Side-well reverberatory melting furnace. Ideal for scarp melting. During the charging period, the melt is pumped through the charge well, where it melts the scrap and then recirculates back into the main furnace chamber for reheating.
gas-fired vs electric resistance crucible furnace

Test Bar Mechanical Properties - Relative Mean Values

Number of standard deviations from mean (0)  Blue = Electric  Red = Gas-fired
gas-fired vs electric resistance crucible furnace

The natural gas melted test bars almost invariably broke at a dross inclusion, a hydrogen gas bubble, or even just a thin film of aluminium oxide, while the electrically melted test bars rarely showed any dross, oxide or hydrogen porosity at the breaks.
Leakage of Combustion Products

- the molten aluminium in the gas-fired furnace is not isolated from the furnace’s combustion chamber at all.
- This is because the sealing gasket between the top of the crucible and the underside of the steel furnace cover is made of compressible fibre insulation to allow the crucible to expand without cracking.
- Because of the positive pressure in the combustion chamber and the porous fiber gasket, combustion gasses freely penetrate the gasket, immediately coming into contact with the surface of the metal bath.
gas-fired vs electric resistance crucible furnace

- With the electric furnace, the relative humidity is always the same inside and outside.
- But with the gas-fired furnace, even though there is a flue that pipes most of the combustion gases outside, the relative humidity inside the foundry is always significantly higher.
- This means, in addition to the combustion gases that are penetrating the crucible gasket, there is additional water vapour present in the air that is coming from various leaks in the burners, refractories, flue pipes, etc. which can react with the molten aluminium.
Effect of Relative Humidity
The net result is that the water vapour coming from both sources is quickly reacting with the molten metal, resulting in higher metal losses and much greater contamination of castings from oxide, dross, and hydrogen gas, all of which degrade the mechanical properties of the castings produced from metal taken from the gas-fired crucible furnace.
Some aluminium foundries suffer from seasonal high relative humidity.

When the dew point reaches a certain value, scrap rates due to excessive dross and H₂ increase to high levels.

Aluminium alloys containing more reactive elements like Mg and Zn lose some of these elements to oxidation, altering the alloy composition.

Alloys such as Almag 35, which contains magnesium, develop thick dross layers, putting casting quality at risk. Foundries casting such alloys would worsen the problem by employing gas-fired melting furnaces that increase the relative humidity.
gas-fired vs electric resistance crucible furnace

**Skimming Test** to verify that combustion gasses are indeed present and reacting with molten aluminium in gas-fired crucible furnaces. Simply skim the molten metal surface, do not further disturb it, and watch what happens. Note that the clean, skimmed surface will slowly darken, the surface will change from a shiny, reflective surface to a dull, non-reflective surface, and the oxide “skin” which is thin after skimming will progressively become thicker and darker.

This is all caused by water vapor in the products of combustion from the furnace reacting with the melt.
gas-fired vs electric resistance crucible furnace

the surface will appear highly reflective after skimming and the shiny surface will remain that way much longer in an electric resistance crucible furnace than on the gas-fired furnace. Also, the oxide “skin” will remain thin much longer. The surface will slightly darken after a lengthy period of time, but at nowhere near the rate of the gas-fired furnace. This demonstrates that the metal stays much cleaner substantially longer in an electric resistance melting furnace.
gas-fired vs electric resistance crucible furnace

Simple skimming test demonstrates aluminium surface reaction with products of combustion. Note clean, highly reflective surface in electric melting furnace.
Tilting crucible furnaces

- The crucible tilts to discharge metal into casting ladles.
- Popular for batches of aluminium up to 700 kg.
- The tilting crucible furnace, which may be electric or gas, is popular as a bulk melter.
crucibles

Carbon bonded, ceramic bonded, clay-graphite (clay-bonded) and silicon carbide (carbon or resin bonded) crucibles are used in melting and holding aluminium alloys.
Clay graphite crucibles

- These crucibles consist of special graphites with clay as the bonding agent.
- The clay forms a ceramic bond, some silicon carbide may be added to improve resistance to thermal shock.
- The graphite provides thermal and electrical conductivity and resistance to wetting by molten metal or salts.
- The crucible is coated with a glaze which prevents oxidation of the graphite.
Silicon carbide crucibles

- They consist of SiC and special graphites.
- They are carbon bonded using pitch, tar or a resin.
- The crucibles are glazed to ensure high resistance to oxidation.
- While silicon carbide crucibles are more expensive than clay graphite, their life is longer.
- Crucible life has increased with advances in manufacturing methods, and in furnaces used mainly for holding, crucible lives of twelve months or more are possible with careful use.
Using crucibles

The main points to pay attention to are:

- Avoid mechanical shock!
- Use padded tools for transport!
- Do not roll the crucible on its bottom edge or side
- Avoid damage to the protective glaze
- Crucibles can absorb moisture which can give rise to spalling of the glaze when heating up
- Store in a dry place, not on a damp floor
- The crucible should always be preheated before charging.
- It should be charged as soon as it has reached ~ 800°C.
- The crucible wall must be cleaned immediately after emptying to remove slag or dross.
- If not removed immediately the slag or dross will harden and be difficult to remove.
Selecting melting crucibles

- Must be resistant to natural gas, fuel oil and propane.
- Must be conic to allow the flame to rise by travelling around inside the furnace (uniform heating)!
- Must be resistant to oxidation effects!
- Must resist thermal shocks and T changes.
- Must have high thermal conductivity (to transfer the heat inside the furnace to the load and for uniform heating)
- High graphite crucibles offer high thermal conductivity for a rapid melting!
Selecting melting crucibles

- Melting is slow in electric resistance furnaces. Hence, crucibles with a superior thermal conductivity are required.
- Crucibles with a higher graphite ratio are appropriate.
- Crucibles used in resistance furnaces are straight cylindrical to maintain a constant distance between the crucible and the heating elements.
- While high SiC crucibles are selected for low frequency induction furnaces, high clay content crucibles are used in high frequency furnaces.
Selecting melting crucibles

Crucibles for induction furnaces often exhibit straight cylindrical shape. However, for those operations where the crucible must be removed from the furnace, heating coil is wound conically.
Selecting melting crucibles

- Crucible must be resistant to thermal shock if the temperature variations in melting operation are frequent and large.
- Graphite offers high thermal conductivity and nonwettability.
- Thermal shock resistance is high in an oriented graphite structure.
- These features may be critical in melting operations during which the temperature changes by a couple of hundred degrees in several seconds.
Selecting melting crucibles

If the crucible is always loaded with molten metal, resistance to physical damage is not critical. However, crucibles with high mechanical strength and resistant to physical damage are employed if a fraction of the load is in the form of large and heavy blocks and if loading is carried out manually instead of with an automatic loading system. High carbon and oriented graphite crucibles provide excellent impact and mechanical shock resistance.
Selecting melting crucibles

- All crucibles are resistant to chemicals and to corrosion to some degree.
- However, some of the fluxes used in melting aluminium are highly corrosive. Hence, crucibles are desired to be resistant to chemical interactions.
- Crucibles must be manufactured from dense materials and must be coated with a protective glaze.
Degassing of aluminium alloys is often performed by purging aluminium melt with an inert gas and often with nitrogen. This degassing treatment leads to the erosion of the crucible and also has chemical effects.

Hence, dense, mechanically durable crucibles with high resistance to chemical attacks must be used. SiC based crucibles are resistant to high temperature erosion and to chemical corrosion.

