

IAI Report

Sustainable Aluminium Dross Management Guidance

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Sustainable Aluminium Dross Management Guidance

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SUMMARY

Aluminium dross is an unavoidable by-product of primary and secondary aluminium production. This guidance provides a comprehensive overview of aluminium dross generation, handling, processing, transportation, regulatory considerations, and sustainable management practices. The report defines and describes key terms, including white dross, black dross, salt cake, and non-metallic residues. Its goal is to highlight technologies and operational approaches that minimise dross formation and maximise aluminium recovery, consequently, minimising environmental impacts.

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International Aluminium Institute (IAI)

The International Aluminium Institute (IAI) was established in 1972. Current IAI membership includes global bauxite, alumina and aluminium companies in all major producing regions. IAI member companies are engaged in the production of bauxite, alumina, aluminium, the recycling of aluminium, or fabrication of aluminium or as joint venture partners in such.

Through the IAI, the aluminium industry aims to promote a wider understanding of its activities and to demonstrate both its responsibility in producing the metal and the potential benefits to be realised through its use in sustainable applications and recycling.

The IAI commissioned SINTEF to develop this sustainable management guidance on aluminium dross, in collaboration with industry partners. The IAI would like to acknowledge the following steering group members and organisations for their valuable review, expertise and contribution to the preparation of this guidance:

- Alcoa Corporation
- Aluminum Association
- Aluminum Corporation of China Limited
- Australian Aluminium Council
- Emirates Global Aluminium
- European Aluminium
- Metlen
- Rio Tinto
- Wirtschaftsvereinigung Metalle

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Disclaimer: The information contained in this publication is presented to the best of the knowledge of the IAI and SINTEF but is without warranty. The application of the methods, systems and processes for aluminium dross management outlined in this publication is beyond the control and responsibility of the IAI and SINTEF and should be undertaken in compliance with applicable local and national regulatory requirements.

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Abbreviations

BDSC	Black Dross & Salt Cake
EOL	End of life
EPA	Environmental Protection Agency
GHG	Green House Gases
GHS	Globally Harmonized System
HOWM	Hazardous and Other Wastes Management
ICP	Induced Coupled Plasma
IMDG	International Maritime Dangerous Goods
LCI	Life Cycle Inventory
NMC	Non-Metallic Compounds
NMP	Non-Metallic Product
OECD	Organisation for Economic Co-operation and Development
PPE	Personal Protective Equipment
PTRF	Plasma Torch Rotary Furnace
RSF	Rotary Salt Furnace
SDS	Safety Data Sheets
TDG	Transport of Dangerous Goods
TRF	Tilting rotary furnace
TWA	Time Weight Average
UBC	Used Beverage Containers
VOC	Volatile Organic Compounds
WSR	Waste Shipment Regulation
XRD	X-Ray Diffraction
XRF	X-Ray Fluorescence

Executive summary

Aluminium dross is an unavoidable by-product of primary and secondary aluminium production. While dross formation cannot be eliminated, its generation, handling, processing and utilisation can be significantly influenced by operational practices, technology selection and management systems.

This guidance, commissioned by the International Aluminium Institute (IAI) and developed by SINTEF, provides a practical framework for aluminium producers, recyclers and dross processors to improve dross management throughout the value chain. It examines dross generation mechanisms, handling and cooling practices, processing technologies, regulatory requirements, safety considerations, and opportunities to improve resource efficiency and circularity.

The guidance is intended to support the industry's dual objectives of maximising aluminium recovery and minimising environmental impact.

As aluminium production and recycling continue to grow globally, the absolute quantity of dross generated is also increasing. At the same time, improvements in operational practices and recovery technologies have significantly reduced disposal and increased resource recovery. These trends reinforce the importance of sustainable dross management and support the industry's transition towards greater circularity and resource efficiency.

Understanding Dross and its Management Challenges

Aluminium dross is generated whenever molten aluminium is exposed to oxygen during melting, alloying, transfer and recycling operations. The quantity and characteristics of dross are influenced by furnace design, operating conditions, metal handling practices and feedstock quality.

The report addresses the principal dross streams encountered across the industry:

- white dross generated primarily during primary aluminium production and cast house operations;
- black dross generated during secondary aluminium recycling;
- salt cake produced during rotary furnace processing; and
- non-metallic residues generated from both conventional and emerging processing technologies.

Because these materials differ significantly in composition and recovery potential, management approaches must be adapted to local operating conditions and processing objectives.

Improving Operational Performance

The report identifies operational practices as the primary driver of dross generation and recovery performance.

Most dross is generated during melting and molten metal transfer. Consequently, reducing oxidation at source offers the greatest opportunity to improve both economic and environmental performance.

Key operational practices include:

- minimising melt (surface) turbulence and oxygen exposure;
- controlling furnace temperatures;
- optimising charging and alloying procedures;
- implementing standardised skimming practices;
- rapidly cooling dross after removal; and
- maintaining effective operator training and governance systems.

The report highlights that operator competence and operational discipline are often as important as technology selection in determining recovery outcomes.

Processing Technologies and Recovery

A wide range of technologies are available for recovering aluminium from dross. Pyrometallurgical processing remains the dominant industrial approach, with tilting rotary furnaces widely used because of their high recovery efficiency and operational maturity. Alternative technologies, including plasma-based systems and low-salt or salt-free processes, may offer environmental advantages through reduced emissions and residue generation.

The report also reviews hydrometallurgical processing routes and emerging technologies designed to improve resource recovery and reduce environmental impacts. Technology selection should consider:

- aluminium recovery performance;
- energy consumption;
- environmental footprint;
- residue generation;
- economic viability; and
- regulatory requirements.

Safety, Transport and Regulatory Compliance

Safe handling and regulatory compliance are fundamental components of sustainable dross management. Dross may present risks associated with heat generation, oxidation, gas evolution, moisture interaction and transportation. Appropriate handling, cooling, storage and transport procedures are therefore essential. The report notes that regulatory classification varies significantly between jurisdictions, with waste classified as hazardous in some regions and non-hazardous in others. International transportation requirements, including those relating to moisture control, ventilation and documentation, must be carefully managed. Companies should implement management systems that ensure regulatory compliance, traceability, risk management and workforce competency throughout the dross management chain.

Advancing Circularity and Resource Efficiency

Modern dross management should seek to maximise resource recovery and minimise waste generation. Current technologies can achieve high aluminium recovery rates while creating opportunities for beneficial use of non-metallic residues. Potential applications include cement production, refractory materials, metallurgical additives and other industrial uses. The report also highlights the role of emerging low-salt and salt-free technologies in reducing waste generation, lowering environmental impacts and supporting circular economy objectives. Improved utilisation of dross residues can reduce landfill dependency while increasing the overall value recovered from aluminium production and recycling processes.

Key Conclusions

The report concludes that sustainable aluminium dross management is best achieved through the integrated application of:

Operational Excellence

- Reduce dross formation during melting and transfer.
- Standardise handling, cooling and recovery practices.
- Invest in operator training and governance systems.

Appropriate Technology Selection

- Match processing technologies to material characteristics and recovery objectives.
- Evaluate emerging technologies that improve environmental performance and circularity.

Safety, Compliance and Governance

- Maintain robust systems for handling, storage, transportation and regulatory compliance.
- Ensure traceability and effective risk management throughout the value chain.

Circularity and Sustainability

- Maximise aluminium recovery.
- Increase beneficial utilisation of residues.
- Reduce landfill disposal and environmental impacts during operation.
- Monitor and improve resource efficiency, energy consumption and carbon performance.



1 Objective and Scope

The objective of this work is to provide a comprehensive overview of aluminium dross generation, processing, and recycling practices worldwide. In the main report Chapter 1 below important terms and terminology are defined and will be used throughout the report. In Chapter 2 statistics from aluminium production and dross generation are presented. In Chapter 3 dross generation and processing in industry demonstrates that dross formation is an inevitable by-product of aluminium melting, heavily influenced by furnace type, melt handling practices, scrap cleanliness, temperature control, and exposure to oxygen. In Chapter 4 operational best practices dross generation, handling, safety issues, sampling and processing in industry is explained. Chapter 5 regulatory and transportation frameworks is essential for compliant and responsible dross management. Chapter 6 sustainability and circularity demonstrate that dross recycling plays a major role in achieving a circular aluminium industry. Case studies are also included in the main report.

Fundamental theory of how oxidation leads to dross formation, how to theoretically reduce dross formation, a short history of dross treatment and common methods are given in the appendixes. These are critically important as two key criteria for dross processing is as follows: (i) metal yield (economic feasibility), and (ii) environmental sustainability which are determined by the laws of nature, technologies and processes.

1.1 Definitions

The terms used for dross in the aluminium industry have natural variations. Some terms are local and some are more regional. However, the use of misleading or duplicative terms for a dross material can lead to misunderstandings. The terms white and black dross, non-metallic compound as well as salt cake are defined below. This report will utilize the same terms consistently to help provide a standard and clear usage. Therefore, in Table 1 (p. 17) a list of common similar terms is also provided.

In this report the general term dross is used for either white or black dross, or both.

WHITE DROSS

- **Origin:** White dross is the material generated during primary aluminium production as well as cast house melting, alloying, degassing and transfer operations. White dross is produced at potlines during the tapping and transfer operations, but the greatest volume of white dross is generated in various melting/alloying furnaces.
- **Composition:** Primary aluminium production white dross generally contains fluoride salt carryover from bath tapping and crucible cleaning at levels of 4 % with up to possible 20 %. Cast house white dross generally contains little fluoride salts but can contain chloride salts (up to 4 %) and has a relatively high metal content (50-90 %). Chloride salts in the cast house white dross can come from salt fluxes introduced to the molten bath to reduce alkali metals in the molten aluminium. If the white dross contains a high fraction of metal can be called a “wet dross”, a white dross with a high fraction of oxides can be termed a “dry dross.”
- **Appearance:** As its name suggests it is often a mixture of white oxides combined with silvery metallic residues (see Figure 1)



Figure 1: White dross. Photo: Ray Peterson, Real Alloy

BLACK DROSS

- **Origin:** Black dross is the material generated during the remelting of aluminium scrap (typically thin, coated, high surface area, or otherwise contaminated scrap) where chloride and fluoride salts are intentionally added to improve metal recovery.
- **Composition:** Depending on the nature of the material being processed the composition of black dross can vary widely. In general, it may contain 20 to 50 % residual salt, a similar level of oxides and 10 to 20 % metallic aluminium.
- **Appearance:** Black or dark grey in appearance and may be powdery or lumpy (see Figure 2).



Figure 2: Black dross. Photo: Ray Peterson, Real Alloy

SALT CAKE

- **Origin:** Any material melted or processed in a tilting rotary furnace with salt will produce salt cake as a by-product. Those inputs can include white dross, black dross, or scrap.
- **Composition:** Containing less than 5 to 10 % metallic aluminium, the balance being a mixture of oxides/nitrides and salts.

Appearance: Typically, a grey/black granular solid (see Figure 3).



Figure 3: Salt cake. Photo: Ray Peterson, Real Alloy

NON-METALLIC COMPONENTS

- **Origin:** When dross or salt cake are processed by alternative processes without the addition of salt, an oxide rich material with low aluminium content may be produced.
- **Composition:** Containing less than 10 % metallic aluminium, the balance being a mixture of oxides and nitrides.
- **Appearance:** Typically, a grey or white solid that can be a powder or granular depending up on the process used to treat the input material (see Figure 4).

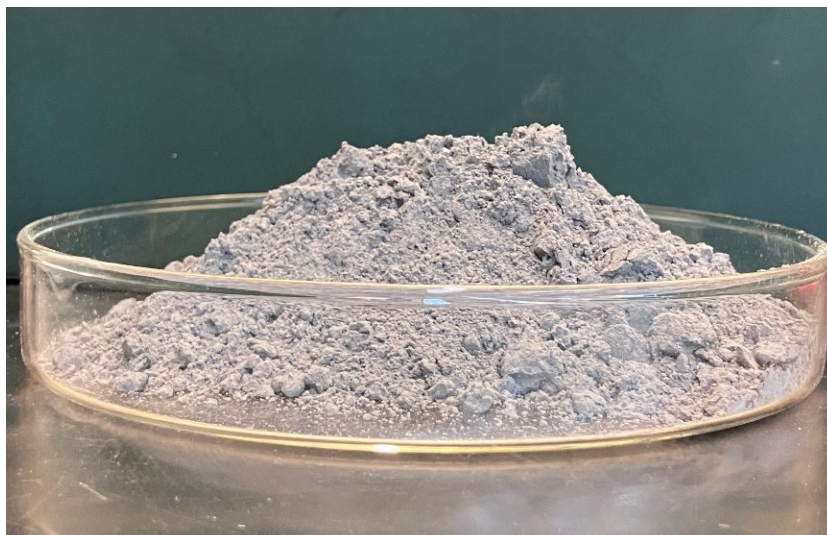


Figure 4: Non-metallic compound. Photo: Courtesy of RioTinto

In Table 1, in addition to the terms above mentioned definitions similar terms used in the field are presented to clarify this situation.

Table 1: Synonyms of dross types.

NAME USED IN THIS REPORT	SIMILAR TERMS USED IN THE FIELD ¹
WHITE DROSS	Primary dross Primary white dross Secondary white dross Slagg Aluminium skim Skimmings Skulls Cast house dross
BLACK DROSS	Secondary dross Salt slag Salt dross
SALT CAKE	Salt slag Salt dross

¹ Certain companies and regions use descriptive terms that have different meanings in other companies and regions. This is most likely a historical artifact. Examples of these multiple meanings are salt slag and salt dross which could potentially encompass at least two materials with different sources and compositions. For this reason, we are proposing that only the primary descriptors presented here be used for the by-products in order to eliminate confusion.

1.2 Definition of furnaces

In the report various furnaces are mentioned. In Figure 5 furnaces are classified by shape: the 100- series are reverberatory type furnaces, 200 -series are crucibles, and the 300-series are rotary type furnaces. Most commonly, rotary furnaces are used for dross processing.

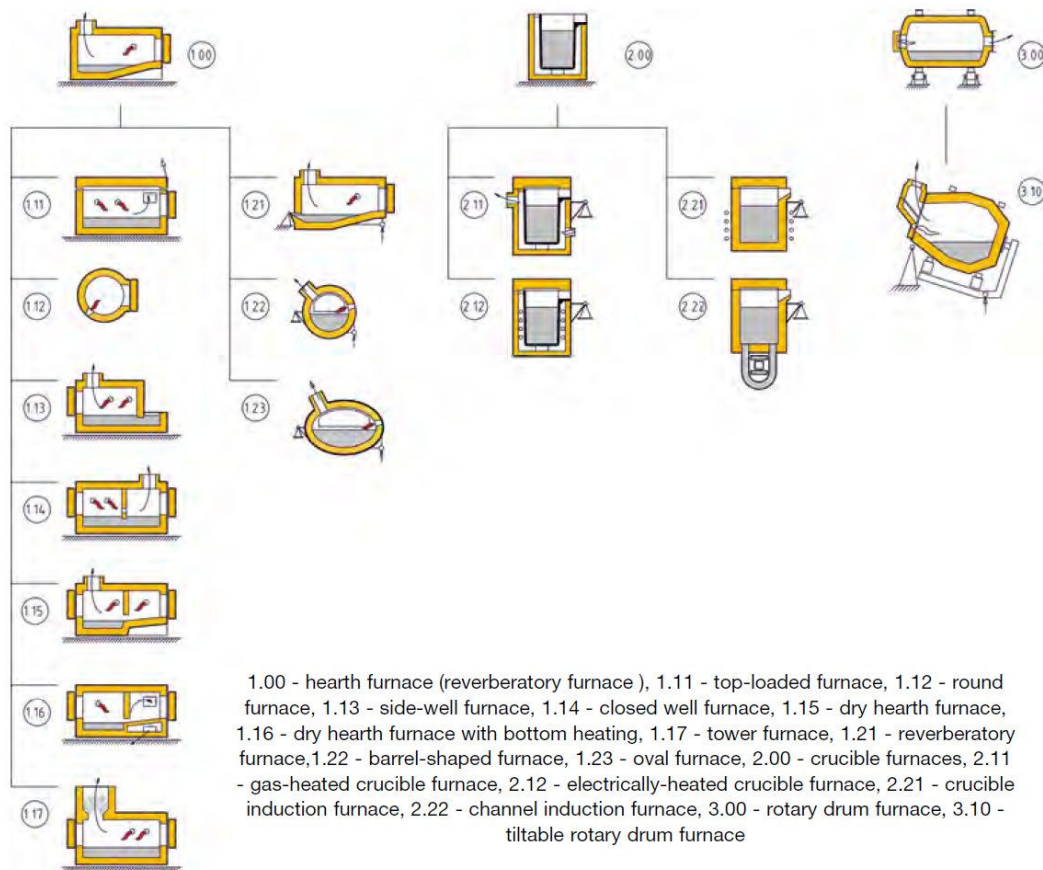


Figure 5: Family tree of furnaces [1]

1.3 Definition of metal recovery rates

The recovery rate and metal yield are important parameters in dross processing. Hence, it is important to be accurate in terms of how it is calculated. Often, in the industry, this is how it is measured:

$$\text{Recovery rate} = \frac{\text{mass of metal out}}{\text{mass of charge}}$$

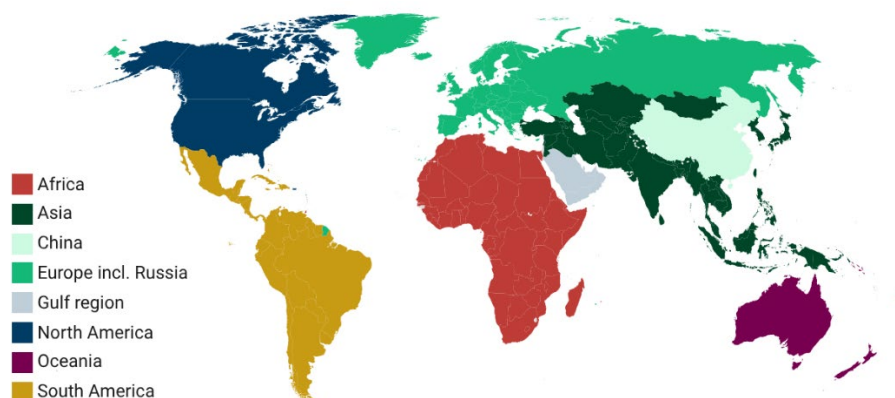
Then, a precise yield calculation can be made based on dross input to the furnace.

In laboratory studies, yield is sometimes defined by the metal content in the dross that is put in the process.

$$\text{Metal yield} = \frac{\text{mass of metal out}}{\text{mass of metal in the charge}}$$

1.4 Definition of regions for aluminium

Statistics are calculated by the regional definitions of the International Aluminium Association [2]. The existing 8 regions are given in Figure 6. A detailed list of countries used in the statistics² as subgroups are summarized in Table 2.



Source: Int. Aluminum Association • Created with Datawrapper

Figure 6: Definition of regions used in IAI Regional Aluminium Flow Model

Table 2: Region names and participated countries

REGION NAME	REGION CODE	PARTICIPATED COUNTRIES
GLOBAL	GLO	
AFRICA	AFR	South Africa, Mozambique, Guinea, Egypt
ASIA EX CHINA	OAS	India, Kazakhstan, Türkiye
CANADA	CAN	Canada
CHINA	CNA	China
EUROPE (WEST & CENTRAL)	EUR	Germany, Greece, France, Iceland, Norway, Spain, Sweden
GULF COOPERATION COUNCIL	GCC	Bahrain, Oman, Qatar, Saudi Arabia, UAE
NORTH AMERICA	NAM	Canada, USA
OCEANIA	OCA	Australia New Zealand
RUSSIA AND EAST EUROPE	ROE	Montenegro, Russia, Slovenia, Slovakia, Ukraine
SOUTH AMERICA	SAM	Argentina, Brazil, Jamaica, Guyana, Venezuela
OTHER PRODUCING COUNTRIES	OPC	Azerbaijan, Cameroon, Egypt, Ghana, Guinea, Kazakhstan, Mozambique, Nigeria, Russia, Sierra Leone, Solomon Islands, South Africa, Tajikistan, Tanzania, Zimbabwe

² "LCI Data" which is based on Regional Aluminium Flow Model. In the flow model, Russia is included as part of Europe. On the other hand, in LCI Survey analysis, Russia is explicitly reported separately. The same applies to Canada. They are included as North America in Flow Model whereas they are separately evaluated in the LCI Survey data. IAI conducts a comprehensive Life Cycle Inventory (LCI) survey every five years covering mining, refining, smelting, anode production, and casting, including selected waste and by-product streams such as dross. This is referred to herein as the "LCI Survey". Also, "Gulf Region" is same as "Middle East" in the statistics.

1.5 Definition of scrap

In the statistics of IAI, the terms are defined as below:

- **New scrap**

Scrap arising from the various production stages of aluminium products before the aluminium product is sold to the final user.

Examples:

- rolling trim
- extrusion offcuts
- machining chips

- **Old scrap** (often aligned with “post-consumer scrap”)

Scrap arising from products after use by the final consumer/end user.

Examples:

- used beverage cans
- demolished building materials
- end-of-life vehicles

- **Internal scrap**

A subset of new scrap:

- new scrap that is remelted/recycled within the same company where it was generated.
This is usually not traded on the market and often invisible in trade statistics.

1.6 Hazardous hierarchy

The term “hazardous” is described in different context in Table 3.

Table 3: Hazardous terminology and hierarchy

TERM	MEANING
HAZARDOUS CHARACTERISTICS	Physical, health, or environmental hazards intrinsic to a material (e.g., reacts with water, generates flammable gases).
HAZARD CLASSIFICATION	The regulatory classification assigned under a framework such as Globally Harmonized System or Transport of Dangerous Goods.
HAZARDOUS MATERIAL	A material classified as hazardous under Globally Harmonized System or transport regulations.
HAZARDOUS WASTE	A waste legally classified as hazardous under a waste regulation in a particular jurisdiction.

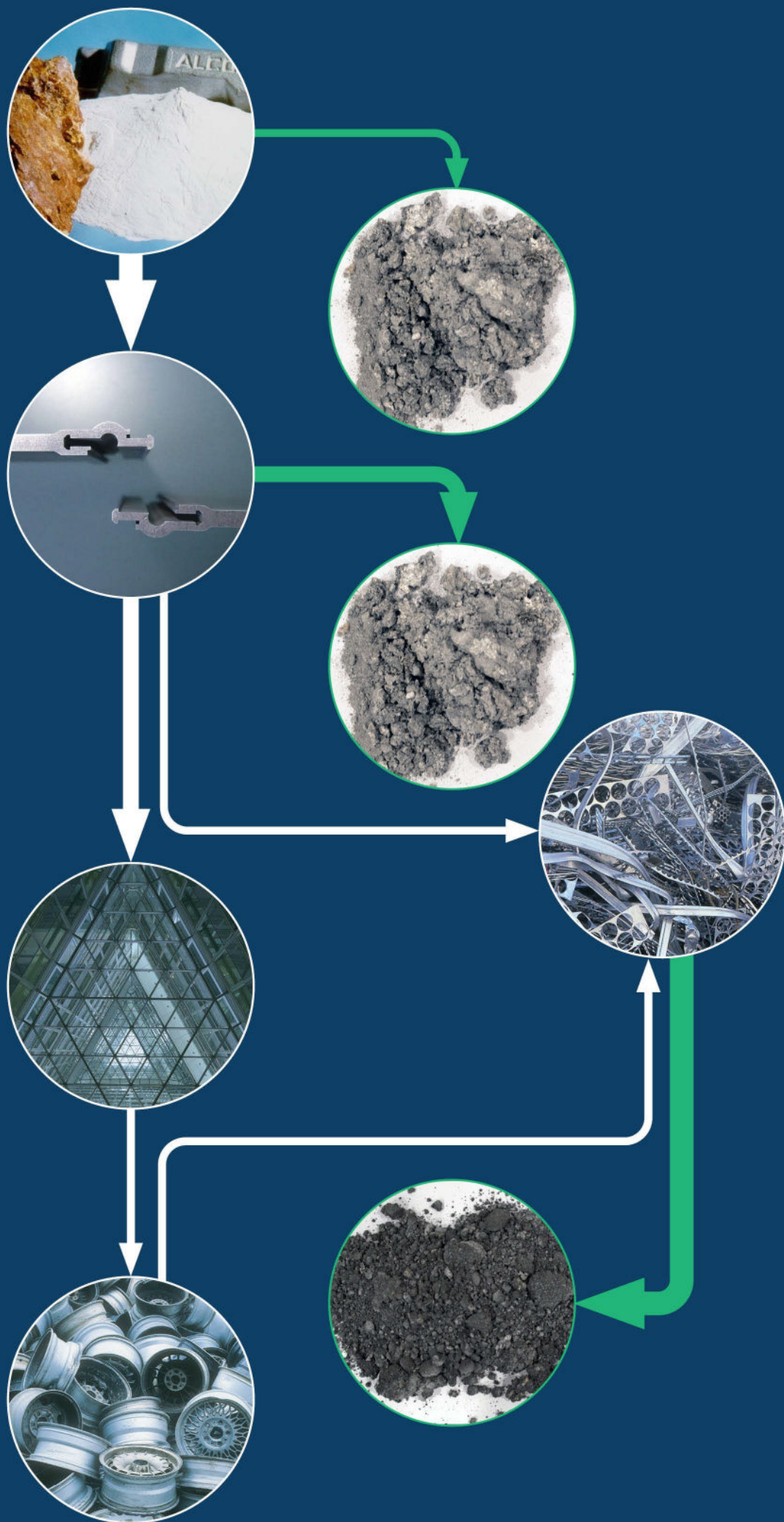


Figure: SINTEF. Photos: SINTEF and IAI

2 Statistics

IAI maintains several long-term industry data collection programmes covering production, energy, emissions, and broader sustainability indicators. Some datasets, such as production statistics, date back to the 1970s. This is referred to herein as the “LCI Data” which is based on Regional Aluminium Flow Model. In addition, IAI conducts a comprehensive Life Cycle Inventory (LCI) survey every five years covering mining, refining, smelting, anode production, and casting, including selected waste and by-product streams such as dross. This is referred to herein as the “LCI Survey”. The reference year 2019, rather than 2020, was selected to avoid distortions associated with the COVID-19 pandemic.

