Chapter 6

The Extraction of Aluminum

The University of Jordan

Chemical Engineering Department

Spring 2022

Prof. Yousef Mubarak

Introduction

- Aluminum ranks amongst the world's most abundant elements.
- After Silicon and Oxygen, it is the most common element found in the Earth's crust, accounting for approximately 8 wt% of the Earth's mass (5.97×10^{24} kg).
- Despite this abundance Aluminum only occurs in Nature in more complex compounds, and perhaps due to this its discovery was prolonged to 1808 by British Scientist Sir Humphry Davy giving the metal a relatively recent history.
- Since then, the production of the metal has developed hugely.

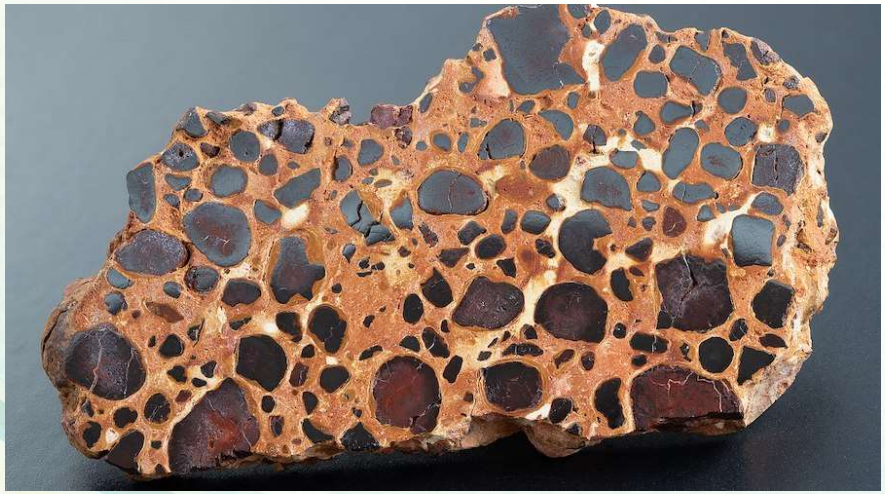
Abundance

- In the Earth's Crust, in every million atoms, around 82 000 of them are Aluminum, (82000 ppm), by weight.
- This is around 8 % or almost one in every 12 atoms.
- This places aluminum amongst the world's most abundant elements, behind only Oxygen and Silicon.
- This high level of abundance is not replicated for aluminum in the oceans where it is only 0.01 ppm.
- Despite being present in such incredibly vast quantities on Earth, the metal never occurs on its own in nature.

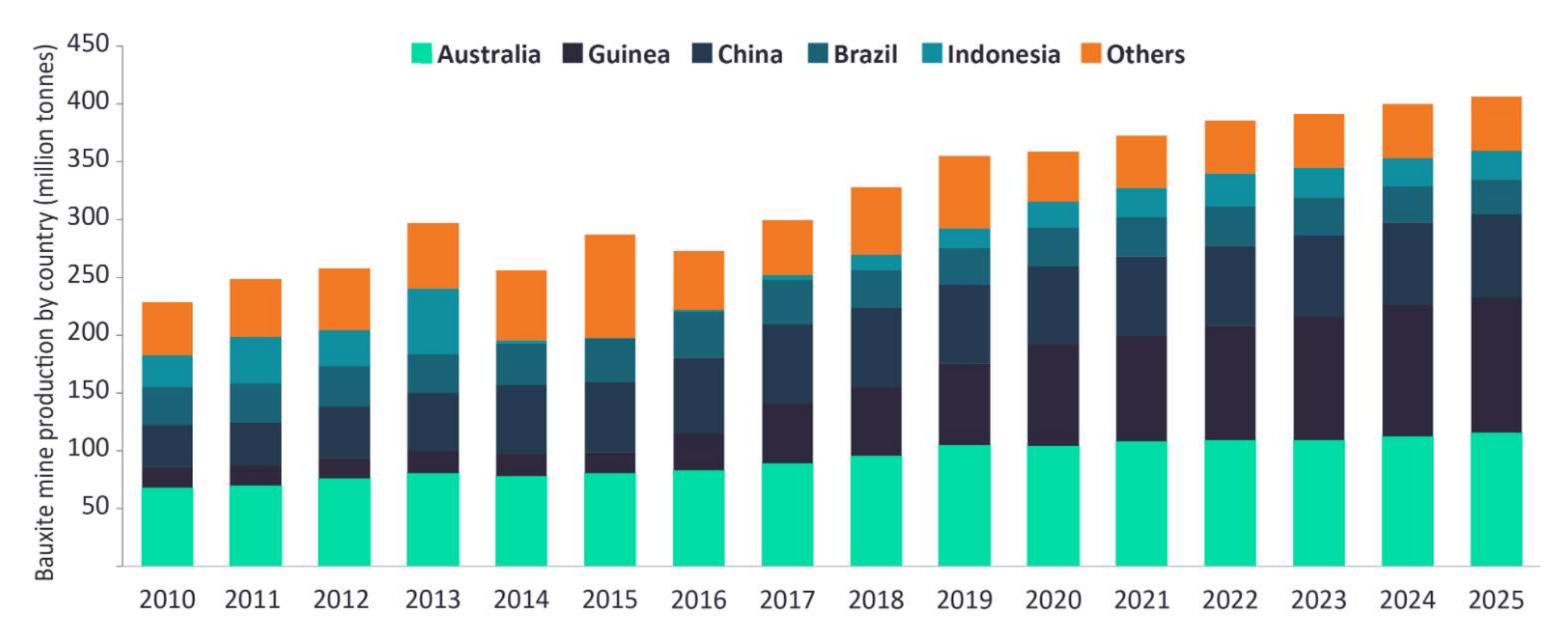
- *Instead of existing free like Gold and Silver, due to its higher level of reactivity, it is always chemically bonded in compounds when it normally occurs.*
- *The most common of these compounds is Bauxite, or Aluminum Ore which contains large quantities of Aluminum Oxide.*
- *Bauxite is the primary mineral for alumina and thus ultimately aluminum production. It is named after the town of Les Baux in southern Franc.*
- *Typically, this is a combination of Aluminum and Oxygen in the formula* $Al_2O_3 .2H_2O$.

- There are also the impurities Fe_2O_3 and SiO_2 , amongst others, present in Bauxite, which have to be removed.
- Bauxite reserves are spread across the world.
- The top 5 countries, Guinea, Australia, Brazil, Vietnam and Jamaica, hold over 70% of the world's documented bauxite resources.
- Around 85% of all Bauxite mined from the Earth is used to produce aluminum metal, which goes on to be used for a huge variety of uses.
- The remaining 15% goes towards chemical and refractory materials, along with making aluminum compounds.

Bauxite Ores



World Distribution



- *Australia, China, and Guinea were the most dominant bauxite-producing countries in 2021, having produced 110 million, 86 million, and 85 million metric tons of bauxite, respectively, that year.*
- *Although it is the third-largest producer of bauxite, Guinea has the largest reserves of bauxite in the world, amounting to 7.4 billion metric tons as of 2021*
- *Aluminum has become an essential metal in our everyday lifestyles and luckily the known reserves of Bauxite are thought to be plentiful enough to maintain supplies of aluminum for some centuries to come.*
- *In the year 1999 there were around 25 billion metric tones of Bauxite Ore, that is just about enough for everyone on the planet to have 4000 kg of Bauxite each, which means approximately 500 kg of Aluminum.*
- *It is estimated that if the amount of production does not increase, that the supplies could last over 200 years.*

Aluminum Prices

- At 4.1 million tonnes per annum (mtpa), India has the second-largest aluminum production capacity in the world, followed by Russia at 3.9 mtpa. China has the largest capacity.
- Aluminum prices have already had an upward bias in the current year as the international market was facing around one million tonne supply shortage, mainly due to production cut by China.
- The price of the metal increased by over 8% month-on-month in February to around $3,230/tonne.
- Russia's absence from the market on account sanctions on exports from the country might help Indian firms to occupy the vacant space.