Graphite crucibles produced with isostatic pressing for high density are resistant to erosive and corrosive service conditions.
Selecting melting crucibles

drossing
A dense and nonwetting crucible will avoid dross build up inside the crucible wall and will facilitate crucible cleaning.
Induction heating

process of heating an electrically conducting object by electromagnetic induction, through heat generated in the object by eddy currents.
An induction heater consists of an electromagnet, and an electronic oscillator that passes a high frequency alternating current (AC) through the electromagnet. The rapidly alternating magnetic field penetrates the object, generating electric currents inside the conductor called eddy currents.
The eddy currents flowing through the material heat it by Joule heating. In ferromagnetic materials like iron, heat may also be generated by magnetic hysteresis losses.
The frequency of current used depends on the object size, material type, coupling (between the work coil and the object to be heated) and the penetration depth.
**Induction heating**

<table>
<thead>
<tr>
<th>Technical features</th>
<th>Economic features</th>
</tr>
</thead>
<tbody>
<tr>
<td>High melting rate</td>
<td>High energy efficiency</td>
</tr>
<tr>
<td>Flexible melting operation without heel</td>
<td>Low construction cost through compact design</td>
</tr>
<tr>
<td>Easy change of metal grades</td>
<td>Minimum assembly times through pre-assembled modules</td>
</tr>
<tr>
<td>Short start-up times, rapid charge sequences</td>
<td>Low labour cost through high power density and melting shop automation</td>
</tr>
<tr>
<td>Adaptable to metallurgical requirements, e.g. by multi-frequency technology, power shift capability, etc.</td>
<td></td>
</tr>
</tbody>
</table>
Induction furnaces
Induction furnaces

- Induction melting is a clean melting process where the heat source is never brought into direct contact with the aluminium melt.
- High frequency alternating current is used to heat metals with high electrical conductivity.
- Heat is generated directly within the metal to be melted. The efficiency is thus high.
- This is different from other melting practices where the heat is generated with a flame or inside a heating element.
Induction furnaces

Advantages

- %60-75 efficiency
- low oxidation losses
- low emissions
- clean and uniform aluminium melt

- Induction melting offers the further advantage of mixing the melt leading to improved thermal and chemical homogeneity.
- It is the most suitable melting method for aluminium scrap and returns.
- Energy consumption is relatively smaller with respect to other melting methods.
Induction furnaces are energy efficient melters. Energy consumption is affected by the density of the charge and the melting practice used. Batch melting is less efficient than using a molten heel, a 50% molten heel being most efficient. Energy consumptions vary from 540 kWh/ton for a high bulk density charge (small scrap and ingot) to 600 kWh/ton if lower density scrap (such as pressure diecasting runners and ingot) is melted. While energy consumption is low, costs for melting may be higher than for gas-fired furnaces because of the generally high cost of electricity as a source of heat.
The stirring effect of the induction power can be advantageous since the charge is mixed well.

but it exposes the molten aluminium to oxidation.

the oxide may be drawn into the melt which can be harmful and lead to high melting losses.

The stirring effect causes fluxes to be entrained in the melt,

so it is usual to melt without flux cover, then to switch off the current before adding the flux. Sufficient time must be allowed for the oxides to float out before transferring the metal.
The linings are usually a dry alumina refractory, vibrated around a steel former according to the supplier’s instructions and heated to 750°C at 80-100°C/hr, then held for 1-4 hrs depending on the size of the furnace and cooled naturally before removing the former. Dross build-up on the linings can reduce furnace efficiency and contribute to lining failure. Dross should be scraped from the walls at the end of each melt cycle while the furnace is hot. Once a week, the furnace should be allowed to cool and any remaining dross carefully removed using chisels.
Coreless induction furnaces

Medium frequency induction furnaces are efficient, clean and rapid melting units for aluminium. Aluminium induction furnaces usually range from 500 kg to 2 tonnes capacity and operate at frequencies of 250-1000 Hz.
Coreless induction furnaces

While induction furnaces are excellent melting units, they are not efficient holders. When used for melting, it is advisable to transfer the molten metal to an efficient holding furnace as soon as it has reached the required temperature.
Coreless induction furnaces

- Metal is charged into a crucible placed inside a water cooled selenoid coil carrying alternative current!
- Energy consumption is higher!
- But longer service life!
- Easier to pour the melt!
- Turbulence at the surface is more!
Coreless induction furnaces

Metal is heated by the outer primary coil. Less efficient than the channel type furnaces. However, melting capacity is higher. Preferred for melting fine scrap. Is more economical in fine scrap melting than gas fired crucible furnaces.

Advantages:
Melting efficiency %50-70
Low emissions / low oxidation losses
Homogeneous melt

Disadvantages:
High investment and process costs
Channel type induction furnaces

- Often employed as holding furnaces
- Operates at 60 Hz frequency.
- Inductor is underneath the crucible (metal)
- Melt surface is still (hence they are preferred in melting copper which is very sensitive to oxygen pick up).
- Provides a turbulence-free mixing of the molten alloy
- Energy efficiency is higher than coreless furnaces.
Channel type induction furnaces

Offers flexibility in geometrical design and configuration
### Induction furnaces - comparison

<table>
<thead>
<tr>
<th>Furnace with channel inductor</th>
<th>Furnace with coreless inductor</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cleaning cycles</strong></td>
<td></td>
</tr>
<tr>
<td>52 cleaning cycles</td>
<td>no cleaning cycles</td>
</tr>
<tr>
<td>3 man-days each (1,248 h)</td>
<td></td>
</tr>
<tr>
<td>52 production downtimes due to cleaning</td>
<td>no production downtime due to cleaning</td>
</tr>
<tr>
<td>2 x 24 h each (2,496 h)</td>
<td></td>
</tr>
<tr>
<td><strong>Inductor change</strong></td>
<td></td>
</tr>
<tr>
<td>At least 5 inductor changes / shutdowns for repair</td>
<td>½ – 1 vessel change / shutdowns for repair</td>
</tr>
<tr>
<td>10 man-days each (400 h)</td>
<td>(1-3 man days → 8-24 h / 3 staff)</td>
</tr>
<tr>
<td>5 production downtimes</td>
<td>½ – 1 production downtimes</td>
</tr>
<tr>
<td>5 x 24 h each (120 h)</td>
<td>10-30 h</td>
</tr>
<tr>
<td>At least 5 repair deployments</td>
<td>½ – 1 repair deployment</td>
</tr>
<tr>
<td>€10,000/piece each → €50,000</td>
<td>€10,000/piece each → €3,300-10,000</td>
</tr>
<tr>
<td><strong>Refractories</strong></td>
<td></td>
</tr>
<tr>
<td>5 levelling processes and conditioning work on rectangular flange</td>
<td>½ – 1 levelling process and conditioning work on round flange</td>
</tr>
<tr>
<td>5 x 3 h (15 h)</td>
<td>1-3 h</td>
</tr>
</tbody>
</table>
Recycling

Aluminium scrap
Furnaces for recycling scrap
Rotating furnaces

With a capacity of 1-20 tons, rotary tilting furnaces are employed in melting fine scrap and returns and in recovering aluminium metal from dross.
Rotating furnaces

The furnace is tilted upwards to achieve maximum heating efficiency when heating dross. The furnace is repositioned for tapping once the aluminium inside the dross is recovered and the melt is poured into moulds.
Rotating furnaces

- ideal for melting scrap and dross (with Al >%35)!
- Metal is charged into furnace with flux!
- Rotation of the furnace increases the contact of the metal with the burner flame allowing faster transfer of the heat from the refractories.
- capacity 2-5 ton

**Advantage**
- Ability to process scrap as well as dross

**Disadvantage**
- Low efficiency
- Frequent maintainence
- Salt residues
Shaft (tower) furnaces

- Higher thermal efficiency!
- These furnaces are both melting and holding units. They consist of three chambers, the first is a preheating area charged with a mixture of foundry returns and ingot by a skip charging machine.
- Waste heat from the melting and holding burners heats the charge removing moisture and oil before melting takes place.
- The preheated charge then enters the gas-fired melting zone and the liquid aluminium runs down into the holding bath.
- Temperature is accurately controlled within ±5°C.
Shaft (tower) furnaces

1. Waste gas temperature control
2. Waste gas hood
3. Baffle
4. Preheating zone
5. Holding chamber
6. Charging door
7. Charging car
8. Charging unit
9. Shaft/melting zone
10. Furnace body