2.1 Global and regions primary production and dross

Below is the primary world aluminium production for 2025 (in million tonnes (Mt) from LCI Data. The total production is 72.9 Mt in 2025 of which 43 Mt is produced in China covering 59 % of aluminium production globally (Figure 7). Middle East is the second largest producer with 7.14 Mt and covering 9.8 %.

Based on IAI LCI Survey, the total amount of dross formation has an *average 10 kg per tonne of aluminium*. Regarding the IAI LCI Data, 72.9 Mt of primary aluminium production in 2025 sums up to 0.73 Mt of dross formation (Figure 7). China being responsible for 59 % of primary production globally would produce 0.43 Mt of dross based on this ratio. Then, Middle East and Other Producers are producing 0.07 Mt dross for each which is 1/10th of the global dross formation.

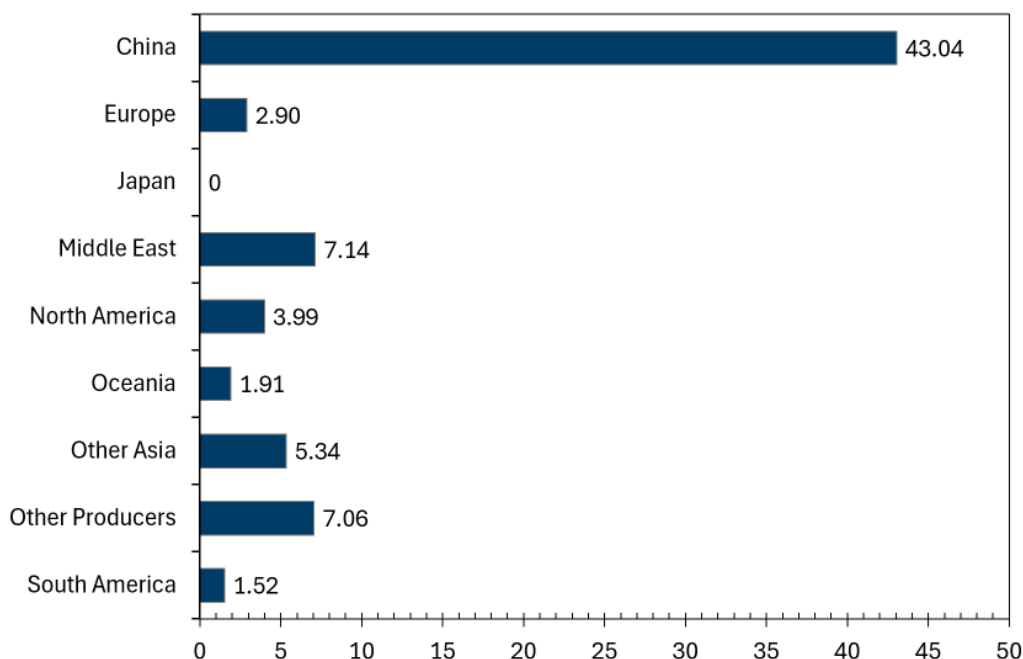


Figure 7: 2025 primary aluminium production numbers in Mt
(data from IAI Data)

In Figure 8, the dross formation in kg per tonnes of aluminium is given over the years 2010 towards 2024. It can be seen that the average dross formation has decreased significantly over 15 years from around 16 kg towards 6.5 kg with landfilling decreasing from 5.3 to ≤ 0.1 kg/tonnes of aluminium produced. 6.5 kg/tonnes in 2024 simply corresponds to 0.65 % of dross formation.

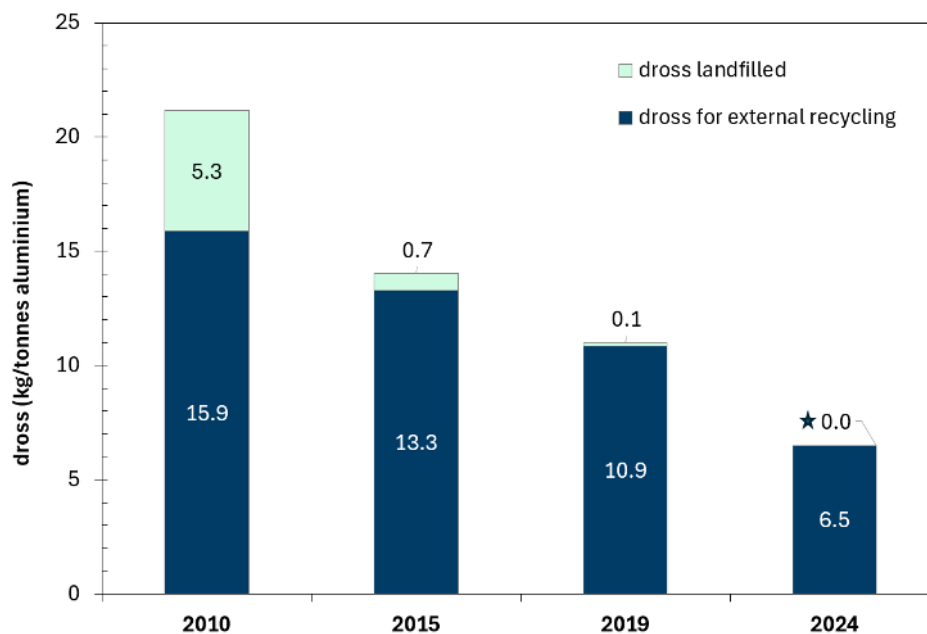
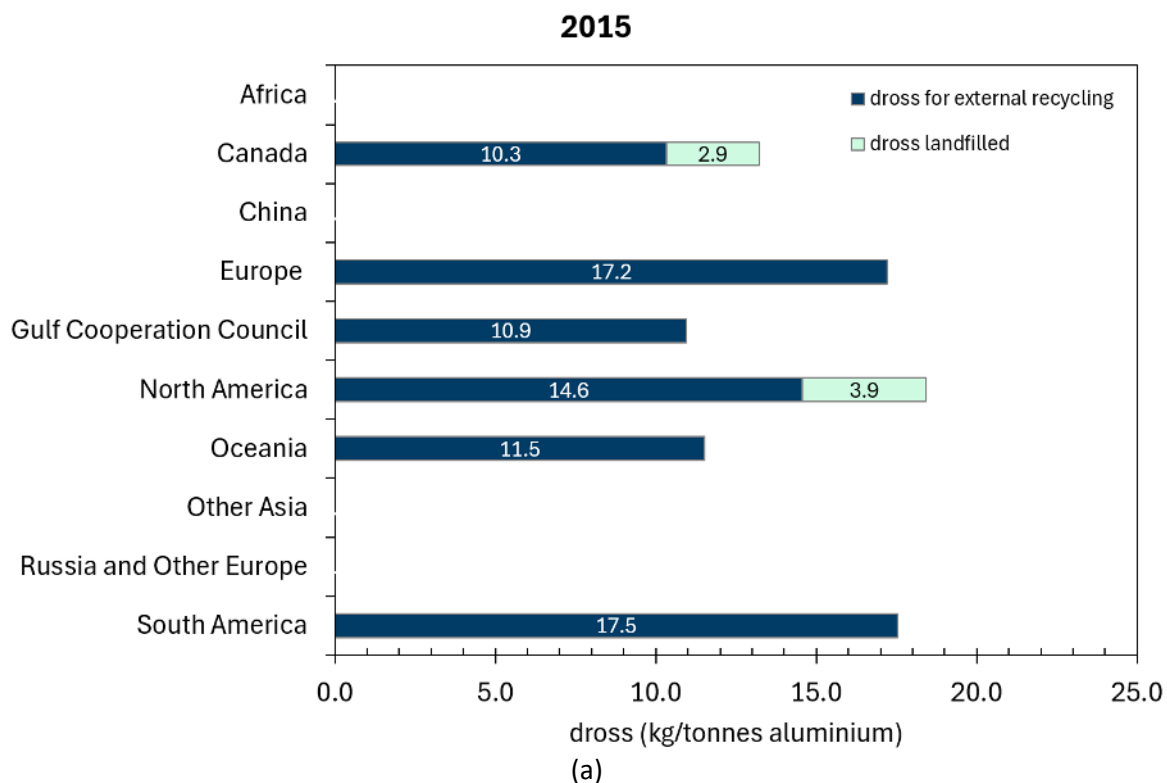


Figure 8: Global average dross per tonne of aluminium produced by years
(★: no data collected) (LCI Survey)

In Figure 9, detailed regional numbers are given for 2015 and 2019 LCI Survey data where producers have provided data for the amount of dross for external recycling and landfilling. It can be seen that some regions have not reported numbers for both periods. Also, in 2019, the dross formation has increased for Canada and North America. While in Gulf area, there is no change in dross for external recycling, the rest appears to have a decreasing trend.



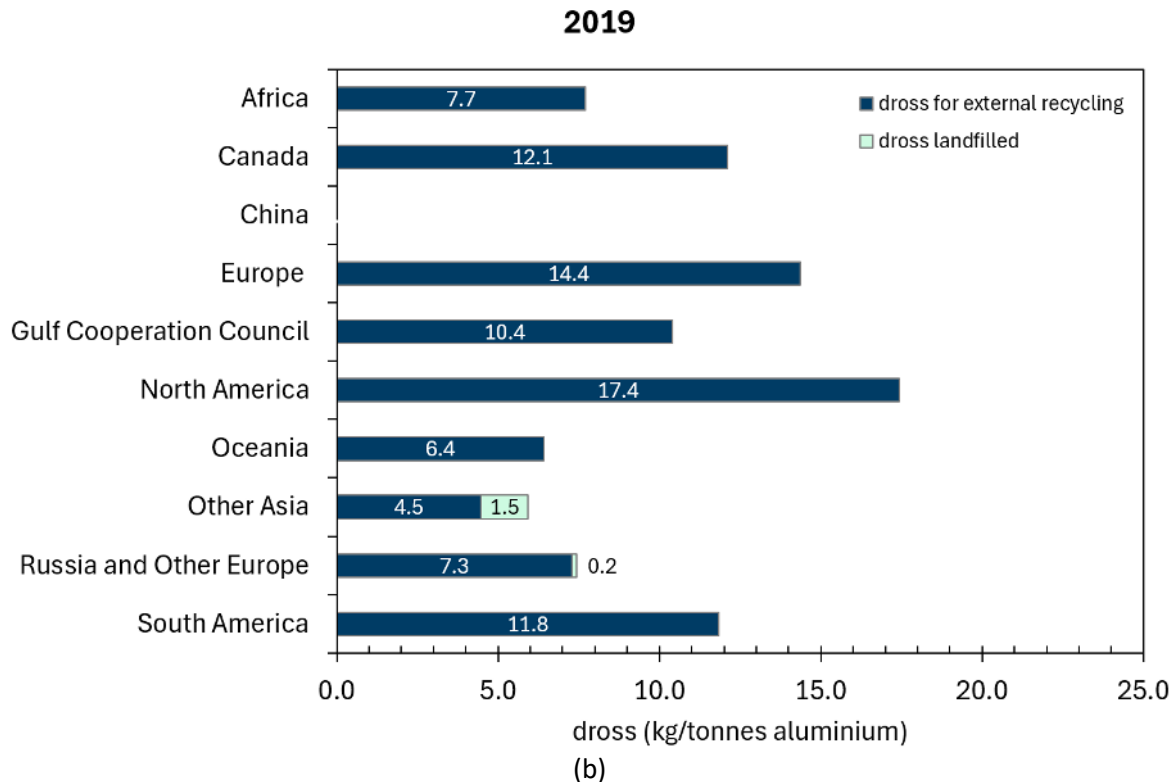


Figure 9: Reported dross formation in kg per tonnes of aluminium produced for (a) 2015 and (b) 2019

2.2 Global and regions primary production with new and old scrap

Figure 10 below is the mass flow data presented at the IAI home page (LCI Data) to highlight the breakdown of primary production and secondary production from 2024. The cycle includes mining of bauxite and production of alumina for electrolysis. In 2024 the total primary production of aluminium was 71.4 Mt. Total recycling summed up to 42.8 Mt, where 25.3 Mt out of this data is old scrap and 17.5 Mt is the new scrap.

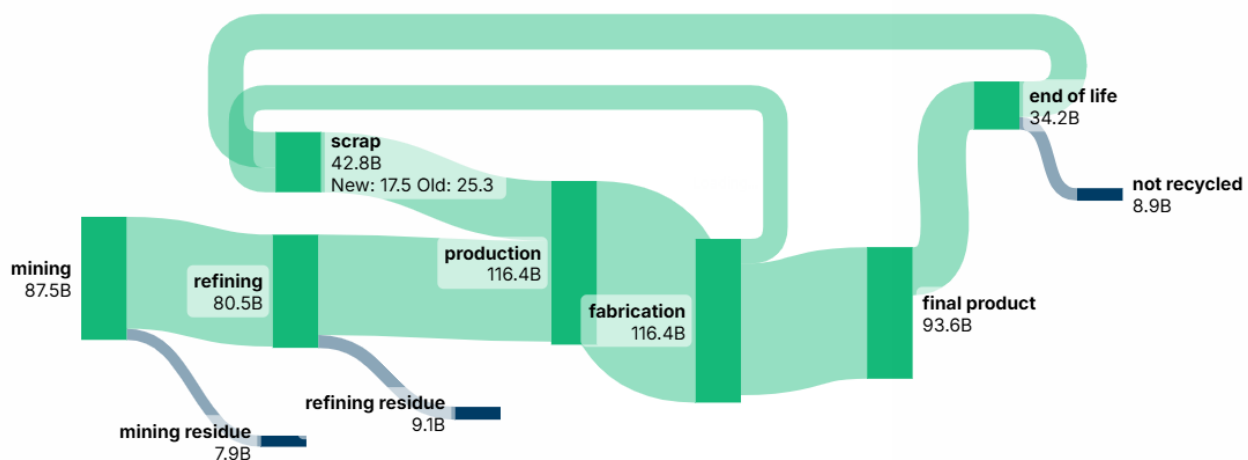


Figure 10: IAI's global aluminium cycle shown for 2024 (data from IAI Regional Aluminium Flow Model)

Figure 11 shows the global recycling ratio (LCI Data). In 2024, the global total recycled aluminium was 41.8 Mt (this is about 1 Mt less than the LCI Aluminium Flow Model data) where the percentage of new to old scrap is 41.5/58.5 % respectively.

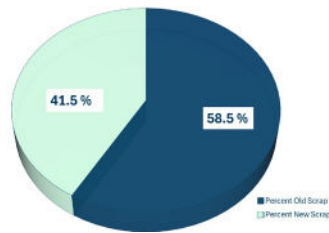


Figure 11: Global recycling ratio
(LCI Data)

Figure 12 shows the old/new scrap usage over the regions in 2024. China uses almost 50/50 new/old scrap with 17.4 Mt in total. The highest old scrap usage is observed in South America with 78.8 % (1.9 Mt) followed by Japan with 72 % a total of 1.3 Mt.

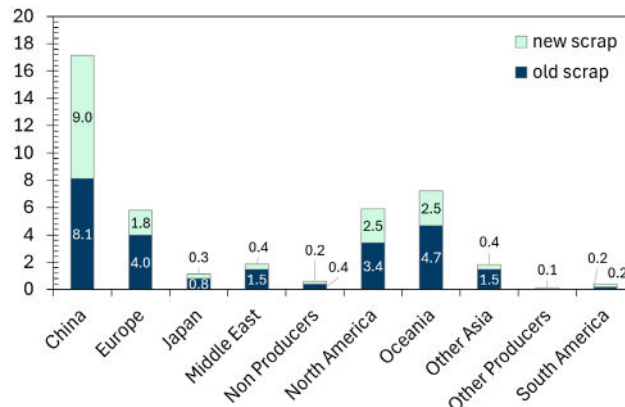


Figure 12: Scrap ratio usage 2024
(LCI Data)

The recycled aluminium ratio from 2024 in the mass flow analysis provided by IAI LCI Data, the internal scrap in the world is 35.9 Mt. General overview is given in Figure 13. China contributes with 54 % of the total which corresponds to 19.5 Mt. Second largest region is Other Asia with 5.0 Mt (14 %) and Europe is the third largest with 4.0 Mt (11 %) followed by North America with 3.4 Mt (9.6 %). Rest of the regions uses less than 1 Mt internal scrap.

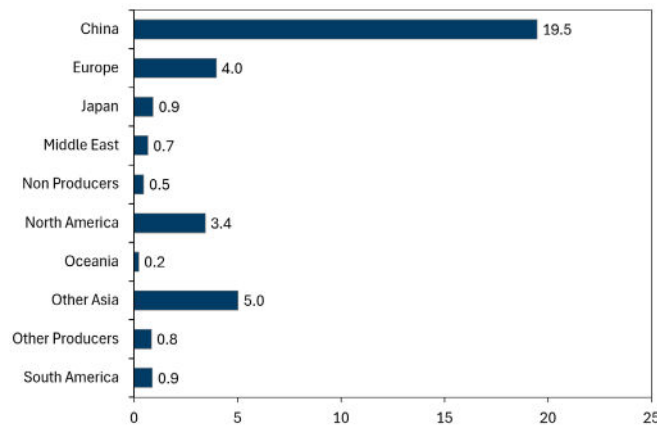


Figure 13: Aluminium recycled from internal scrap
(LCI Data)

2.3 Dross statistics and estimates

There are no standard reports of dross produced on a worldwide basis. In order to derive an estimate of worldwide dross production, estimation of dross production rates coupled with known production rates will be used. Based on IAI LCI Data, the dross quantity is approximately 1 % of the primary aluminium produced. The internal scrap usage is approximately 40 % while old scrap usage is around 60 %. For the internal scrap, heavy material will have a good recovery and low dross formation while high surface area scraps like cold mill side trim, scalper chips and saw swarf will have lower recovery and higher dross formation. Therefore, an average of 3 % dross formation was used in the estimations. Similarly, for the old scrap (end-of-life returns), the dross formation rate could vary by scrap type and furnace technology (contaminations, coatings, paint, lubrications). For example, building and constructions would probably have 3-4 % dross formation while UBC would be 10 %. Dross from wrought alloys and clean scrap was estimated as 5.2 % in reference EAA [3]. Therefore, based on these considerations, the dross formation was taken as an average of 8 % for the old scraps for the estimate calculations.

The IAI LCI Survey is coupled with the assumed dross formation rates:

- i. 1 % dross from primary,
- ii. 3 % dross from new scrap,
- iii. 8 % dross from old scrap

The results are presented in terms of Mt as seen in Figure 14. Over the years, with the increase of aluminium production, the dross quantity has increased from 0.98 Mt in 2000 towards 3.28 Mt in 2024. The orange marks give the old scrap dross percentage on the secondary axis which has increased from 40 to 45 %. The absolute dross quantity has increased nearly 4 times from 0.58 to 2.02 Mt for the old scrap.

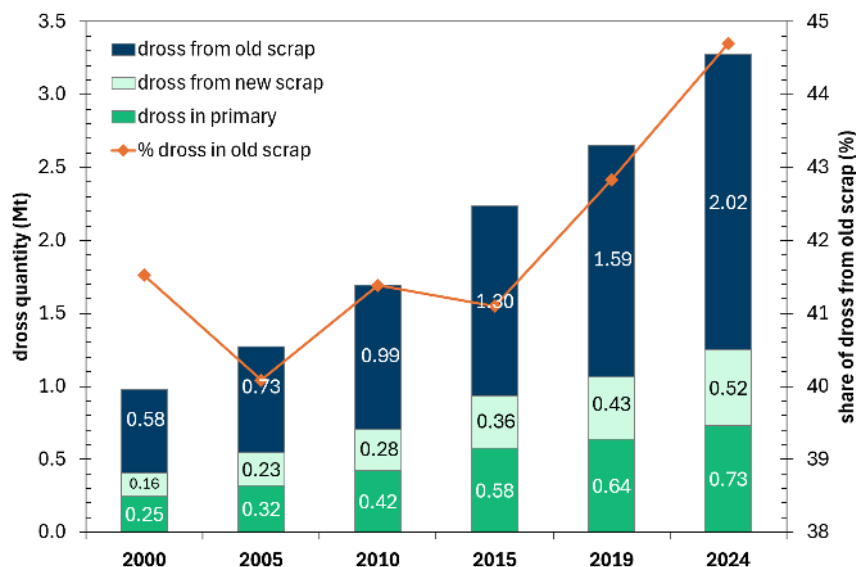
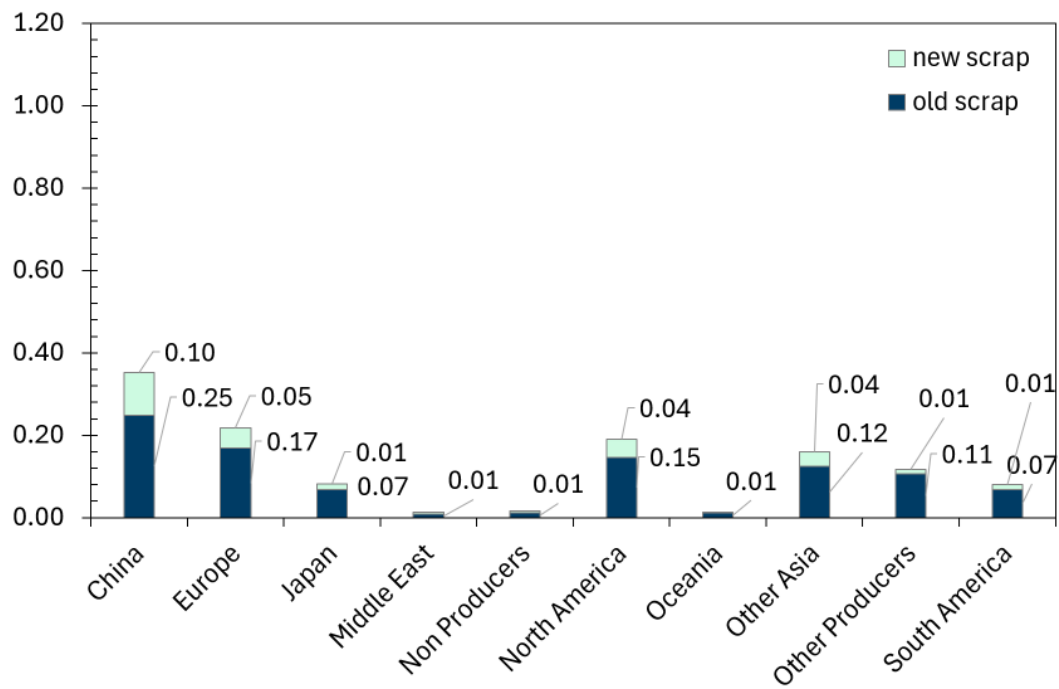


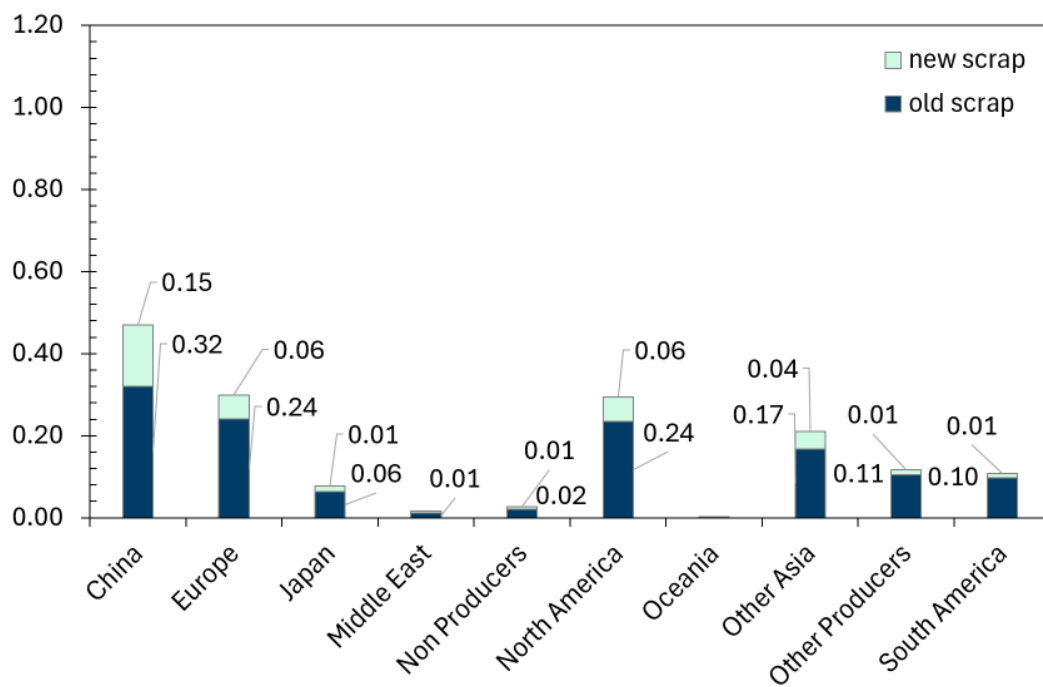
Figure 14: Development of dross from 2000 to 2024
(LCI Survey)

In Figure 15, the dross quantity calculated by the estimated dross ratios from new and old scrap based on the numbers from IAI LCI Survey for various regions through the years of 2010, 2015, 2019 and 2024.