Aluminium 3,022.00 -30.50 (-1.00%)
3,500
3,250
3,027.00
2,750
2,500
2,250
2,000
1,750
1,500
1000k
500k
Investing.com
Jul
2018
Jul
2019
Jul
2020
Jul
2021
Jul
2022
J

Why Aluminum

- Aluminum is incredibly popular because it is:
  - ✓ Lightweight and strong
  - ✓ Resistant to corrosion
  - ✓ Durable
  - ✓ Ductile, Malleable, and Conductive
  - ✓ Odorless
- Aluminum is also theoretically 100% recyclable with no loss of its natural properties.
- It also takes 5% of the energy to recycle scrap aluminum than what is used to produce new aluminum.

Aluminum Uses

- *Aluminum is one of the most common non-ferrous metals and it is used for a range of practical applications.*
- *These include, utilization in the aerospace industry, food and drink packaging / storage, kitchen wear, electronics, construction, automotive industry, shipping and many more, too numerous to list.*
- *When in use, aluminum is normally 'alloyed' (combined with other metals / compounds), in order to enhance its mechanical properties, such as improving machinability, overall tensile strength and casting properties.*
- *The uses of aluminum are extremely diverse due to its many unusual combinations of properties.*
- *Aluminum and aluminum oxide going into other separate processes, like the manufacture of glass.*

1- Packaging

- One of the most common end uses of aluminum is packaging, including drinks cans, foil wrappings, bottle tops and foil containers.
- Aluminum's natural resistance to corrosion aids it in its role in packaging (and many other areas), as unlike in iron, aluminum oxide forms a protective and not destructive layer.
- Aluminum is also completely impermeable, (even when rolled into extremely thin foil), and also doesn't let the taste out of food packaging, the metal is non-toxic making it perfect for packaging.

2- Transportation

- Aluminum's unbeatable strength to weight ratio gives it many uses in the transport industry.
- As aluminum is so lightweight this means that less energy needs to be used to move a vehicle made with aluminum than one made from a heavier metal, say steel.
- In modern planes aluminum makes up 80% of their weight, and a normal Boeing 747 contains about 75 000 kg of the metal.
- Its corrosion resistance is an advantage in transport as it makes painting planes unnecessary saving some hundreds of kilograms of further weight.

3- Electrical Transmission

- Weight is also important in aluminum's electrical uses, where its low density makes it the first choice for long distance power lines despite having just 63% of the electrical conductivity of (much denser) copper but just 30% weight of copper.
- Since 1945 aluminum has been used in high voltage electrical transmission, in place of copper as it is the most cost-efficient power line material.
- Aluminum is also more ductile than copper, so it is easier to draw it into wires to produce the power lines.
- Its corrosion resistance completes aluminum's profile as the perfect choice for long-distance electricity distribution.
- Aluminum has other electrical applications too including TV aerials, satellite dishes, and being the standard base for bulbs.

4- Construction

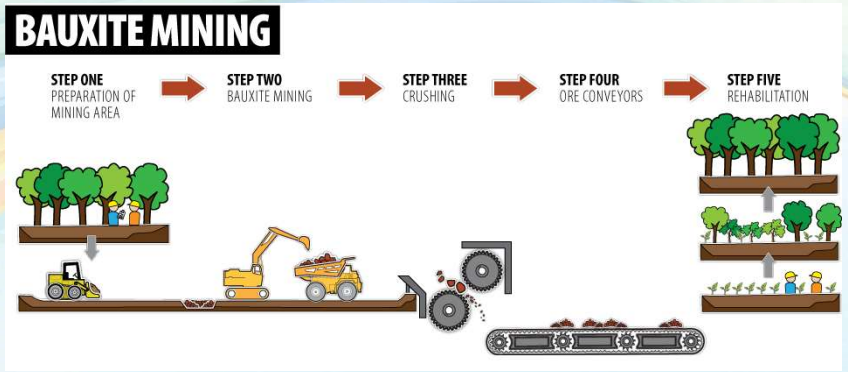
- Buildings made with aluminum are virtually maintenance free due to the strength of aluminum's corrosion resistance.
- Due to this and its light weight it is used in cladding, windows, skylights, door frames, and roofing.
- Insulated aluminum cladding is also very thermally efficient, keeping homes warm in winter, and cool in summer.
- One layer of insulated aluminum cladding is as effective as four inches of brick or ten of stone.
- Aluminum can also be painted and used with other material to achieve a particular effect on the appearance of a building.
- The metal is extremely versatile, and it can be curved, tapered, welded, bonded and cut to any shape to be used for a certain job.

5- Household

- Aluminum also has further end uses in products used more readily around the home.
- Furniture items made from aluminum include tables, chairs, lamps, picture frames and decorative panels.
- Of course, the foil in your kitchen is aluminum, as well as pots and frying pans which are frequently made from aluminum. These Aluminum products conduct heat well, are non-toxic, resistant to rust, and are easy to clean.
- Aluminum cans are used to package food and beverages. Coca-Cola and Pepsi have been using aluminum cans since 1967.

Extraction

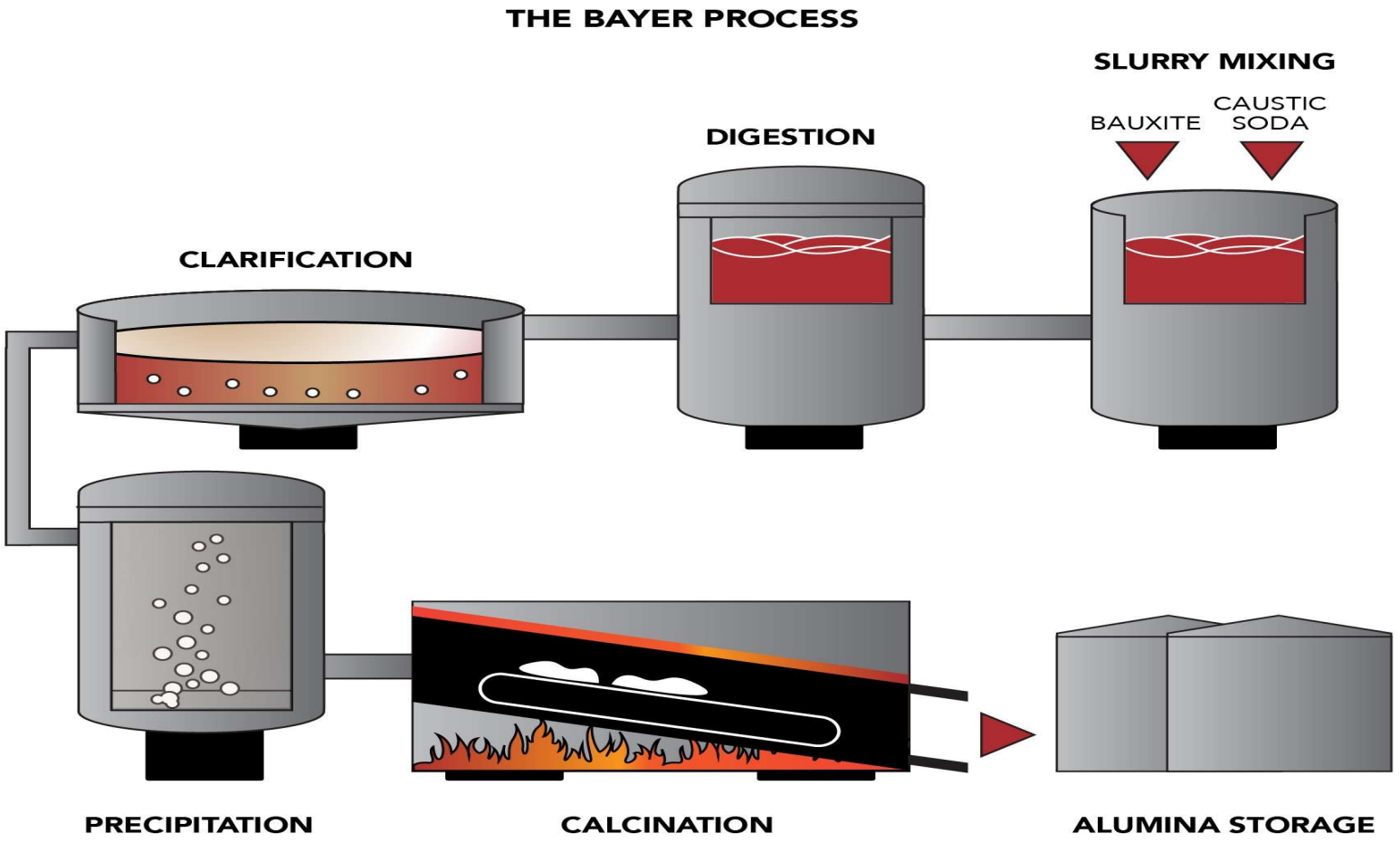
- The first step in extracting aluminum is to remove it from the Earth in mining.
- This is relatively simple given the abundance of the material. However, aluminum is never found isolated in the Earth (due to its reactivity) but instead it is found bound to other elements in compounds.
- This means that aluminum alone can never be dug up, but compounds of it, often containing oxygen and silicon (bauxite).

