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Rotary-Furnace Recycling of Aluminum Scrap and Dross: A Critical Review of Feedstock–Flux–Furnace Interactions, Metal Recovery, Emissions, and Circularity

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Abstract

Rotary furnaces remain important in secondary aluminum production because they can process oxidized, coated, low-density, contaminated, and dross-rich feeds that are difficult to recover in conventional bath furnaces. Their flexibility creates a recovery–residue trade-off: heat, rotation, and chloride–fluoride fluxes can liberate and coalesce metal droplets, but may also increase oxidation, emissions, refractory attack, and salt-slag generation. This structured critical narrative review evaluates a coded corpus of 106 publications from 2020 to August 2026. The review is auditable from the final 106-record coding stage onward, but the discovery-stage corpus cannot be independently reconstructed because original exports, duplicate counts, exclusion logs, and query dates were not retained. Retrospective A–E classification was performed by one reviewer and therefore represents interpretive judgments of industrial transferability rather than reliability-tested study-quality grades. Reported values—including a 9% yield increase with NaCl in one rotary-converter study, 73.99% recovery for a selected dross size/salt condition, 97.14% recovery in intensified laboratory separation, and >90% recovery for a prepared salt-free chip route—are presented as examples of basis dependence, not as comparative technology rankings. Feed assays, equipment, salt basis, product specification, energy, emissions, residue routing, and uncertainty must be matched before performance can be compared. No level-A repeated industrial campaign with closed aluminum–salt–energy–quality balances was identified. Accordingly, the proposed nine-gate Feedstock–Flux–Furnace–Residue framework is a testable decision architecture rather than a validated control model; low-salt and salt-free strategies remain feed-specific and require prospective industrial validation.

Keywords: Aluminum recycling; Rotary furnace; Salt flux; Metal recovery; Aluminum salt slag; Secondary aluminum

Highlights

- No study met the strict level-A criterion for repeated industrial operation with closed aluminum–salt–energy–quality balances.
- The A–E hierarchy is a single-reviewer judgment of industrial transferability, not a reliability-tested score of methodological quality.
- Published recovery maxima are basis-dependent and cannot rank technologies without matched feed, salt basis, product quality, energy, emissions, and uncertainty.
- The nine-gate framework targets specification-compliant saleable alloy and requires prospective plant validation; low-salt and salt-free routes are feed-specific.

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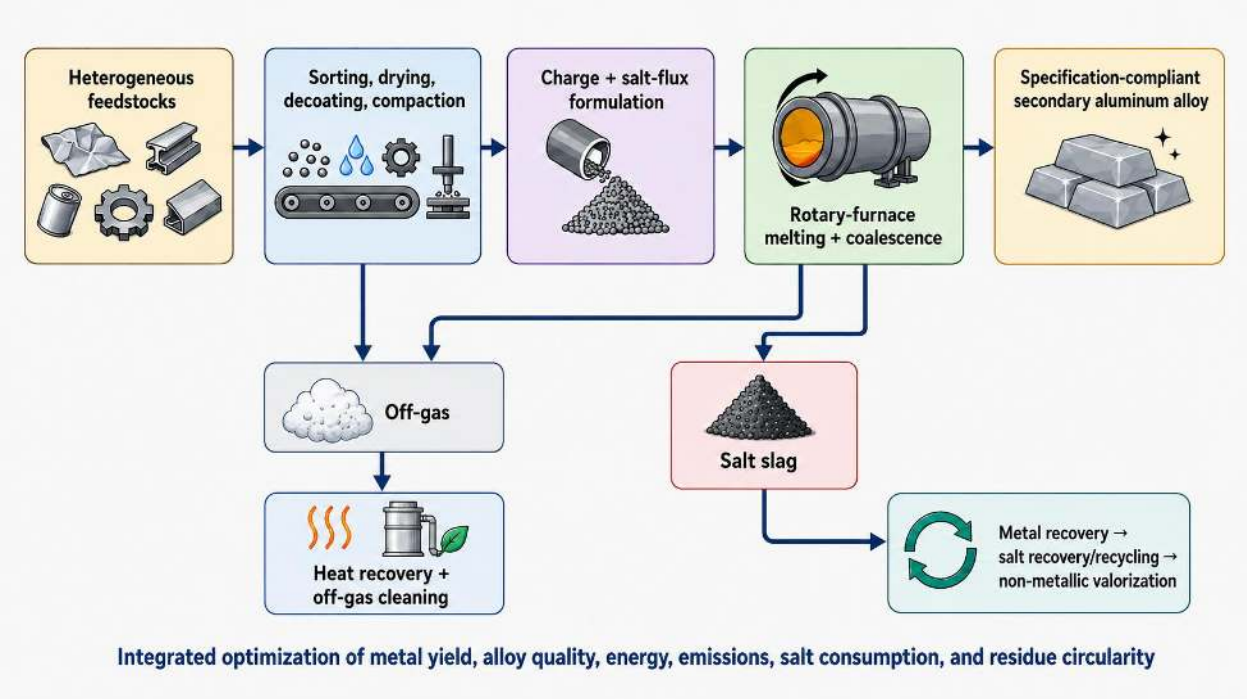
Graphical abstract

The graphical abstract summarizes the coupled main-product and side-stream logic used throughout this review.



Graphical abstract. Integrated rotary-furnace recycling from heterogeneous feedstocks to qualified secondary alloy, with off-gas treatment and salt-slag recirculation.
Note. Author-developed conceptual synthesis.

Nomenclature and status of proposed indicators

FRI, proposed feedstock recyclability indicator; SF_{ox}, salt mass per oxide-rich/non-metallic feed fraction; CSF, fresh salt makeup per saleable alloy; Yg, gross tapped-metal yield; Rm, recovery relative to metallic aluminum in the feed; Ys, saleable-alloy yield; NR, not reported on a comparable basis. All proposed indicators are heuristic unless calibrated against prospective plant campaigns.

1. Introduction

1.1. Aluminum recycling and the role of secondary smelters

Secondary aluminum production is not a single remelting operation but a sequence of collection, identification, preparation, melting, refining, qualification, and residue management.