2010



2015



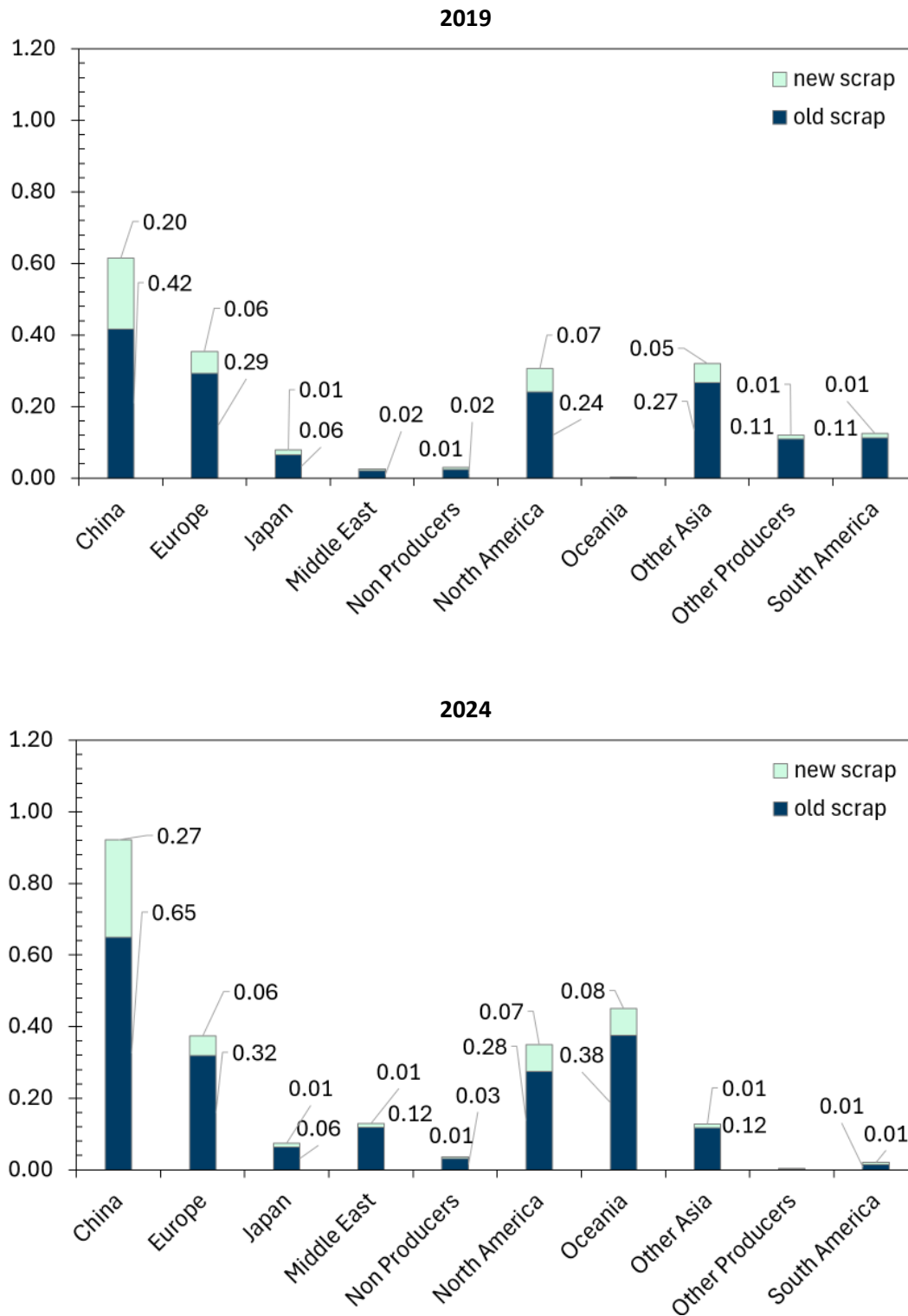


Figure 15: Dross formation in recycled aluminium production (Mt)

(LCI Survey) for 2010, 2015, 2019, and 2024



Photo: Rio Tinto

3 Dross Generation and Processing in Industry

The chart in Figure 16 is a general overview of the dross flow (in blue boxes) with important parameters as bullet points addressed in the chapter sections. The green boxes relate to the generation and processing of white/black dross and salt cake.

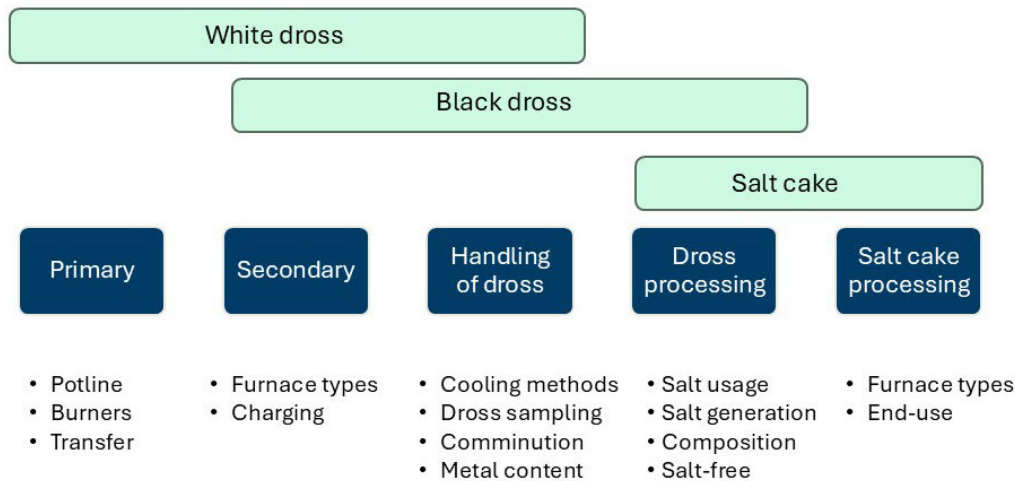


Figure 16: Overview of dross generation and processing in industry

3.1 Generation of white dross

Aluminium primary smelting is the electrolytic process in the potline, known as the Hall–Héroult process, that extracts pure aluminium from alumina (aluminium oxide) dissolved in a bath of molten cryolite. This process involves passing a high electric current through the pots, which causes the alumina to break down into molten aluminium and oxygen. Due to gravity, the molten aluminium then sinks to the bottom, where it can be sucked up and out into transport crucibles, and transferred to the casthouse furnaces for alloy adjustment and melt treatment. The molten metal then proceeds to the casting line to produce ingots or other products.

In the melting processes of aluminium in the cast house, because of its high affinity to oxygen, dross formation becomes inevitable. Whenever a volume of molten aluminium changes shape, or the oxide skin on the surface is ruptured, fresh aluminium metal is exposed to the atmosphere. This happens during filling of a furnace with metal from electrolysis cells, remelting of solid material (cold metal), gas purging, alloying and mixing, and transfer to casting moulds or pits.

As seen in Figure 17, the burners provide the energy to melt the aluminium but also creates an oxidizing environment. Thus, the major dross formation occurs in furnaces during melting practice (Appendix A.2). The second largest contributor to dross formation occurs when transferring the liquid where splashing and turbulence of the liquid will generate air entrapment and bubble formation. The oxygen in the air will react with the aluminium to further oxidize the liquid.

Primary cast houses and remelters of clean scrap use little and no salt and thus produce white dross. The amount of dross is typically 1-2 % but can be up to 10 % relative to the charged material.

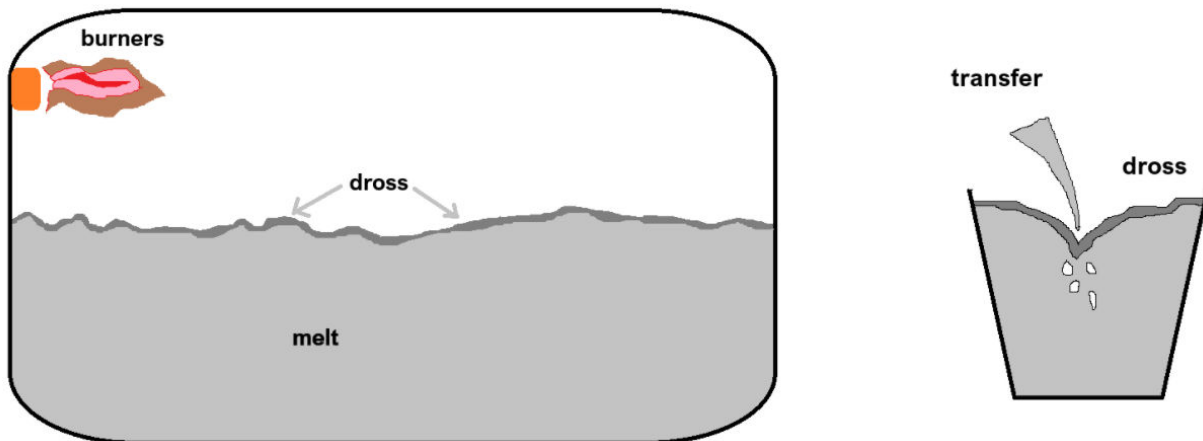


Figure 17: Two potential dross formation (a) melting, (b) transfer

3.2 Generation of black dross

In secondary aluminium production, recycled materials such as scrap and returns are melted in furnaces to be re-cast into raw materials (e.g. sheet, billet, ingot) or die cast parts with a dross generation up to 10 %. These furnaces could be of the reverberatory or tilting rotary furnaces styles. Therefore, salt may be added to reduce the metal oxidation or trapped metal in the dross. Salt is also added to reduce metal loss to oxidation and dross formation. The dross that is formed after such operations is called black dross and contains metallic aluminium together with oxides and other non-metallic compounds.

3.3 Handling of dross

In the furnace, dross is removed using a long tool mounted on a mobile equipment to “skim” or scrape the dross mixture from the surface of the molten metal onto a shelf/preheating ramp for drainage before it is raked into dross pans or other suitable containers (Figure 18). During the skimming step in the furnace, the dross is carefully held at the furnace lip to drain off as much free metallic aluminium as possible before scraping into the container positioned beneath the furnace door.

Several cooling methods or immediate treatment can be applied while the dross is still hot:

- spread on floor,
- let the dross cool in the pan e.g. with argon blanket,
- stirring by e.g. transfer the dross into a rotary cooling device, or
- process the dross in a dross press.



Figure 18: Skimming of the dross out of furnace into dross pan. Photo: Courtesy of Rio Tinto

During skimming, transfer and dross cooling, personal protective equipment is required. Hot aluminium dross is dangerous and can ignite. If the dross starts to burn and converts into aluminium oxide, the amount of recoverable aluminium metal decreases and the value of the material drops.

Cooling the dross to safe temperatures makes it manageable for storage and subsequent processing. Aluminium cold dross storage involves keeping cooled, solidified dross in a dry, cool, and well-ventilated place to prevent further oxidation and chemical reactions, which can reduce the economic value of residual aluminium.

Following is a case study with three cooling methods commonly used, presented. The three methods are benchmarked for comparison of metal yield of the various methods. The numbers were collected in 2017.

CASE STUDY: Cooling of Dross Practice – Hydro

Various cooling methods for dross are used in Hydro. Below three methods are described for comparison (Figure 19 and Figure 20).

Dross press:

The dross press works on the principle of compressing and cooling dross as quickly as possible. The hot dross is placed in a pan with holes in the bottom. A hydraulic stamp forces the metal out of the dross and the aluminium is collected in a mold underneath the press container. The remaining dross is solidified into a large block with a metal content ranging around 35–55 %. Metal content varies with type of alloy, furnace practice, and dross treatment processes. In Hydro the plants (2017) at Høyanger, Husnes, Sunndal and Årdal are using dross presses.

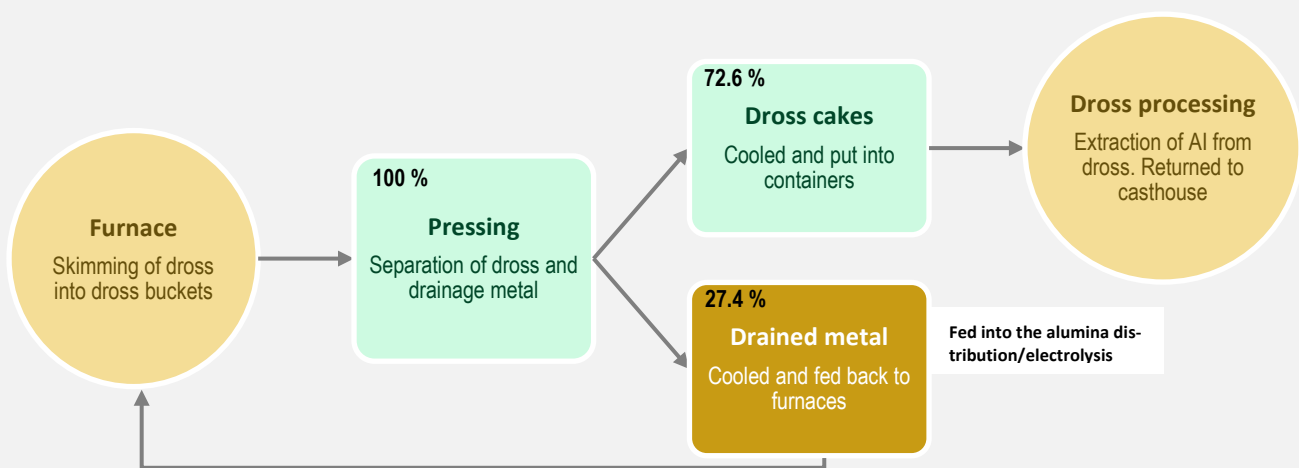


Figure 19: Flowchart of dross presses for some plants in Hydro

Argon cooler:

The Inert Gas Dross Cooler (IGDC) from the STAS company is an argon-based dross cooling solution. The heart of the inert gas dross cooler is a large thermal heat sink in the form of a ductile cast iron pan in which dross is skimmed. As soon as a pan is filled, it is moved directly into an inert gas cooler where the injection of argon prevents further oxidation. This gas performs no cooling as such; it simply excludes oxygen. In Hydro the plant at Karmøy has an argon cooler.

Drum cooler:

With this technology dross is fed by a vibration conveyor or a chute into a rotating drum. The shell of the drum is cooled by water-spray. The material is transported through the drum by a helical screw and reaches the screening section of the drum. This section is designed as a rotation screening drum and forms one unit with the cooling section. Three fractions of the dross are obtained in the dross cooler. The dust created during the charging and discharging of the drum cooler can be pulled out by exhaust ducts connected to a dust treatment system. The dross cooler is a very efficient system, but it requires a certain production capacity. The resulting dross is very rich with regard to aluminium content. The plant at Sunndal has a drum cooler.

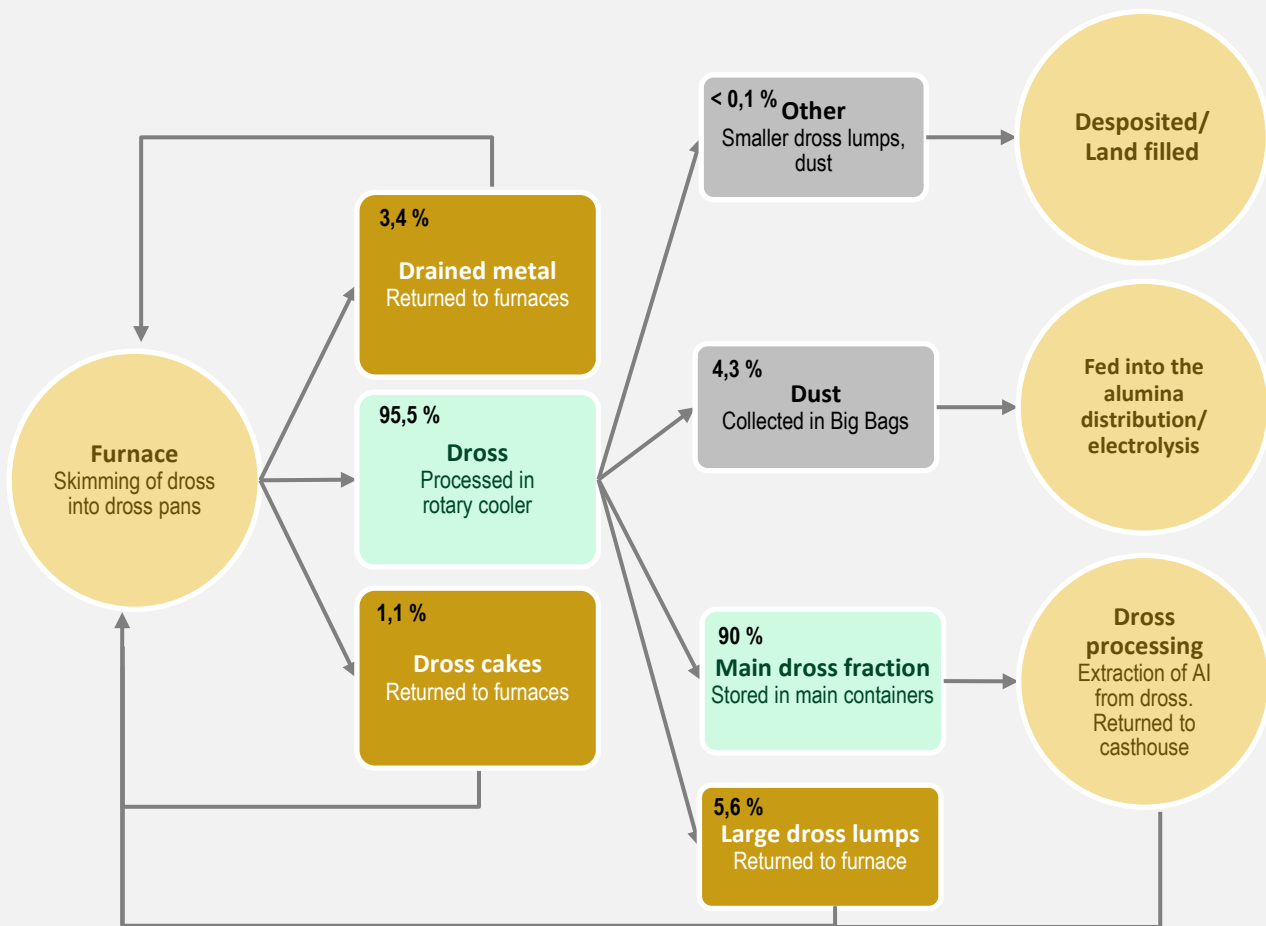


Figure 20: Flow chart with drum cooler for some plants in Hydro

Conclusion:

For a comparison of the efficiency of the dross press and the rotary tumbler in this case study, the drained metal has to be included:

Approx. 62 % is recovered from Dross press

Approx. 58 % of the metal is recovered from Drum cooler

Approx. 55 % is recovered from STAS/Argon cooler

The difference is much smaller than the uncertainty for the respective numbers involved. A conclusive statement about the efficiency of the dross press versus the tumbler remains indefinite.

3.4 Dross sampling

The dross is usually skimmed off by several types of equipment and usually dropped into a container box where it can be further processed (for example, pressed to drain liquid aluminium) and then moved to a storage area where it will be taken to recycling afterwards.

Therefore, five types of sampling can be undertaken at 5 key stages:

1. From inside the furnace, for instance by a sieve
2. From the melt surface with small sampling ladle
3. During skimming
4. After it is collected in the container box
5. After it is cooled down in the storage area before sending for recycling

Each of these stages have their own advantages and disadvantages. Sampling from the melt would only reveal the type of oxides that are in the dross. For example, is it purely Al_2O_3 , or spinel oxide such as MgAl_2O_4 , or what other types of oxides present within the dross itself. Typically, the dross sample is crushed into powder form and are thereafter small volumes of the dross is characterised for the composition by XRD, XRF and/or ICP analysis.

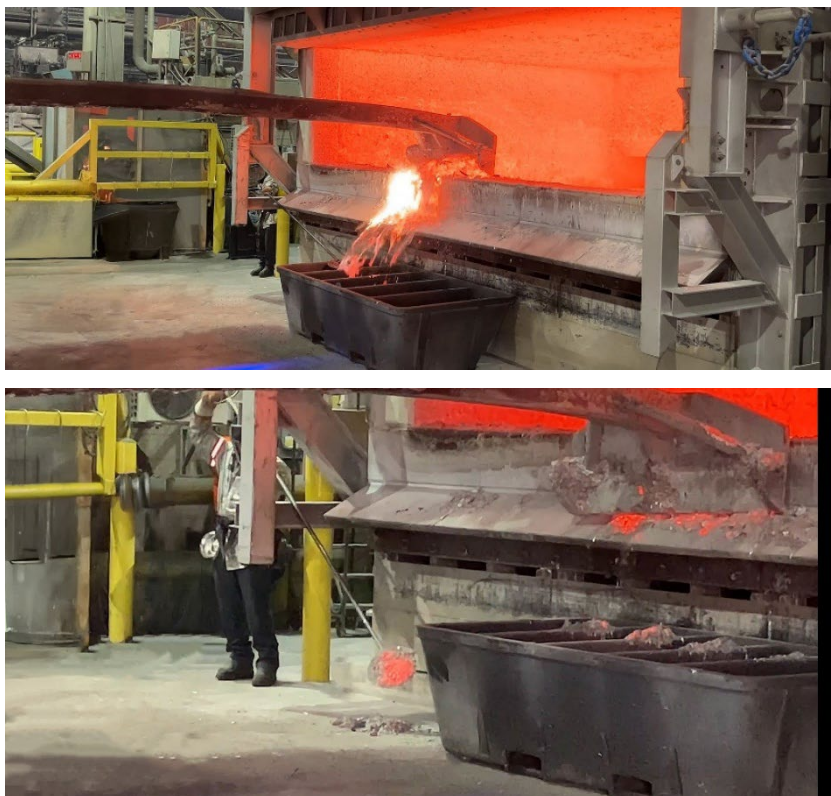


Figure 21: Sampling during skimming.
Photo: Courtesy of Rio Tinto

In the second method, samples could be collected from various locations of the dross while it is still hot, and left to cool in the ambient air to room temperature. The samples can be subjected to characterisation tests. However, one of the critical points is the location of where the sample is taken. Dross is recognized to be very heterogenous and metal drainage in the colling pan can make it even more so. There could be a location in the furnace where entrapped liquid aluminium is high in quantity, or there could be an area where there

is little liquid aluminium, but high amounts of the oxide itself. In such cases, the ratio of the metal collected in the dross will vary significantly.

Additionally, another problem could arise from how the dross is skimmed off. If the skimming tool is dipped too deeply in the melt, the collected dross will contain a high amount of liquid aluminium. Thus, even the way the dross is skimmed can play a significant role. To get a better number for metal content in the dross, the samples should be taken when the dross has been taken out of the furnace. The third method (as shown in Figure 21) can be done by using a ladle positioned above the dross pan and collecting a sample as the dross falls down into the pan. This will give the metal content at that point in the process. However, there is a risk of oxidation of metal from a sample (with higher surface to mass ratio), if the sample is not cooled down fast.