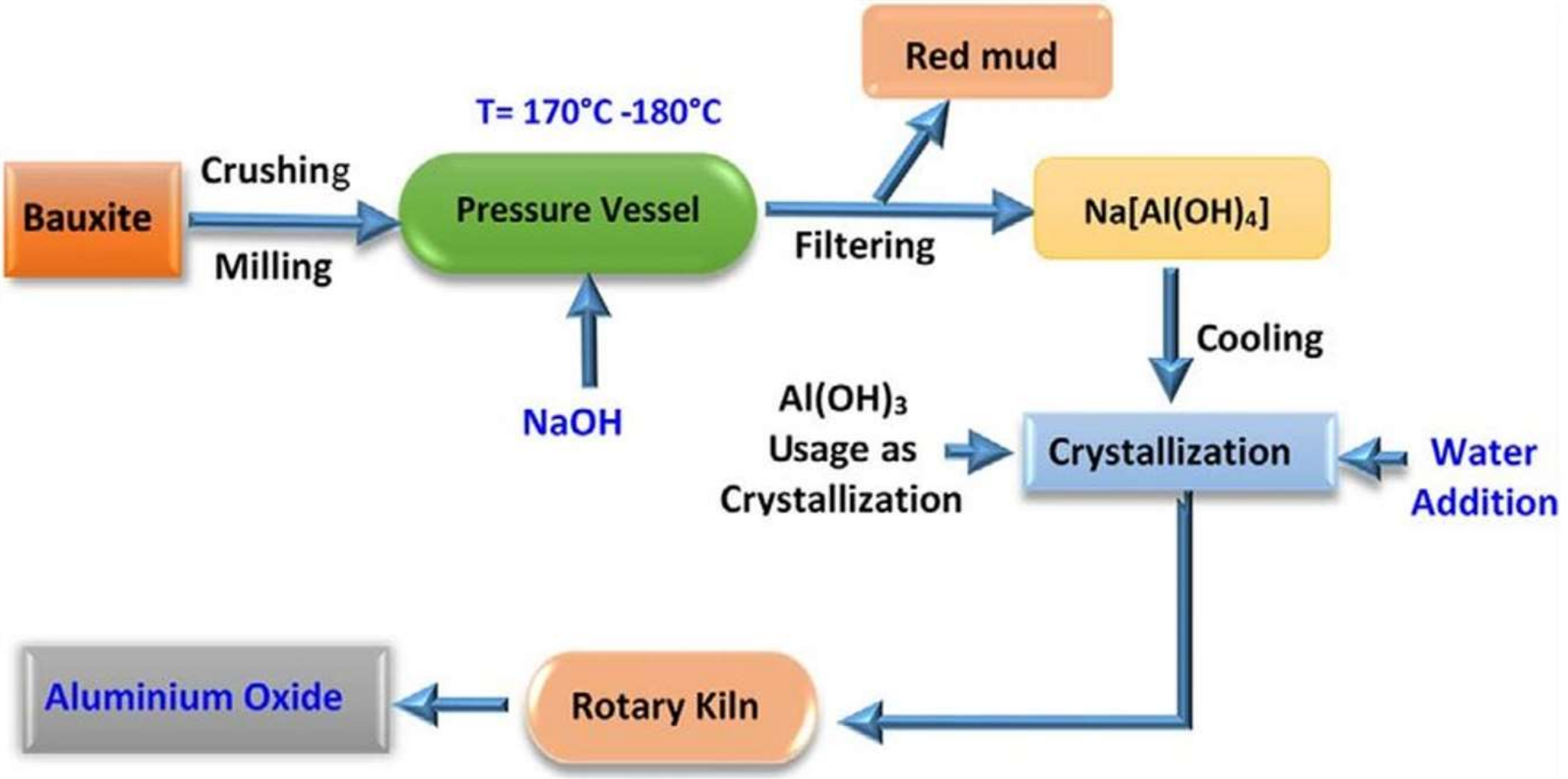


Extraction

- The bauxite then has to be purified using the Bayer process, whose development changed the course of aluminum's history.
- It is a heavily energy intensive process and thus, is often produced in regions where energy costs are the lowest.
- Recycling of aluminum can lower the cost of electric power in aluminum production and also prolong the existence bauxite reserves.
- Nevertheless, reserves remain fairly high even at current production levels.

- The Bayer process occurs in two main steps.
- Firstly, the aluminum ore is mixed with the sodium hydroxide in which the oxides of aluminum and silicon will dissolve, but other impurities will not.
- These impurities can then be removed by filtration.
- Carbon dioxide gas is then bubbled through the remaining solution.
- Carbon dioxide gas forms weak carbonic acid neutralizing the solution and causing the aluminum oxide to precipitate, but leaving the silicon impurities in solution.
- After filtration, and boiling to remove water, purified aluminum oxide can be obtained.