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The climate and resource advantages of recycling are strongest when scrap is directed to compatible alloy families and when the recovered metal displaces primary metal without excessive dilution, downgrading, or residue generation. Foundational secondary-aluminum practice and recent syntheses alike emphasize that scrap preparation, furnace selection, remelting, melt treatment, dross handling, and product quality are coupled rather than independent operations (Schlesinger, 2013; Doutre & Kvithyld, 2024; Hannula et al., 2020; Padamata et al., 2021; Pereira, 2025a; Pereira, 2025b).

Within that chain, rotary furnaces occupy a deliberately difficult part of the feed spectrum. They accept materials with substantial oxide, entrained metal, coatings, oils, irregular geometry, low apparent density, and variable composition. Packaging, food tubes, motor scrap, machining chips, foils, incineration-derived aluminum, and drosses illustrate the diversity of physical and chemical behavior that can be delivered to a secondary smelter (Bao, Eggen, et al., 2023; Bao, Kvithyld, et al., 2023; Bazhin et al., 2025; Bhaskar et al., 2022; Chen et al., 2025; Gökelma et al., 2024; Palimąka, 2020; Philipson, 2020; Zhu et al., 2025). Feed flexibility is economically valuable, but it transfers variability to fuel demand, salt use, tapping practice, alloy correction, off-gas treatment, and residue processing.

1.2. Why rotary furnaces remain industrially relevant

Rotation renews the contact between solid feed, liquid metal, salt, refractory, and furnace atmosphere. This mechanical action can rupture oxide envelopes, expose entrained droplets, accelerate heating, and promote collision and coalescence. Tilting designs add flexibility in charging, bath management, slag discharge, and tapping, while fixed-axis designs retain operational simplicity. The literature on rotary converters, tilting furnaces, combustion, and digital operation nevertheless shows that furnace geometry alone does not define performance; bath inventory, charging sequence, burner momentum, infiltration, internal pressure, and material rheology are equally important (Crego et al., 2024; Dzurňák et al., 2020; Dzurňák et al., 2021; Illés & Kékesi, 2023; Kheirkhah et al., 2025; Lawrence et al., 2020; Makwana et al., 2026; Rimár et al., 2020; Rostamian & Bertherat, 2025).

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1.3. The recovery–residue paradox

Salt fluxes can protect the metal surface, detach or react with oxide films, modify interfacial behavior, and provide a liquid medium in which metal droplets can separate from solids. Foundational fluxing practice distinguishes covering, drossing, and cleaning functions and shows why flux selection must be tied to the intended metallurgical duty (Gallo & Neff, 2008). The same flux becomes part of a salt-bearing slag that may contain residual metal, chlorides, fluorides, aluminum nitride, aluminum carbide, oxides, spinels, and trace elements. More flux may improve separation for a difficult feed, yet it also heats additional non-product mass and increases the inventory requiring recovery or disposal. Conversely, aggressive salt reduction can raise metal entrapment or oxidation if preparation, bath management, and mixing are not improved at the same time (Becker & Friedrich, 2021; Cai et al., 2024; Çapkın & Gökelma, 2023; Gyarmati et al., 2025; Illés & Kékesi, 2023; Kulikov et al., 2025; Milani & Timelli, 2023; Milani et al., 2023; Moodispaw et al., 2024; Peterson, 2020; Shi & Li, 2023; Wan, Li, Liu, et al., 2020; J.-F. Wang et al., 2026; G. Zhang et al., 2023; Z. Zhang et al., 2022).

1.4. Limitations of existing reviews

Recent reviews provide strong coverage of chip remelting, salt fluxes, dross recovery, salt-slag treatment, molten-salt electrolysis, residue valorization, and inclusion removal. Their boundaries, however, often begin after the feed has been defined or after the slag has been generated. This separation makes it difficult to determine whether a residue-treatment benefit compensates for inefficient melting upstream, or whether a high metal recovery was obtained at the expense of excessive salt, energy, off-specification chemistry, or secondary effluent (Chen et al., 2025; Harmaji et al., 2024; Milani & Timelli, 2023; Modalavalasa & Ayyagari, 2024; Padamata et al., 2021; Padilla et al., 2022; M. Wang et al., 2025; R. Wang et al., 2026; Wu et al., 2025; Yang et al., 2025; Yuan et al., 2023; Zou et al., 2026).

1.5. Objective, research questions, and contribution

This review critically evaluates the connected relationships among aluminum-bearing feed characteristics, furnace configuration, flux chemistry, operating conditions, heat and mass transfer, recovery, alloy quality, emissions, refractory integrity, and residue circularity. Ten questions guide the synthesis: which feeds are suitable; how feed condition affects salt and yield;

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how fixed and tilting designs differ; which flux properties control separation; how temperature, rotation, time, atmosphere, and charging interact; when low-salt or salt-free routes are credible; how alloy quality changes the definition of performance; which energy and emission controls matter most; when salt-slag treatment provides a net benefit; and which validation gaps prevent closed-loop operation. The original contribution is the Feedstock–Flux–Furnace–Residue Framework, which rejects metal recovery as a stand-alone optimization objective and replaces it with product-oriented, mass-balanced, site-specific evaluation. The functional object of evaluation is one tonne of specification-compliant secondary alloy, not one tonne of charged scrap or tapped metal.

2. Review Methodology and Evidence Appraisal

2.1. Review design and corpus

This study is a structured critical narrative review that uses systematic searching principles, retrospective evidence coding, and industrial-readiness appraisal. It is not a systematic review, meta-analysis, or PRISMA-compliant study. Discovery-stage hit lists, platform exports, duplicate records, screening counts, exclusion logs, and exact query dates were not retained; missing selection counts are therefore not estimated. The auditable stage begins with the final bibliography of 106 publications from 2020 to August 2026, reconciled for duplication and coded on 6 August 2026. Five pre-2020 foundational sources were added only to anchor durable principles of secondary-aluminum remelting, fluxing, dross/salt-slag chemistry, and melt cleanliness; they are contextual anchors and are excluded from the 106-record A–E counts. The synthesis follows a decision-science/process-metallurgy logic: heterogeneous engineering evidence is integrated into conditional process relationships, reporting requirements, and industrial decision criteria rather than pooled effect sizes.

The search combined aluminum recycling with various processes, using Google Scholar, publisher searches, and citation chaining. It focused on evidence related to feed prep, furnace operation, flux behavior, recovery, alloy quality, energy, emissions, modeling, economics, and environmental impact. Studies unrelated to aluminum, calcination furnaces, untraceable records, or non-recycling residues were excluded. Platform details and screening data are unavailable and noted as limitations.