Gas-fired shaft furnace
Shaft (tower) furnaces

- Typical shaft furnaces range in size from a holding capacity of 1000 kg and a melting rate of 1000 kg/hour to over 3000 kg holding and 3000 kg/hr melting capacity.
- Shaft furnaces of much larger capacity are also available.
- Molten aluminium is discharged to a transfer ladle or launder either by hydraulically tilting the holding bath or by a tap-out system.
- Energy consumption of 580-640 kWh/ton (2-2.3 GJ/ton) can be achieved with melting losses of 1-1.5% when melting 50/50-ingot/foundry returns.
Shaft (tower) furnaces

- Operating the furnace below rated capacity has a significant effect on energy consumption.
- A furnace working at 50% of its rated throughout may use almost twice as much energy per ton (1070 kWh/ton, 3.8 GJ/tonne).
- Typical metal loss in a shaft furnace melting about 50% ingot + 50% foundry returns: 1-1.2%
- Refractory life is high, with relining needed every 3 or 4 years.
- Cleaning once per shift is necessary to avoid corundum build-up.
Shaft (tower) furnaces

- Efficiency is higher than that of reverberatory furnaces.
- Efficiency increases further when the flue gases are utilized to heat the charge.
- Charge heats up as it moves down the shaft and is melted by the burners when it arrives at the bath.
- Energy efficiency is around 40-50%.
- Metal loss drops from around 4-8% in reverberatory furnaces to about 1%.
Shaft (tower) furnaces

The material to be melted is loaded into the vertical shaft where it is preheated with the flue gases from the melting and holding region of the furnace!

Hot flue gases

Skip loader

Oxide and iron debris

burner

molten aluminium
Shaft (tower) furnaces

- The shaft is offset from the bath so that unmelted debris does not enter the liquid metal directly - metal enters the bath by first melting and then running over a supporting platform, and so joining the bulk of the melt.
- The oxide skins are left behind at the base of the shaft, together with other unwanted debris such as iron inserts in scrapped castings.
- The sloping hearth of the furnace can be scraped clean of such accumulations from time to time as melting progresses.
Shaft (tower) furnaces

Ergitme brülörrleri
## Comparison of furnaces

<table>
<thead>
<tr>
<th>Furnace - fuel</th>
<th>capacity</th>
<th>metal</th>
<th>loss</th>
<th>efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crucible (gas)</td>
<td>15 lbs - 1.5 tons</td>
<td>Aluminum</td>
<td>4-6%</td>
<td>7-19%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Magnesium</td>
<td>4-6%</td>
<td>7-19%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Copper-base</td>
<td>2-3%</td>
<td>7-15%</td>
</tr>
<tr>
<td>Cupola</td>
<td>100 lb/hr - 20 tons/hr</td>
<td>Iron</td>
<td>3-12%</td>
<td>40-50%</td>
</tr>
<tr>
<td>Direct Arc†</td>
<td>1.5 tons - 100 tons</td>
<td>Steel</td>
<td>5-8%</td>
<td>35-45%</td>
</tr>
<tr>
<td>Immersion (low temp melting)</td>
<td>1,600 lb/hr</td>
<td>Zinc</td>
<td>N/A</td>
<td>63-67%</td>
</tr>
<tr>
<td>Induction</td>
<td>2 lbs - 50 tons</td>
<td>Aluminum</td>
<td>0.75-1.25%</td>
<td>59-76%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Copper-base</td>
<td>2-3%</td>
<td>50-70%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Magnesium</td>
<td>2-3%</td>
<td>59-76%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Iron</td>
<td>1-2%</td>
<td>50-70%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Steel</td>
<td>2-3%</td>
<td>50-70%</td>
</tr>
<tr>
<td>Reverb.</td>
<td>0.5 tons - 125 tons</td>
<td>Aluminum</td>
<td>1-2%</td>
<td>59-76%</td>
</tr>
<tr>
<td>Electric</td>
<td></td>
<td>Zinc</td>
<td>2-3%</td>
<td>59-76%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Aluminum</td>
<td>3-5%</td>
<td>30-45%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Zinc</td>
<td>4-7%</td>
<td>32-40%</td>
</tr>
<tr>
<td>Reverb. gas</td>
<td>0.5 tons - 125 tons</td>
<td>Aluminum</td>
<td>N/A</td>
<td>35%</td>
</tr>
<tr>
<td>Rotary furnace</td>
<td>N/A</td>
<td>Aluminum</td>
<td>N/A</td>
<td>35%</td>
</tr>
<tr>
<td>Stack melter (gas)</td>
<td>1 ton/hr - 10 tons/hr</td>
<td>Aluminum</td>
<td>1-2%</td>
<td>40-45%</td>
</tr>
</tbody>
</table>
Melting furnaces

- Small foundries may use lift-out crucible furnaces in which the metal is melted and treated in a crucible which is then lifted out of the furnace for pouring.
- Large foundries usually melt aluminium alloy ingot and foundry returns in a bulk melting furnace, then transfer the metal to smaller holding furnaces near to the casting area.
- Degassing and metal treatment are usually carried out in the transfer ladle.
- The bulk melting furnaces can be coreless induction furnaces or, more commonly, gas-fired reverberatory or shaft furnaces.
- The tilting crucible furnace, which may be electric or gas, is also popular as a bulk melter. Holding furnaces may be electric or gas.
Holding furnaces

- Melting aluminium in a bulk melting furnace exposes the liquid metal to turbulence and oxidation.
- The low density of aluminium retards the “float out” of oxide inclusions, and it is desirable to allow the liquid alloy to stand in tranquil conditions to allow the non-metallics to float out before transferring to the casting ladle.
- A holding furnace is used to overcome this problem.
- They are frequently resistance-heated crucible furnaces, or radiant-roof bath furnaces, in which high insulation allows low holding power to be achieved.
- Capacities are typically 250-1000 kg, although much larger holding furnaces are possible.
Holding furnaces

Electrically heated crucible furnace.

Radiant roof holding furnace.
Dosing furnaces

- Pressure displacement dosing furnaces are designed to hold aluminium at temperature at the casting station and to automatically meter accurately.
- Charges of metal to the die by pressure displacement through a refractory riser tube.
- Accuracy of pour is within ±1.5%.
- They can be used to feed pressure diecasting machines and gravity-die carousels.
Choice of melting unit

- The number of alloys required by the foundry is a major factor in deciding the type of melting furnace used.

- A sand foundry may use several different alloys each day. In this case, tilting crucible furnaces may be the best solution even though they may not be the most fuel or labour efficient.
Choice of melting unit

- A pressure die casting foundry, on the other hand, may melt only a single alloy; so a bulk-melting tower furnace or induction furnace supplying small holding furnaces at each die casting machine is likely to be the lowest cost solution.

- Most gravity die casting foundries have some alloys which do not warrant bulk melting, so in addition to a bulk melter the foundries usually have some smaller melting furnaces, often of the crucible type.
Choice of holding unit

- In less critical applications, such as pressure die casting, or in foundries where inclusion control is accomplished by filtration of the metal in the mould, the holding furnace need not be so large and may be designed to allow alloy adjustment, temperature control and some metal treatment before transfer to the casting ladle.