THE BAYER PROCESS
SLURRY MIXING
BAUXITE
CAUSTIC SODA
DIGESTION
CLARIFICATION
PRECIPITATION
CALCINATION
ALUMINA STORAGE

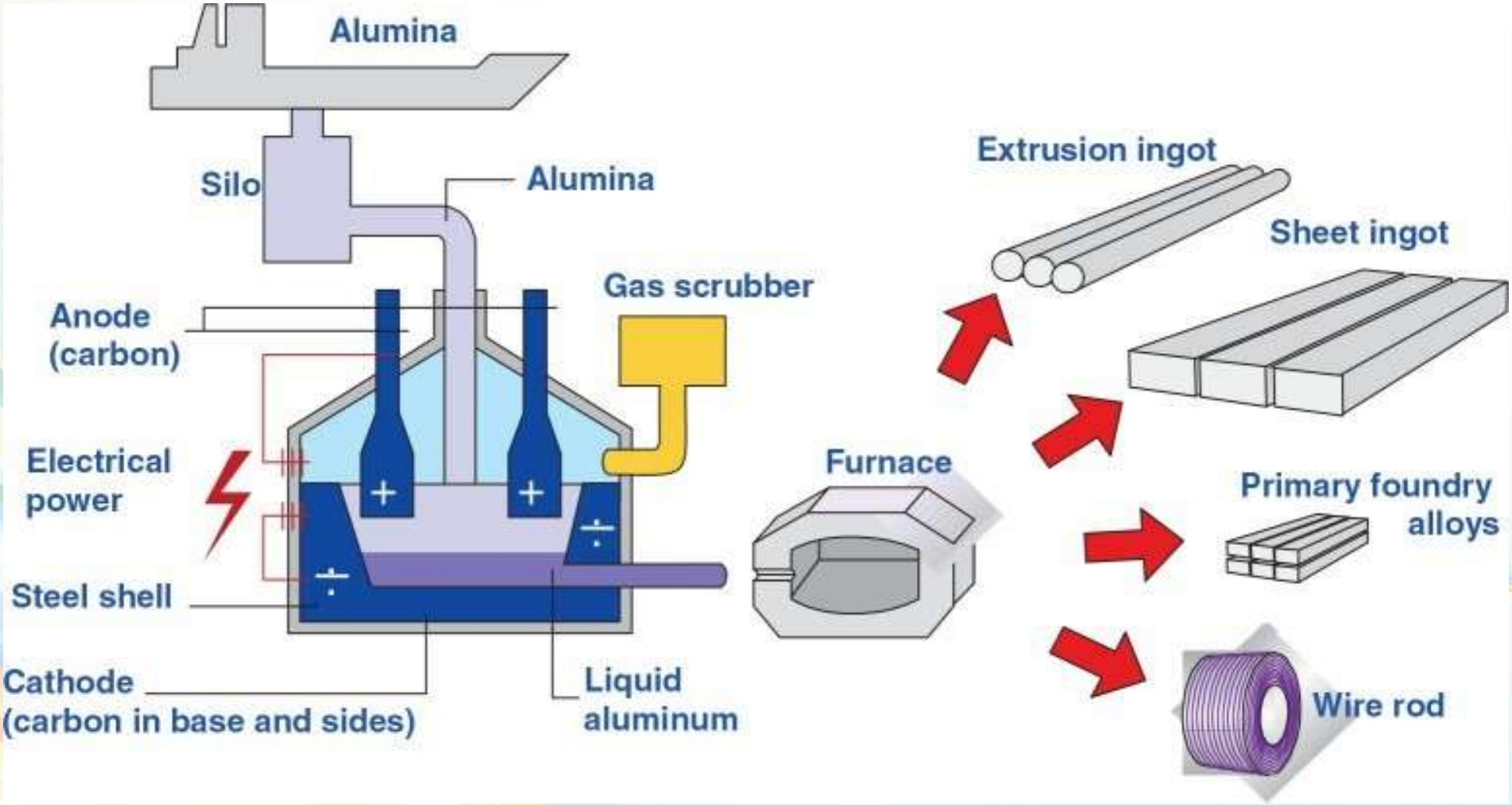

Red mud
T= 170°C -180°C
Bauxite
Crushing
Milling
Pressure Vessel
Filtering
Na[Al(OH)4]
Cooling
NaOH
Al(OH)3
Usage as
Crystallization
Crystallization
Water
Addition
Aluminium Oxide
Rotary Kiln

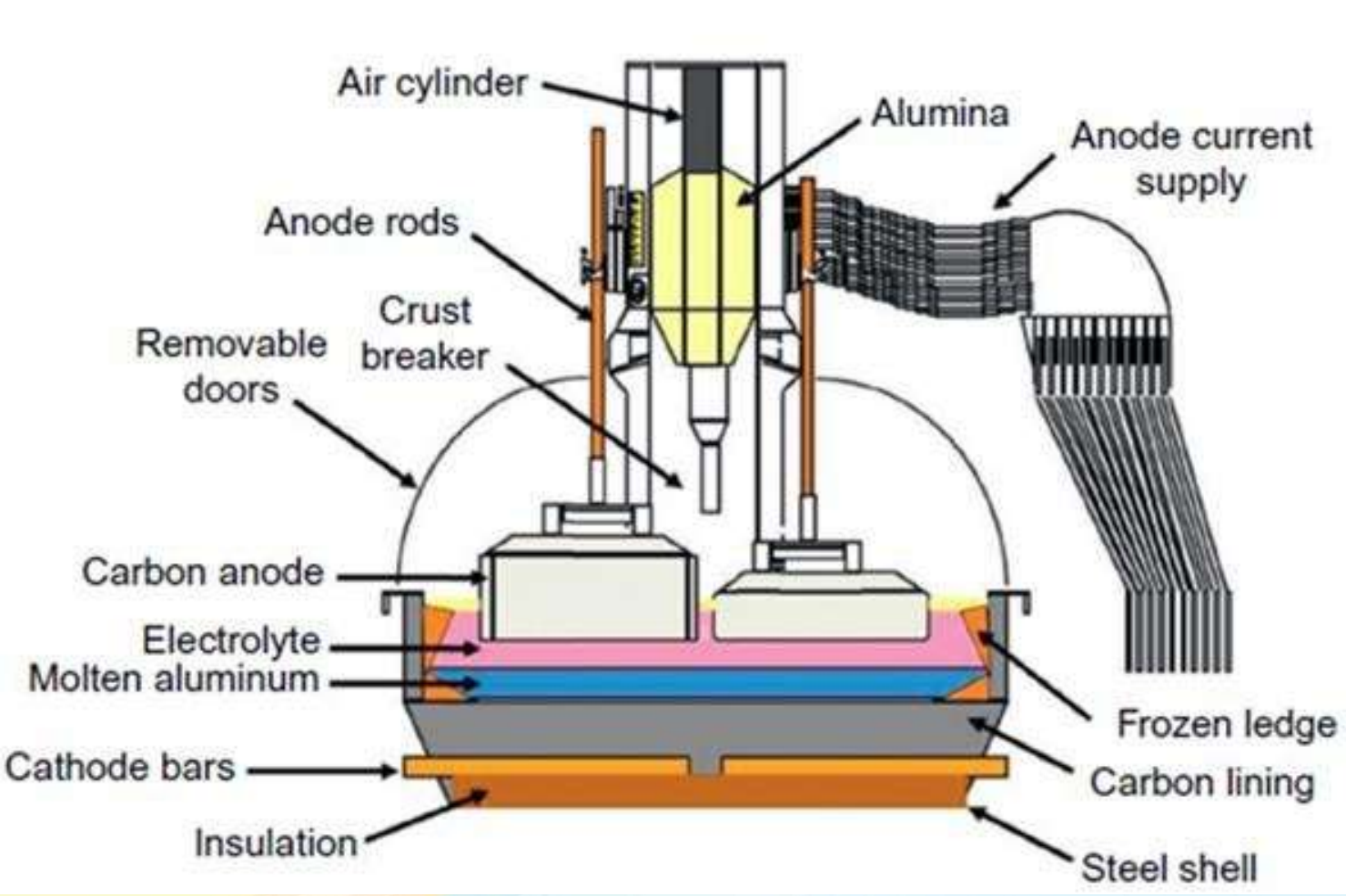
- Once purified aluminum oxide has been manufactured, aluminum can be removed from it by the Hall-Heroult Method.
- The Hall-Heroult process is the major industrial process for the production of aluminum.
- In the Hall-Heroult process alumina, Al_2O_3 is dissolved in a carbon-lined bath of molten cryolite, Na_3AlF_6 .
- Aluminum fluoride, AlF_3 is also present to reduce the melting point of the cryolite.
- The mixture is electrolyzed, and liquid aluminum is produced at the cathode.
- The carbon anode is oxidized and bubbles away as carbon dioxide.

- The overall chemical reaction is

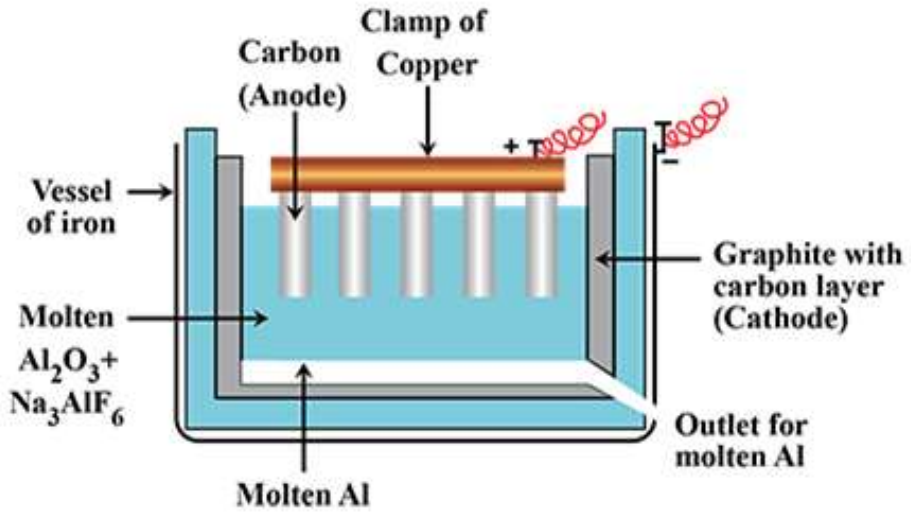
$$2\ Al_2O_3 + 3\ C \rightarrow 4\ Al + 3\ CO_2$$

- The liquid aluminum product is denser than the molten cryolite and sinks to the bottom of the bath, where it is periodically collected.
- The top and sides of the bath are covered with a crust of solid cryolite which acts as thermal insulation.
- Electrical resistance within the bath provides sufficient heat to keep the cryolite molten.
- As the process is so long and requires so much energy (in electricity) the aluminum metal obtained is quite expensive, but still it is competitively priced in relation to other metals.