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Figure 1 shows the recoverable and non-recoverable parts of the search history prior to technical interpretation.

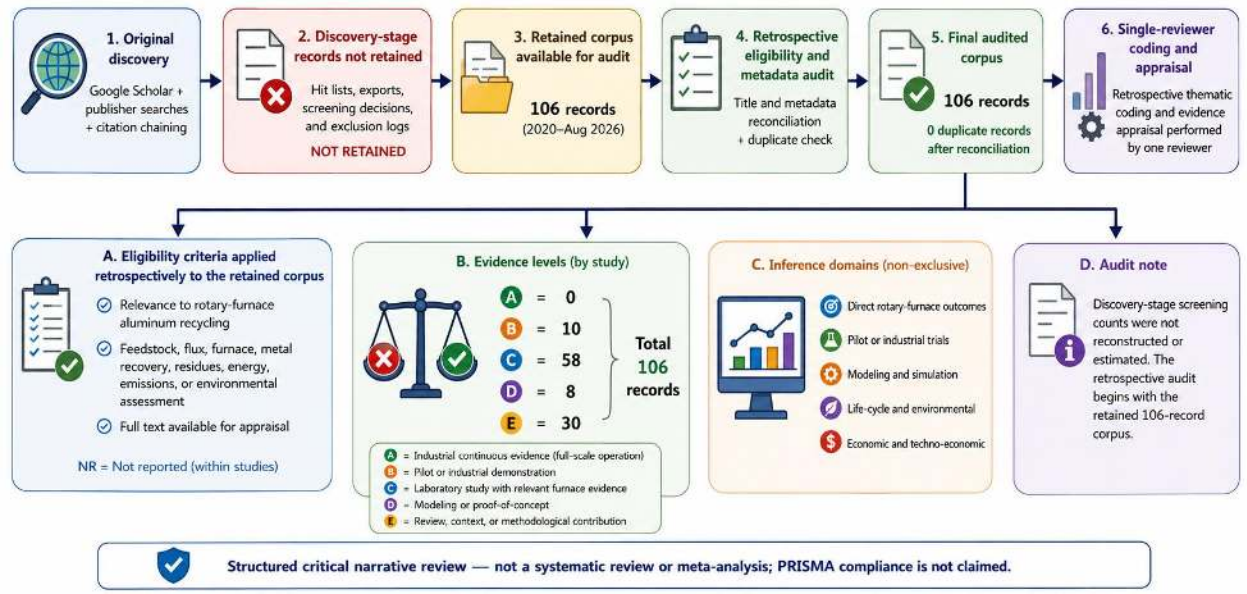

Figure 1. Retrospective search reconstruction and evidence-appraisal boundary
Note. Author-developed conceptual synthesis. NR = not recoverable from the retained discovery records. This is not a PRISMA flow diagram.

The diagram separates the unavailable discovery history from the auditable 106-record coding stage. It prevents the final bibliography from being presented as a fully reproducible selection process for systematic reviews.

2.2. Coding fields and evidence hierarchy

Each publication in the 106-record corpus was classified by feedstock, pretreatment, furnace or treatment setup, flux or additive, operating variables, outputs, scale, main limitation, and inference class. The inference classes include direct rotary-furnace evidence, remelting evidence from other equipment, flux or melt-quality evidence, residue-treatment evidence, modeling, economic/environmental assessment, and contextual evidence. Five transferability levels were used: A, repeated industrial operation with product-quality and closed mass-balance data; B, documented industrial or pilot campaign; C, laboratory work with real or representative industrial material; D, validated model; and E, reviews, models, conference perspectives, posters, or indirect evidence. These A–E levels rank industrial transferability only; they are not grades of general scientific merit or risk of bias. One reviewer performed all retrospective coding without

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calibration or independent duplicate coding. Consequently, the levels are explicitly treated as single-reviewer interpretive transferability judgments, and no Cohen's kappa, Krippendorff's alpha, or other inter-rater statistic is reported.

Table 1. Retrospectively reconstructed search and appraisal protocol

Component	Documented procedure	Status and residual limitation
Review design	Structured critical narrative review with systematic searching principles and retrospective coding	Not systematic, not a meta-analysis, and not PRISMA-compliant
Discovery sources	Iterative Google Scholar and publisher searches; backward/forward citation chaining	Original exports and exact platform dates were not retained
Search logic	Aluminum/aluminium recycling combined with rotary furnace, dross, chips, salt flux, recovery, emissions, modeling, LCA, and salt-slag terms	Complete platform-specific strings cannot be reproduced
Final corpus audit	106 references reconciled on 6 August 2026; no exact-title duplicate in the final list	Initial hits, duplicate removals, and exclusion counts are not recoverable
Evidence coding	Feed, preparation, configuration, flux, conditions, recovery, quality, energy, emissions, residue, scale, limitation	Single reviewer; no independent calibration or inter-rater statistic
Transferability tiers	A repeated industrial; B pilot/campaign; C laboratory-real feed; D validated model; E contextual	A = 0; B = 10; C = 58; D = 8; E = 30
Bibliographic verification	DOIs inserted only when verified or deterministically matched; unresolved entries left without DOI	Final publisher-level verification remains advisable before submission
Internal methodological-quality screen	Design appropriateness; feed/process characterization; outcome definition; uncertainty and balance completeness	Narrative weighting only; not collapsed into a universal risk-of-bias score and does not alter A–E transferability tier
Foundational contextual anchors	Five pre-2020 sources on	Contextual only; excluded from

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Component	Documented procedure	Status and residual limitation
	secondary-aluminum recycling, fluxing, dross/salt-slag chemistry, and melt cleanliness	the 106-record 2020–August 2026 coding counts

Note. The protocol reports discovery-stage information as unavailable rather than estimating counts. The A–E level ranks industrial transferability, not general scientific merit or methodological quality. The complete 106-record evidence matrix is provided in Supplementary Table S1 for auditability.