Figure 22: A typical dross with various shape and size.
Photo: Speira

After the dross is cooled down in the storage area, the physical appearance of the dross would look like a pile of dust with chunks of rock in between as seen in Figure 22. During cooling in the dross pan, there is a risk of metal draining down in the pan, giving gradients in the metal content. Therefore, sampling must be made from different positions in the material for more reliable analysis of characterisation. For such cases, as seen in Figure 23, the recovered dross can be crushed into various dimensions and then subjected to analysis.



Figure 23: Crushed dross fractions sieved into several size ranges [26].

3.5 Comminution

Aluminium dross comminution is the crushing or grinding of aluminium dross to separate the entrapped metallic aluminium and aluminium oxide particles, allowing for their separation from the overall material. This physical separation process is a key initial step in various methods for recovering valuable aluminium metal and other products from dross. The conventional dross oxide treatment consists of grinding the dross, sieving to recover the metal value followed by water leaching to dissolve the salt in water from residue oxide. The salt is recovered back by filtering the slurry and evaporation of the clear brine.

3.6 Measurement of metal content of dross

Measurement of metal content is important for many reasons such as choosing the subsequent processing method, evaluation of the processing yield, or determining the financial transaction rate. Below are some methods to determine the aluminium metal content in dross. It is important to note that improper sampling will cause the largest variation in metal measurement. Thus, having representative sampling is the most important part of measurement.

Salt test (fire assay): The dross is weighed and recorded. Same quantity of the salt mixture of 50/50 NaCl/KCl + a few % fluoride compound is added to the crucible with dross. (See section A.1.5 for discussion on salt mixture.) Melt at 750 °C and depending upon the sample size and equipment holding the molten contents from a few minutes up to several hours. Then, the mixture is let to solidify in air. After it is cooled, the salt is mechanically removed from the sample, the remaining metal is weighed and the percentage of dross versus metallic aluminium is measured. An alternative route is to pour the salt out when it is still liquid, then the metal can be poured which then leave the leftovers to solidify. The bottom mixture can be evaluated in the same manner as described above, depending upon the accuracy of the measurement needed.

Density measurement: By means of a pycnometer, the volume of the dross can be measured, and the weight of aluminium is calculated according to the following equation (Eq. 1):

$$m_{Al} = \frac{(\rho_{Al} \cdot \rho_{oxide} \cdot V_{dross}) - (m_{dross} \cdot \rho_{Al})}{(\rho_{oxide} - \rho_{Al})} \quad (1)$$

ρ_{Al} : density of aluminium

ρ_{oxide} : density of aluminium oxide

V_{dross} : volume of dross

m_{dross} : weight of dross

An uncertainty in this method is to know the oxide density. This will be dependent on the ratio between all the oxide or nitride types in the dross. This can be found with quantitative XRD-analysis.

Leaching: The dross can be leached in HCl (hydrochloric acid). The dissolution of aluminium gives direct information about the content of undissolved material (mainly Al_2O_3). The dross is grounded to -8 mm before mixing with HCl (35 % HCl:H₂O 1:2). The aluminium content dissolved in the solution is measured by ICP method or titration, giving the amount of aluminium metal in the dross.

Hydrogen evolution: At high pH, metallic aluminium is dissolved, with generation of hydrogen according to the following reaction (Eq. 2):



The material can be placed in a cell with a tube filled with 50 ml of a 1 M sodium hydroxide solution. This cell is then hermetically closed and the volume of gas released is measured by keeping the pressure in the cell equal to the atmospheric pressure. The experiment is started by pouring the sodium hydroxide on to the powder. The gas volume increase is proportional to the amount of metallic aluminium. Care must be taken that all the aluminium has reacted. This test is usually applied to small volumes [4].

The comparison of pros/cons of different methods used to measure dross metal content is given in Table 3.

Table 4: Pros/cons of different metal content measurement methods

METHOD	PROS	CONS
SALT TEST	Most commonly used. Large samples, simple, accurate, mimics industrial large-scale recovery	Requires special equipment (small furnace and lab facility), energy and time consuming, skilled staff, good ventilation is required
DENSITY MEASUREMENT	Easy testing method, simple, fast	Difficult to get accurate results, less accurate depending on dross structure, not commonly used
LEACHING	Precise, high precision of specific alloying elements	Small sample, Slow, ICP needed, requires acid/alkali consumption, costly
HYDROGEN EVOLUTION	Accurate	Small sample, slow, lab needed, hydrogen safety measurements needed, potential errors due to AlN presence

3.7 Dross processing

After cooling, the dross can be stored and then processed further. The cold dross is often crushed and screened to separate metal-rich particles from the aluminium oxide. The fine fraction can be further processed in the salt slag recovery process. Pyrometallurgical methods, such as those using rotary salt furnaces or advanced salt-free technologies (see Section 6.3 Case Study by Scepter), melt the dross to separate the entrapped aluminium. Hydrometallurgical processes can yield various products, including high-purity alumina, while hydrothermal processes can produce materials like zeolites and molecular sieves. By-products and materials recovered from dross processing can be beneficially reused in applications such as brick, cement, and ceramic manufacturing, reducing waste and supporting more efficient use of natural resources.

When salt fluxes are used in melting operations, the practical application is usually between 0.5 to 2 kg of salt per tonne of liquid metal. There are potential emissions to air of dust, metal compounds, chlorides, HCl and products of poor combustion such as dioxins and other organic compounds from the melting and treatment furnaces. Ammonia and other gases can be emitted from the dross due to improper storage, treatment and transport of dross with salt flux. Therefore, the potential releases to air are:

- dust and smoke
- metal compounds
- organic materials (VOC, and dioxins) and CO
- oxides of nitrogen (NO_x)
- sulfur dioxide (SO₂)
- chlorides, HCl and HF
- ammonia (NH₃)

Fume extraction is an important element of secondary aluminium production and dross processing operations, where dust and smoke may be generated. The presence of several possible emission points on a furnace is significant, and the collection of the emissions from such points needs to be addressed. In addition, various systems may be employed to reduce fugitive emissions during the charging phase of the process. For example, docking cars that seal against the charging door can be used to prevent emissions during charging. In addition, hazardous gases such as NH_3 , CH_4 , PH_3 , H_2 , and H_2S can be formed when dross reacts with water. More detailed discussion is given in Appendix A4.6.

3.8 Generation of salt cake

Salt cakes are generated as a result of the melting stage in a TRF when salt fluxes are used to process white or black dross. It is the material remaining from the dross recovery process where metallic aluminium is extracted. Salt cake usually consists of very low aluminium content and non-metallic components (NMC). The largest fraction of NMC is aluminium oxide. A typical composition of the salt cake is (in wt %):

- Aluminium: 3-7 %
- Aluminium oxide: 10-75 %
- Sodium chloride: 30-50 %
- Potassium chloride: 0-30 %
- Fluorides (cryolite, chiolite, AlF_3 , etc.): 0-5 %
- Other aluminium compounds like aluminium carbide, aluminium nitride and aluminium phosphide: 0-2 %

These resulting oxides and NMC can possibly be used for reinforcing materials for several applications such as cement and asphalt, as well as refractory applications. Small portions may be being landfilled (0.13 kg of dross per tonne of primary aluminium produced according to IAI 2019 statistics).

3.9 Salt Cake processing

During dross processing in rotary salt furnaces, salt cake is generated. While opportunities exist to recover or beneficially reuse components of this material, landfill disposal may still be necessary in some circumstances. Following is a case study of landfilling of salt cake.

CASE STUDY: Landfilling of Saltcake – Aluminum Association

Humanity has a long history of disposing of its waste on or in the land. Recently it has been recognized that landfills for disposing of waste need to be properly designed and managed to minimize their impact on the environment. Landfills are excavated or engineered sites where waste materials are deposited and covered for final disposal. Disposal of saltcake in landfill is generally considered the least preferable management practice based on the waste management hierarchy. However, for some sites and situations, recycling, reuse or recovery is not a feasible economic option, and landfill is a necessary part of the waste management plan. In such cases, it is important for disposal and landfilling to be conducted in a responsible manner.

Every country has landfill facilities for municipal waste and for hazardous wastes and in each jurisdiction the rules and regulations may demand specific features for the design and management of the landfill. It is important to consult with relevant stakeholders including site owners, regulatory authorities and local communities when disposing of salt cake. In all cases, disposal of saltcake should be carried out in compliance with all regulatory requirements, and all necessary permitting should be obtained.

During landfill planning stages, specific consideration should be given to the design and operation of the landfill site including assessment of specific saltcake chemical and physical properties, suitability of the proposed site, landfill cell design, cell liner material suitability, and monitoring systems for environmental contaminants. Generally, it is good practice to dispose of saltcake in cells with engineered barrier-liner systems.

Liquid that has been in contact with the material (leachate) should be collected and either treated to minimize contamination from the landfill site or disposed of responsibly. It should be noted that the suitability of landfill and disposal systems will vary significantly across different jurisdictions and should be evaluated on a site-specific basis.

In the US, landfills are located, designed, operated, and monitored to ensure compliance with relevant federal and state regulations. They are also designed to protect the environment from contaminants which may be present in the waste stream. Landfills cannot be built in environmentally sensitive areas, and they are placed with on-site environmental monitoring systems. These monitoring systems check for any sign of groundwater contamination and for landfill gas, as well as providing additional safeguards. Today's landfills must meet stringent design, operation and closure requirements established under the Resource Conservation and Recovery Act (RCRA).

Saltcake waste does not meet the criteria to be classified as a hazardous waste in the US, and as such it is typically managed as a non-hazardous waste per Subtitle D in the RCRA regulations. This Subtitle establishes a federal program to manage non-hazardous wastes. To this end, there are regulations for the transportation and treatment, storage, and disposal of saltcake.

Landfills are selected and designed to minimize the chance of release of hazardous waste into the environment. In the US, design standards for non-hazardous waste landfills require:

- composite liner with both compacted clay and a synthetic geomembrane,
- leachate collection and removal systems,
- groundwater monitoring and contaminant detection program,
- run on, runoff, and wind dispersal controls,
- construction quality assurance program, and
- financial assurance mechanisms to ensure that funding for closure and post-closure care is available.

Operators must also comply with inspection, monitoring, and release response requirements.

Since landfills are permanent disposal sites and are closed with waste in place, they are subject to closure and post-closure care requirements including:

- installing and maintaining a final cover to minimize water infiltration,
- continuing operation of the leachate collection and removal system during the post-closure care period,
- maintaining ground water monitoring,
- preventing storm water run on and runoff, and
- installing and protecting surveyed benchmarks.

Like many other materials, saltcake can be disposed of in an environmentally sound and economic manner.



4 Operational Best Practices

A flow chart of best practices is summarised in Figure 24 where general flow is given in blue and important bullet points. The green boxes show which goals can be achieved in different parts of the value chain.

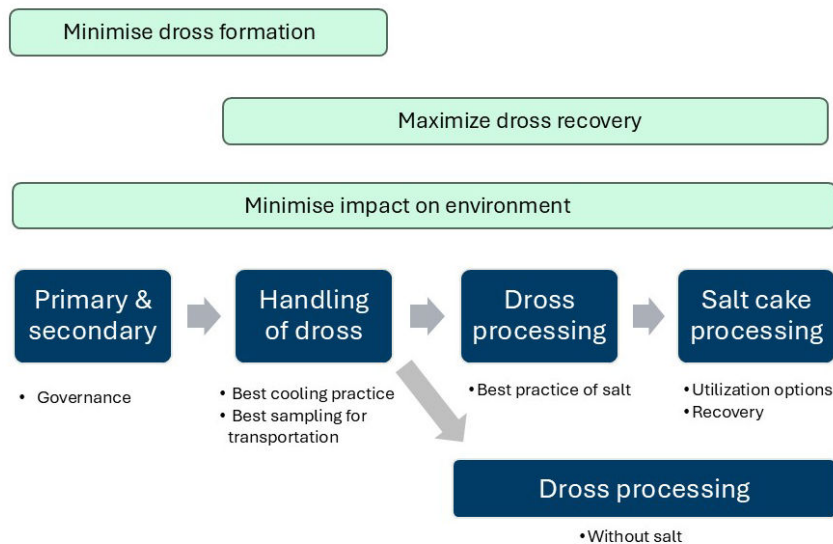


Figure 24: Flow chart of best practices

4.1 Primary and secondary production - governance

Effective governance provides the framework for managing dross safely, responsibly, and in compliance with applicable requirements. This includes clearly defined roles, responsibilities, accountabilities, decision-making processes, and oversight mechanisms across the dross lifecycle, from generation and storage through transport, processing, and final use. Transparency, documented controls, and appropriate reporting support accountability at all levels of the organization, from senior leadership to operators and contractors.

More broadly, good governance should include:

- A set of values and code of ethics applicable to employees, suppliers and for relationships with authorities and other stakeholders.
- Training for employees on transparency, accountability and ethical conduct.
- Having systems in place to ensure compliance with all legal and regulatory requirements.
- On dross storage reduce risks/hazards by enclosed, well-vented, prevent water ingress e.g. on mobile vehicles, gas monitoring systems.
- Best practices for transport (enclosed containers that are vented, dry, etc.).
- Payment of all applicable local, national and regional taxes and duties.
- Development and promotion of open communication channels for employees and other stakeholders to provide feedback, raise concerns or discuss issues.
- Public disclosure of management plans, activities and performance.
- Documentation of corporate policies and procedures including business decision-making.
- Development KPI's of key areas for performance to be tracked and managed.

Following is a case study of industrial dross treatment.

CASE STUDY: Overall Dross Treatment in China – Chinalco

Chinalco divide aluminium dross into two categories: **Primary and secondary aluminium dross.**

Primary aluminium dross is the aluminium dross skimmed from a melting, holding and/or casting furnace. It is mainly a mixture of metallic aluminium (20-90 %) and aluminium containing compounds. It may contain a small amount of chloride salts such as NaCl and KCl, and fluorides. In China, primary aluminium dross undergoes remelting, with a recovery rate of over 85%.

Secondary aluminium dross is a term used for both the dross remaining after the primary dross has its metallic aluminium extracted from scrap remelting processes. Its main components include alumina, aluminium nitride, a small amount of metallic aluminium (generally < 3%), and typically more chloride salts such as NaCl and KCl and fluorides, than primary aluminium dross.

Recovering metallic aluminium from aluminium dross can be divided into two processes:

Thermal treatment and cold treatment.

1. Technology for recovering metallic aluminium from primary aluminium dross at Chinalco

Thermal treatment of aluminium dross typically uses rotary kiln or other melting chambers. The dross is heated either internally (due to exothermic reaction between aluminium metal and oxygen), or externally (electrically heated or gas/oil burners) together with a salt flux (may contain NaCl, KCl, and fluorides). After melting of the dross, most of the metal is separated out.

Small domestic enterprises generally use the internal heat for thermal melting. A few domestic enterprises also use externally heated tilting rotary furnaces for dross melting to recover aluminium; these are typically larger-scale aluminium processing and recycling companies.

2. Regarding secondary aluminium dross hydro- and pyrometallurgical treatment technologies at Chinalco

Cold treatment of aluminium dross residue involves processing the residue after thermal aluminium recovery. Domestically, ball milling and screening are commonly used. Based on the ductility of aluminium, ball milling increases the metal particle cross-section (flattening) while the other components fracture and decrease in size. By screening, the metal particles are separated from the finer oxide and salt particles.

Hydrometallurgical treatment technology: Secondary aluminium dross hydrometallurgical/wet treatment primarily uses water, acid, and alkali solutions as solvents. Its main principle is to passivate the reactivity of the aluminium dross through wet hydrolysis and leaching reactions. The hydrolysis reaction mainly converts active components such as AlN, Al, and Al_4C_3 in the aluminium dross into gases such as ammonia, hydrogen, and methane, thereby eliminating reactivity and achieving efficient leaching of chlorides and fluorides. Hydrochloric acid treatment generally produces $AlCl_3$, alkali treatment generally produces alumina products, and water treatment yields inert high-alumina materials (substitute raw materials for aluminium-based products).

Pyrometallurgical treatment technology: The core of secondary aluminium dross pyrometallurgical treatment is to convert active components such as AlN, Al, and Al_4C_3 into Al_2O_3 through a roasting reaction, thereby eliminating the reactivity of aluminium dross. Without the addition of auxiliary materials, inert high-alumina materials can be obtained. By adding various auxiliary materials, calcium aluminate, sodium aluminate and other aluminate materials can be sintered. Other high-value-added products such as mullite can also be produced.

4.2 Minimize dross formation at cast house

In Appendix A3, the methods for reducing oxidation and dross formation both inside and outside the furnace is summarized, primarily by minimizing exposure to oxygen and reducing turbulence, as well as minimising overheating in the furnace.

4.3 Handling of dross

Effective handling of dross immediately after skimming is important to maximise metal recovery, minimise oxidation and maintain safe operating conditions. A range of technologies and practices are used across the aluminium industry to cool, contain and process dross prior to further treatment. The following sections describe commonly used approaches and their relative advantages and limitations.

Floor spreading is used to reduce the dross formation by decreasing the temperature of the dross as quickly as possible, reaching low enough temperatures to hinder further oxidation. By doing so, the heat and energy in the dross itself would not contribute to oxidising the metallic aluminium entrained within the dross any further. This methodology is not considered efficient as it required a large area for distribution of the dross on the floor. Due to the gases generated during cooling, it was also not desirable to have the dross on the floor inside. As reactions between the dross and potential rain/water would allow the generation of the gases even quicker, distributing the dross outside was not found to be a viable alternative.

Argon blanket has been used since the 1970s. This process uses a gas cover over the dross to prevent oxygen from reacting with the hot dross surface. The approach has since been further developed, and inert dross cooling systems are now used in several casthouses. In these systems, dross bins containing skimmed dross are placed under steel covers purged with argon (Ar) to inhibit oxidation of the metallic aluminium entrained within the white dross.

Dross presses are used after skimming the melt into specially designed dross bins, usually located in front of the holding furnace. The bin is then moved to the press, where pressure is applied from above, using the dross bin as a counterpart, to press out as much metallic Al as possible while it remains molten or semi-molten. The metallic Al is forced through holes in the bottom of the dross bin and recovered before the remaining dross is sent for external treatment.

Best practices for aluminium dross processing prioritize maximizing metal recovery and ensuring safe, environmentally compliant operations. Cooling aluminium in an inert atmosphere or by other means minimizes further oxidation and the risk of exothermic reaction of aluminium metal, which helps to reduce metal loss. If the dross is cooled rapidly, this makes it safer to handle for subsequent processing and metal recovery, which can be done via pyrometallurgical or hydrometallurgical methods. Figure 25 illustrates the results from processing a single variety of dross, using different recovery methods. Floor spreading in this case gave the lowest recovery based on opinions from the industrial interviews in Ref [5]. Table 4 summarizes the pros/cons of these methods.

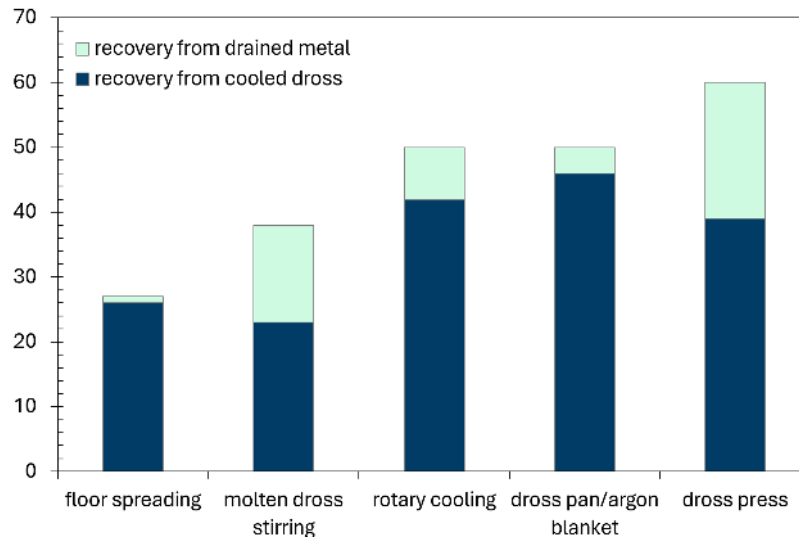


Figure 25: Metal recovery from different dross processing techniques
Reproduced from Ref [5]

Table 5: Pros/cons of dross processing methods

METHODS	PROS	CONS
FLOOR SPREADING	Low cost, no machinery needed, easy	Lowest recovery of metal, poor environmental performance, fumes, large floor area needed
MOLTEN DROSS STIRRING	High metal recovery, easier to crush dross, decreased dust and fume	Uncontrolled stirring leads to oxidation, investment cost, high mechanical maintenance, precise control needed
ROTARY COOLING	Stops thermiting, rapidly reserves metallic aluminium, minimise dross for landfilling	Equipment needed, high investment cost, requires large volume of dross
ARGON BLANKET	Efficient in preventing further oxidation and loss of metal	Requires gas supply throughout the cooling cycle
DROSS PRESS	Press action helps cooling, fast, high recovery of metal	Equipment needed, investment cost, may leave residual metal in dross

4.4 At the dross processor

Various pyrometallurgical processes have been developed specifically for dross recycling. These processes typically employ rotary mechanisms to homogenize the feed material and use different heating methods. In conventional rotary salt furnaces, salt flux is added to facilitate metal recovery and process efficiency.

Rotary furnaces are usually gas/oil fired and the salt fluxes are added such that the weight of the flux can be up to 50 % of weight of the oxides in the dross charged. The salt flux added has its own advantages: It protects the metal from oxidation, enhances the agglomeration of metal and its separation from the oxide.

Common aluminium dross recovery methods include dross processing machine, tilting rotary furnace, and squeeze recovery. Dross is physically separated into required size and dimension, then metallic aluminium is extracted, and the remaining oxide is used for the production of several applications listed as in Section 6.

Following is a case study regarding industrial dross treatment in tilting rotary salt furnace.

CASE STUDY: Tilting Rotary Salt Furnace Dross Processing – Real Alloy

Use of the tilting rotary salt furnace is the most common manner for processing dross worldwide. The justification is due to the high metal recovery efficiency, lower energy costs and high production efficiency per employee and unit of physical space.

A tilting rotary furnace consists of:

- A cylindrical steel barrel lined with refractories that rotates about its cylindrical axis and powered by an electrical drive system. Additionally, the barrel is supported by a steel framework that allows the barrel angle to change from an inclined operating angle to an emptying angle to remove the contents. Barrel holding capacity can vary from 0.5 to 30 tonnes.
- The barrel and its contents are heated with a combustion system. Most rotary furnaces use natural gas as the fuel although other combustibles like fuel oil and propane can be used. The oxidant is most commonly air although oxygen or an air-oxygen mixture can be used to lower the total energy requirements. Most commonly the burner system is mounted to a door that covers the barrel mouth.
- An environmental system is used to capture and clean the furnace off-gases. Typically, this includes hooding around the furnace mouth and barrel along with ductwork to an off-gas treatment system. Commonly, a bag filter system is used and is often complemented with a lime injection system to neutralize any acid gases that may be generated.
- A control system is part of any modern tilting rotary furnace. In addition to safety interlocks, the control system can manage the burner system, the mechanical systems, and monitor key process variables. Additionally, the key process variables for each cycle should be collected in real time and stored for future analysis.
- Ancillary equipment like charging equipment, molten metal troughs to other furnaces, transport crucibles, or solidification molds are required.

A tilting rotary salt furnace is normally operated in a batch mode. White dross and salt flux are charged to the furnace. While the barrel and its contents are rotated, heat is applied by the burner system. The heat and movement will release the aluminium metal from the oxide matrix and allow it to pool in the bottom of the furnace. With continued melting time, the contents will continue to rise in temperature. Once the correct temperature has been reached, the barrel is tilted downward and the metal is poured out of the furnace's mouth to a furnace, crucible, or solidification molds. The remaining material is called salt cake and is a mixture of salt flux, metal oxides (primarily aluminium oxide), and residual entrapped aluminium metal. Once the aluminium metal has been removed, the salt cake is poured from the furnace. Depending on the location the salt cake may be responsibly landfilled or sent to a closed loop processing facility for recovery of the primary components.

Since each white dross is different, key process variables are adjusted to optimize the furnace performance regarding metal recovery. If the dross being processed is for an external customer, recovered metal chemistry and weight are reported to the customer. The dross processor is also responsible for the environmental integrity of the process and proper handling of the final by-products. The recovered aluminium metal has a

very low carbon footprint due to the high efficiency of the process. Carbon footprints range from 0.1 to 0.5 Mt CO_{2e} / Mt Al_{out} based on the burner technology employed and the recovery of the white dross.