Alumina
Silo
Alumina
Gas scrubber
Anode
(carbon)
Electrical
power
Steel shell
Cathode
(carbon in base and sides)
Liquid
aluminum
Furnace
Extrusion ingot
Sheet ingot
Primary foundry
alloys
Wire rod


Air cylinder
Alumina
Anode current supply
Anode rods
Crust breaker
Removable doors
Carbon anode
Electrolyte
Molten aluminum
Cathode bars
Insulation
Frozen ledge
Carbon lining
Steel shell

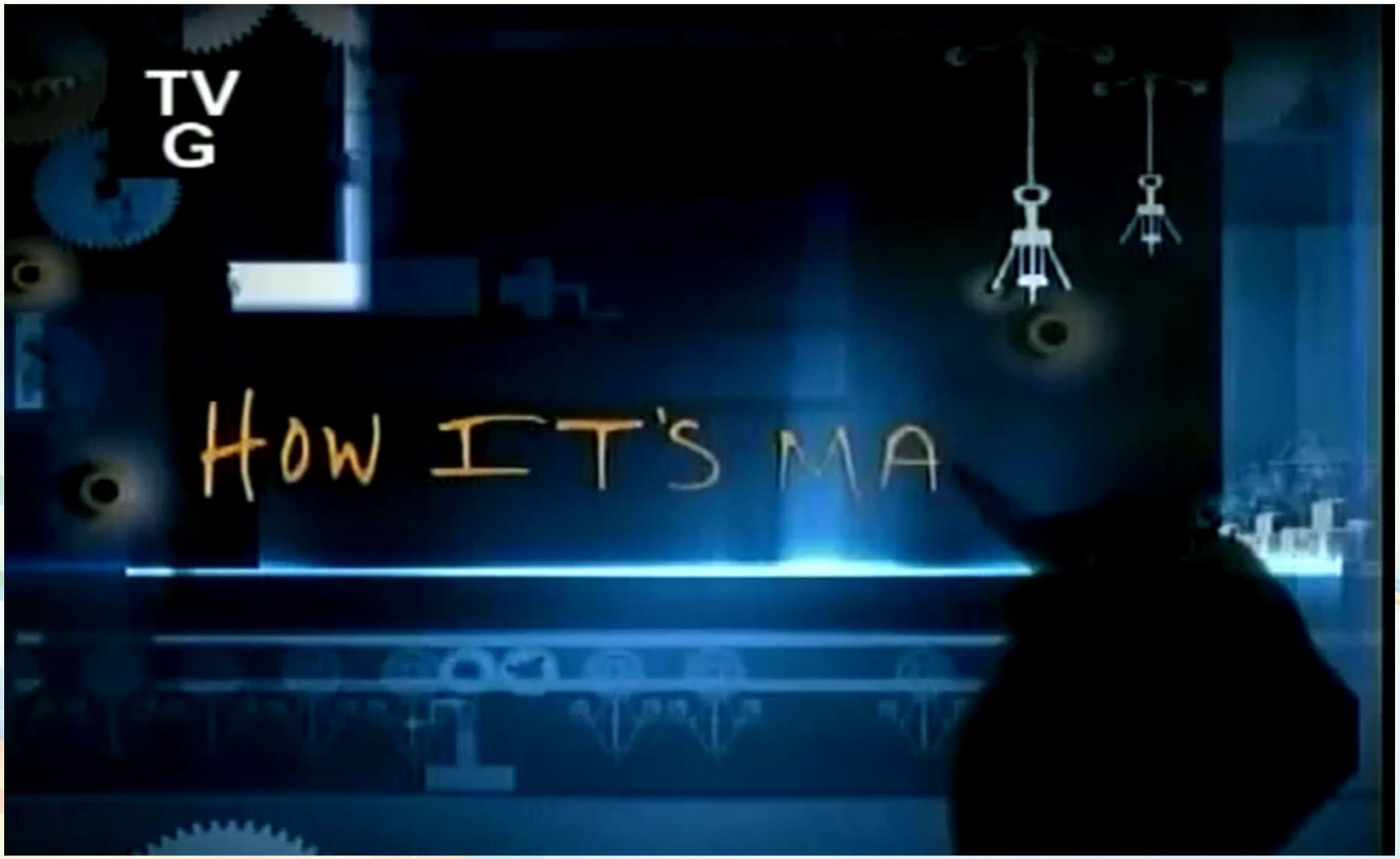
Electrolysis of Aluminum



Ionization of Alumina: $2Al_2O_3 \rightarrow 6O^{-2} + 4Al^{+3}$

Reaction at Cathode: $4Al^{+3} + 12e^- \rightarrow 4Al$

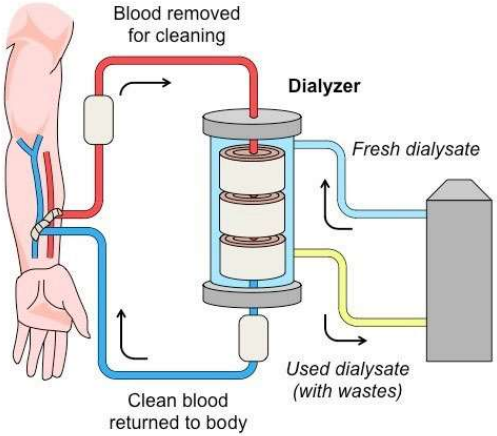
Reaction at Anode: $6O^{-2} \rightarrow 3O_2 + 12e^-$, $C + O_2 \rightarrow CO_2$


TV
G
How IT'S MA

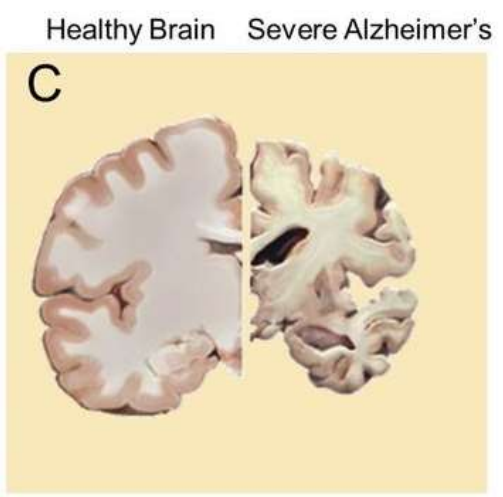

HALL HEROULT
PROCESS

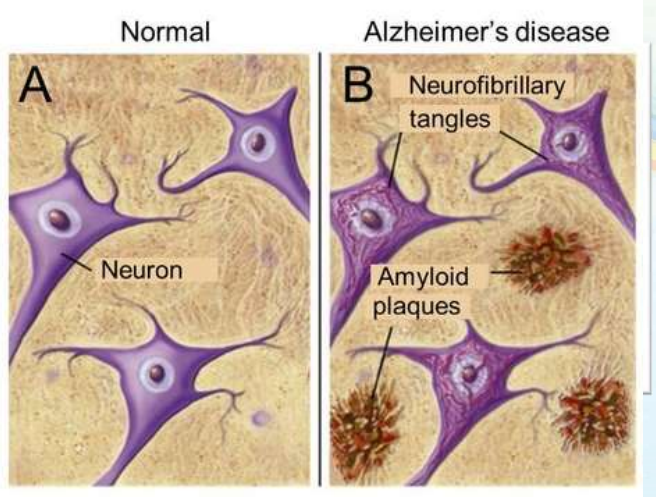
Weaknesses

- *Aluminum is a remarkable material; its range of properties make it unique and essential to the modern world.*
- *However, like anything, it comes with its drawbacks. Aluminum is not the perfect material.*
- *Aluminum is thought to cause problems for kidney patients when it enters their body during dialysis.*
- *Inhaling aluminum dust is currently linked with some lung problems.*



- *In 1965 Aluminum first became linked with Alzheimer's Disease after injecting rabbits with compounds of the metal caused tangle-like formations of nerves.*
- *Although "no causal relationship has yet been proved" there are still many concerns about the effect of the metal on human health.*