- In pressure and gravity die casting foundries, it is convenient to have a holding furnace adjacent to the die casting machine in which metal is held at the correct temperature and from which it may be baled out to fill the die.
Lost Crucible Process
Alcan invention / Lost Crucible Process.

disposable fibre-ceramic crucible
Lost Crucible Process

- means of preventing poor metal transfer.
- a pre-weighed slug of material is rapidly melted in an induction furnace.
- instead of the normal refractory crucible, a disposable fibre-ceramic crucible is used.
- Once the charge is molten and at the required temperature, the base of the crucible is pushed out by a vertically moving piston.
- As the piston continues to move upwards, the base of the crucible acts as a seal and the molten metal is introduced through the bottom of the mould at a controlled rate.
Lost Crucible Process

- This new Alcan Lost Crucible Process will conserve the quality of the alloy as produced by the primary producer.
- However, for all other processes, where the metal has to be melted in a furnace and then transferred for casting, the problem exists of how to test the quality of the metal.
melt contamination
Melt contamination

- When its surface is cleared of oxide, liquid aluminium looks like quicksilver.
- However, the quality of the liquid underlying the silvery surface is likely to be anything but pure or clean metal.
- In fact, it is necessary to develop a view of the liquid as a slurry of sundry solid debris in suspension.
- It is only the size and quantity of solid debris which is changed from melt to melt and from one melting practice to another.
Melt contamination

$2\text{Al} + 3\text{H}_2\text{O} \rightarrow \text{Al}_2\text{O}_3 + 3\text{H}_2$

$2\text{Al} + \frac{3}{2}\text{O}_2 \rightarrow \text{Al}_2\text{O}_3$

Diagram:
- Dross
- Al$_2$O$_3$ film
- Trapped Al
- Inclusions
- H$_2$/H$^+$
- Al melt
- Dissolved impurities
impurities in molten aluminium

Oxides: potential sources:
- ingots
- foundry returns
- scrap
- additives
- melting practice

Hydrogen gas

Trace elements: e.g. alkalines
origin of oxide inclusions

- oxide skins on the surface of the material to be melted (the oxide skin on commercial ingots is not especially thick) arrive in the melt right from the start of melting.
- Upon melting the charge, the oxides float free and become dispersed in the melt.
- In the case of remelting foundry returns from a sand casting foundry, the oxide skin is especially thick and can remain intact during remelting and float into the area where metal is transferred to the casting station.
Such films finish up as complete, massive, film-like or dross-like inclusions in finished castings.

This direct recycling of the oxide skins occurs when the material to be remelted is introduced directly into the molten aluminium.

This happens in common types of melting furnace, such as crucible furnaces or reverberatory furnaces.

Whatever is added to these furnaces is automatically submerged and is redistributed inside and remains in suspension in the melt.
Oxides in molten aluminium

1. Fine dispersion of oxides following rotary degassing.
2. Large oxide from remelted returns.
3. High quality melt after filtration.
Molten aluminium is an extremely efficient 'getter' for oxygen and calculations show that a vacuum of less than $10^{-40}$ atms would be required to prevent oxide film formation.

Molten aluminium and its alloys immediately oxidise forming an oxide skin.

In pure aluminium this is $\text{Al}_2\text{O}_3$ but the presence of Mg in the alloy can cause the oxide to form as $\text{MgO}.\text{Al}_2\text{O}_3$ (spinel).

$\text{Al}_2\text{O}_3$ and $\text{MgO}.\text{Al}_2\text{O}_3$ have nearly the same density (only 5% less) with liquid aluminium; so flotation of oxide inclusions is slow.
oxidation-oxides

- The oxide skin has a protective effect, preventing catastrophic oxidation of the melt (which occurs when magnesium is melted) but it causes problems during melting and also during casting.
- An oxide film can form even as the metal is filling the mould and can give rise to entrained oxide in the casting harming the physical properties of the casting and possibly causing leaking castings.
- Entrained oxide films in aluminium alloy castings have harmful effects.
oxidation

temperature $\uparrow \rightarrow$ Oxidation $\uparrow$

furnaces
transfer systems
in-line rafination unit HEAT LOSSES MUST BE AVOIDED!

excessive heating of the melt must be avoided!

melting furnace $\ T < 760^\circ C$
holding furnace $\ T < 730^\circ C$

TEMPERATURE CONTROL!
SOUND PRACTICES!
Oxidation rate (mg/cm²/h) vs. T (°C)
Forms of oxides in liquid aluminium alloys

<table>
<thead>
<tr>
<th>Growth time</th>
<th>Thickness</th>
<th>Description</th>
<th>Possible source</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01–1 sec.</td>
<td>1 μ.m</td>
<td>Confetti-like fragments</td>
<td>Pour and mould fill</td>
</tr>
<tr>
<td>10 sec.–1 min.</td>
<td>10 μ.m</td>
<td>Flexible, extensive films</td>
<td>Transfer ladles</td>
</tr>
<tr>
<td>10 min.–1 hr</td>
<td>100 μ.m</td>
<td>Thicker films, less flexible</td>
<td>Melting furnace</td>
</tr>
<tr>
<td>10 hr–10 days</td>
<td>1000 μ.m</td>
<td>Rigid lumps and plates</td>
<td>Holding furnaces</td>
</tr>
</tbody>
</table>

(From Castings, Campbell, J. (1991), Butterworth-Heinemann,
Oxides due to surface turbulence

Surface turbulence in liquid metals
Oxide Formation

- When a metal is poured rapidly into a mould, it enters in a turbulent manner, and it is inevitable that the oxide film folds over itself so that oxide-to-oxide contact occurs.
- Furthermore, as the metal tumbles over and churns about, the oxide film is continually being stretched and ruptured and also re-growing.
- In the case of grey cast irons, this is not too serious since the liquid silicate films can meet and fuse together, agglomerating to form droplets which generally float out of the molten iron.
- Even if they remain in the iron, they normally have a shape which does not have a detrimental effect on properties.
In contrast, when the solid alumina (Al$_2$O$_3$) films on molten aluminium meet, they do not ’knit’ together, but instead form crack-like defects which remain in the casting as it solidifies.

These introduce a mechanical weakness into the casting which will probably result in it being less reliable in service.

Such crack-like defects also often result in leakage problems in castings which are required to contain a liquid or a gas.

Unfortunately, aluminium castings have an unenviable reputation for being prone to leakage defects as a result of poor filling practice.
oxides

- For inclusion-free castings it is advisable to use metal filters to clean the metal as it enters the mould.
- Fluxes are used during melting to protect the metal from oxidation and to trap oxides as they float out of the melt.
Corundum \((\text{Al}_2\text{O}_3)\) growth

- Corundum is formed when aluminium comes into contact with silica in the furnace lining. Corundum growth is well known in the aluminium melting industry.
- It is a composite of alumina and metal which grows on the refractory wall above the metal level in holding furnaces.
- They are extremely hard, smooth and initially hemispherical.
- When viewed in the hot furnace they are generally grey or black, a few mms to tens of cms in size.
- They are difficult to remove from the walls!
Corundum (Al₂O₃) growth
Corundum \((\text{Al}_2\text{O}_3)\) growth

- The growth direction is generally away from the metal line, upwards towards the roof of the furnace in a mushroom shape.
- Corundum growth not only reduces capacity of the furnace but it reduces the thermal efficiency and causes damage to the furnace lining through refractory expansion.
- A significant amount of aluminium metal may also be lost from the furnace charge.
- To avoid serious corundum growth, regular inspection of the furnaces must be carried out and growths removed while they are small.
Corundum growth

- The furnace refractories should be resistant to metal attack, by having a high bauxite content and low free silica content.
- Refractories should be non-wetting and of low porosity to avoid corundum nucleation.
- High temperature, oxidising furnace atmospheres and the presence of unburned hydrocarbons should be avoided.
- Daily cleaning of the furnace refractories with a suitable flux is advisable.
The only gas that dissolves in aluminium in appreciable levels is hydrogen as it does not form compounds with aluminium (oxygen forms $\text{Al}_2\text{O}_3$ and nitrogen forms AlN). Hydrogen has a high solubility in liquid aluminium which increases with melt temperature, but the solubility in solid aluminium is very low, so that as the alloy freezes, hydrogen gas is expelled forming gas pores in the casting.
Hydrogen in aluminium melts

- only 5% of the hydrogen (1 in 20) is retained in solution as the aluminium solidifies.
- The remaining 95% will be rejected and will form gas pores, providing nuclei are present.

\[ H \rightarrow H_2 \rightarrow \text{gas porosity} \]

- As the hydrogen solubility in molten aluminium increases with increasing melt temperature, measures must be taken to avoid excessive heating of aluminium bath!
Hydrogen in liquid aluminium at 660°C: 0.69 ppm drops to 0.039 ppm after solidification.
When there is too much hydrogen in solution and many oxides and other inclusions not wet by aluminium, there will be porosity!