The evidence distribution was A = 0, B = 10, C = 58, D = 8, and E = 30. Figure 2 shows that laboratory and contextual evidence dominate. These counts are descriptive outputs of the single-reviewer transferability appraisal and should not be interpreted as reliability-tested quality scores. The appraisal also revealed a recurring reporting asymmetry: feed and residue studies often characterize composition in detail, whereas furnace papers may report thermal or combustion behavior without closing aluminum and salt balances. Conversely, valorization studies frequently begin with a residue whose upstream generation history is insufficiently specified. Conclusions on furnace configuration, salt reduction, salt-free operation, and alternative fuels were therefore weighted toward direct evidence, while contextual sources were used to explain mechanisms or system boundaries rather than to establish performance.

2.3. Industrial transferability versus internal methodological quality

Industrial transferability and internal methodological quality were considered as separate dimensions. The A–E hierarchy captures scale and closeness to repeated industrial balance closure. Internal methodological quality was considered narratively through four domains: appropriateness of the study design for the stated question; adequacy of feed, material, and process characterization; clarity and traceability of outcome definitions and measurements; and completeness of uncertainty, mass-balance, and boundary reporting. A rigorous laboratory study can therefore have strong internal methodological quality while retaining a lower industrial-transferability level, and a partial industrial report can have higher transferability but weaker internal reporting. Because study designs span experiments, models, reviews, LCA, and industrial reports, these domains were not collapsed into a universal numerical risk-of-bias score. They inform narrative weighting only and do not change the A–E tier.

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2.4. Limitations of the review process

The review has four process limitations. First, the original discovery history cannot be reproduced beyond the retained search logic and final bibliography. Second, all screening reconstruction, coding, and appraisal were performed by one reviewer; therefore the classification is not reliability-tested. Third, inaccessible or incompletely reported variables were coded as NR rather than inferred. Fourth, the heterogeneous evidence base does not support one common study-level risk-of-bias instrument or meta-analysis. These constraints limit corpus-completeness claims and the strength of transferability inference. They are addressed through transparent missing-data notation, separation of transferability from internal methodological quality, separation of direct from contextual evidence, and the accompanying complete Supplementary Table S1 evidence matrix.

3. Feedstock Taxonomy and Suitability for Rotary-Furnace Recycling

3.1. Scrap, chips, dross, and mixed secondary materials

Feedstock classification must distinguish origin, physical form, and metallurgical state. New scrap and foundry returns generally have known alloy history and relatively high metallic content. Post-consumer scrap is more heterogeneous and may combine incompatible alloy families, attachments, corrosion products, coatings, and foreign materials. Chips and fines have large specific surface area, retain cutting fluids, oxidize rapidly, and occupy high furnace volume per unit mass. Drosses and skimmings are not scrap in the ordinary sense: they are multiphase mixtures in which metallic aluminum is physically entrained within oxide, salt, nitride, carbide, and spinel-bearing matrices (Bao, Eggen, et al., 2023; Bao, Kvithyld, et al., 2023; Bazhin et al., 2025; Bhaskar et al., 2022; Chen et al., 2025; Gökelma et al., 2024; Huang et al., 2023; Kudyba et al., 2021a; Liao et al., 2022; Palimąka, 2020; Philipson, 2020; Santos et al., 2025; Solem et al., 2023; Sun et al., 2024; Sun et al., 2025; Vallejo-Olivares et al., 2024; Vallejo-Olivares et al., 2022).

Rotary-furnace suitability therefore increases not simply as feed quality decreases, but when the value of mechanical agitation and a separative liquid phase exceeds the penalties of heating gangue and generating slag. Clean, dense, compositionally compatible scrap may be better processed in a well, reverberatory, induction, or other bath furnace. Rotary processing

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becomes more compelling for oxidized, coated, low-density, or metal-bearing residues whose droplets must be liberated and coalesced. This distinction is essential because using a rotary salt furnace for an easy feed can create avoidable salt and energy burdens, whereas sending a difficult feed to a low-agitation bath furnace may sacrifice metal yield.

3.2. Feed-quality descriptors and a recyclability index

A useful receiving specification should include metallic aluminum, total aluminum, oxide fraction, particle-size distribution, apparent density, moisture, oil and organic content, coatings, ferrous attachments, glass and mineral contaminants, alloy family, and sampling uncertainty. White dross characterization work demonstrates that representative sampling is itself a major technical task, while studies of oxide-film evolution, compaction, and pretreatment show that nominal chemistry cannot represent the physical barriers to melting and coalescence (Huang et al., 2023; Philipson, 2020; Solem et al., 2023; Vallejo-Olivares et al., 2024; Vallejo-Olivares et al., 2022).

For local screening rather than final design, this review proposes a heuristic feedstock recyclability indicator (FRI). It is not a validated universal metric and no numerical acceptance threshold is proposed. Its purpose is to make the expected direction of feed effects explicit and to define variables that a plant may calibrate against its own campaign data. All inputs must first be normalized to bounded, internally consistent scales; positive penalty coefficients then ensure that greater oxide, surface area, organics, moisture, or non-metallic contamination cannot improve the score.

$$FRI = (x_m \times \rho_b) / [1 + ax_{ox} + bA_s + cx_{org} + dx_{moist} + ex_{nm}] \quad (1)$$

where x_m is the metallic-aluminum fraction, ρ_β is normalized bulk density, x_{ox} is oxide loading, A_s is a normalized specific-surface indicator, x_{org} is organic loading, x_{moist} is moisture, and x_{nm} is non-metallic contamination. Coefficients a–e are non-negative site-specific penalties. Sensitivity is monotonic under these assumptions, but predictive validity requires calibration with repeated plant lots.