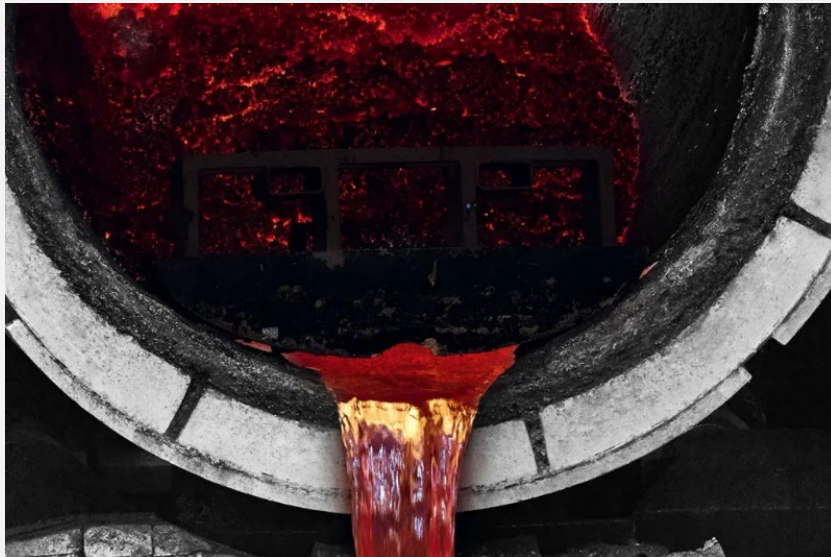


Figure 26: Molten metal pouring out of the TRF. Photo: Real Alloy

4.5 After dross processor

After dross processing, there is a salt cake remaining after the liquid is tapped. The salt cake needs to be treated in an environmental and economically viable process. Following is a case study regarding industrial salt cake processing.

CASE STUDY: Salt Cake Processing - Befesa

The salt cake recycling process operated by Befesa allows the recovery of free aluminium, fluxing salts, and the formation of inert metal oxide products, mainly composed of aluminium oxide. A flow chart is given in Figure 27.

The process consists of:

- mechanical crushing and metal separation,
- the reaction of hazardous components
- aqueous dissolution of salts,
- filtration of the inert material, and
- subsequent crystallisation of the salts.

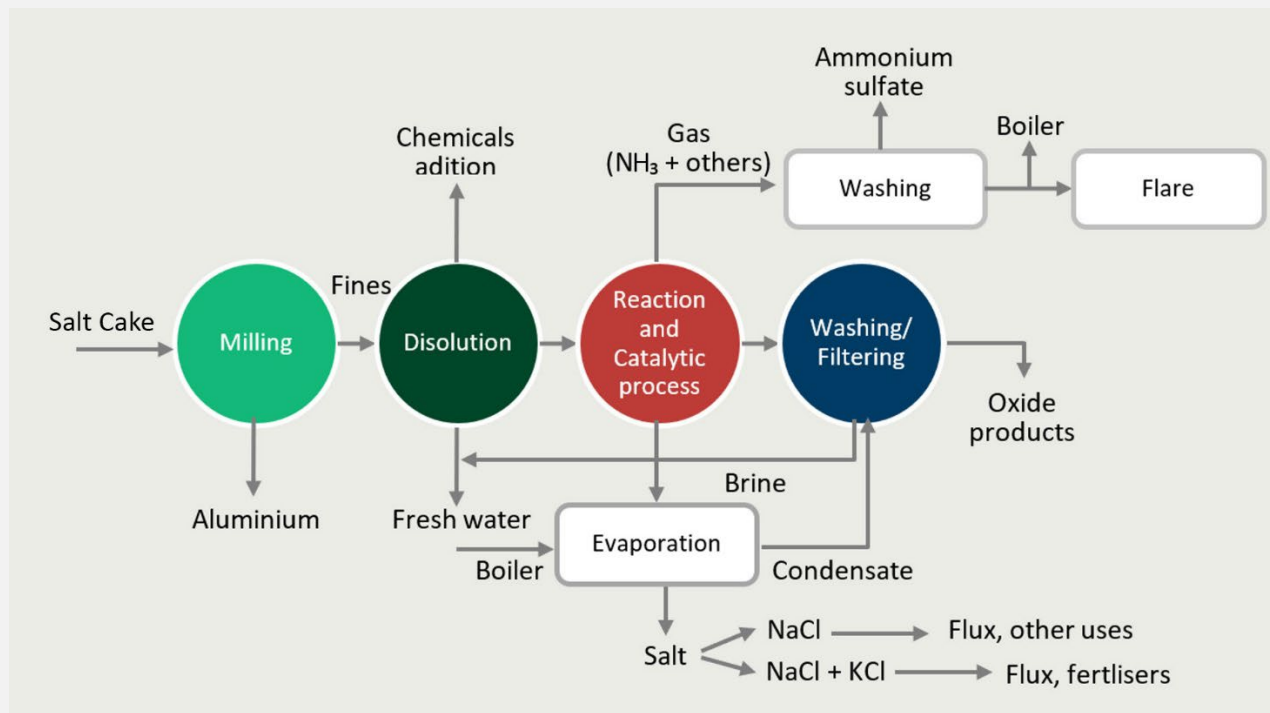


Figure 27: Salt slag processing flow sheet

Specifically, the phases are as follows:

Grinding: The purpose of this treatment is, on the one hand, to extract the metallic aluminium and, on the other, to reduce the size of the particles for a perfect reaction of the reactive components and the dissolution of the salts contained. It consists of breaking up large blocks and, once the material has been crushed, screening is used to obtain the first product of the recycling process, which is aluminium concentrate. The rest is reduced to powder and sent to the next stage.

Dissolution-Reaction: The material (powder) obtained in the previous stage is mixed with water to dissolve the salts. The mixture is reacted in order to eliminate the hazardous nature of the waste. The gases produced in the dissolution process are incinerated. After the reaction process, the decanted sludge goes through the next stage (filtration) and the brine is sent to the crystallisation process, defined below.

Filtration-Drying: The sludge obtained is washed and filtered, then sent to the storage area where it undergoes a multi-stage drying process until it is shipped. Once the final product is ready, it has multiple industrial applications, such as cement manufacturing, the refractory brick industry, or rock wool manufacturing, etc.

Crystallisation: the brine undergoes a process of evaporation and subsequent condensation, obtaining salt (a mixture of NaCl and KCl) and water that is reused in the process.

Gas scrubbing: The ammonia from the previous stages is conveyed to the gas scrubbers where, through scrubbing with sulfuric acid, ammonium sulphate is produced. This material is used by the fertiliser, rock wool and board industries.

4.6 Use of flux to maximize aluminium recovery from dross

The role of salt fluxes in dross processing is three-folds: maximising metal recovery, reducing oxidation and supporting efficient separation of metal from oxides. Peterson [6] reported the effect of salt flux additives on the aluminium droplet coalescence. It was reported that for the standard NaCl-KCl (or MgCl_2 -KCl) molten salt reclamation trials, 50/50 (by weight) flux produced no coalescence of aluminium droplets. A similar result was demonstrated for the addition of other chloride constituents. Chloride salts seem to have no coalescing ability under quiescent conditions. Salt compounds containing fluoride ions encouraged more effective merging of the aluminium globules. Effects of other salt additives to the flux are discussed. As known and practiced by industry, cryolite (Na_3AlF_6) was observed to be one of the most effective aluminium coalescence agents. Various percentages of cryolite additions were scrutinized by examining coalescence and metal recovery of delacquered Used Beverage Containers (UBC) in laboratory scale furnaces. A critical cryolite addition to the salt flux must be exceeded to maximize coalescence to the molten aluminium pool and, thereby, to maximize recovery. An example of UBC, up to 4 wt % Na_3AlF_6 , the recovery yield increases from 40 % to 90 %. With more than 4 wt%, it remains almost the same around 95 % yield.

A flux must:

- have a density less than 2.3 g/cm^3 ,
- not react with or contaminate the metal,
- not attack the refractory walls,
- be non-poisonous,
- have low vapor pressure,
- not be hygroscopic,
- inexpensive or easily recycled at low cost,
- have low viscosity, and
- separate cleanly from the metal.

A flux should:

- Have a melting point less than or equal to 660°C ,
- cover the metal (either solid or molten) and prevent oxidation,
- dissolve or suspend dirt, oxide, and other extraneous material adhering to the metal, and
- promote coalescence of the molten metal by partly dissolving the layer of aluminium oxide or magnesium oxide on the metal surface.

4.7 Minimize impact on the environment

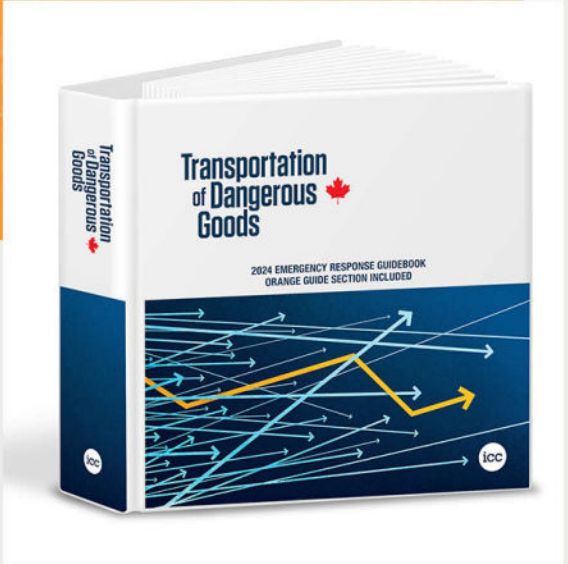
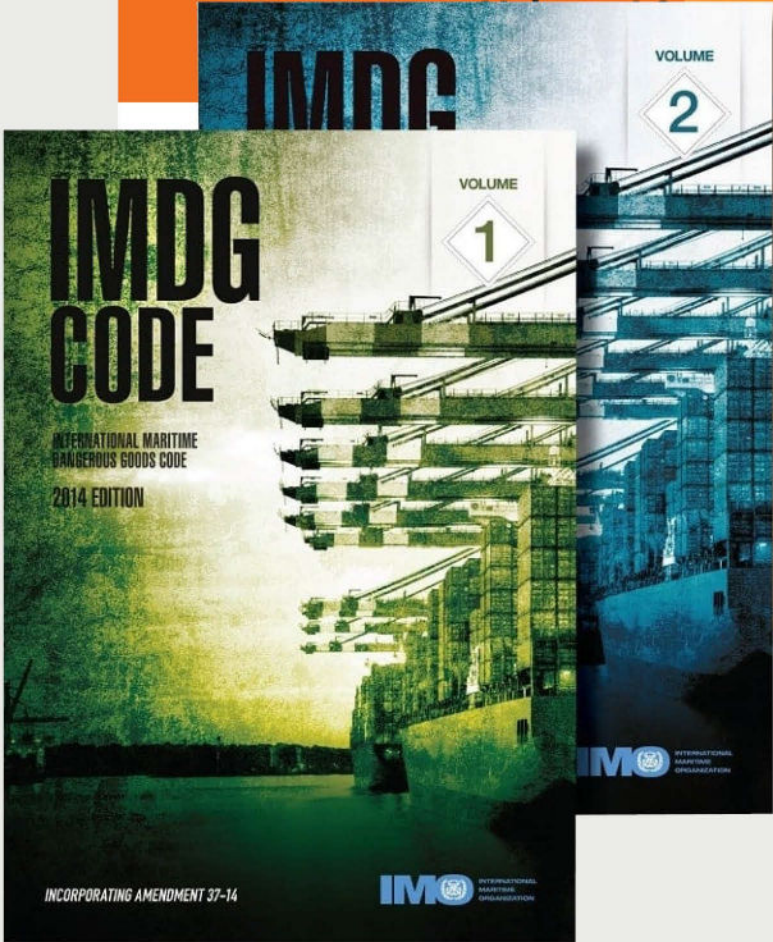
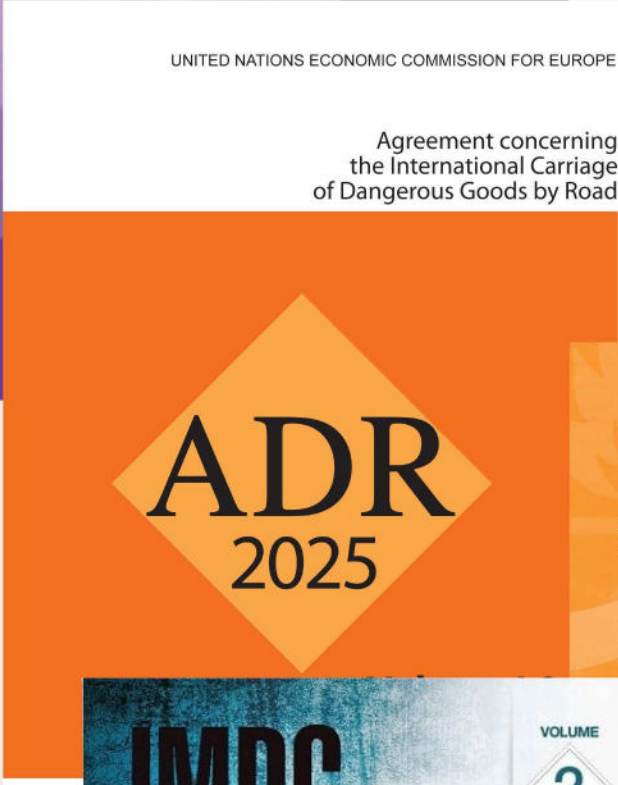
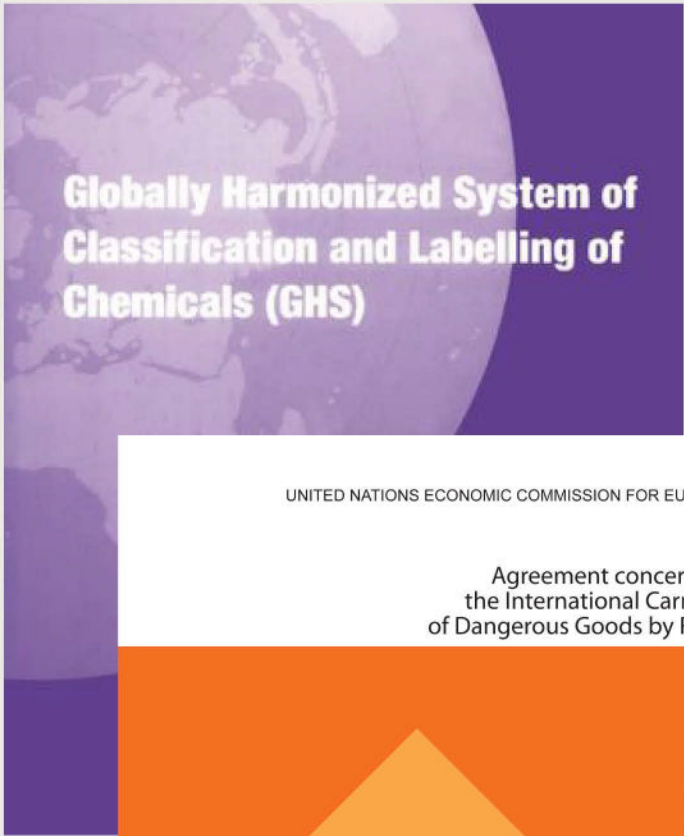
Several companies process black dross and salt cake through wet milling to enrich the metallic concentrate and produce byproduct brines and oxides. The process used in recovering salt from salt cake consists of the following process steps: (a) Crushing/Screening, (b) Water Leaching/Filtering, (c) Gas Elimination/ Brine Purification, (d) Evaporation/Crystallization. The slag as produced in the aluminium foundry is pre-crushed in a mill (impact or jaw crusher). The big lumps of aluminium are separated by screening and then the pre-crushed slag is directly leached in the water by a milling operation in special drums. From the resulting slurry the remaining aluminium grains are washed, separated by means of a rotating screen and finally dried to obtain about 80 % recovery efficiency. The oxide slurry is filtrated on a continuous vacuum belt filter, where the oxides cake is thoroughly washed from the chlorides. The resulting cake has a very low chloride content ($<0.2\%$) suitable for industrial application, as the cement production. The gas evolved during leaching, together with the gas released from the other controlled points, are collected and burnt in a special designed combustor, where the pollutants (mainly hydrogen, ammonia, phosphine and methane) are transformed

into water and inert gases. Finally, a single or a multistage crystallizer unit recovers the salt in form of crystals. The energy source is the steam generated by the combustion (thermal destruction) of the gases.

Traditional dross processing relies on salts to separate metal from oxides while generate salt slag that requires further treatment. Salt-free approaches aim to eliminate this environmental factor. In salt-free processing, aluminium dross is treated mechanically and thermally to maximize metal recovery. Techniques typically include crushing and screening to separate metallic particles, followed by heating in specialized furnaces (plasma torch) where the remaining aluminium is collected. Advanced systems may use inert or controlled atmospheres to minimize oxidation and improve yield. The main advantages of salt-free processing are reduced waste generation and simpler downstream handling. However, achieving high recovery efficiency can be more technically challenging compared to salt-based methods.

The non-metallic residues (mainly alumina) can be used in the production of refractories such as cement, concrete, bricks, tiles, and ceramics, additives as reinforcement in asphalt. Other applications include raw material for mineral wool applications, and applications such as fertilizer. Thus, these non-metallic residues can become a by-product instead of a waste.

The metallic residues can be used as deoxidizer in other metallurgical industries.



5 Regulatory and Transportation Frameworks

The chapter is structured by the practical challenges and regulatory issues that arise with regard to handling dross and salt cake. Companies first need to identify the recovery route they will use to process the materials. Next, they must determine if the material is hazardous.

At the highest level, recovery route at company level and the hazardous questions need to be addressed in relation to both the global harmonised system and transport. At the end of the recovery route is shown below in Figure 28, where green arrows show at what level this must be addressed.



Figure 28: Flow chart of regulatory framework

5.1 Hazardous or Non-Hazardous?

To determine if the material is hazardous, it is important to recognize that hazardous is a relative term depending upon which regulations are under consideration: (1) worker and downstream user protection; (2) environmental protection; and /or (3) transportation. The term "hazardous" is not a "one size fits all concept."

It is possible that a material can be hazardous to workers and downstream users, yet not a hazardous waste. Similarly, it is possible that that same material may be classified as hazardous waste in one jurisdiction but not a hazardous waste in another. It is also possible for a material to be hazardous in a work environment, but not hazardous for transport. The reason for this is that the criteria for classification under one regulation is not always the same as other regulations.

The regulatory framework to consider begins with an understanding of the genesis of the transport and hazard communication regulations. Both national and international regulations start either at the United Nations Subcommittee of Experts on the Transport of Dangerous Goods (TDG) or the United Nations Subcommittee of Experts on the Globally Harmonized System of Classification and Labelling of Chemicals (GHS) as shown in Figure 29.

Normally these UN Subcommittees operate independently. However, recognizing that there can be some overlap in issues between the UN TDG and UN GHS subcommittees, in 2015 there began joint meetings to resolve practical issues affecting both transport and hazard communication.

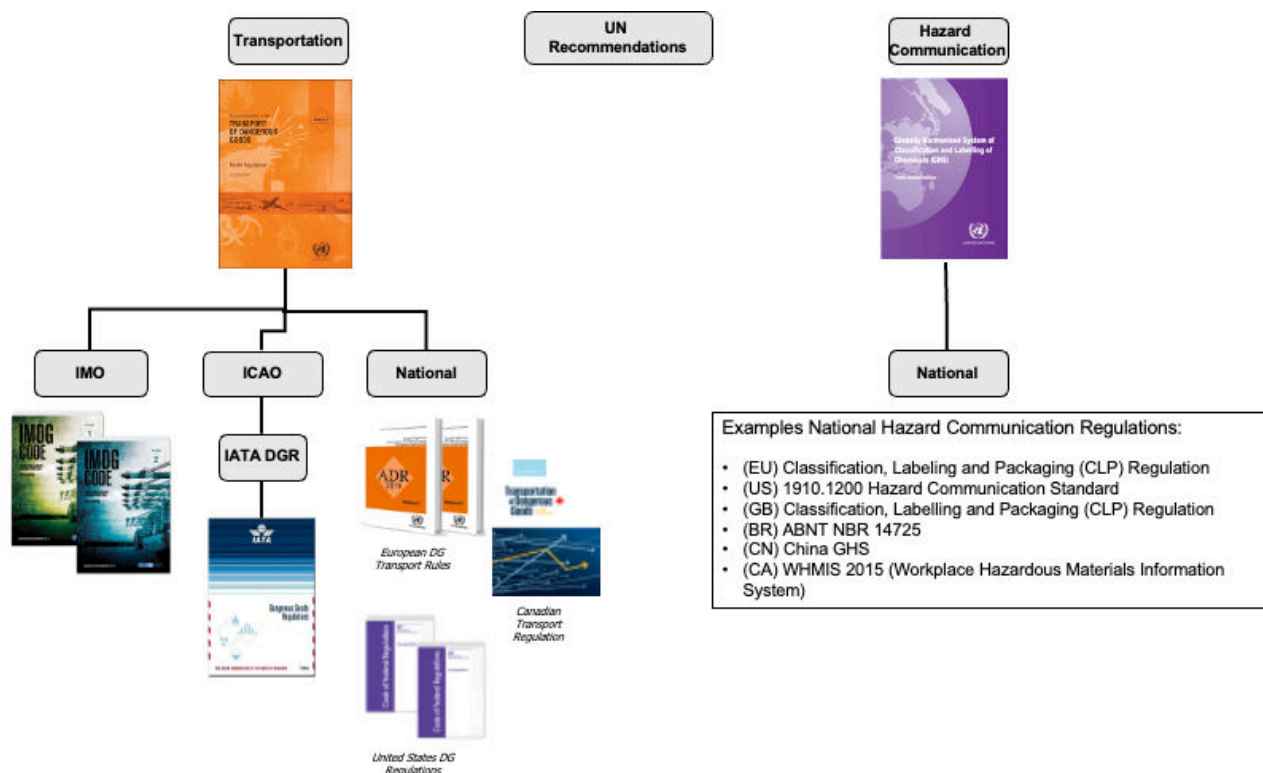


Figure 29: Framework of UN recommendations for Transport and Hazard Communication Regulations (Alcoa)

Globally Harmonized System of Classification and Labelling of Chemicals

Given the reality of the extensive global trade in chemicals, and the need to develop national programs to ensure their safe use, transport, and disposal, it was recognized that an internationally harmonized approach to classification and labelling would provide the foundation for such programs. In 2003, at the United Nations Subcommittee of Experts on the GHS published the first edition of the GLOBALLY HARMONIZED SYSTEM OF CLASSIFICATION AND LABELLING OF CHEMICALS (aka Purple Book). The harmonized system for classification and labeling was subsequently adopted, country by country, resolving many barriers to trade.

The scope of the GHS includes:

- harmonized criteria for classifying substances and mixtures according to their health, environmental and physical hazards; and
- harmonized hazard communication elements, including requirements for labelling and safety data sheets.

The goal of the GHS is to identify the intrinsic hazards found in chemical substances and mixtures and to convey hazard information about these hazards to the target audience. The audiences for the GHS include consumers, workers, transport workers, and emergency responders.

Is Aluminium Dross and Salt Cake Hazardous according to GHS?

Aluminium dross and salt cake may be classified as hazardous within the framework of GHS because it has both physical and health hazards, depending on composition and jurisdiction-specific implementation requirements. Section 2 of a Safety Data Sheets (SDS) alerts users to the classification and labeling elements including pictograms, hazard statements and precautionary statements (prevention, response, storage and disposal). Review of the SDS prior to storage or handling is strongly recommended.

Physical Hazards

The physical hazard common to national SDS's is "Substances and mixtures which, in contact with water, emit flammable gases." This hazard can also be found in the transport classification.

Due to the nature of the physical structure of the dross, it is possible that combustible dust could be created. Take care not to allow small chunks, fines or dust to contact water, particularly in enclosed areas. Avoid situations where dust will be created wherever possible.

Health Hazards

The predominant health hazards are corrosivity to skin and eye and specific target organ toxicity (repeat exposure). Due to differences in cut-off values and specific concentration limits, aluminium dross and salt cake are classified under additional hazards in some countries, so it is well advised to examine country specific SDS's where the recovery route crosses jurisdictions.

Handling and Storage

Prior to handling or processing, consult Section 8 of the SDS for appropriate engineering controls and individual protection measures such as personal protective equipment to protect workers from possible adverse effects.

In storage, keep material dry. Do not allow small chunks, fines or dust to contact water, particularly in enclosed areas. If material becomes wet, remove it to open area. Storage of material in unventilated containers, tanks or railcars can allow toxic or flammable gases to accumulate.

Labelling

GHS labels are required for packages/containers in storage. The labels will contain the required GHS labelling elements:

- Pictograms
- Signal Word
- Hazard Statements
- Precautionary Statement

Safety Data Sheet

Although the SDS is not a transport required document, it is the best way to communicate hazards of aluminium dross and salt cake. For bulk shipments the SDS should accompany the shipment to communicate the hazards contained within the transport unit to downstream users and emergency responders.