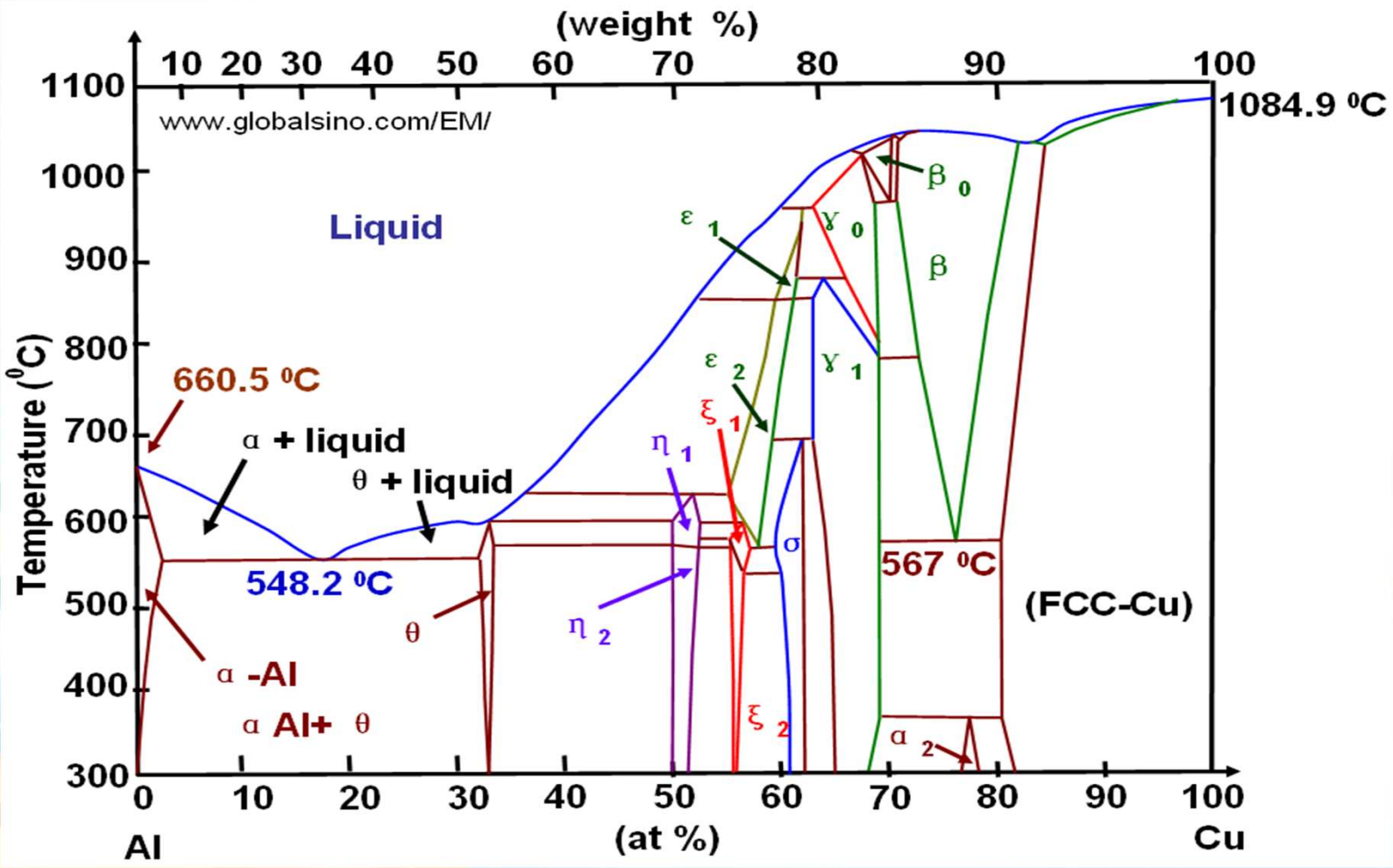
Alloying

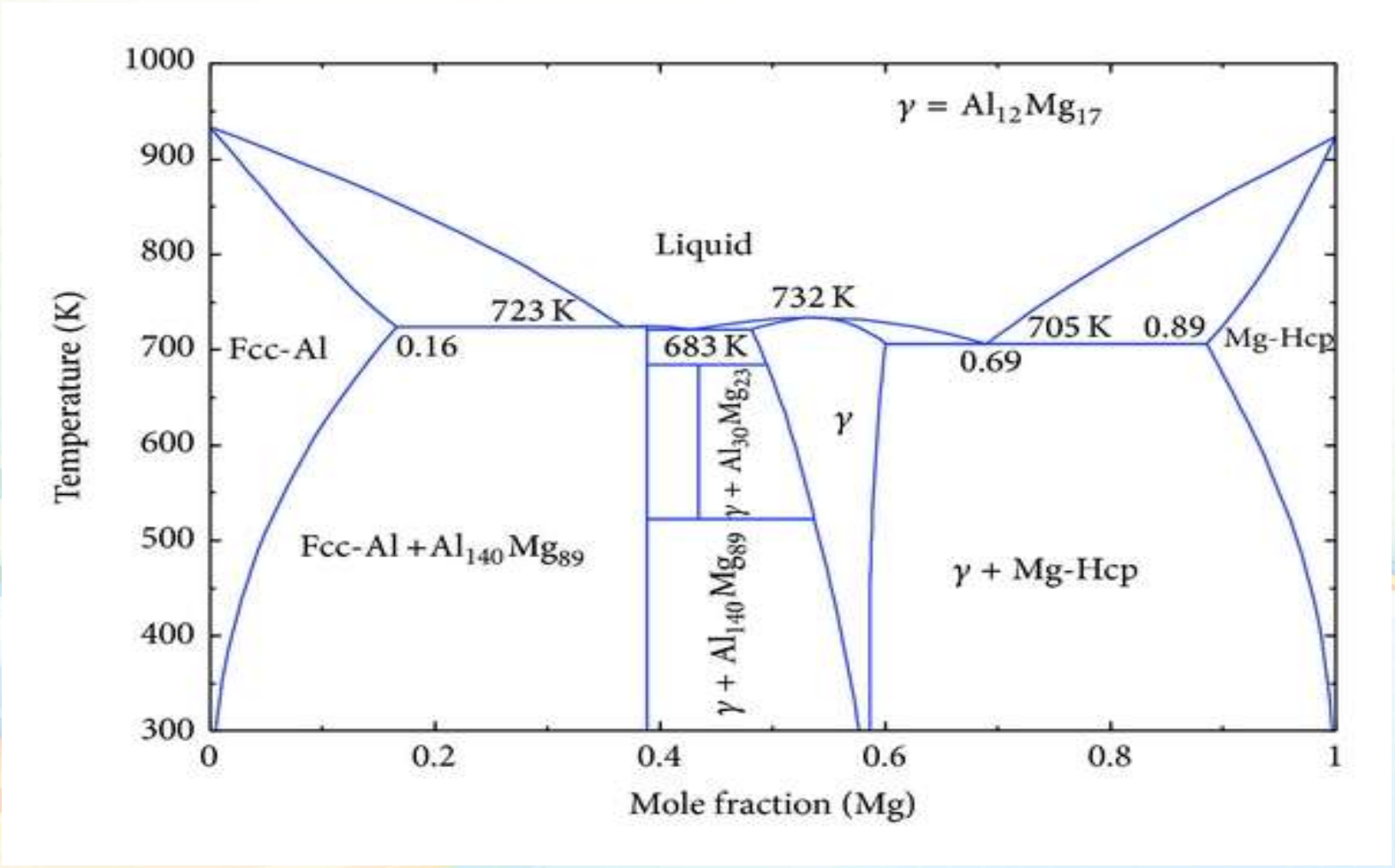
- One of aluminum's weaknesses is its lack of strength in its pure form.
- To get around this and preserve aluminum's low density and lightweight other elements are added to reduce the ductility but increasing strength.
- By this method, some aluminum alloys can be as strong as steel.
- Adding different elements achieves slightly different effect but almost all alloys are stronger than the original aluminum metal.