Table 2. Feedstock characteristics, rotary-furnace suitability, and principal controls

Feed class	Dominant risks	Preferred controls	Relative rotary suitability

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Feed class	Dominant risks	Preferred controls	Relative rotary suitability
Clean dense returns	Alloy mismatch; oxide generated during handling	Lot segregation; rapid charging; minimal functional flux	Low to medium
Coated packaging and thin sheet	High area; organics; low bulk density; off-gas load	Decoating; compaction; compatible-alloy blending	Medium to high
Chips and turnings	Oil; moisture; oxidation; floating; dust	Centrifuging; drying; briquetting; controlled submergence	High when preparation is effective
Mixed post-consumer / automotive scrap	Residual elements; attachments; uncertain chemistry	Sensor sorting; magnetic removal; charge optimization	Medium; quality-limited
Incineration-derived aluminum	Oxides; mineral matter; size dependence	Sizing; mechanical cleaning; density or sensor separation	High for selected fractions
White/black dross and skimmings	Entrained droplets; salts; AlN/Al_4C_3; variable metallic content	Representative sampling; crushing/sizing; metal-first recovery	High when metal value covers residue treatment

Note. Suitability is conditional on local alternatives, product specification, and residue infrastructure. Author-developed conceptual synthesis informed by (Bao, Eggen, et al., 2023; Bao, Kvithyld, et al., 2023; Bazhin et al., 2025; Bhaskar et al., 2022; Chen et al., 2025; Gökelma et al., 2024; Kudyba et al., 2021a; Liao et al., 2022; Palimąka, 2020; Philipson, 2020; Sahoo et al., 2025; Santos et al., 2025; Solem et al., 2023; Sun et al., 2024; Sun et al., 2025; Vallejo-Olivares et al., 2024; Vallejo-Olivares et al., 2022; Zhu et al., 2025).

3.3. Feedstock–furnace compatibility

Figure 2 summarizes the evidence-level distribution and makes the transferability imbalance explicit.

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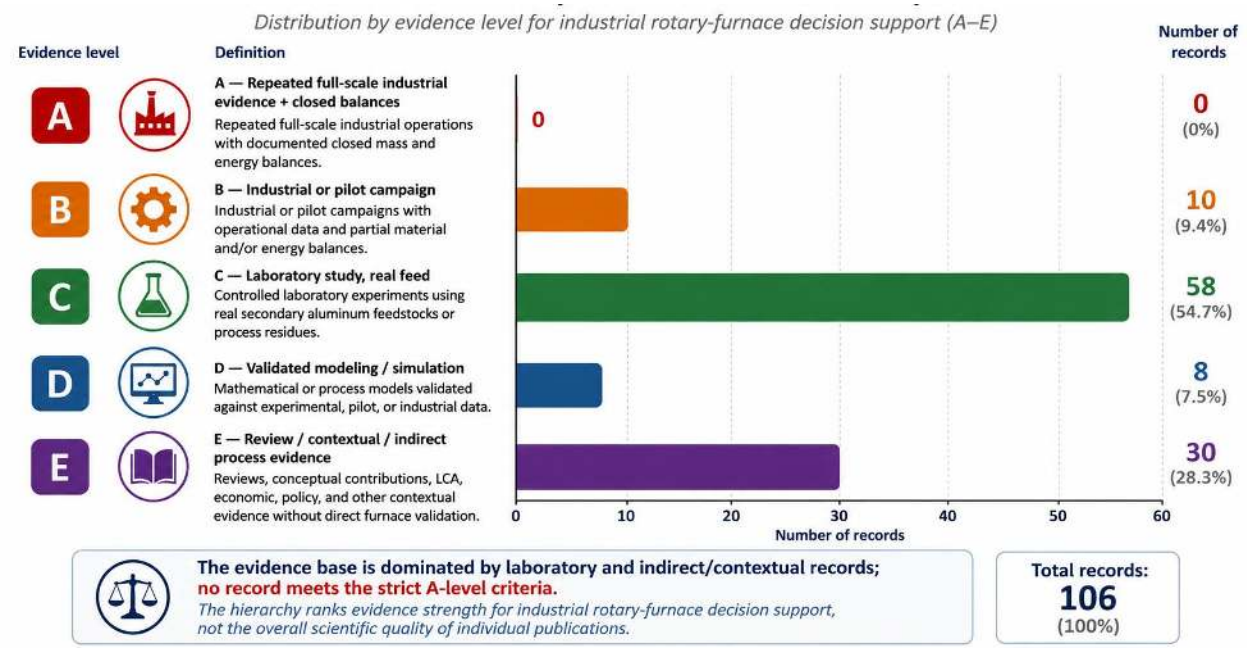

Figure 2. Evidence landscape and industrial-transferability levels in the 106-record corpus

Note. Author-developed visualization of retrospective single-reviewer transferability judgments. A = repeated industrial operation with closed balances; B = industrial/pilot campaign; C = laboratory with real feed; D = validated model; E = contextual or indirect evidence. These categories are not reliability-tested study-quality grades.

The absence of A-level evidence is significant: the corpus supports mechanism-based and conditional recommendations but not universal claims about industrial performance.

4. Rotary-Furnace Configurations and Process Flowsheets

4.1. Fixed-axis and tilting rotary furnaces

A fixed-axis rotary salt furnace generally performs batch charging, heating, melting, droplet coalescence, metal tapping, and slag discharge in a horizontal rotating shell. Its advantages include mechanical simplicity and established practice, but it faces constraints in charging and tapping logistics, bath access, and coordination of rotation with changing liquid and solid fractions. A tilting rotary furnace can change shell angle during charging, melting, tapping, and slag discharge, improving operational flexibility and reducing some dead time while adding mechanical complexity and a dynamic geometry. Furnace capacity should therefore be expressed not only as nominal tonnes per batch but also in terms of usable volume, bath fraction, feed bulk density, and cycle-specific thermal load.

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Combustion studies show that air infiltration and oxygen-enhanced operation alter flame conditions and gaseous emissions, while transient and furnace-design models show the importance of thermal boundary conditions and geometry (Crego et al., 2024; Dzurňák et al., 2020; Dzurňák et al., 2021; Flores Saldívar et al., 2021; Rimár et al., 2020). Digital and smart-combustion reports further indicate that repeatability depends on charge timing, burner control, and endpoint prediction rather than on equipment label alone (Lawrence et al., 2020; Makwana et al., 2026; Rostamian & Bertherat, 2025).

4.2. Conventional, low-salt, salt-free, and hybrid operation

The technology should be classified along two axes: mechanical configuration and process chemistry. A tilting furnace can operate with conventional salt, reduced salt, or an adapted salt-free strategy; a fixed-axis furnace can similarly be integrated with improved preparation or downstream salt recovery. Hybrid heating includes oxy-fuel, hydrogen fuel, electrical assistance, and plasma. These options affect flame radiation, gas volume, water vapor partial pressure, NO_x behavior, oxidation potential, and melt quality, so decarbonization cannot be inferred from fuel carbon content alone (Dahiya, 2022; Kheirkhah et al., 2025; Makwana et al., 2024; Tichy, 2025).