Transport of Dangerous Goods

As described in Figure 29, The UN Recommendations on the Transport of Dangerous Goods, often called the Model Regulations, provides a globally harmonized framework for the transport of dangerous goods.

The Model Regulations cover principles of classification and definition of classes, listing of the principal dangerous goods, general packing requirements, testing procedures, marking, labelling or placarding, and transport documents.

Transport of dangerous goods is regulated to prevent, as far as possible, accidents to persons or property and damage to the environment, the means of transport employed or to other goods.

Is Aluminium Dross and Salt Cake Hazardous Considering Transport?

Certain substances, like aluminium dross and salt cake, in contact with water may emit flammable gases that can form explosive mixtures with air. These materials are easily ignited by ordinary sources of ignition, for example naked lights, sparking hand tools or unprotected lamps. The resulting blast wave and flames may endanger both people and the environment.

Transport Classification

Aluminium dross and salt cake are classified as a “substance which in contact with water emits flammable gases” typically assigned to UN3170, Division 4.3.

Multimodal core requirements for the transport of aluminium dross or salt cake are:

- Temperature control – must be cooled to ambient temperature before loading;
- Moisture prevention – ensure protection against water ingress as moisture reacts with the materials to produce flammable gases like hydrogen and methane;
- Ventilation is mandatory –
 - Sheeted bulk containers used in land transport allow natural airflow.
 - Closed bulk containers require specialized venting devices designed to let gases escape while preventing water or foreign substances to enter.

Handling

Before loading, these by-products must be cooled to ambient temperature (unless they have been calcined to remove moisture). Transport wet or overheated material is forbidden.

Cargo transport units containing bulk loads shall be adequately ventilated and protected against ingress of water throughout the journey.

In the event of an accidental spill or release, do not use water for cleanup as it will trigger gas generation. Instead, cover with dry sand or soil. Use dry cleanup procedures and collect for recycling.

Packing

Aluminium dross and salt cake may be packaged in specification sift proof non-bulk packaging, intermodal bulk containers and bulk containers. However, many national regulations allow non-specification packagings under specific conditions.

Land transport

In 2014 Spain and Norway (ST/SG/AC.10/C.3/2014/10) brought a paper forward at the 45th session of the UN TDG meetings to request a change to the Model Regulation allowing aluminium dross (3170) to be transported in sheeted bulk containers as they had been used for many years in land transport. Previously, only BK2 “transport in closed bulk containers” had been permitted. Earlier that year the Joint Meeting (RID/ADR/ADN)³ had adopted provisions to maintain transport of UN 3170 in sheeted or closed vehicles and containers.

The Sub-Committee adopted the proposal, which authorized the use of BK1 “sheeted bulk containers” for the inland transport of such by-products and required appropriate ventilation and protection against ingress of water for all transport units in the event of bulk carriage.

³ RID: “Regulations Concerning the International Carriage of Dangerous Goods by Rail”, ADR: “Agreement concerning the International Carriage of Dangerous Goods by Road”, ADN: “European Agreement concerning the International Carriage of Dangerous Goods by Inland Waterways”.

ADR Special Provision 244 (as amended)

244 This entry includes e.g. aluminium dross, aluminium skimmings, spent cathodes, spent potliner, and aluminium salt slags. Before loading, these by-products shall be cooled to ambient temperature, unless they have been calcined to remove moisture. Cargo transport units containing bulk loads shall be adequately ventilated and protected against ingress of water throughout the journey. Notwithstanding the provisions of 4.3.2.2, sheeted bulk containers (BK1) may be used for inland transport.

ADR Special Provisions for Carriage

As both open sheeted and closed bulk containers are allowed for land transport, if the shipper chooses a closed bulk container, the following special provisions apply:

CV37 Before loading, these by-products shall be cooled to ambient temperature, unless they have been calcined to remove moisture. Vehicles and containers containing bulk loads shall be adequately ventilated and protected against ingress in water throughout the journey. The cargo doors of the closed vehicles and closed containers shall be marked with the following in letters not less than 25 mm high:

"WARNING
CLOSED MEANS OF CONTAINMENT
OPEN WITH CAUTION"

This shall be in a language considered appropriate by the consignor.

In the US (49 CFR), rail cars, highway trailers, roll-on/roll-off bins, or other non-specification bulk packaging are authorized. Packaging must be sift-proof, prevent liquid water from reaching the hazardous material, and be provided with sufficient venting to preclude dangerous accumulation of flammable, corrosive, or toxic gaseous emissions such as methane, hydrogen, and ammonia. The material must be loaded dry.

In Canada (Canadian TDG), aluminium dross may be handled, offered for transport, or transported in a railway vehicle or a non-specification container. The container must be water-tight, sift-proof, and provided with a venting arrangement that is capable of preventing any accumulation of gaseous emissions that could endanger public safety. Before and during loading, the dangerous goods must be dry, must not come in contact with water, and must not be offered for transport if the temperature of the dangerous goods exceeds 40°C (104°F).

Sea Transport

For transport by sea, International Maritime Dangerous Goods (IMDG) Code Special Provision 244 requires:

- Adequate ventilation to prevent gas build-up.
- Protection against water ingress throughout the journey.
- Ensuring the material is dry and cooled to ambient temperature prior to shipment.

It is important to note that BK1 sheeted bulk containers are not allowed for sea transport, only BK2 closed bulk containers. The ADR specific labelling on closed bulk containers is allowed on intermodal containers shipped via road/sea but is not called out as a requirement in IMDG.

Placarding

The Model Regulations cover placarding requirements for Division 4.3 dangerous goods.

In the EU, the orange panel must meet the requirements of 5.3.2.2 Specifications for the orange-coloured plates. The hazard Identification number to be used is 423. In the US, placarding is also required for any amount of a Division 4.3 dangerous good. Following is a case study for representative sampling, which can be used before transporting of dross and salt cake.

It is important to make a representative sample in particular before transporting. A case study of how to achieve is given below.

CASE STUDY: Achieving a Representative Sampling – WV Metalle

With regard to testing aluminium dross, most errors are made in taking and preparing the sample. This is because aluminium dross is generally very inhomogeneous – it is easy to obtain a non-representative sample which is then inadequately prepared. Therefore, the dross specific sampling must meet the judgement target, take specific inhomogeneities into consideration and be economically feasible.

In particular, the following aspects must be considered:

- Representative sampling on both a mathematical-statistical and empirical knowledge basis can only be carried out with a great deal of effort. In practice, a suitable compromise must be found which avoids hazards.
- Samples should only be taken by experienced samplers; suitable training is recommended.
- In the run-up, the testing laboratory is to be integrated in the sampling plan.
- The sampling instructions must conform to the different points of origin in detail. The expedience of the specific sampling strategy must be verified at every point of origin by tests; retesting should be carried out if there are procedural changes in the casting process.

Contrary to samplers at point of origin (with non-varying production conditions), samplers at vehicles must take different types of dross into consideration. Especially in this event, the testing laboratory should be integrated into the sampling strategy, and the samplers must receive appropriate training.

If sampling at a vehicle (e. g. during inspection by police or customs) is required, the condition of the load should be as comprehensively documented as possible. This should include a description of the pieces, the documentation of the site where the sample was taken and an estimate on the size distribution of the dross. Pictures of the load can be helpful in this case. If possible, the despatching company should be involved by providing comprehensive documentation. If possible, the involvement of an independent and qualified sampler is recommended. The sampler should also take a duplicate sample for later tests, so that the required information on the physical composition of the dross (coarse and fine particles) is well documented for later laboratory analysis.

With inhomogeneous material, such as dross, and storage / transport amounts of several tons it is hardly practical to take a statistically sound, representative sample due to the time-consuming and labour-intensive effort. Less elaborate but practical sampling naturally equals more sampling errors. However, this can be reduced by the experience of the sampler with the material to such a degree that a reliable assessment is possible.

5.2 Waste

Globally, aluminium dross regulations vary by country, but a major international treaty, the Basel Convention, governs its transboundary movement if classified as hazardous waste. The list of signatories can be found on the Basel Convention website⁴. In some regions, like India, aluminium dross is explicitly listed as hazardous waste requiring disposal in authorized facilities, while in other countries End-of-Waste regulations

⁴ <https://www.basel.int/>

define criteria for when it ceases to be waste. The U.S. Environmental Protection Agency (US EPA) has not listed it as a hazardous waste, but in other countries, it is hazardous due to its reactive nature, including the potential to generate flammable gases when in contact with water. Waste classification should not be confused with GHS hazard classification or transport classification. A material may exhibit hazardous characteristics and be classified under GHS or transport regulations while not being classified as hazardous waste in a specific jurisdiction.

Resource recovery (post-treatment residues)

Management of aluminium dross focused on total resource recovery in the following order:

Metal Extraction

The first priority in management is reclaiming high-purity metallic aluminium through mechanical and thermal processes:

- Mechanical Pre-treatment: Dross is crushed, milled, and screened to separate aluminium-rich particles from oxides as described in Section 2 and 3.
- Pyrometallurgical Processing (Section A4.3):
 - Rotary Salt Furnaces: The traditional method uses salt fluxes (NaCl, KCl) to protect the metal from oxidation during melting creating a salt slag as by-product.
 - Salt-Free Technologies: Using plasma torches with inert atmospheres or plasma arcs to recover metal without salt, significantly reducing secondary by-products.

Hydrometallurgy

When metallic content is too low for melting, chemical leaching could be used to extract aluminium ions and neutralize hazards (Section A4.4):

- Alkali/Acid Leaching: Dross is treated with sodium hydroxide (NaOH) or sulfuric acid (H₂SO₄) to dissolve aluminium and produce value-added chemicals like alum or polyaluminium chloride (PAC) for water treatment.
- Gas Recovery: Controlled hydrolysis can capture generated gases like Hydrogen (H₂)

Non-Metallic Product Utilization

The remaining residue (mainly alumina and silica) is increasingly diverted from landfills into industrial applications as shown in Section 6.

- Construction materials: Used as a raw material in cement clinker, bricks, and as a reinforcement in concrete to improve durability.
- Refractories & Ceramics: Processed dross is used to manufacture high-temperature furnace linings, ceramic tiles, and zeolites for industrial filtration.
- Agriculture: Some treated residues are explored for use as soil conditioners or fertilizers, though this is strictly regulated due to heavy metal content.

Integrated Waste Management Strategies

- Detoxification: Neutralize reactive components like aluminium nitride (AlN) and soluble fluorides before any landfilling or secondary use is permitted.
- Co-treatment: Co-processing dross with municipal solid waste incinerator ash to stabilize heavy metals and create new cementitious materials.
- On-site management: Many smelters are installing "hot dross" processing units to immediately treat dross upon skimming, preventing the oxidation of metal and reducing the total volume of waste transported (see Section A3).



6 Sustainability and circularity considerations

Variables that are important for the sustainability, energy and GHG are discussed in blue in Figure 30.

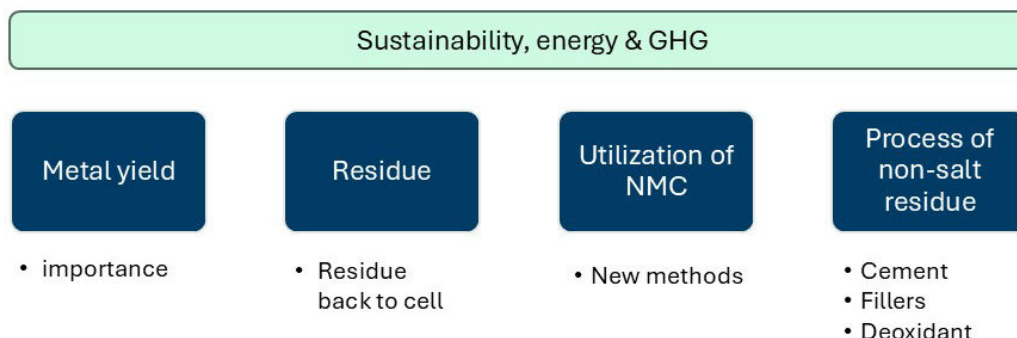


Figure 30: Important variables for sustainability

Dross recycling is critical for sustainable aluminium production, as it transforms a byproduct (white/black dross) from melting into valuable materials, preventing landfill disposal and reducing dependence on raw material mining of bauxite ore. Increased environmental regulations demand stricter management of emissions and waste. Modern, high-efficiency recycling techniques can recover over up to 95 % of aluminium content which supports the circular economy goals. Best practice dross recycling focuses on maximising recovery of aluminium metal and identifying beneficial uses for non-metallic residues, thereby reducing landfill disposal and improving resource efficiency across the aluminium value chain. Recycling transforms aluminium oxide within the dross into usable materials, such as raw materials for cement, ceramics, or artificial aggregates. The future of dross management focuses on reducing dross formation at the source and utilizing efficient methods for total resource recovery.

Main products and valorisation pathways of aluminium dross of the metal and the residues are:

- Aluminium metal
- Salt fluxes
- Oxides (alumina, spinels)
- Construction materials
- Refractory materials
- Metallurgical additives
- Chemical feedstocks
- High-purity products via advanced processing

Table 6: Specific uses of dross and residue

CATEGORY	SPECIFIC USES
METAL RECOVERY	Recovery of metallic aluminium through rotary furnaces, plasma furnaces, mechanical separation.
CONSTRUCTION MATERIALS	Filler in concrete and asphalt, lightweight concrete production; substitute for limestone or silica sand, improves stiffness, road construction material.
REFRACTORY & CERAMICS	Production of calcined alumina, refractory bricks, ceramics, sintered calcium aluminates for molten metal protection.
METALLURGICAL APPLICATIONS	Desulfurizer, deoxidizer in steel refining, reductant for silicon alloys, slag conditioners (e.g., calcium aluminates).

CHEMICAL PROCESSING	Production of AlCl_3 via acid leaching; production of alumina via hydrometallurgical processes, production of ammonium sulfate via scrubbing.
SALT RECOVERY	Recovery of NaCl/KCl salts via crystallization processes from salt cake.
NMC APPLICATIONS	Zeolites, molecular sieves, high-alumina materials, inert granular solids via HADES thermal processing.
ADVANCED INDUSTRIAL USES	Plasma-processed NMP products such as Noval™ and NovaCal® for steel slag conditioning.
ENVIRONMENTAL USES	Engineered landfill fillers (when non-recyclable), emissions-neutralization in scrubber systems.
ENERGY / HYDROGEN GENERATION (EXPERIMENTAL)	Hydrogen production through aluminium–water reaction using fine dross particles.

6.1 Metal Yield

Dross processing typically occurs in rotary furnaces. Modern rotary furnaces can achieve metal yield rates exceeding 95 % (relative to metal input, not total charge: as defined in Chapter 1.3) when they are correctly charged and processed. Aluminium dross processing energy consumption varies significantly, from over 2500 kWh/tonne aluminium produced for older, conventional salt-rotary furnace methods to as low as 375 kWh/tonne aluminium produced with advanced energy-efficient processes.

GHG emissions from electrical generation are primarily determined by the fuel and technology mix of a country's power system. Energy efficiency itself varies substantially with melting technology, operational practices, and heat-recovery. GHG emissions are typically expressed as CO_2e .

6.2 Applications of residue

There are several suggestions for different applications where dross residue is used with the aim of utilising the waste. Aluminium dross residue can be used as a filler when producing asphalt such as replacing limestone (CaCO_3), which gave promising results. It can also be used as a reinforcement to produce lightweight concrete. The lower density concrete was obtained following a reaction between the dross residue and OH-generating H_2 bubbles in the material. concrete and cements containing aluminium dross residue have also given promising results resulting in higher stiffness of the product. Generation of different gases, e.g., H_2 , NH_3 and CH_4 , can also be a result when the dross residue is in contact with water, as these are all exothermic reactions. A novel utilisation process also studies the use of aluminium dross residue as a reductant to produce Si alloys. Another application for aluminium dross residue is in the production of calcined alumina by mixing limestone and non-metallic residues from the dross, forming a calcium aluminate (CaAl_2O_4) phase suitable to use as a reductant for the iron and steel industry. The applications can be specifically listed as below:

- Conditioned dross (obtained by washing with boiling water) is used as a filler in concrete and it results in 25 % higher flexural strength and a 5 % higher compressive strength compared to pure cement.
- Dross of particle size $<70 \mu\text{m}$ can be used as a filler in concrete and asphalt to improve abrasion and control microcracks. However, this application is not proved.
- Aluminium dross residue can be used as a source of calcined alumina which is used in refractory applications.
- Dross residue can be used to produce sintered calcium aluminates that can be used as a protective cover for liquid metals.

- Aluminium dross residue has been used to substitute green silica sand in mould material for aluminium alloy castings.
- Aluminium dross residue can be used in steel plant as desulfurization, deoxidizer agent in refining furnace.

Following is a case study regarding recycling of dross by returning material back to the electrolysis cells.

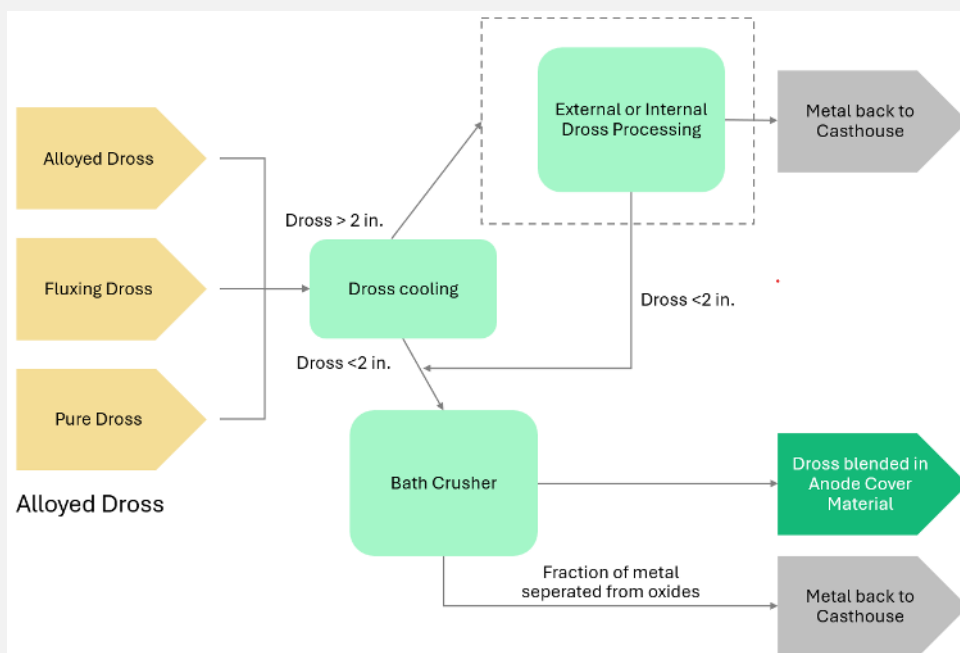
CASE STUDY: Dross Alumina back into Electrolysis – Alcoa

The Alcoa Dross to Pot (D2P) process enables the recycling of cast house dross and other residues back into the aluminium smelting process.

The D2P process (as taught in Patent WO 2025/221914 A1) implements systems and methods in the cast house, bath treatment center, and pot room of an aluminium smelter to eliminate the landfilling of dross and capture the value in this residue material. Cast house operations must ensure that contaminants are not present in the process so that the dross is compatible for D2P. An example would be the elimination of the use of phosphorous-containing non-wetting agents or ceramics in the cast house. Alcoa has been able to successfully remove these contaminants without negative process, safety, or financial impact to the cast house. Beyond the select contaminant mitigation, the cast house will have minimal changes to the dross handling process, skimming, cooling, storage, and shipment to processor. Dross prepared for the D2P process can be received entirely from a compatible salt-free external processor, in Alcoa's Baie Comeau Smelter this material is received from Lefebvre Industri-AL's RAME (Recyclage d'aluminium en mode écoresponsable) process.

Once the processed dross is received there are multiple methods by which the dross can be added to the smelting pots. Examples taught in the patent include adding to the anode cover, direct additions through the pot tap hole or as part of the automated alumina feed. In order to sustainably manage the addition of the dross, critical process modifications are required.

The process has been successfully demonstrated across a range of alloys, which includes pure aluminium, foundry alloys, 3xxx, 5xxx, and 6xxx alloys. Both laboratory studies and plant tests have resulted in a thorough understanding of the behavior of dross impurities when different alloys are recycled. Not only do



changes to the metal chemistry have to be considered by the addition of the dross, but the impact on bath chemistry must be taken into account. Alcoa's unique experience with the use of STARProbe™⁵ for bath chemistry and temperature measurement has allowed it to successfully manage the recycling of high magnesium dross and the resulting modifications to bath chemistry.

6.3 Utilization of NMC

After the extraction of all metal possible from the dross, the salt cake needs to be treated by viable process. In the following case study, a new method to treat the non-metallic compounds is described.

CASE STUDY: Thermal Processing of Black Dross/Salt Cake (BDSC) - HADES

Bartz GMBH is developing a new process for the treatment of BDSC that is called HADES.

During the HADES process the BDSC is charged into rotary furnace that has been preheated to between 1200 and 1400 °C. The ensuing rapid heating of the charge causes any residual aluminium and other oxidizable components (carbides, nitrides, carbon etc.) present to ignite resulting in intense local heating. The energy released is absorbed by and vaporizes the salts. (This limits the temperature rise to approximately 1430 °C, the boiling point of NaCl/KCl. The salt vapor is quenched in air forming a fine white powder which is collected in a baghouse. The oxide residue is a granular solid that is non-reactive/non-hazardous.

Advantages/Characteristics of the HADES process include:

Familiar technology and equipment

- Rotary furnaces are already widely used for processing aluminium scrap and white dross.
- The HADES furnace can also be operated as a "conventional" scrap melting furnace.
- Alternatively, HADES can be operated as a "two-step" process where scrap is first melted, and the salt cake is processed immediately after pouring out the molten metal.

In-House Treatment of aluminium recycling residues

- Independent from third party waste processing services.
- No shipping/transport of hazardous waste outside of the plant.
- Solid residues are chemically inert, odour -free and non-reactive with water or moisture.

Closed loop recycling of the salts during scrap recycling

- The salt is recovered as a dry white powder and can be charged directly back into the melting furnaces or if desired pelletized using conventional technology.
- Virtually eliminates the need to purchase and transport salt.
- Less exposure to price volatility of KCl.

Environmental aspects

- No water use- purely thermal process.
- No Hazardous/explosive gases generated during processing.
- Lower overall CO₂ footprint compared to current wet recycling/treatment process.
- Waste heat from the inert granular solids can be recovered.
-

⁵ a probe that measures the "Superheat, Temperature, Alumina concentration, Ratio (cryolite acidity)" parameters in real time



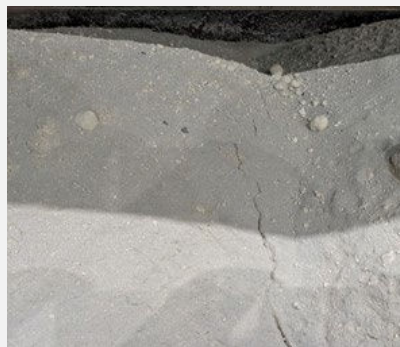
Salt slag (~3000 kg) in charging machine



Adding the charge to the preheated furnace.



Discharging the oxides residues at the end of the cycle.



Oxide residue after cooling.



Recovered salt after compaction.

Figure 31: The sequence of the method (top row) and the resulting oxide and salt (bottom row)

6.4 Process with non-salt residue

One of the most commonly used method for dross processing is the rotary furnace treatment with salt. The below case study is an alternative method that can treat the dross without salt using plasma heating.

CASE STUDY: Plasma Processing of Dross – Scepter

Scepter's Plasma Torch Rotary Furnace (PTRF)

Scepter operates two furnaces using plasma-torch, rotary-furnace technology for aluminium dross processing, in Saguenay, Quebec, Canada. The PTRF uses renewable hydropower to melt aluminium from dross with extremely low energy consumption and carbon emissions.

The system requires only 0.3 MWh per tonne of input material, yielding aluminium at 0.5 MWh per tonne of output, which represents a 97 % reduction in energy use, compared to primary aluminium electrolysis, and roughly 75 % less energy than conventional aluminium recycling furnaces.

Because the facility is powered by hydropower, its combined Stage 1 and Stage 2 carbon footprint remains exceptionally low: 0.004 tonnes of CO_{2e} per tonne of aluminium produced. Fossil fuels usage at the facility is limited to mobile equipment and mould preheating. This carbon footprint compares very favourably with typical recycling operations (0.3–0.5 t CO_{2e}/t) and far outperforms global primary aluminium production averages (~8 t CO_{2e}/t).