If the melt is free of inclusions then the gas will be unable to precipitate and will remain in solid solution. will form H₂ gas during high temperature annealing treatments.

\[ H \rightarrow H_2 \rightarrow \text{gas porosity} \]
Sources of hydrogen in castings

Hydrogen can come from:

- **Melting and/or subsequent handling**: a common problem is hydrogen pickup from the use of damp refractories in furnaces or ladles. Another source is from burning hydrocarbon fuels, such as gas or oil.

- **Reaction with the mould during passage through the running system**.

- **Reaction with the mould and core materials during and/or after filling**.
Hydrogen in aluminium melts

Foundries are hot and humid places. Hydrogen comes from:

- Water vapour in the atmosphere
- Water vapour from burner fuels
- Damp refractories and crucible linings
- Damp fluxes
- Oily or dirty scrap charges
- Dirty or damp foundry tools
Hydrogen in aluminium melts

The reaction of moisture with aluminium forms Al₂O₃ while releasing H which then dissolves in molten aluminium.

\[ 3 \text{H}_2\text{O} + 2\text{Al} = \text{Al}_2\text{O}_3 + 6\text{H} \]

Scrap melting: 0.50 ml/100g
Wrought alloys: 0.18 ml/100 g
Foundry alloys: 0.40 ml/100g
Sources of hydrogen in castings

- Gas dissolved in the melt is in the form of atoms. These atoms can diffuse to the surface, combine to form gas molecules, and evaporate into the environment.
- A furnace gains or loses gas from contact with its environment, the rate of transfer of gas depending on the ratio of surface area to volume.
- However, in many cases, a surface oxide film is present, or a slag or flux layer.
- These additional layers present a further barrier to the release of gas atoms from the melt.
Sources of hydrogen in castings

- Melting and/or subsequent handling
  - Damp refractories
  - Gas/oil fired furnaces
- Passage through the running system
- Reaction with mould/core materials

Metal dies:
- dry, relatively free from $\text{H}_2$
- metal being cast tends to lose $\text{H}_2$

Chemically-bonded and greensand moulds:
- Heat $\rightarrow$ steam $\rightarrow$ decomposition to $\text{H}_2$
  $$3 \text{H}_2\text{O} + 2 \text{Al} = 3 \text{H}_2 + \text{Al}_2\text{O}_3$$
- Metal being cast tends to gain $\text{H}_2$
To reduce hydrogen pick-up, refractories, crucibles, tools and oily scrap should be thoroughly preheated to remove water.

Burner flames should be slightly oxidising to avoid excess hydrogen in the products of combustion.

The melt temperature should be kept as low as possible since more hydrogen is dissolved at high temperatures.

Nevertheless, hydrogen will still be present. Cannot be totally eliminated!
The amount of porosity that can be tolerated in a casting is determined by the method of casting and the end use of the component.

If the metal cools relatively slowly, as in a sand mould, the ejected gas can build up into small bubbles which are trapped in the pasty metal.

These are then uncovered by any subsequent machining or polishing operation and show as a “pinhole” porosity defect in the finished surface.

The mechanical strength and pressure tightness can also be seriously affected.
Hydrogen + casting method

- Where the rate of solidification is more rapid as in gravity and low pressure diecasting, the emerging bubbles are usually small and well dispersed.
- Therefore, they affect mechanical properties less, and indeed often have a beneficial effect in offsetting possible localised shrinkage unsoundness that might otherwise cause the casting to be scrapped.
- For high integrity gravity and low pressure castings, it may still be necessary to apply a full degassing process.
In the past, it has not been usual to degas metal for pressure diecasting since diecastings usually contain gas porosity arising from air entrapped in the casting during metal injection.

The additional porosity from hydrogen in the melt was not considered serious, particularly since the metal holding temperature for pressure diecasting is usually low, reducing the amount of hydrogen pick-up.

Recently, with the improvement in diecasting technology (marked reduction in entrapped air), more diecasters are using degassed metal.
Sources of impurities

- Primary metal from electrolysis
- Smelter Grade Alumina (SGA)
- Secondary alumina (from scrubbing)
- Cryolite ($\text{Na}_3\text{AlF}_6$) bath and $\text{AlF}_3$ make-up
- Anode carbon
- Steel tools and current collectors.
- Secondary ‘re-melt’ of previously solidified primary metal - primary impurities, plus processing and alloying elements
- Tertiary metal (recycled scrap, new or old)
Alkaline metals

- Na and other alkalines and alkaline earth elements come from the Hall-Heroult cell of the primary production cycle!
- Ca, K, Li and Na increase the hydrogen solubility of aluminium melt and encourage hydrogen porosity after solidification.
- Alkaline metals also impair the hot rolling properties.
- They lead to hot tearing and increase brittleness.
- They degrade surface quality by causing colouration in moist atmospheres (blue haze corrosion).
Dissolved impurities originating in electrolysis

<table>
<thead>
<tr>
<th>Impurity</th>
<th>Al$_2$O$_3$ (wt%)</th>
<th>Na$_3$AlF$_6$ (wt%)</th>
<th>AlF$_3$ (wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO$_2$</td>
<td>0.007-0.020</td>
<td>0.12-0.13</td>
<td>0.10-0.15</td>
</tr>
<tr>
<td>Fe$_2$O$_3$</td>
<td>0.008-0.022</td>
<td>0.04-0.11</td>
<td>0.01-0.02</td>
</tr>
<tr>
<td>TiO$_2$</td>
<td>0.002-0.008</td>
<td>0.001</td>
<td>0.008-0.0012</td>
</tr>
<tr>
<td>CaO</td>
<td>0.003-0.035</td>
<td></td>
<td>0.06-0.10</td>
</tr>
<tr>
<td>ZnO</td>
<td>0.001-0.011</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V$_2$O$_5$</td>
<td>0.0012-0.004</td>
<td>0.001-0.005</td>
<td>0.0002-0.0003</td>
</tr>
<tr>
<td>P$_2$O$_5$</td>
<td>0.0004-0.0011</td>
<td></td>
<td>0.015-0.02</td>
</tr>
<tr>
<td>Cr$_2$O$_3$</td>
<td>0.002</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ga$_2$O$_3$</td>
<td>0.007-0.008</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Na$_2$O</td>
<td>0.3-0.45</td>
<td></td>
<td>0.10-0.15</td>
</tr>
<tr>
<td>K$_2$O</td>
<td>0.01-0.08</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H$_2$O</td>
<td></td>
<td>0.17-0.3</td>
<td>0.2-0.3</td>
</tr>
<tr>
<td>Ca</td>
<td></td>
<td>0.0-0.08</td>
<td>0.009-0.070</td>
</tr>
<tr>
<td>SO$_4$</td>
<td></td>
<td>0.54-0.69</td>
<td>0.9-1.5</td>
</tr>
</tbody>
</table>

Thonstad et al. (2001)
Dissolved impurities

Petroleum Coke Used for Anodes

<table>
<thead>
<tr>
<th>Impurity</th>
<th>PPM</th>
<th>Impurity</th>
<th>PPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>50-250</td>
<td>B</td>
<td>1</td>
</tr>
<tr>
<td>Fe</td>
<td>50-400</td>
<td>Na</td>
<td>30-120</td>
</tr>
<tr>
<td>Ti</td>
<td>2-50</td>
<td>Mg</td>
<td>100</td>
</tr>
<tr>
<td>Zn</td>
<td>2-50</td>
<td>Ca</td>
<td>20-100</td>
</tr>
<tr>
<td>V</td>
<td>30-350</td>
<td>Mn</td>
<td>4</td>
</tr>
<tr>
<td>Cr</td>
<td>1-2</td>
<td>Ga</td>
<td>14</td>
</tr>
<tr>
<td>Ni</td>
<td>50-220</td>
<td>Pb</td>
<td>3</td>
</tr>
<tr>
<td>Cu</td>
<td>1-3</td>
<td>Al</td>
<td>50-250</td>
</tr>
<tr>
<td>S</td>
<td>5000-35000</td>
<td>Ash</td>
<td>1000-2000</td>
</tr>
</tbody>
</table>