Figure 3 distinguishes mechanical furnace configuration from process chemistry so that performance comparisons remain tied to feed type, salt basis, bath inventory, heating mode, and scale.

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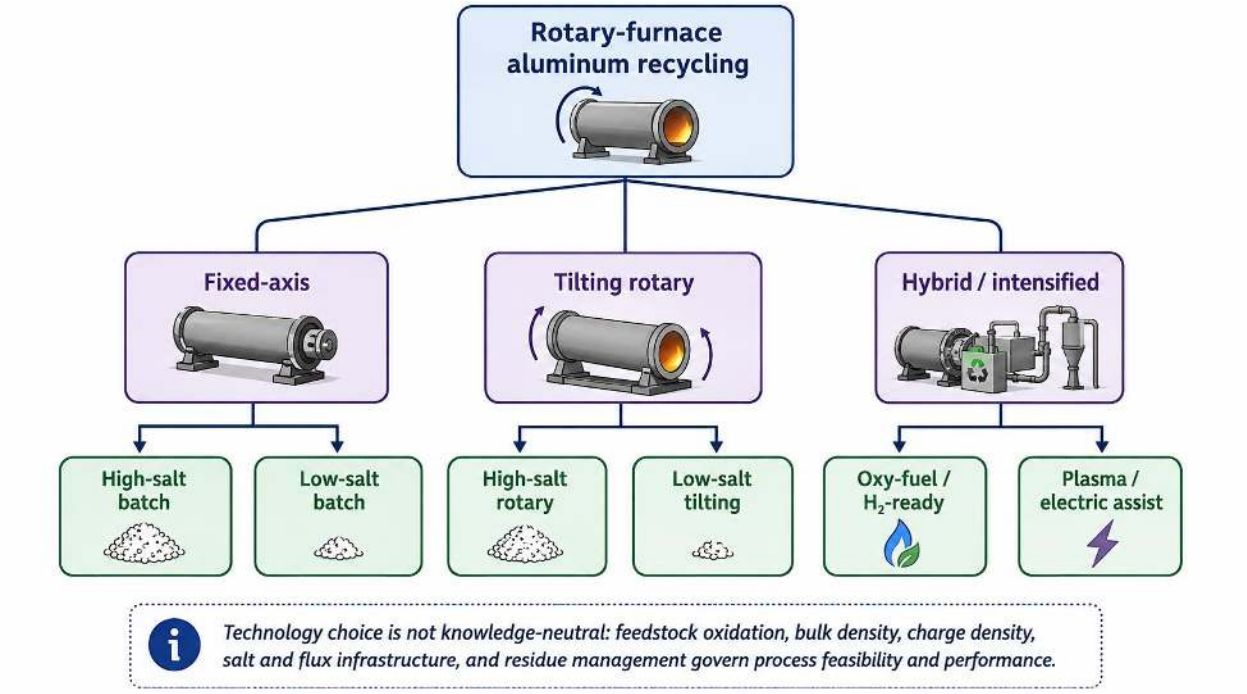

Figure 3. Classification of rotary-furnace configurations and process-chemistry variants

Note. Author-developed conceptual synthesis informed by (Crego et al., 2024; Dzurňák et al., 2020; Dzurňák et al., 2021; Illés & Kékesi, 2023; Kheirkhah et al., 2025; Lawrence et al., 2020; Makwana et al., 2026; Rimár et al., 2020; Rostamian & Bertherat, 2025; Sahoo et al., 2025; Tichy, 2025).

The classification shows why performance claims should be tied to feed type, salt basis, bath inventory, burner mode, and scale. Transfer from a laboratory tilting furnace to an industrial fixed-axis high-salt furnace is not automatic.

Table 3. Comparison of major rotary-furnace configurations

Configuration	Strengths	Critical limitations	Maturity and evidence need
Fixed-axis rotary salt furnace	Established for difficult feed; strong mixing; robust phase separation	Salt burden; batch logistics; air ingress; slag handling	Mature equipment; complete industrial Al–salt–energy balances still needed
Tilting rotary furnace	Flexible charging/tapping; adaptable heel and cycle strategy	Changing geometry; seals; control complexity; scale dependence	Mature/deployable; matched-feed comparison still needed

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Configuration	Strengths	Critical limitations	Maturity and evidence need
Low-salt rotary operation	Lower salt heating and residue mass	Narrower operating window; feed-preparation dependence	Emerging/deployable for selected feeds; long campaigns needed
Salt-free rotary / liquid-state route	Avoids chloride salt slag; may simplify residue system	Oxidation and entrapment risk; feed restrictions	Emerging; independent pilot and alloy-quality validation needed
Hybrid heat / oxy-fuel / H_2-ready	Potential fuel and gas-volume reduction; control flexibility	Flame–metal interaction; water vapor; NO_x; retrofit complexity	Development/retrofit-dependent; full-site carbon and quality accounting needed

Note. Author-developed conceptual synthesis informed by (Crego et al., 2024; Dzurňák et al., 2020; Dzurňák et al., 2021; Kheirkhah et al., 2025; Lawrence et al., 2020; Makwana et al., 2026; Makwana et al., 2024; Rimár et al., 2020; Rostamian & Bertherat, 2025; Sahoo et al., 2025; Tichy, 2025).

4.3. Auxiliary systems as part of furnace performance

Storage, weighing, salt dosing, charge transfer, burner and oxidant supply, pressure control, post-combustion, cooling, filtration, slag transport, metal holding, and salt recovery must be included in the process definition. A furnace can show an attractive melt-cycle fuel figure while shifting energy to decoating, salt evaporation, compressed oxygen, refrigeration, or residue drying. Likewise, an apparent productivity gain can be offset by baghouse cleaning, refractory repair, or downstream metal treatment. The correct unit operation for comparison is therefore the integrated melting cell, not the rotating shell alone.

5. Feedstock Preparation and Charging Strategy

5.1. Sorting, impurity removal, and alloy routing

Preparation begins with lot identity and purpose. Magnetic separation removes free iron but not dissolved iron-bearing alloys. Eddy-current separation, density separation, optical methods, X-ray fluorescence, and laser-induced breakdown spectroscopy can improve metal concentration and alloy routing, yet their value is realized only when the resulting fractions correspond to furnace recipes and product specifications. Automotive scrap-flow analysis illustrates that collection and dismantling decisions determine later alloy-mixing constraints (Zhu et al., 2025). Thermodynamic and experimental work on iron removal also shows that correcting

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mixed scrap after melting may require additional alloying or phase-separation steps and can reduce saleable yield (Sinha et al., 2025).