The factory was built in 1995 by Alcan to develop the plasma torch melting technology for aluminium dross. Scepter purchased the factory in 2002. Over 30 years, the plant has processed over 700,000 tonnes of dross, recovered more than 400,000 tonnes of aluminium, and maintained less than 10 % downtime. More than 250,000 tonnes of residual non-metallic product (NMP), branded Noval™, have been valorised, diverting substantial waste from landfills.

A major advantage of the PTRF is its ability to avoid added salt fluxes – common in rotary salt furnaces – and instead rely on the small amount of flux entrained naturally within the incoming dross. This design minimizes the generation of salt cake waste and makes the remaining Noval™, which is mostly alumina, suitable for uses in other products. Noval™ production supports a circular economy by enabling downstream applications, such as calcium aluminate and cement.

Today, 70–85 % of Noval™ generated is converted into NovaCal®, a fused calcium aluminate, through a patented process. This process removes impurities from the Noval, valorising the residual alumina, while offering steelmakers a high-performance slag conditioner. Over 120,000 tonnes of NovaCal have been produced.

Central to the PTRF is the electric plasma torch, which heats gases – typically nitrogen and oxygen – to the point of dissociation and ionization. This produces a high-temperature, low-reactivity plasma gas that melts aluminium efficiently while reducing oxidation. Radiant heat transfer efficiency reaches 70–80 %, compared to 30–40 % for natural-gas-fired RSFs. The sealed furnace environment minimizes water vapor and combustion by-products, keeping oxide layers on the molten aluminium thin and aiding aluminium coalescence without added salt. The reduced gas volume also significantly reduces and simplifies exhaust gas treatment. Residual baghouse dust can be recycled back into Noval™ product streams.

Performance comparisons between PTRF and traditional rotary salt furnaces show no statistical difference in aluminium recovery, though the recovery mechanisms differ. It is important to note that high metallic recovery – no matter the furnace type or process – depends not only on equipment but also on process expertise. In all aluminium recycling processes, poor operators and/or low technology equipment may inadvertently oxidize aluminium to reduce costs or harm aluminium recovery. Following strict best-practice protocols combined with excellent technology leads to high metal yields.

6.5 Sustainability Benefit

In 2025, it was estimated that about 2-3 % of the greenhouse gases (GHG) on a global level were caused by the aluminium industry (at about 1.1 Gt CO_{2e} annually). The most significant contribution to GHG originates from the electrolysis and the Hall-Hèroult process. However, to lower the aluminium industry's emissions, there is a need to evaluate all contributions.

The environmental benefits of reducing dross formation extend beyond the recovery of valuable aluminium metal. Every tonne of aluminium recovered from dross reduces the need for additional primary or secondary aluminium production, helping to conserve resources and reduce associated greenhouse gas emissions.

Dross recycling can also reduce the volume of material requiring disposal, while beneficial reuse of processing residues further supports circular economy outcomes. In addition, reducing dross generation can lower transport requirements, processing costs and associated emissions. For these reasons, minimising dross formation and maximising recovery remain important objectives for both environmental and economic performance. Below in Table 6 is a summary of sustainability benefits of dross processing.

Table 7: Dross recovery and reuse pathways

ALUMINIUM METAL RECOVERY	RETURNS ALUMINIUM TO THE VALUE CHAIN AND REDUCES THE NEED FOR PRIMARY PRODUCTION
RECOVERY OF SALTS FROM SALT CAKE	reduces consumption of virgin materials and supports circular material flows
PRODUCTION OF ALUMINA AND ALUMINIUM COMPOUNDS	generates secondary raw materials and reduces reliance on virgin resources
CONSTRUCTION MATERIALS (CEMENT, CONCRETE, CERAMICS, REFRACTORIES)	beneficially reuses residues and reduces waste disposal
OTHER INDUSTRIAL APPLICATIONS (MINERAL WOOL, FERTILIZERS, METALLURGICAL ADDITIVES)	creates value from materials that may otherwise require landfill
EMERGING TECHNOLOGIES (E.G. HYDROGEN PRODUCTION)	future opportunities for additional value recovery

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8 Appendix

A.1 Oxide formation

A.1.1 Oxide formation thermodynamics

The oxidation of liquid and solid metals in various atmospheres is important in melting and casting operations. Many of the problems that arise in these operations originate from oxidation. With the exception of gold, no pure metal and no alloy are stable in air at room temperature. All metals and alloys tend to react with air to form oxides and/or nitrides. As the temperature increases, the oxidation or nitridation rate increases. In Figure 32, the Ellingham diagram for reactions of metal with oxygen is given. In this figure only Mg and Ca have lower Gibbs energies than Al, that is, they form more stable oxides than aluminium oxide.

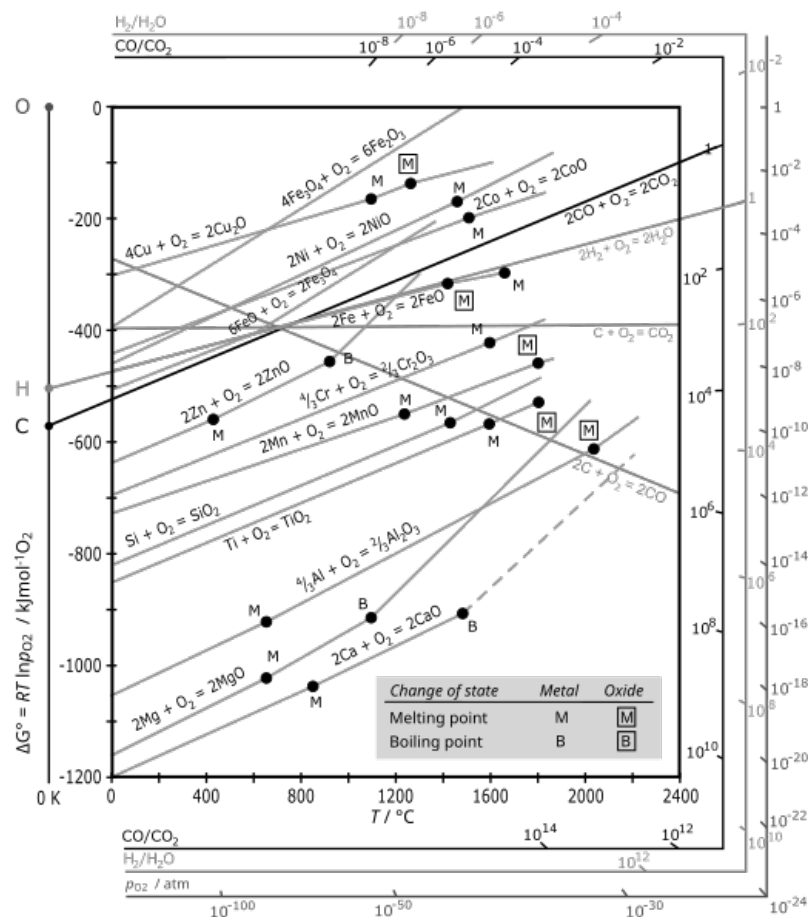


Figure 32: Ellingham diagram for reactions with oxygen [7]

Aluminium naturally forms a thin, protective oxide layer when exposed to air [8–13]. This layer, primarily amorphous aluminium oxide (Al_2O_3), forms almost instantly and is crucial for the corrosion resistance of aluminium and its alloys. (Stage I in Figure 33) The natural oxide layer is typically very thin, around 5 nm, and as long as oxygen is present, self-repairs if damaged. Stage II describes the phase transformation from amorphous to crystalline $\gamma\text{-Al}_2\text{O}_3$.

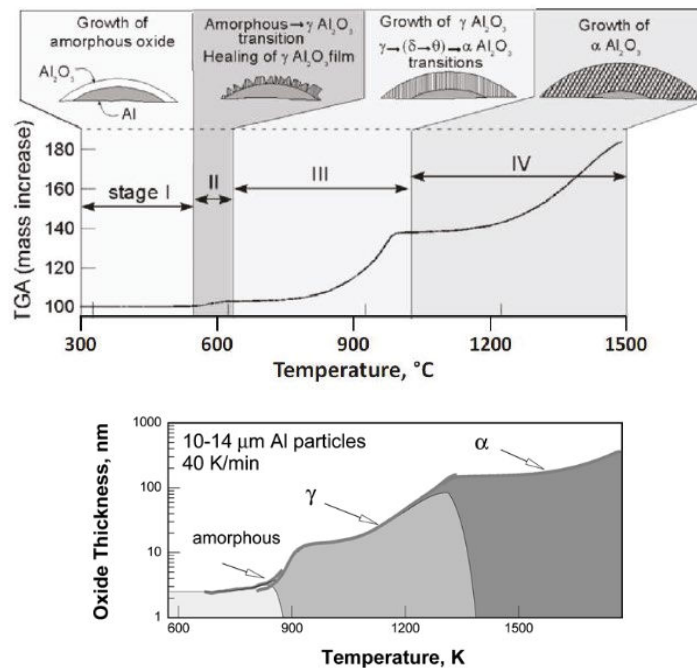


Figure 33: Oxidation stages of pure aluminium [14]

In Stage III, breakaway oxidation occurs due to volume shrinkage when the oxide is transformed from gamma to alpha oxide. When the density of the oxide layer is higher, its volume decreases. This decreases in its volume, physical cracking occurs and so-called breakaway oxidation occurs (Figure 34).

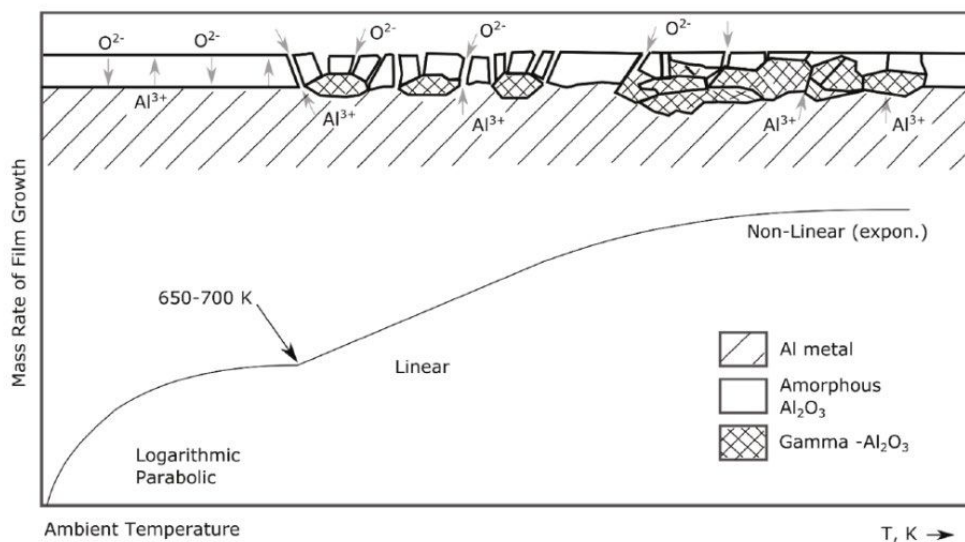


Figure 34: Visualisation of oxidation kinetics of aluminium oxidation [15]

Alloying elements affect the growth and composition of the oxide. Small concentrations of elements can increase or decrease the oxidation rate. It has been shown that small amounts of Mg added to aluminium increase the oxidation rate [10-17]. It is also known that a high concentration of Mg causes growth of relatively large MgO particles on the surface (Figure 35). Same scenario exists in the presence of Sr as well where $\text{SrO} \cdot \text{Al}_2\text{O}_3$ spinel oxides form.

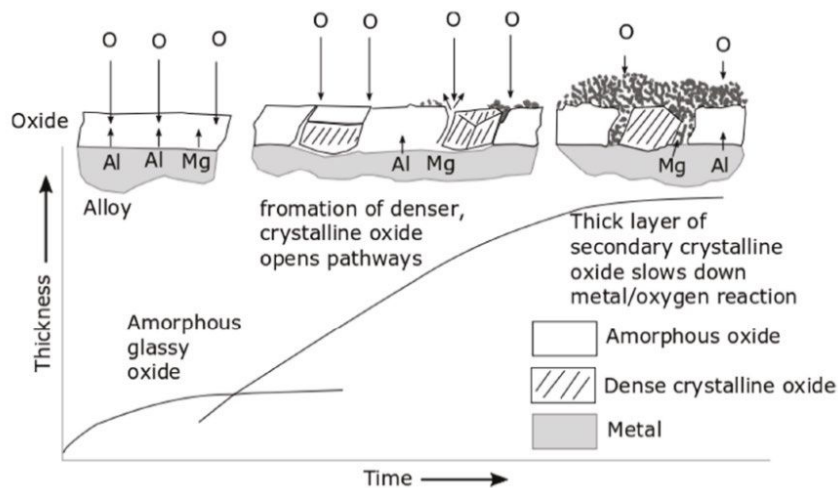


Figure 35: Schematic diagram of Al-Mg oxide formation [19]

A.1.2 Oxide formation on solid Al

The nature, composition, structure, and thickness of the oxide depend on the environmental conditions and the composition of the alloy. The thickness of the oxides formed on pure aluminium during oxidation in dry oxygen for 5 hr at room temperature and at 250 °C are reported to be 1.5 and 2.2 nm [8–13], respectively. The oxide layer formed on aluminium below 400 °C is amorphous. The growth of the amorphous oxide follows an inverse logarithmic rate law. Thin films grow at low temperatures, predominantly by cation migration, under the influence of a potential accumulation across the growing film. At about 400 °C, the crystalline oxide, γ -Al₂O₃, is nucleated at the metal-oxide interface. The growth of the dense γ -Al₂O₃ layer is controlled by diffusion and therefore follows the parabolic rate law. Surface properties such as the corrosion resistance of metals are determined by the properties of the surface oxide products formed during exposure to an oxidizing environment.

A.1.3 Oxide formation on liquid Al

Since in their molten/liquid state, many metals and alloys exhibit a solid surface film of oxide, the oxidation of liquid metal in various atmospheres plays an important role in melting, melt refining, and casting operations. For pure aluminium, because it is so very reactive with oxygen, oxidation starts by the rapid formation of an amorphous alumina layer within milliseconds, where the film grows by outward diffusion of aluminium ions.

Rossel [20] described melt loss and dross formation when remelting scrap with various thicknesses (i.e. specific surface area.) He concluded that large surface area increased oxidation of the bulk metal.

A.1.4 Ratio between oxide and the metal

The Pilling-Bedworth Ratio [21] calculates how well an oxide covers the metal below when it is in contact with oxygen by calculating the volume ratio between oxide and the metal it comes from. This is defined as:

$$PBR = \frac{M_{ox}/\rho_{ox}}{nM_{met}/\rho_{met}} \quad (A1)$$

Where the M and ρ are molar mass and densities for the oxides and metal, and n is the number of metal atoms per unit oxide. The interpretation of the PBR is that if $PBR < 1$, the oxide does not cover or protect the

metal against further oxidation. If $PBR > 2$, there will be high tension in the oxide during growth leading to oxide breakup and exposure of fresh metal. If $1 < PBR < 2$, the oxide will be dense and protect the metal below against further oxidation. Table 8 gives the PBR for various selected metals with its oxide and explains (1) why Al_2O_3 protects aluminium while MgO does not protect Mg, (2) why Fe_2O_3 does not protect Fe, and (3) why there is a breakaway oxidation during the transformation of $\gamma-Al_2O_3$ to $\alpha-Al_2O_3$.

Table 8: Calculated PBR for various metals with its oxide

Element	Oxide	M_{met}	ρ_{met}	M_{ox}	ρ_{ox}	n	PBR
Li	Li_2O	6.9	0.5	29.9	2.0	2	0.54
Na	Na_2O	23	1	62	2.3	2	0.59
Sr	SrO	87.6	2.6	104	4.7	1	0.65
Ca	CaO	40.1	1.6	56.1	3.3	1	0.68
Mg	MgO	24.3	1.74	40.3	3.69	1	0.78
Al	$\alpha-Al_2O_3$	27	2.35	102	3.97	2	1.12
Y	Y_2O_3	88.9	4.5	226	5.0	2	1.14
Al	$\gamma-Al_2O_3$	27	2.35	102	3.5	2	1.27
Ti	TiO_2	47.9	4.11	79.9	4.3	1	1.59
Be	BeO	9.0	1.9	25.0	3.0	1	1.76
Cu	CuO	63.5	9	79.5	6.4	1	1.76
Si	SiO_2	28.1	2.3	60.1	2.6	1	1.89
Fe	Fe_2O_3	55.9	7.86	160	5.2	2	2.16

A.1.5 NaCl+KCl salt mixture

It is common to use a chloride-based salt for protection against oxidation of aluminium during characterisation and/or melting of dross. Different salt has different melting point. Pure sodium chloride (NaCl) has a melting point of 800 °C, pure potassium chloride (KCl) melts at 770 °C, and magnesium chloride ($MgCl_2$) melts at 714 °C. The best way is to use a salt with low melting temperature and binary mixtures of salt will reduce the melting temperature significantly. Figure 36 shows a calculated phase diagram of the NaCl-KCl mixture. For an equimolar mixture, the melting point is 657 °C, which is about the melting point of pure aluminium. The cheapest salt is NaCl so there will be an economic gain by using somewhat higher ratio of NaCl compared to KCl. For instance, 30 wt% KCl + 70 wt% NaCl will have a melting range of 668-725 °C. This will then be cheaper salt than an equimolar mixture, and not that much higher solidus temperature. It might even be better since the salt slurry layer might be thicker.

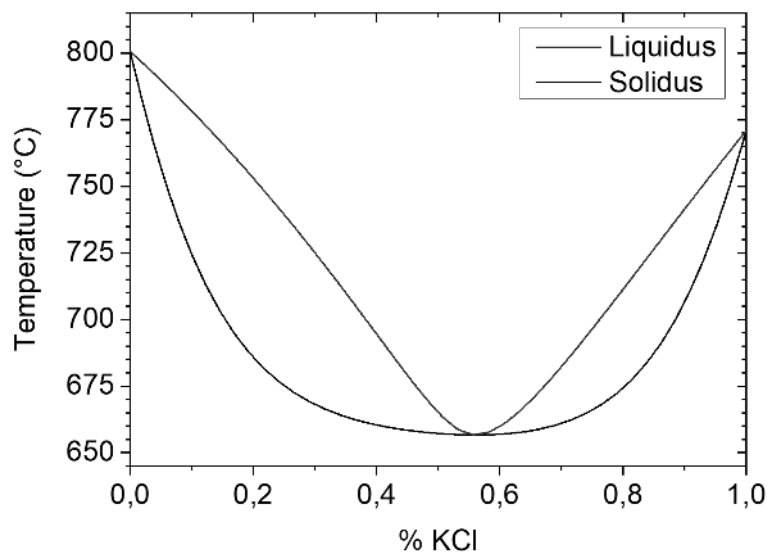


Figure 36: Phase diagram for mixture of NaCl + KCl as calculated by FactSage 8 (x axis in wt).

A.2 Dross formation

A.2.1 Process cycle steps and impact on dross formation

The cycle steps in a cast house can be divided into filling, treatment, stirring, dross removal, alloying, scrap addition, sludge (dross in the bottom of the furnace) removal and at last cleaning. The number of adding scrap and alloying and the sequence of the operations might vary. Figure 37 represents answers from interviews of cast house personnel regarding dross production during cast house operations. One should keep in mind that these are not actual measurements but rather estimates according to observers. It is however striking how explicitly the furnace and filling are dominant for melt loss contributions from these interviews with respectively 80 and 60 percent.

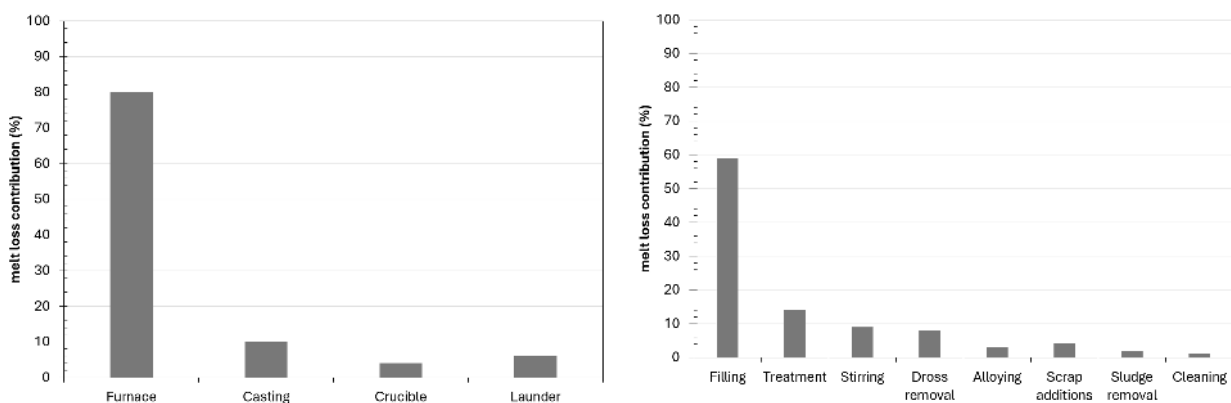


Figure 37: Distribution of dross formation
Reproduced from Ref [1]

A.2.2 Impact of charge material

Rossel [20] showed in 1990 that higher ratios of surface area to volume in scrap material leads to more dross formation. In addition, coated or lacquered scrap (such as UBC) may increase dross formation unless proper pretreatment is performed [22]. If the scrap is covered with oil or connected (e.g. glued) to other material types enhanced dross formation will also likely occur. Finally, due to stability and availability of alloying elements, the presence of elements like magnesium, sodium, and calcium influences dross formation.

A.2.3 Impact of process variables

Melt Temperature:

Impact:

Higher temperatures increase oxidation rate → more dross formation.
More dross, higher metal loss.

Suggestions:

Monitor the melt temperature and prevent overheating.

Atmosphere / Oxygen Exposure:

Impact:

Aluminium reacts rapidly with oxygen → forms oxide skin instantly.
Exposure to air increases dross formation.

Suggestions:

Consider furnace type (open vs closed).
Eliminate air intrusion during charging or transfer.

Moisture and Humidity:

Impact:

Moisture causes reactions with melt → oxide formation.
Leads to wet dross, which contains more entrapped metal.

Suggestions:

Preheat scrap and tools.
Control ambient humidity when possible.

Melt Turbulence / Handling Practices:

Impact:

Turbulent flow folds oxide films into melt (double oxide films).
Creates entrained dross particles.
Increases internal defects and surface dross.

Suggestions:

Lower pouring velocity. Use smooth, laminar flow handling.
Avoid poor transfer design (splashes, falls). Design runners/transfer launders carefully.
Minimize melt agitation.

Charge Material Quality

Impact:

Dirty, oxidized, or painted scrap increases.
Alloying elements (e.g., Mg, Si) may oxidize preferentially.

Suggestions:

Use clean, sorted and pre-treatment (decoating, cleaning) scrap.
Reduce oxidation-prone alloy exposure.

Fluxing Practices:**Impact:**

Fluxes help separate metal from oxide, reduce dross metal content.
Improper use can increase dross volume, introduce impurities.
Good fluxing → low metal loss to dross.
Poor fluxing → sticky, metal-rich dross.

Suggestions:

Optimize flux type and amount.
Ensure proper mixing and reaction time.

Holding Time:**Impact:**

Longer holding → more exposure to oxidation.
Oxide layer thickens continuously over time.
Increased surface dross accumulation.
Higher total metal oxidation.

Suggestions:

Minimize holding time.
Use covered furnaces or lids.

Alloy Composition:**Impact:**

Certain alloying elements increase dross formation.
Mg-containing alloys (e.g., 5xxx series) and Sr produce more reactive dross.

Suggestions:

Adjust process conditions depending on alloy type.
Use protective atmosphere for Mg alloys.

Furnace Type and Design:**Impact:**

Open furnaces → more oxidation.
Poor circulation → local overheating → dross hotspots.
Reverberatory furnace: higher dross due to large exposed surface.
Induction furnace: lower oxidation (less exposure).

Suggestions:

Use covered or sealed furnaces.
Optimize burner positioning and airflow.

Skimming Practices:**Impact:**

Improper skimming can remove excessive metal with dross.

Suggestions:

Gentle skimming → less disturbance.
Regular intervals prevent thick buildup.

Table 8: Variable increase and the following dross forming trend.

Variable	Dross Formation Trend
Temperature ↑	Strong increase
Oxygen exposure ↑	Strong increase
Moisture ↑	Increase
Turbulence ↑	Increase (entrainment)
Holding time ↑	Gradual increase
Scrap contamination ↑	Increase
Mg/Sr content ↑	Increase

A.3 Methods to reduce dross

A.3.1 Control of dross formation

List of the most critical method of reducing the formation of dross is by:

- i. Reduce splashing of metal, particularly when filling the furnace with primary metal from electrolysis
- ii. Avoid direct contact between burner flame and solid material
- iii. Avoid creating hot-spots in dross layer
- iv. Use electromagnetic stirrer, but with care.
- v. Add alloying elements as master alloys (particular those prone to oxidation)
- vi. Reducing the contact of the hot metal with atmospheric oxygen
- vii. Reduce aluminium oxide formation by adding specific alloying elements in small quantities
- viii. Reducing the turbulence of the hot metal during its transportation, promoting the smooth flow of the hot metal during transfer to avoid surface turbulence.
- ix. Have correct charging procedure
- x. Control furnace temperature and time

A.3.2 Correct filling

Correct procedures of filling the furnace can affect the dross generation. As seen in Figure 38 below, the charging of material increases the oxide entrapment and entrainment.