Thonstad et al. (2001)
typical impurities in electrolysis and re-melt aluminium

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Smelter</th>
<th>Remelt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composition</td>
<td>≥ 99.7% Al</td>
<td>Alloyed or close to final composition</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>0.1 – 0.3 ppm</td>
<td>0.2 – 0.6 ppm</td>
</tr>
<tr>
<td>Alkali Na</td>
<td>30 – 150 ppm</td>
<td>≤ 10 ppm</td>
</tr>
<tr>
<td>Ca</td>
<td>2 – 5 ppm</td>
<td>5 – 40 ppm</td>
</tr>
<tr>
<td>Li</td>
<td>0 – 20 ppm</td>
<td>&lt; 1 ppm</td>
</tr>
<tr>
<td>Inclusions (PoDFA scale)</td>
<td>&gt; 1 mm²/kg Al₄C₃</td>
<td>0.5 &lt; mm²/kg &lt; 5.0 Al₂O₃, MgO, MgAl₂O₄, Al₄C₃, TiB₂</td>
</tr>
</tbody>
</table>
melt treatment
Before casting aluminium alloys, the molten metal must be treated in order to:

- **Degas**
  Molten aluminium contains undesirable amounts of hydrogen which will cause porosity defects in the casting unless removed

- **Grain refine**
  Mechanical properties of the casting can be improved by controlling the grain size of the solidifying metal

- **Modify**
  The microstructure and properties of alloys can be improved by the addition of small quantities of certain “modifying” elements
Melt treatment operations

- degassing
- rafination-fluxing
- inclusion removal
- drossing
- mixing-homogenization
- alloying
- modification
- grain refinement
- filtration
- melt quality control
Degassing aluminium alloys

● maximum concentration of dissolved hydrogen possible in aluminium alloys can be as high as 0.6 ml H₂/100 g.

● By careful attention to melting practice this can be reduced.

● However, even with the best practice, remelted foundry alloys may be expected to contain 0.2-0.3 ml H₂/100 g Al.

● The degassing process involves bubbling dry, inert gases through the melt to reduce the hydrogen level to around 0.1 ml/100 g.
Degassing foundry alloys

- Liquid and solid solubilities of hydrogen are different in different alloy systems and a hydrogen level of 0.12 ml/100 g will give castings free from porosity in Al-Si5Cu3Mn0.5.

- While the low silicon Al-Cu-Ni alloy will be porosity free at 0.32 ml H₂/100 g.

- If levels of hydrogen are taken too low, it is difficult to avoid some shrinkage porosity in the castings.

- Shrinkage is often compensated by H₂ gas!
Degassing via tablets

- For many years, the use of chlorine gas, developed by plunging hexachloroethane ($C_2Cl_6$) in the form of DEGASER tablets, was the standard method of treatment.
- The use of $C_2Cl_6$ was prohibited in EU in 1998.
- $C_2Cl_6$ tablet degassing has been replaced by degassing with dry nitrogen or argon using a lance or preferably a specially designed rotary impeller which ensures even dispersion of fine bubbles throughout the melt.
- Tablets which produce nitrogen, when plunged under the metal surface gas can also be used.
Hexachloroethane is used in metal and alloy production, and as an ingredient in insecticides. Hexachloroethane acts primarily as a central nervous system (CNS) depressant in humans acutely (short-term) exposed to it. Hexachloroethane is also moderately irritating to the skin, mucous membranes, and liver in humans. Neurological, liver, and kidney effects have been observed in animals exposed to hexachloroethane. No information is available on the chronic (long-term), reproductive, developmental, or carcinogenic effects of hexachloroethane in humans. Hepatocellular carcinomas (liver tumors) were observed in mice following oral exposure to hexachloroethane. EPA has classified hexachloroethane as a Group C, possible human carcinogen.
Degassing via purging

- Inert gases (argon or nitrogen) are purged into molten aluminium with lances that are lined with ceramics.
- Measures must be taken to avoid turbulence inside the bath and to maintain the stability of the bath surface.
- Purging gas may contain a small fraction of Cl if the bath is too dirty.
Lance degassing

Gas bubbles release the $\text{H}_2$ into the furnace atmosphere when they reach the surface!

Inert gas bubble filled with: $\text{H}_2$

Inert gas bubble: low $\text{H}_2$ partial pressure! $\text{H}^+$ diffuses into the inert gas bubbles!
The size of bubbles from such a lance are large and disturb the melt:

Little gas is purged from the liquid, and the melt comes into equilibrium with the surrounding environment because the freshly presented surface is ideal for re-introducing fresh hydrogen into the melt.

In addition, the rolling action of the surface creates extra oxide and may stir this into the melt. Furthermore, the impurities in the purge gas will generate additional oxide in the liquid.
Furthermore, the impurities in the purge gas will generate additional oxide in the liquid due to leaks in the gas line.

The extended time for such low efficiency degassing methods means that much additional oxide is introduced.

Where degassing with N is carried out, as in some large holding furnaces, and where the alloy contains some Mg (quite common), there is an additional danger of the build-up of nitrides in the melt.

This can become so prolific that the melt takes on the appearance of a slurry.
The mechanical properties of the resulting castings are low because of the embrittling effect of the large concentration of nitrides. The only way to avoid such disasters when attempting to degas continuously is to use a truly inert gas such as argon. In addition, of course, the gas lines should be soundly plumbed in metal throughout.
Lance Degassing

Degassing is often carried out poorly, using an open-ended lance to introduce a purge gas into the melt.

- **nitrogen**

  **disadvantages**

  - Size of the bubbles
  - Surface disturbance
  - Leaks in gas line
  - Impurities in gas
  - Formation of Mg nitrides
  - Limited purging effect
  - Gas pick up & Oxide incorporation
  - Additional oxides
  - Poor properties
For any degassing technique to be efficient, it is necessary that very fine bubbles of a dry, inert gas are generated at the base of the melt and allowed to rise through all areas of the molten aluminium: rotary degassing.

A central hollow rotor introduces a purge gas (usually nitrogen) into the centre of a melt, where the emerging bubbles are fragmented and dispersed by the rapid rotation of the rotor.