5.2. Decoating, drying, and compaction

Thermal decoating removes organics before the furnace, reducing uncontrolled pyrolysis and enabling heat recovery, but can oxidize thin metal if temperature, oxygen, and residence time are not controlled. Comparative work on loose and compacted material shows that pretreatment changes both dross formation and off-gas generation (Bao, Eggen, et al., 2023; Bao, Kvithyld, et al., 2023; Vallejo-Olivares et al., 2024; Vallejo-Olivares et al., 2022). Compaction improves bulk density, reduces floating, and can lower the area directly exposed to the atmosphere; excessive compaction, however, may trap liquid, delay heating, or create unsafe moisture pockets. For chips, centrifuging and low-oxygen drying should precede briquetting or controlled liquid-state charging (Bhaskar et al., 2022; Chen et al., 2025; Palimąka, 2020; Philipson, 2020; Sahoo et al., 2025; Sun et al., 2024; Sun et al., 2025).

5.3. Charge blending and sequence

Charge formulation must satisfy four balances simultaneously: recoverable metal, alloy chemistry, furnace volume, and contaminant capacity. Dense material and a metallic heel establish heat-transfer contact and bath stability; low-density or oxidized feed is then added at a rate that avoids prolonged exposure. Flux timing should follow its function. A protective cover may be needed before a high-area feed, whereas adding the full salt charge too early heats non-productive mass and can reduce thermal efficiency. Final alloy corrections should be based on element-specific recovery rather than assuming that all input alloying elements report quantitatively to tapped metal.

Table 4. Controlled feed–preparation–flux studies and reported outcomes

Study/feed	Preparation or variable	Flux/basis	Conditions	Reported outcome	Product/residue information	Comparability warning
Philipson (2020), Al foil 15–300	Compaction density	Salt flux; exact ratio NR	Controlled remelting; other conditions NR	99–100% recovery for 15 µm foil compacted to ~2.6 g cm^{-3}; oxidation decreased above	Product chemistry NR	Laboratory foil geometry; mixed-scrap transfer

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Study/feed	Preparation or variable	Flux/basis	Conditions	Reported outcome	Product/residue information	Comparability warning
µm				~2.4 g cm^{-3}		uncertain
Kudyba et al. (2021a), white dross	Milling 3 h at 35 rpm; >1 mm fraction	NR	Remelting at 900 °C	Coarse particles ~80% metallic Al; remelted matrix >96 at.% Al and ~99% total metallic components	Fine non-metallic fraction separated	Laboratory batch; no full energy/gas balance
Illés & Kékesi (2023), Al dross	Rotary-converter melting	Simple NaCl; exact mass basis NR	Temperature/time/rotation NR in comparable extract	Metal yield increased by 9% relative to no-NaCl condition	Secondary dross generation decreased	Short study; industrial closure unavailable
Santos et al. (2025), dross fractions	Particle sizing	15 wt% salt/feed in best condition	Melting conditions not reported on common basis	73.99% recovery for particles >7.5 mm	Product quality and uncertainty NR	Single feed; basis differs from oxide-normalized salt factor
Sahoo et al. (2025), Al chips	Prepared liquid-state route	Salt-free	Laboratory processing; detailed common basis NR	>90% Al recovery	Negligible hazardous salt-dross generation reported	Industrial scale and full LCA require validation
Sun et al. (2024), waste chips	Controlled collection + supergravity	Salt-free/cleaning route	Supergravity; exact common thermal basis NR	Approximately 97% recovery; one condition 94.3%	Pure-Al-focused product	Intensified laboratory separation, not direct rotary-furnace evidence

Note. NR = not reported on a comparable basis in the source information extracted for this review. Values are descriptive and must not be pooled because feed assay, equipment, salt basis, and system boundary differ.

5.4. Feedstock safety

Moisture, closed containers, volatile substances, reactive fines, and salt-bearing residues require formal acceptance and storage rules. Safety is inseparable from metallurgical performance because emergency ventilation, interrupted charging, and uncontrolled gas

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evolution also destroy process repeatability. Reactive dross compounds require particular attention: water contact can generate alkaline leachate and gases, and acid treatment before storage does not automatically create a technically or environmentally preferable route (Li et al., 2024; Liu et al., 2025; Samara et al., 2020; Wu et al., 2025; Zou et al., 2026).

6. Thermodynamic and Physicochemical Fundamentals

6.1. Oxidation, nitride/carbide formation, and oxide-film evolution

Aluminum is protected under ambient conditions by a thin oxide film, but repeated recycling deforms, fractures, folds, and thickens that film. During heating and stirring, fresh metal can be exposed, while oxide fragments are incorporated into the melt or slag. The rate and consequence depend on temperature, oxygen potential, surface area, alloy composition, and mechanical renewal. Thin chips, foils, and foams are especially sensitive because their metal inventory is small relative to exposed area (Huang et al., 2023; Liao et al., 2022; Philipson, 2020; Yamamoto et al., 2020; Z. Zhang et al., 2022).

Dross chemistry also evolves through reactions with nitrogen, carbon, magnesium, silicon, and salts. Aluminum nitride is important because it stores chemically bound nitrogen and becomes reactive when treated with water. Aluminum carbide, spinels, magnesium oxide, and mixed oxides influence density, wettability, and residue behavior. Recent work on AlN formation and thermal or additive-assisted removal confirms that the upstream furnace atmosphere and cooling history affect downstream detoxification requirements (Li et al., 2024; Li et al., 2026; Li et al., 2021; Liu et al., 2025; Lv et al., 2022; Ni et al., 2022; Wang et al., 2021; Wei et al., 2023; Xie, Guo, Xu, & Zhang, 2023; Xie, Guo, Xu, Zhang, et al., 2023).

