnel junction layers with n-p AlGaAs. The ratios were simplified to 50-50 and an aluminium bottom and top contact layer as well as an ARC layer was added, patterned with PL.

FPGAs

todo
Compare to MFR’s rednet controllers and Project Red’s ICs

Papermaking

Ceramics & Cement industry

Extractive Metallurgy

Personally I have not seen any mod or game which does ore refining at least somewhat realistically. The whole "you mine iron ore, then you put it in a furnace and you get iron" thing is bullshit, but at least for most games which do not focus on realistic ore refining it works well enough.

The process goes as follows.

1. The first step is always grinding it into smaller pieces, and even though Greg increases the output from that operation (similarly to other mods such as IC2 and TE), in fact not much changes in the content of the composition here. In fact, this first step I would not increase the yield, but only have it as a prerequisite for other steps.

2. All the other steps except for grinding serve to separate the constituents of the ore. If the main product from the ore is going to be copper, you want to recover as pure copper as possible from it. For this you need to separate off:
- gangue (the stones around the ore, mostly consisting of Silica and some alumina)
- Other impurities, often for metals these consist of salts that have the same anions but different cations, or vice versa, as the main constituent. These ions often replace the ones in the main material directly and are often found nearby in the periodic table. So for instance for copper ore, it could have impurities that contain Nickel, Cobalt, Silver, Gold, or Platinum Group metals.
- These Winning steps, as they are called, separate some of the constituents of the ore depending on their physical or chemical characteristics. For instance:
  - Sizing separates them based on particle size (which is what a Sifter in GT5/6 does),
  - Gravity separation based on gravity (what a Ore Washer/Sluice does - some minerals float on water better than others or sink faster),
  - Froth flotation separates hydrophobic from hydrophilic materials (currently not in game, though maybe Greg tried to represent it using chemicals in a Bath),
  - Magnetic separation separates magnetic from non-magnetic materials
  - Leaching separates materials which are more or less soluble in certain chemicals such as acid (in-game in a Bath)
  - Pyrometallurgy changes the composition of the material through heating (and often reaction with other things such as cokes)
  - Electrowinning separates the ions using electrolysis, this is often done in an acid solution retrieved from leaching.

Each step usually produces a couple different substances, either solids, solutions, liquids, or sometimes gases, and at each step the parts become smaller and lighter.

This also means that most of the primary material is going to be in one of the outputs of each process, not in both. So the GT6 thing of putting copper ore in sulfuric acid, and then yielding back copper sulfate together with solid refined copper ore and more solid refined copper ore byproducts I think just misses the point. In reality, all of the copper should dissolve into the acid, only giving a solution of copper sulfate, but no solid copper, and the solids would consist of a slurry containing materials not soluble in sulfuric acid, such as silver, gold, and platinum group metals. That process is probably what I'm gonna do in my mod sometime.

Now for your idea of getting more copper at each refining step, in reality the ore contains a certain amount of copper, and at each step the copper becomes more pure. More steps can be done depending on how pure your end product needs to be and which byproducts you want to extract from it, and how much effort you are willing to pay for that, as each step consumes energy. Now in Gregtech, energy is usually cheaper than ores so you just do any number of steps you can afford the machines for.

Also in Gregtech, you could see the more pure materials as represented by greater quantities. This is because it does not make sense to have 99% pure copper and 90% pure copper with 5% cobalt and 5% noble metals, and whatever other combination, in game. In reality, this does happen, and in metallurgical plants chemists often take a sample and use things like spectrometry to see if the product has the right composition.

In game, you want to reward players in some way for building more complex setups, and just giving more of the primary material is in my opinion a decent in-game alternative for a more pure material retrieved by separation steps.

Roadmap

Roadmap for GT6X.

[Name] means that someone with that name is currently working on it.

1. Platinum Group Metals processing
    1. Advanced recipes, easy and hard mode
    2. Default oregen changes, Chalcocite ore addition with PGM byproducts
2. Combustion engine overhaul
    1. "Filter" machine part, change Sifter/Sifting table, filter covers/blocks recipes and maybe some other recipes that make sense to use it
    2. Change diesel engines to require Platinum catalytic converter (small stainless pipe + platinum filter), gas turbine to require Rhodium CC
    3. add Startup time to diesel engine just like steam turbine/engine so it starts at 25% efficiency and increase gradually until it hits 100%. Add textures on side of diesel engine with green/yellow/orange/red square to indicate how hot it is
    4. Improve maximum GU/t of Diesel fuel in Diesel engine
    5. Add Petrol Engine which functions like diesel engine but without startup inefficency but can only burn Petrol or Ethanol
    6. disable all other liquid fuels in Diesel Engine or Turbine, and add those (except Petrol/Ethanol/Diesel) and add them to the large Gas Turbine
3. Heat Reactor
    1. single block machine tiered like Distillery which has similar I/O to mixer but requires only HU
    2. move some recipes that make sense from the PGM chain and others from the mixer to the Heat Reactor
4. Synfuels and mixtures
    1. add E85 fuel (15% petrol, 85% ethanol) which is the most efficient fuel in a Petrol Engine
    2. steam cracker: Methane/Natural Gas/Coal Dust + steam -> Syngas, mixing CO & H2 -> Syngas (both run in gas turbine). Distillery: syngas to H2 + CO
    3. syngas in heat reactor with Ru catalyst to small amount of Synthetic Oil + water, Synthetic Oil can be distilled in dist. tower
    4. biodiesel from plant oils and ethanol with NaOH catalyst, glycerol as byproduct, remove glycerol from biomass distillation, add to Diesel Engine
    5. (important) test and make sure no infinite oil loopholes exist by making synoil from methane and methane from synoil by cracking
5. Oil & Gas refining
    1. oil distillation produces naphtha instead of petrol
    2. natural gas cryo-distillation
    3. new cracking recipes and olefins (hydrocracking, steamcracking, catalytic), see document
    4. recipe for synthetic rubber and glue

    5. plastics (epoxy, ptfe, pvc), pipes made from ptfe/pvc, ptfe drums/cans with good storage capacity (and acid handling)
6. Refractory metal processing
    1. Sintering tungsten e.a.
    2. Preparing V, Mo, Cr, Ta, Nb, Zr, Hf from ores
7. Metallurgy
    1. add blast furnace multiblock, recipe for pig iron
    2. sponge iron for wrought iron, pig iron to steel/alloys
    3. electric arc furnace multiblock
    4. direct reduced iron
8. Circuit industry
    1. use epoxy to make gold/platinum circuit boards instead of plastic
    2. advanced components for t4 and up circuits using currently useless elements such as Ga, In, P, N, Se, REE, rebalance recipes so higher tier circuits are "cheaper" and use less base materials such as Si, Cu, plastics but have more steps and require more (small amounts) of rare trace elements
    3. electroplating using Ruthenium to produce platinum circuit boards
    4. photolithography machine to produce t6 circuits. Maybe some cleanroom stuff but make it cool, not too tedious/expensive
    5. make the crystal processor recipes more complex using all these steps (and maybe some extra)
9. Seismic exploration
    1. primitive geophone that prints traces on paper, requires a seismic source such as dynamite (decent output) or a prospecting hammer (bad output)
    2. electronic node which is placed on the ground and from which the data can be downloaded and shown on a screen/GUI
    3. electric vibe block to save dynamite/hammers