- *Adding copper to aluminum increases aluminum's strength, and hardness and makes it heat treatable.*
- *Under a classification system that is currently in place all aluminum alloys are give a four-digit number.*
- *Those with copper come in the form 2XXX.*
- *Alternatively adding magnesium causes increased tensile strength, resistance to marine corrosion and ease at which welding can occur. The code for these alloys begins with a 5.*

Al-Cu alloy

Al-Mg alloy

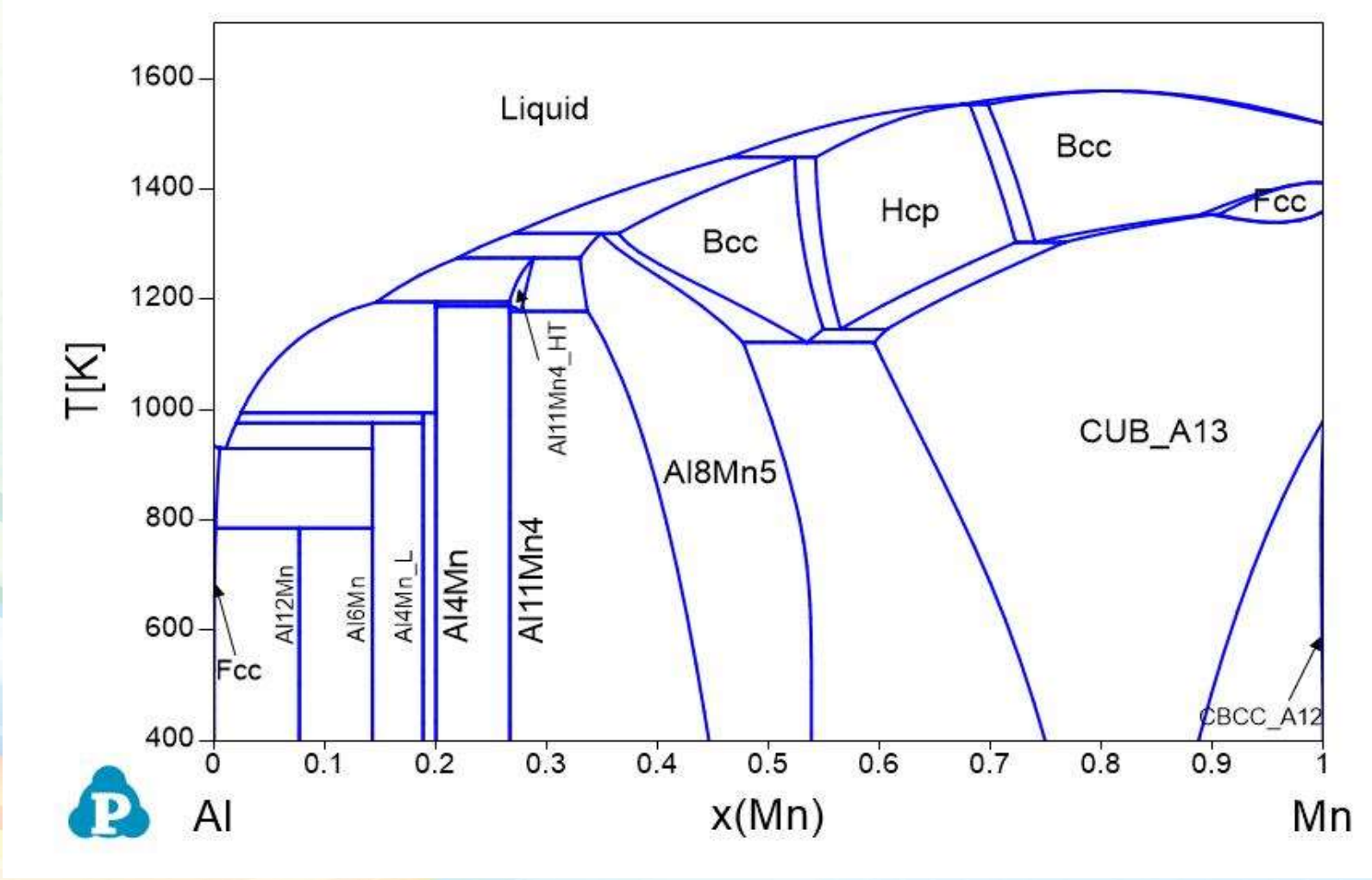

(weight %)
10 20 30 40 50 60 70 80 90 100
1100
1000
900
800
700
600
500
400
300
Temperature (°C)
www.globalsino.com/EM/
Liquid
1084.9 °C
660.5 °C
α + liquid
θ + liquid
548.2 °C
α -Al
α Al+ θ
θ
η 1
η 2
ε 1
ε 2
ξ 1
ξ 2
γ 0
γ 1
β 0
β
σ
567 °C
(FCC-Cu)
α 2
0 10 20 30 40 50 60 70 80 90 100
Al
(at %)
Cu

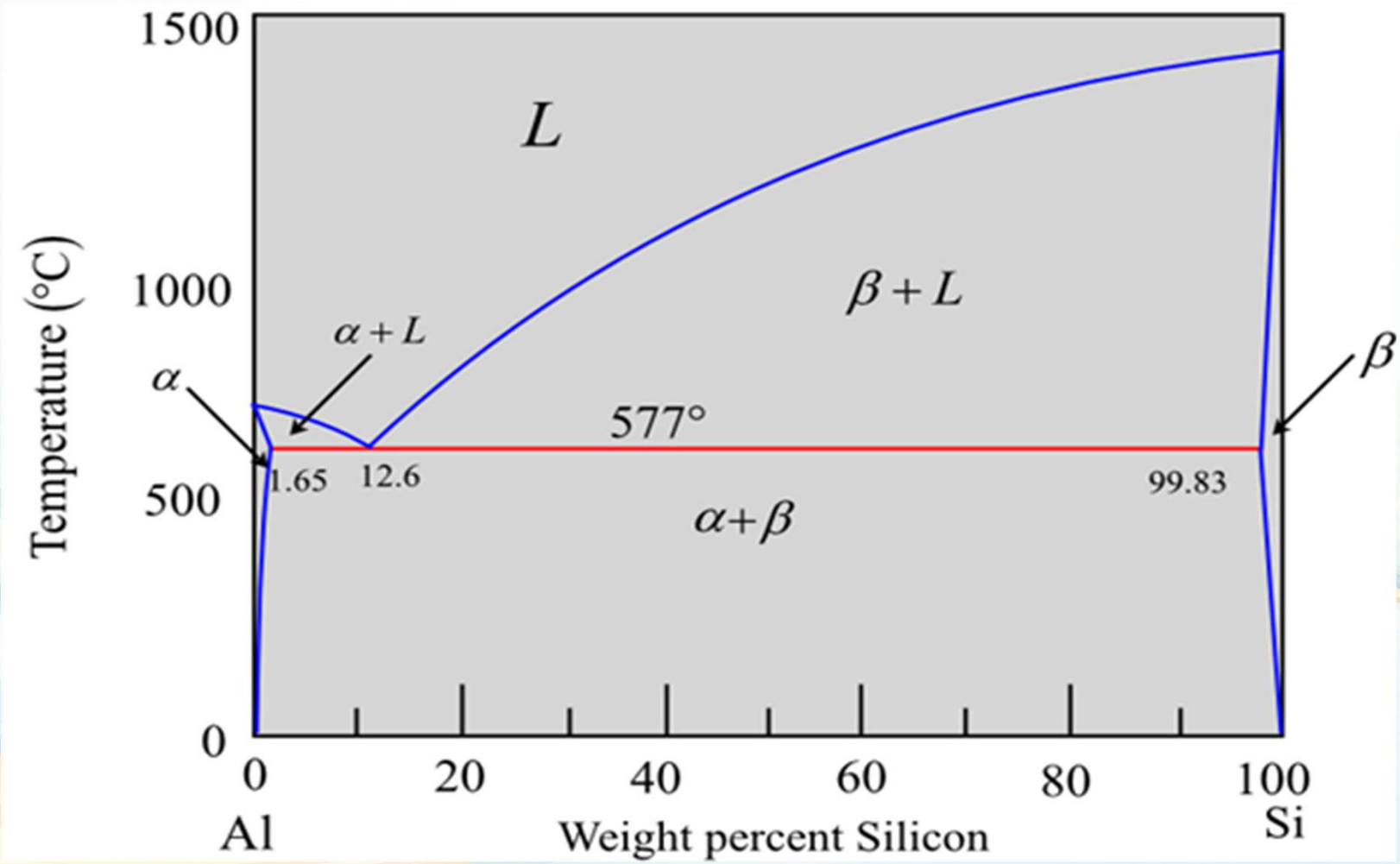

1000
900
800
700
600
500
400
300
Temperature (K)
0
0.2
0.4
0.6
0.8
1
Mole fraction (Mg)
γ = Al12Mg17
Liquid
723 K
732 K
705 K
0.89
Mg-Hcp
Fcc-Al
0.16
683 K
0.69
γ + Al30Mg23
γ
Fcc-Al + Al140Mg89
γ + Al140Mg89
γ + Mg-Hcp