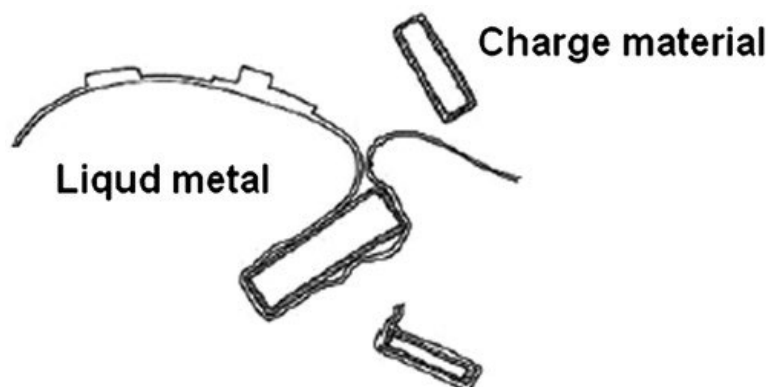


Figure 38: Increased dross formation during charging [23]

The charging guideline should be developed to minimise dross formation and must always take into account the risk of explosion from for instance, rusted scrap, and water on/in the scrap.

The procedure one of various options for safe charging should be followed. These include:

- A. Charging into a dry hearth (no molten heel),
- B. Charging onto a molten heel that has been solidified by either cooling the furnace or by charging known dry material to freeze the molten heel,
- C. Charging wet material onto a sufficiently large bed of dry scrap that has been previously charged into a molten heel; provided the charging is performed in a manner so that the wet material will not fall or tip over into the molten heel when charged and will be dry prior to entering the molten heel during the melting process [24].

A.3.3 In furnace

Optimization of the furnace operating parameters can reduce the dross formation by a large margin. Thermal isolation of the furnace, temperature control, optimized temperature in the furnace can significantly reduce the oxide layer thickness that reduces dross generation. The most critical point in melting operations is the direction of the flame in the furnace during gas firing. The burner flames must be directed parallel to the melt surface with radiating heating from the furnace walls. Otherwise, if there is a direct flame towards the melt surface (as seen in Figure 39), the oxidation will increase significantly and rapidly. In addition, the oxide layer over the melt surface will act as an insulating layer, and the heat transfer to the metal and hence burner efficiency will be significantly reduced.

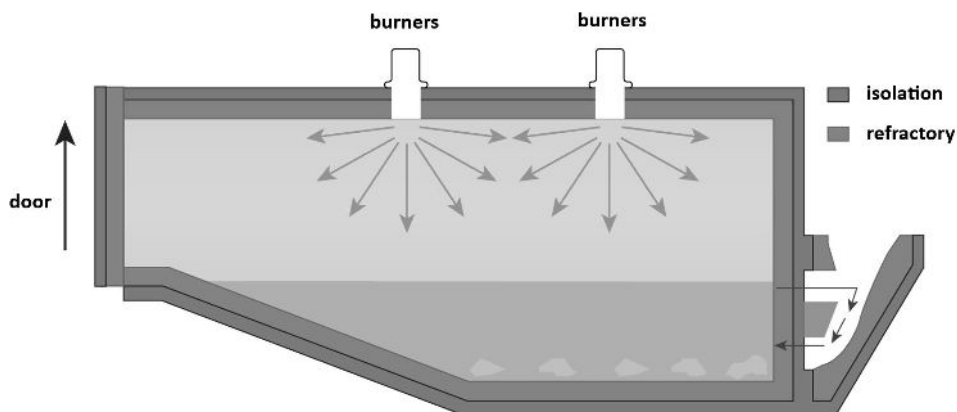


Figure 39: Wrong flame direction: direct flame towards the melt surface

During melt treatment where flux is purged through the melt with a carrier gas (argon or nitrogen), the surface of the melt is disturbed with the bubbles bursting through the surface. Freti [25] showed this effect with a classic schematic explanation as shown in Figure 40. It is very typically seen many casthouses that bursting the bubbles with high gas low rate together with the flux application seems to be the proper way of cleaning the melt, because the stirring action observed in the melt is considered as a way of more effective cleaning. Bursting of bubbles over the melt surface will generate more dross and oxide formation, therefore it must be avoided and flow rate must be adjusted.

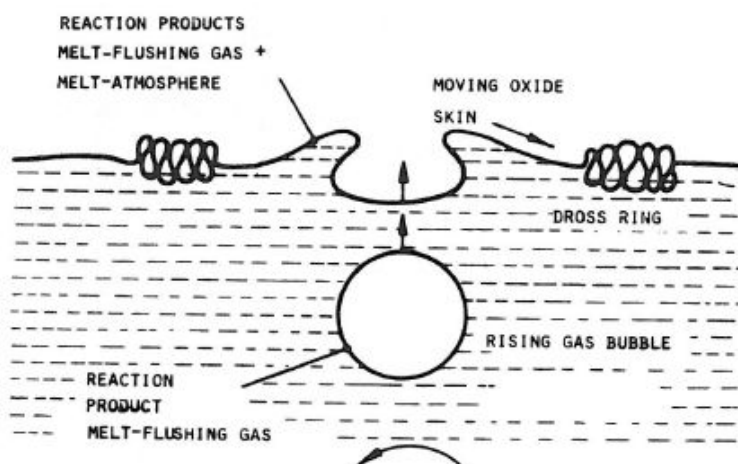


Figure 40: Dross formation as a result of fluxing gas treatment [25]

Oxidation of aluminium has been a challenging topic for a long time, and this is also the case with inhibition of oxidation. The affinity of aluminium to oxygen is extremely high. Thermodynamically the partial pressure of oxygen must be less than 10^{-43} Pa to avoid formation of Al_2O_3 [23]. This corresponds to one oxygen molecule in a volume of 10^{25} m^3 , or a sphere with radius about 10^5 km (far larger than a sphere defined by earth's radius of geostationary satellite orbit). Thus oxidation is unavoidable.

Several parameters have been investigated as potential inhibitors aiming to slow down the oxidation process and thereby increasing the metallic aluminium yield. Main inhibitors are the elements in the periodic table with regard to Ellingham diagrams that are located below aluminium which is an indication that these elements will chose to oxidize first prior to aluminium.

There is also the potential to choose an element that has higher affinity to oxidation than aluminium and give a desired PBR value (see Table 8). In that sense, Beryllium (Be) could be the first candidate for such protection of aluminium oxidation [26]. It is well-known that as low as 0,0001 wt% Be presence in aluminium could reduce oxide formation, however, due to its toxic nature, Be is seldom used as a micro alloying element. Calcium (Ca), Magnesium (Mg) and Strontium (Sr) are also in the same group as Be and have higher tendency to oxidation, although all these have $\text{BPR} < 1$. Ca is an unwanted element in aluminium alloys due to negative effects and tendency on hot cracking during deformation. Sr and Mg form spinel oxides due to breakaway oxidation, thus, increases oxide formation. Occasionally, CO_2 , argon and/or nitrogen protective gas is used over the melt surface to protect aluminium from further oxidation [8].

A.3.4 Molten metal transfer

With the gravity, liquid aluminium is forced to fall downwards naturally. In any melting process, the liquid needs to be transferred either to a casting line or to a transfer crucible. During such free fall of the liquid, if the fall height is sufficiently large, turbulence will occur. Campbell [23] has calculated this critical height to be 11 mm for aluminium, below which no turbulence occurs. An example of such a turbulence can be seen in Figure 41. The turbulence will result in air entrapment. The disturbance to the surface will result dross formation. Freti [25] showed that in the case of free fall, the melt stream surrounds itself with an oxide skin as seen in Figure 41 (right). Since there exists an oxide layer on the surface of the melt, when a charge material is fed into the melt, the oxide entrapment is unavoidable.

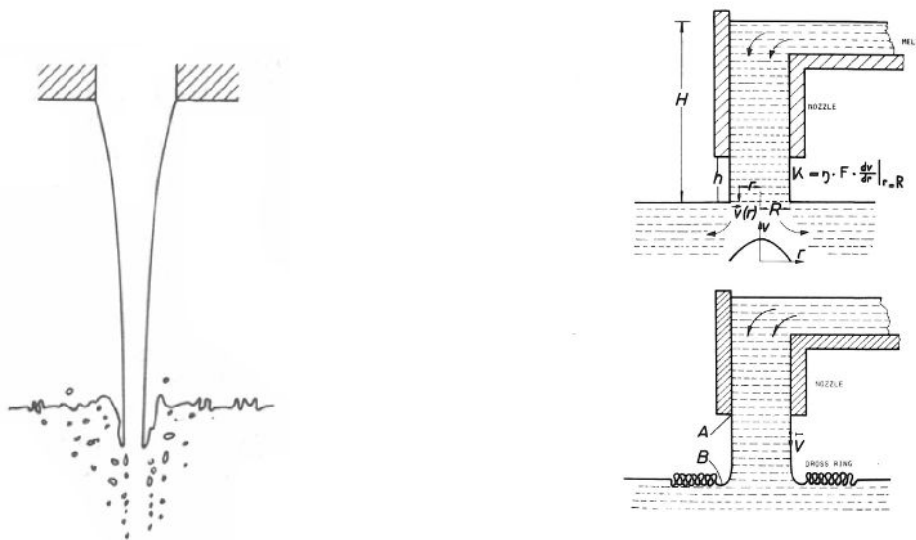


Figure 41: Schematic view of turbulence (left) and its effect on dross formation (right) [23]

A.4 Dross treatment

A.4.1 Historical Review

As long as aluminium has been manufactured and melted, dross (a mixture of aluminium metal and aluminium oxide) has been generated [27]. Due to the inherently high value of the aluminium, innovation has transpired in methods to effectively and economically separate the metallic values from this mixture.

The first US patent that deals with dross recovery was issued to Diack in 1910 [28]. He teaches a process for recovering metal from aluminium dross and skimmings whereby the material is charged under the surface of a molten metal pool in an externally heated crucible. Atmosphere control and use of fluxes are mentioned. Another early patent to directly mention the processing of drosses was issued in Great Britain (GB 109,746) in 1917 to H.A. Gill of William F. Jobbins, Inc. Rather than recovering the metal from the dross, this patent claims the use of an aqueous process to convert the aluminium to sodium aluminate and to eventually make alumina. Following these two patents a continual string of patents has been issued following various processing paths to reclaim value from the dross.

The many processes for handling aluminium dross can be generally broken down into one of three categories:

A. *Crushing / grinding for liberation of aluminium metal*

These processes seek to create an enriched metal concentrate by crushing and removing the friable oxide compounds. If the metal content of the dross is too high, the efficiency of the milling drops significantly. This process works well for black dross, salt cake, and low metal content white drosses. Advantages for this processing method are the avoidance of thermal or chemical processing and the normally expensive equipment associated with these processes. Disadvantages associated with crushing and grinding drosses are the dusts created if dry crushing or the production of a reactive material in an aqueous slurry that can liberate troublesome gases. An example of a crushing and grinding process is taught in a patent (US 3,037,711) devoted entirely to liberation of aluminium metal by crushing and grinding that was issued in 1962 to A. Businger of Metallwerke Refonda,

Weiderkehr & Co for a dry milling process which uses a mill to flatten aluminium pieces which are then separated from the friable oxides by screening or air classification.

B. Low temperature aqueous chemical processing

The common concept for these processes is to create an aluminium compound with value in other industries, such as aluminium sulfate or aluminium trihydrate. Advantages of aqueous processes are that they are generally not energy intensive and that all material is usually consumed in some manner. The disadvantages are:

1. The loss of the valuable metallic aluminium,
2. Sophisticated processing systems are usually required to handle the off-gasses,
3. Quality of the final products can be impacted by the variable nature of dross sources, and
4. The economics for processing by aqueous methods are often disadvantageous compared with conventional thermal processing.

A patent issued in 1981 to Huckabay and Skiathas (US 4,252,776) teaches an aqueous process operated at elevated temperatures to convert both white and black dross to aluminium tri-hydrate.

C. Melting

The melting group can be further broken down into four sub-categories:

1. Conventional furnaces
2. Batch reactors
3. Induction furnaces
4. Rotary furnaces (fixed axis or tilting)

Each of the first three methods have been proposed or practiced in the past. One of the earliest patents (US 1,180,435) in 1917 centers on the use of a reverb furnace to heat and melt a salt flux mixture which in turn melts and cleans drosses charged into the salt flux to yield clean aluminium metal. Other patents involve intimate mixing of dross with molten metal and a flux layer (US 1,550,192 and US 1,729,631). In some cases, externally heated crucibles are mentioned as the furnace type (US Patents 1,630,361 and 3,155,494). By the 1960's, these sorts of process were no longer being proposed due to the development of more efficient furnaces and methods

The first mention in the patent literature of a rotary furnace for processing aluminium is the Schmidt patent (GB 520,533) in 1940. A fixed-axis wet-salt flux rotary furnace system was described. Use of a NaCl – KCl eutectic flux mixture was mentioned as well. The bulk of dross processed today is with a tilting rotary furnace. The unpatented and proprietary technology was first used by IMCO Recycling and a few others in the early 1980's. The new technology being employed was often referred to as a "dry flux" tilting rotary furnace. The most common variant of this system utilizes an air-fuel burner system and the addition of a salt flux. Rather than requiring a high ratio of salt flux to charge material to ensure slag fluidity as the fixed axis rotary furnace required, the tilting rotary furnaces were able to use other salt flux ratios and decrease flux consumption. The performance of this furnace type was very dependent upon operator skill and the type of support equipment used. Generally, this system has the highest metal recovery, lowest operating cost, and highest processing rate. One alternative that is receiving more interest is a tilting rotary furnace using a plasma torch or an electric arc as the heat source and operating in the salt-free mode. This system variant has the benefit of not producing by-products requiring further processing or land filling which can be advantageous in some situations.

It is likely that dross processing technology will continue to evolve as new societal and environmental pressures are increasing. The desire for high recovery will likely remain as aluminium metal has a high inherent value.

A.4.2 Most Common Methods used today

Typically, 5–25 kg of dross is generated per tonne of molten aluminium. The metallic aluminium content of the dross is 50 wt% or more depending on the skimming method, alloy, type of flux (if it has been used), and the dross-cooling process. Due to the fact that the metallic aluminium is therefore extensively recovered from the dross by several processing methods [29]. The metallic aluminium recovering has significant economic and energy saving issues, as well environmental benefits, applying an appropriate treatment process is essential in the sustainable aluminium management. At present, the mainstream aluminium dross recycling processes are divided into two categories, namely hydrometallurgy and pyrometallurgy processes. Hydrometallurgy is a lower energy consumption dross recycling process with more application prospects. However, the industrial scale hydrometallurgical process has several disadvantages such as uncontrolled process parameters, economical difficulty in upscaling etc. Therefore, the most commonly used method in industry is the pyrometallurgical routes.

A.4.3 Dross: Pyrometallurgical route

Most aluminium-bearing scrap is recycled through a smelting process. Although the details of the smelting process differ between various installations, most involve melting the scrap in the presence of chloride-based dross, generally rotary furnace. This salt is typically a eutectic or near-eutectic mixture of sodium and potassium chlorides (NaCl/KCl) containing low levels of fluorides (cryolite) or other additives. It serves two primary functions. First, since the material is molten and fairly fluid at typical aluminium smelting temperatures, the salt coats the metallic aluminium being melted and minimizes oxidation losses during processing. Second, the presence of the fluorides and other additives assists in breaking down prior surface oxide layers on the aluminium charge and promotes improved separation between the aluminium and the residual non-metallic in the charge. A schematical representation is given in Figure 42.

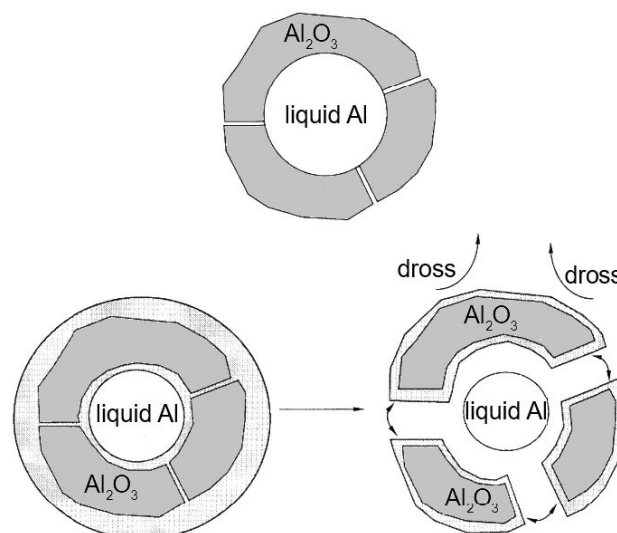


Figure 42: Reaction of salt flux with aluminium oxide in the melt [30]

Therefore, there are alternative flux-free dross treatment processes [31]:

Alcan plasma torch dross treatment process

Instead of using a gas or fuel burner, as in the RSF, a plasma torch is used to provide the required heat for heating the charge in the rotary furnace. The torch is mounted on the charging door of the rotary furnace which is designed to maintain close control of the atmosphere composition. The plasma torch consists of two water-cooled internal electrodes separated by a small gap through which the process gas, such as air or nitrogen, is continuously injected. An electric arc between the torch electrodes heats the gas to a very high temperature, causing the gas to dissociate and partially ionize. The charge is heated to 700–800 °C while the furnace is rotated. The aluminium in the dross is finely divided and wrapped in oxide films.

Hydro-Quebec DROSCAR graphite arc process

DROSCAR uses a DC electric arc, stretched and maintained between the two graphite electrodes, to heat the charge above the aluminium melting point. The energy transfer mechanism is mainly radiation from the arc and conduction between the heated refractories and the charge. The furnace rotates during heating of the dross to provide mechanical stirring.

ALUREC process

A rotary tiltable converter type furnace is used for the process. The oxy-fuel burner heats the converter refractory wall in a short time to about 1000 °C. Through the furnace rotation, the heat is transferred to the charge by conduction, and the heat is further distributed within the charge by mixing. The metal is collected at the bottom of the converter, and the solid NMP floats on top.

ECOCENT process

ECOCENT, developed by FOCON in Austria, is based on the idea of treating the hot dross as quickly as possible in a single operation to avoid exothermic losses, intermediate storage and unnecessary handling as well as to save energy. In the ECOCENT process the hot dross is fed without any fluxing salt additions into a converter where the relevant parameters for separation like temperature and viscosity can be adjusted. In the ladle or alternatively in the mould of the centrifuge the centrifugal forces are used for the separation of the metal from the aluminium oxide, the major constituents of the dross.

PyroGenesis DROSRITE process

Hot dross is charged to a refractory-lined rotary furnace, immediately after skimming from the aluminium holding furnace. The furnace is sealed and maintained under an argon atmosphere. The furnace is rotated, as it is necessary to gently tumble the charge, for roughly 15–30 min. The tap hole is opened, and the metal is poured into the receiving vessel or ladle. A controlled amount of oxygen is then injected into the furnace cavity, burning some of the non-recoverable aluminium metal contained in the residue. When the temperature reaches the target value, typically in the range of 800–900 °C, oxygen injection is stopped. Purging with argon is repeated before discharging the residues.

A.4.4 Dross: Hydrometallurgical route:

- Recycling of aluminium and Al_2O_3 using alkali leaching
- Recycling of aluminium and Al_2O_3 using acid leaching
- Recycling of aluminium dross to Al_2O_3 products
- Recycling of aluminium dross to AlN , Al , and SiO_2 products
- Treatment of fluoride and heavy metals in dross

Aluminium dross is a good raw material for the generation of hydrogen gas using aluminium-water reaction. Use of very fine particles of aluminium dross (45 μm) for reaction with water generates hydrogen gas. The fine particles of dross are produced by high energy ball milling. However, this process is highly energy

intensive, and the final sample size is very small for any commercial application. Understanding the trends for hydrogen gas evolution using aluminium scraps and wastes, it is seen that aluminium reacts with water when the surface of the metal is exposed to water. This is hindered by the oxide layer of alumina which is formed readily. The removal of alumina layer from the surface is therefore essential for the metal-water reaction. The reaction of aluminium with water is shown in Eq. 2.



There are various methods described in the literature for the removal of surface of alumina to generate fresh aluminium. Mechanical shredding of aluminium, chemical attack by acidic and alkaline solution, use of salts for the removal of alumina are various methods for initiating the process. Along the same track, the use of aluminium dross as a raw material is also investigated. Aluminium dross is a heterogeneous material, comprising of mainly aluminium metal and aluminium oxide. The amount of metallic aluminium is one of the main governing factors for the final yield of hydrogen. Theoretical calculations show that 1 g of aluminium produces nearly 2.5 L of hydrogen gas (at 0 °C and 1 bar). Considering the heterogeneity of the dross and lower aluminium content present in it, the volume of gas generated is expected to be lesser. The use of alkaline solutions for the hydrogen evolution has been investigated with the use of NaOH and KOH in water. With the alkaline solutions, the production of aluminates takes place. Sodium aluminate and potassium aluminate are formed with NaOH and KOH, respectively. During the formation of these aluminates in the solution, the hydrogen gas evolution takes place.

A.4.5 Salt Cake

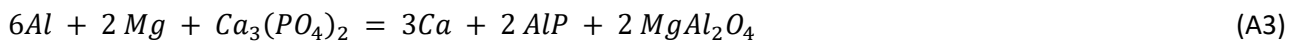
Developed in the mid-1960s, the RSF is the primary method for recovering aluminium from dross [5]. It is primarily used to treat high-grade non-salt drosses and the concentrates produced by milling and screening salt and low-grade non-salt drosses. The furnace operates on a batch basis, with a total charge of up to 25 tonnes per batch. The charge is a mixture of dross and/or dross concentrate, along with fluxing salt. The fluxing salt composition is a eutectic mixture of sodium chloride and potassium chloride, similar to that used in fluxed melting operations. As before, a flux with a few percent of an added fluoride salt (typically cryolite) helps to break the oxide skin around the molten aluminium as the contents is heated. This allows the molten aluminium to coalesce and increase the recovery. The added salt also protects the metal underneath from oxidation by forming a molten blanket on top. The amount of salt added varies with the composition of the added dross, ranging from 50 to 500 kg of added salt per tonne of charged dross. In older RSFs, the goal is for the mass of salt to equal the mass of non-metallic oxides in the dross. In newer furnaces, a lower ratio (0.2:1–0.4:1) is used. In either case, a higher-grade charge (i.e. more metal content) will use less salt than a low-grade charge.

A.4.6 Phosphine gas

Phosphine, PH_3 , is a colourless gas which is not only flammable, but more important toxic. According to safety data sheets at Linde gas the TWA (8h Time-Weighted Average) exposure limit is 0.1 ppm while STEL (Short Time Exposure Limit) is set to 0.2 ppm.

There is risk of generating phosphine from aluminium dross. One source can be bone ash (that has traditionally been used in the casthouse to fill cracks, and cover moveable joints [32]. Bone ash (calcium hydroxyapatite or simply calcium phosphate) itself is non-toxic and environmentally benign. However, the bone ash can be reduced upon contact with aluminium alloys to produce metal phosphides. Metal phosphides can in turn react with water or water vapor to liberate phosphine (PH_3).

With available magnesium in the metal, this can react with the bone ash according to



And further react spontaneously with water



or, if there is more Mg available:



With following possibility



Therefore, dross should always be stored (and transported) dry to minimize the risk of phosphine formation.

Clearly, to form phosphine, the phosphorus components must come in contact with water molecules. However, when processing dross, new surfaces will be created and hence expose previously protected materials to available moisture. Therefore, the processing of materials that seems inert can trigger the release of PH₃ gas rapidly and unexpectedly. It is therefore important to be aware of the materials potential for PH₃ formation and not rely on measurements taken while the material is in storage.

During melting of dross in a gas fired furnace, there will be high concentration of water vapour in the atmosphere, it is therefore also important to be aware of the risk of PH₃ formation and ventilate the work area properly.

Not only bone ash contains phosphorus. Phosphate is also used as binder in some ceramic foam filters (CFF) or may also be used as binder in refractory bricks. Over time, refractories are worn (either due to chemical reaction with the melt or due to mechanical abrasion). This could act as a source of phosphorus into the metal and dross. One should also be aware of that some alloying elements can contain phosphorus. For instance, metallurgical silicon will contain typically 20-50 ppm.