The large total area of the bubbles and their wide dispersion throughout the melt give a rapid degassing action.
Rotary degassing

- While the hollow lance might give only poor degassing in an hour or so, the rotary technique typically reduces hydrogen to very low levels in only 10 mins.
- A correctly designed rotor produces many small bubbles into which dissolved H atoms diffuse to be ejected into the atmosphere when the bubble reaches the surface.
- The rising bubbles also collect inclusions and carry them to the top of the melt where they can be skimmed off.
- The graphite rotor is designed to produce the optimum bubble cloud throughout the whole of the melt.
Degassing with a rotating diffuser

Advantages
- Smaller inert gas bubbles //
- More inert gas surface area-
  increased contact
- Efficient degassing
- Much less disturbance of the surface
- Oxides uniformly distributed
- Smaller $\text{H}_2$ porosity!
- CLEAN METAL
Rotary degassing
Rotary degassing

The metal temperature should be as low as possible during this operation. Melts of 400-1000 kg can be treated in 1.5 to 5 minutes with gas flow between 8 and 20 litres/minute. The graphite rotor has a life of 100-150 treatments according to the temperature of the melt.
Rotary degassing

- The treatment time, gas flow and speed of rotation are critical operation parameters and are preset for a given furnace capacity for a treatment that lasts 3 to 5 minutes.
- Rotor rotation speed is typically around 400-500 rpm and at this speed the optimum quantity of purging gas is dispersed giving very fine bubbles, resulting in high degassing efficiency and thorough cleansing of the melt through oxide flotation.
- After treatment the rotor is raised from the furnace or ladle, the metal skimmed clean and is ready for casting.
Rotary degassing

Diagram of a rotary degassing process showing the drive, shaft, rotor, and furnace/ladle. The process involves the use of Ar or N2, and the reaction involves H₂ and H₂O, resulting in the production of Ar and H₂.
Commercial degassers
Rotary furnace degassing

Before fluxing

After fluxing
“Porous plug” degassing

Degassing with inert gases introduced into molten aluminium through porous ceramic plugs mounted at the bottom of reverberatory furnaces offers more uniform and much more efficient removal of Hydrogen gas.
porous plug degassing
Degassing

![Graph showing the decrease of hydrogen gas (H₂) in ml/100g Al with degassing time in minutes. The graph includes points for 0.243, 0.130, 0.091, and 0.067 ml/100g Al at different degassing times.](image-url)
Oxide removal during degassing

inert gas bubbles help to float the inclusions in suspension!
Bubble formation in the graphite rotor
Hydrogen removal in degassing
inclusion removal in degassing
flux degassing

- A logical development of the rotary degassing system is the injection of fluxes into the melt along with the inert purge gas.
- Early attempts to do this were plagued with difficulty because the fluxes melted in the injector nozzles causing total or partial blockage.
- Granular fluxes has greatly assisted in this respect.
- The flux feeder gives accurate dosing rates and the flux is fed into the molten aluminium at the base of the melt so that full reaction can take place before the additive reaches the metal surface.
flux degassing

- Flux is introduced into the melt during the first part of the treatment cycle followed by a degassing cycle.
- The combined effect of flux injection and degassing produces cleaner alloy (fewer inclusions) than degassing alone and mechanical properties, particularly elongation values, are improved. In addition, metallic aluminium in the dross skimmed from the melt is reduced by 20-40%.
- The Rotary Degassing Unit and the Metal Treatment Station are widely used in gravity, low pressure and high pressure diecasting foundries.
The rotor and shaft of the Metal Treatment Station have been designed to allow the free passage of the additive into the metal melt, reducing to a minimum the problem of fusion of the treatment product in the shaft.
Effect of flux degassing

- A treatment which cleans and simultaneously degases the melt.
- Powered chloride and/or fluoride flux is blown into the melt in a carrier gas, usually nitrogen.
- **Oxides and gas are not totally eliminated**
  - If oxide content is reduced by %95 and if gas content is reduced by %75;
  - Remaining %25 gas precipitates on %5 remaining nucleation sites.
  - Overall porosity in the casting is reduced but is 5X worse locally.
- **Environmental disposal problems.**
Effect of flux degassing

- the system may actually be introducing a new dispersion of fine oxides, possibly by fragmenting the large films which were originally in suspension, or possibly by reaction with the oxide or moisture contamination of the purge gas, which can arise either from trace impurities in the original gas or impurities introduced from sources in the local plumbing.

- An additional dispersion of nitrides is to be expected if nitrogen is used for degassing melts which contain some Mg.
Effect of flux degassing

- This fine dispersion of solids may have some benefits to melts intended for the production of shaped castings (provided that very high mechanical properties are not required).

- The low hydrogen content, together with the high density of nuclei on which the hydrogen can precipitate, will probably ensure that the residual hydrogen porosity, if present at all, is extremely fine and well dispersed.

- Thus the quality of the melt will be expected to be quite different from that produced by flux degassing.
Case study: State of melt

- In a major low pressure die casting plant, the quality of alloy sitting in the well is good at the beginning of the Monday morning shift.
- However, as the shift progresses, the slopping of the metal up and down the riser tube, and the consequent disturbance of the sediment on the furnace bottom, results in a considerable increase in oxide level.
- A further major increase occurs when the furnace is topped up. The churning and surging of the melt and the thorough mixing-in of floor sediments greatly impair the melt quality further.
- During the day, the melt continues to deteriorate.
Alcan Compact in-line degasser (ACD)
in-line degassing

snif-sheer system with lifting roof
When nitrogen is used for degassing and if the melt contains Mg, there is an other problem.

- Nitrides form during and after degassing treatment.
- Castings suffer poor mechanical properties since the nitrides are brittle ceramic particles.
- This can be avoided by using argon for degassing Mg-bearing aluminium alloy melts.
Fluxes

Flux salts

Spent flux salts could be a major source of problems

NaCl-KCL mixtures

Cover fluxes

Rafination fluxes

Drossing off fluxes

Wall cleaning fluxes
why do we need fluxes!

Oxidation of molten aluminium is inevitable!

\[ \rho_{\text{Al}_2\text{O}_3} \sim \rho_{\text{siv1 Al}} \Rightarrow \text{inclusions in suspension!} \]

\[ < \rho_{\text{siv1 Al}} \Rightarrow \text{inclusions float!} \]

\[ > \rho_{\text{siv1 Al}} \Rightarrow \text{inclusions sink!} \]

Fluxing is essential in order to

- to avoid the contact of aluminium melt with the furnace atmosphere
- to release inclusions in suspension and to improve melt quality
- to get a dry dross after skimming
- to maintain clean furnace walls

Flux selection is critical!
Critical features of fluxes

- Melting point must be lower than that of Al (660 °C)! the lower the melting point of the cover flux, the more efficient its use.
- Density must be lower than that of molten Al (~2.3g/cm³)!
- Must be inert to furnace refractories!
- Vapour pressure must be low!
- Fluidity must be high!
- Must be recyclable!
- Must conform to the health-safety codes!
- Must be cheap!
issues of flux practice

- fluxes immediately absorb atmospheric moisture: damp fluxes do more harm than good!
- Packaging is thus critical!
- fluxes must be packaged in addition dose!
- fluxes must be added in packages!
- fluxes must never be exposed to the furnace atmosphere)
Flux types

- cover fluxes
- drossing off fluxes
- rafination fluxes
- wall cleaning fluxes
Cover fluxes

- must be liquid and must cover the melt in order to avoid contact with the furnace atmosphere.
- must melt at the operation temperature.
  
  \[ Tm \uparrow \rightarrow \text{Flux-dross layer mushy} \rightarrow \text{metal loss} \uparrow \]
  
  wet (high Al content) dross

  \[ Tm \downarrow \rightarrow \text{Flux-dross layer liquid} \rightarrow \text{metal loss} \downarrow \]
  
  flux inclusions handling difficult!

- the liquid flux layer protects the melt from oxidation and hydrogen pick-up.
Cover fluxes

- NaCl + KCl : (%44 + % 56)
  binary eutectic : 645°C

- NaCl + KCl + NaF mixture
  ternary eutectic : 607°C

- Cover flux must not be intermixed with aluminium alloy melt!

- Cover flux must be employed after all treatments are over, for melt held for casting!

- Binary and ternary mixtures are also ideal carriers!
Cover fluxes

KCl-NaCl binary phase diagram
Cover fluxes

Most fluxes contain sodium and it is possible for the metal to pick up as much as 0.001% Na from them.

For most aluminium alloys the sodium has no effect or is beneficial, but alloys containing more than 2% Mg may become brittle with even trace amounts of sodium, so they are treated with sodium-free fluxes.

Approximately 0.5% of the flux is put onto the solid charge and a further 2% sprinkled evenly over the surface when the alloy is fully molten.