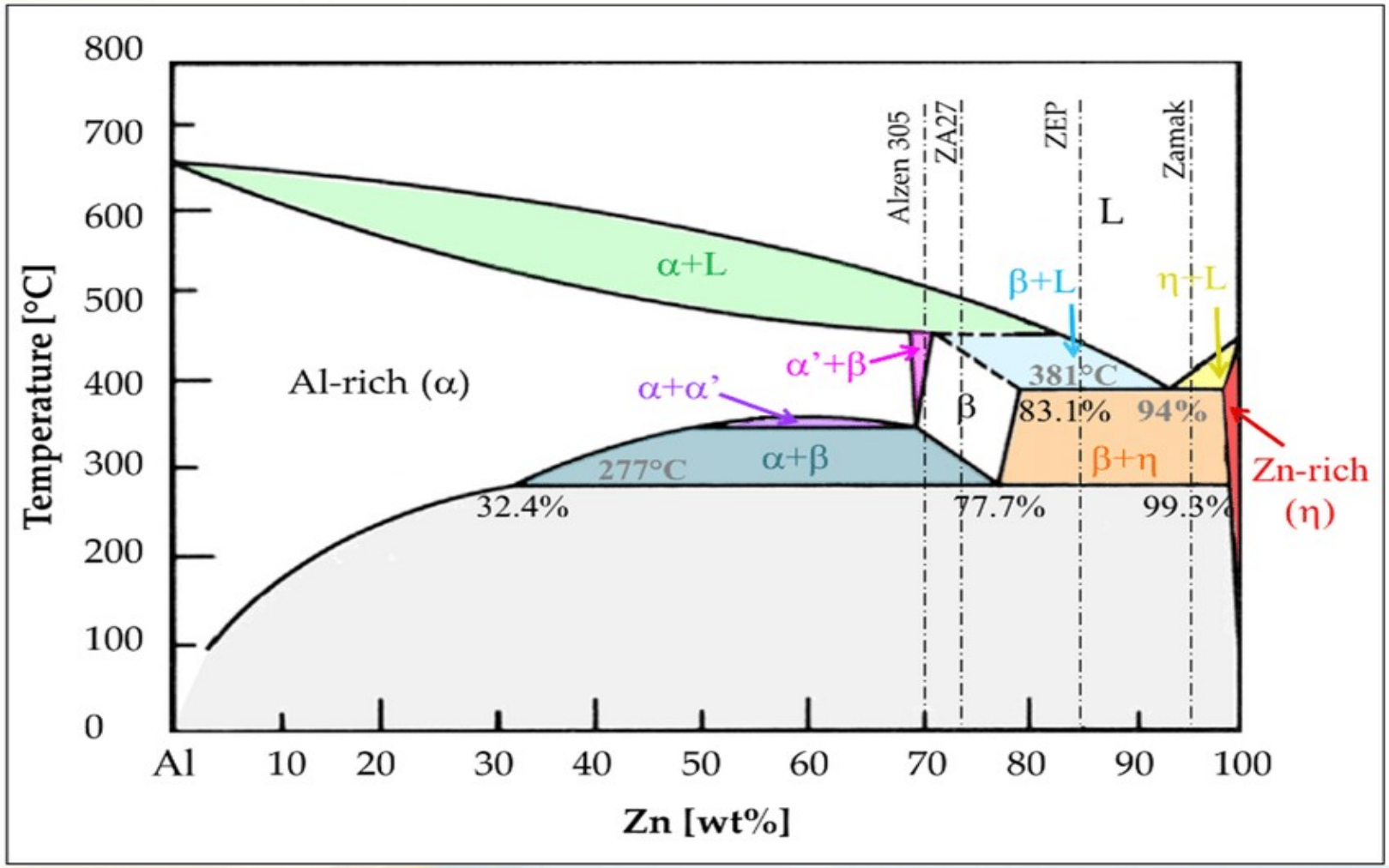
- There are three further common elements which can feature in aluminum alloys.
- Manganese is often added to give increased strength and resistance to corrosion.
- The addition of silicon lowers the melting point and improves stability.
- Alloys with zinc have increased strength and hardness.
- What makes these alloys special is they retain the lightweight property of aluminum whilst gaining the extra properties that aluminum itself lacks.

Al-Si alloy

Al-Zn alloy

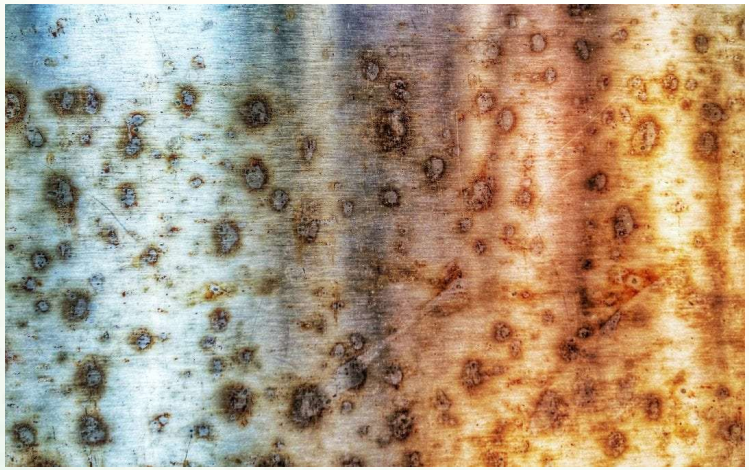

Liquid
Bcc
Hcp
Bcc
Fcc
Al11Mn4_HT
Al8Mn5
CUB_A13
Al12Mn
Al6Mn
Al4Mn_L
Al4Mn
Al11Mn4
Fcc
CBCC_A12
T[K]
1600
1400
1200
1000
800
600
400
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Al
x(Mn)
Mn


1500
1000
500
0
Temperature (°C)
L
β + L
α + L
α
β
577°
1.65
12.6
99.83
α+β
0
20
40
60
80
100
Al
Weight percent Silicon
Si


800
700
600
500
400
300
200
100
0
Temperature [°C]
Al
10
20
30
40
50
60
70
80
90
100
Zn [wt%]
Alzen 305
ZA27
ZEP
Zamak
L
α+L
β+L
η+L
Al-rich (α)
α+α'
α'+β
β
381°C
83.1%
94%
277°C
α+β
β+η
32.4%
77.7%
99.3%
Zn-rich
(η)

Corrosion

- Aluminum's corrosion resistance plays a vital role in many of its uses, from packaging, to jumbo jets, and to building and construction work.
- When exposed to air aluminum forms a 1 nm thick layer of oxide which serves as a brilliant corrosion protector for the metal in most environments.
- The barrier oxide film is bonded very strongly with the surface, and if it does become damaged it reforms almost immediately in air maintaining this very high level of protection.
- This oxide layer changes the properties of the material hugely.



- *Although aluminum is a very reactive metal, in most cases this reactivity cannot be seen due to this natural film which prevents the aluminum reacting with other substances.*
- *Unlike in iron where the oxidation of the metal creates substance (rust) damaging to the metal itself, in aluminum the oxide makes the material even more versatile and useful.*
- *Aluminum would not be used to the extent that it is in outdoor furniture, cars, planes, and on buildings if it couldn't protect itself from the effects of weathering and corrosion. With this layer, it can.*