When the flux becomes pasty or liquid at about 750°C, the flux is worked well into the melt with a bell plunger for about 3 minutes.
Drossing off fluxes

- A drossing-off flux is used to absorb oxides and non-metallic material, cleansing the metal and forming a good metal-free dross which can easily be removed.
- Drossing-off fluxes agglomerate the oxides allowing easy removal from the surface of the melt.
- They are used to remove the dross with the minimum metal loss (dry dross-pure in metal).
- Typical ingredients:
  \[ \text{NaCl} + \text{KCl (carrier)} + \text{KNO}_3 : \text{(nitrate, sulfate, carbonates)} + \text{fluorides} \]
Drossing off fluxes

- Exothermic compounds $\rightarrow$ thermite reactions
  $\triangle Q \rightarrow$ softening in the dross layer
  $\rightarrow$ frees trapped aluminium!

- Exothermic fluxes ensure that liquid aluminium trapped in the dross layer is returned to the melt.

- Floride compounds: contributes to oxide - metal seperation owing to their high wetting capacity!

- if added too much $\uparrow \rightarrow$ metal loss $\uparrow$
  if added too little $\downarrow \rightarrow$ softening effect $\downarrow$
  $\rightarrow$ metal loss $\uparrow$
Drossing-off before pouring

- When the melt is ready for drossing-off, the flux is spread over the metal surface, allowed to stand for a few minutes until fused and then rabbled into the dross for several minutes with a skimmer.
- For best results the melt should preferably be above 700°C although fluxes will function well below 650°C.
- Doors are then closed and the burner is turned on for 10 minutes.
- This helps to activate the flux, heating the dross and giving good metal separation.
- The dross is then pulled to the door, allowed to drain and transferred to a dross bogie.
- If the dross in the bogie is raked, further metal will collect in the bottom.
In reverberatory and shaft furnaces, the quantity of flux needed will depend on the cleanliness of the charge material and on the surface area of the metal.

As a guide, it is recommended that an application of 1-2 kg/m² will suffice.

The behaviour of the flux will indicate whether the dosage needs to be reduced or increased in future applications.
Drossing-off before pouring

- In crucible furnaces, when drossing-off is carried out, the crucible sides are scraped and the required quantity of the selected flux (250 g is normally enough for the lift-out or bale-out furnace) is sprinkled onto the metal surface along with the existing flux cover and mixed into the surface of the melt until a red-glowing dross is obtained.

- This is exceptionally free of metal and can be removed with a perforated skimmer.
Rafination/cleaning fluxes

- they remove non-metallics from the melt by trapping the oxide particles as they float out!
- They help the oxides in suspension float,
- employed continuously in rafination units located in transfer systems or in melting (or holding) furnaces
- Typical ingredients:
  - NaCl + KCl (carrier) + Floride compounds (upto %20 Na₃AlF₆, CaF₂, Na₂SiF₆)
Rafination fluxes

- They penetrate between the oxide particles owing to their low solubility and help to physically separate the oxide particles from the molten metal!
- They strip the oxide films on the molten metal droplets and improve the metal recovery!
- Metal - oxide interface energy is reduced and the oxides are wet by the melt → oxides in suspension are removed from the melt while the aluminium metal entrapped by the oxides return back to the melt; aluminium and oxides are thus separated
- Dry dross is skimmed off!
Rafination fluxes

- if added too much → the fluidity of the flux is impaired due to the high melting point of fluorides → metal loss ↑

- The most effective (yet the most expensive) fluoride salt is: \( \text{Na}_3\text{AlF}_6 \)

- Addition practice: stir the flux into the molten alloy!
  - wait for 5 to 10 minutes - allow enough time for oxides to float
  - dross is skimmed off!
Removal of Alkalines with Cl$_2$/Ar

![Graph showing concentration (ppm) vs. duration of fluxing (min) for Li, Na, and Ca with actual and model data.](chart.png)
Removal of alkalines

Removal of alkaline and alkaline earth metals via flour fluxing

\[ 2 \text{AlF}_3 + 3 \text{Ca} = 2 \text{Al} + 3 \text{CaF}_2 \text{ (slag)} \]
\[ \text{AlF}_3 + 3 \text{Na} = \text{Al} + 3 \text{NaF} \text{ (slag)} \]
\[ 2 \text{AlF}_3 + 3 \text{Mg} = 2 \text{Al} + 3 \text{MgF}_2 \text{ (slag)} \]

Via chlorine fluxing

\[ \text{Ca} + \text{Cl}_2 = \text{CaCl}_2 \text{ (slag)} \]
\[ \text{Na} + \frac{1}{2} \text{Cl}_2 = \text{NaCl} \text{ (slag)} \]
\[ \text{Mg} + \text{Cl}_2 = \text{MgCl}_2 \text{ (slag)} \]
Removal of Mg: demagging

Specialist flux for the removal of excess magnesium from aluminium alloys. DEMAGGER B is a magnesium removing flux suitable for use with aluminium alloys where the magnesium content is over specification. We recommend using this product as manual flux.
Furnace-cleaning flux

- Aluminium melting furnace linings become coated with an oxide build-up and with time the oxide content increases to form the hard corundum phase.
- Metal quality, cleanliness is adversely affected if furnace refractories are not cleaned properly!
- In this case refractories can be cleaned only mechanically by crushing the corundum phase, causing damage to the refractories.
Furnace-cleaning flux

- The flux is mainly for application to the walls and roof of reverberatory and rotary furnaces.
- It can also be used for cleaning large transfer ladles, if these can be independently heated.
- The flux is not recommended for electric furnaces with exposed elements because of the possibility of element attack.
Furnace-cleaning flux

- Furnace cleaning flux is a strongly exothermic flux which attacks and strips oxide films.
- Typical ingredients are:
  \[ \text{NaCl} + \text{KCl} \text{ (carrier)} + \text{Oxygen bearing exothermic compounds (KNO}_3, \text{Alkaline carbonates)} \]
- The heat generated and the stripping action causes entrapped aluminium to melt and run down to the furnace hearth.
- Residues on walls are thus loosened and can be removed more easily by scraping tools.
bath level is brought to a minimum (minimum heel inside the furnace)!

The empty furnace is heated until the lining glows red (800-850°C). the walls are sprayed evenly with flux using a Flux Gun.

furnace doors are closed!

burners work full capacity for 10-15 minutes!

(walls are brought to the maximum possible temperature to help to soften the corundum layer!)
Furnace-cleaning flux

- Then the walls are scraped clean off the softened corundum layer.
- The recovered metal is finally tapped.
- A 10 tonne furnace will need about 25 kg of flux. Furnaces should be treated weekly to prevent accumulation of build-up.
- The flux can be used when making a change of alloy, to prevent contamination of the bath by residues from the preceding charge.
- Application once a week is recommended!
The formulations of fluxes have not changed for many years, being based on powdered halides including fluorides which are of concern environmentally and which can reduce the life of furnace refractories.

Attempts have been made to eliminate fluorides completely from the flux formulations, but unfortunately this rendered the flux ineffective.

The morphology of the flux was found to have a major effect on its efficiency.
**granulated fluxes**

- Granulated fluxes have significant environmental and technical advantages over the powder fluxes and are rapidly replacing them.
- Fluxes for aluminium contain chlorides and fluorides which may give rise to potentially harmful fumes in use on molten metal. Operators must avoid inhalation of the fumes or dust.
- Used flux must be disposed with care, referring to the local authority or a specialist disposal company.
granulated fluxes

granules    powder
By using fluxes in granular form rather than as conventional powders, the effectiveness of the flux can be greatly increased, the handling improved and the undesirable, hazardous emissions can be significantly reduced.

The higher cost of granulated fluxes (arising from the additional manufacturing process involved) is compensated by the much reduced quantities needed.
granulated fluxes

- Conventional powder fluxes are used at more than 0.25% by weight of the metal being melted.
- The granular material is used at only 0.125% by weight so that emissions only half of normal might be expected.
- In fact, tests have shown fume reduction of more than 85%.
- The move from a powder to a granulated flux significantly improves working conditions, reduces the amount of waste material to be disposed of and reduces attack on furnace refractories.