6.2. Wetting, interfacial tension, and coalescence

Metal recovery from dross is fundamentally a separation problem. An aluminum droplet surrounded by an oxide envelope or attached to a solid particle must be exposed, collide with another metal body, drain the intervening film, and merge before it is tapped or immobilized in cooling slag. Salt composition influences oxide wetting, metal–salt interfacial tension, viscosity, and film disruption. Fluoride-bearing additions can improve refining and coalescence, but they introduce corrosion, volatile fluoride, and water-treatment obligations (Gallo & Neff, 2008; Cai

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et al., 2024; Gyarmati et al., 2025; Kulikov et al., 2025; Milani & Timelli, 2023; Milani et al., 2023; Moodispaw et al., 2024; Peterson, 2020; Shi & Li, 2023; Wan, Li, Liu, et al., 2020; J.-F. Wang et al., 2026; G. Zhang et al., 2023).

Mixing has a non-monotonic effect. Insufficient rotation leaves large regions unmixed and preserves entrapped droplets. Moderate rotation renews contacts and raises collision frequency. Excessive agitation can disperse metal into smaller droplets, increase air–metal contact, generate dross, suspend solids, and accelerate refractory abrasion. Model experiments on stirring-induced dross generation and studies of droplet or particle behavior therefore support an operating window rather than a "more mixing is better" rule (Gökelma et al., 2021; Yamamoto et al., 2020; Z. Zhang et al., 2022).

Figure 4 integrates the feed descriptors from Section 3 with the physicochemical mechanisms that govern recovery, product quality, and residue generation.

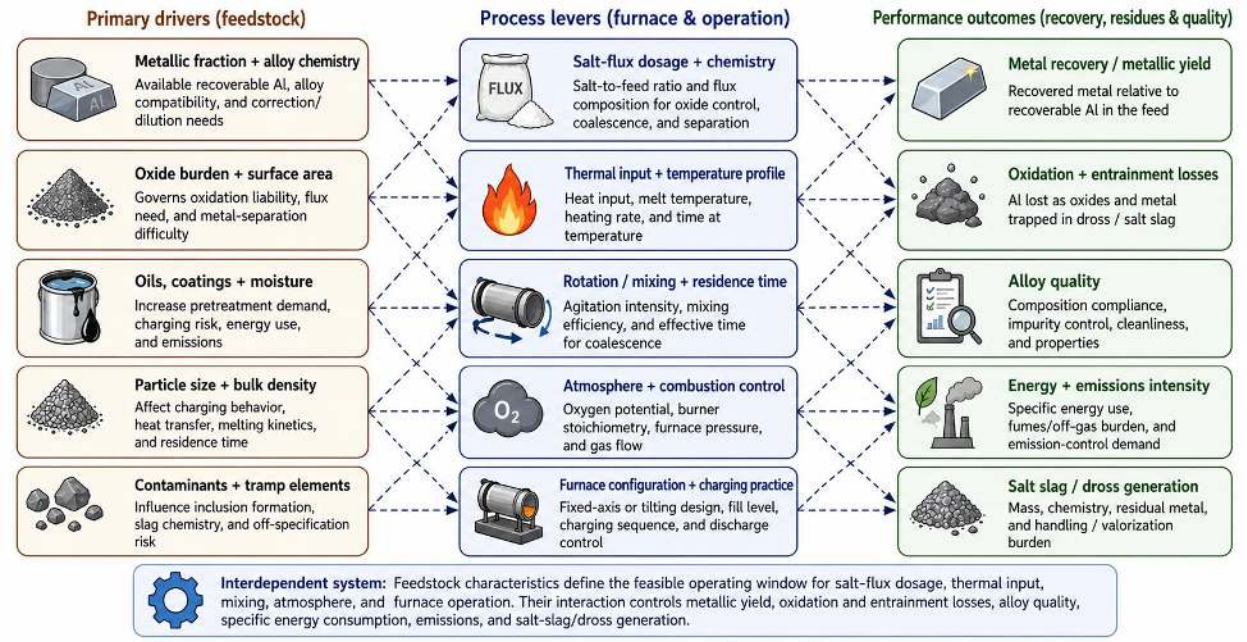

Figure 4. Feedstock–Flux–Furnace–Residue interaction framework
Note. Author-developed conceptual synthesis informed by (Huang et al., 2023; Kulikov et al., 2025; Liao et al., 2022; Milani & Timelli, 2023; Milani et al., 2023; Moodispaw et al., 2024; Shi & Li, 2023; Solem et al., 2023; Yamamoto et al., 2020; Z. Zhang et al., 2022).

The framework is causal rather than merely sequential: feed condition changes flux demand and heat demand, which change mixing and atmosphere requirements, which in turn affect oxidation, coalescence, entrapment, product quality, and residue burden.

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Table 5. Physicochemical mechanisms and measurable consequences

Mechanism	Promoted by	Adverse consequence	Plant-observable indicator
Oxide-film rupture	Thermal stress; deformation; salt–oxide interaction; moderate mixing	Fresh-metal oxidation if atmosphere is uncontrolled	Dross rate and oxygen/CO profile
Droplet collision	Adequate liquid fraction; rotation; low slag viscosity	Redistribution into fine droplets at excessive shear	Metal-size distribution in cooled slag
Film drainage/coalescence	Favorable interfacial properties; sufficient residence time	Persistent non-coalesced metal	Metallic Al in size fractions
Solid suspension	High rotation; fine oxides; viscous slag	Metal entrapment and difficult phase separation	Slag rheology and tapping behavior
Nitride/carbide formation	Reactive metal; N/C exposure; thermal history	Gas-generating residue and downstream treatment burden	AlN/Al_4C_3 assay and gas-evolution test
Volatilization/element loss	High temperature; oxidizing gas; long exposure	Chemistry drift and off-gas metals	Input–metal elemental balance

Note. Author-developed conceptual synthesis informed by (Gökelma et al., 2021; Huang et al., 2023; Li et al., 2024; Liu et al., 2025; Milani & Timelli, 2023; Milani et al., 2023; Shi & Li, 2023; Yamamoto et al., 2020; Z. Zhang et al., 2022).

7. Salt-Flux Chemistry and Slag Formation

7.1. Functions and formulation of chloride–fluoride fluxes

NaCl–KCl mixtures are widely used because an appropriate composition provides a molten, relatively low-viscosity phase at aluminum-melting temperatures. Foundational fluxing practice identifies cover, drossing, cleaning, and wall-cleaning functions, reinforcing that flux composition and dosage must be linked to a defined duty rather than treated as a generic reagent addition (Gallo & Neff, 2008). In recycling, the flux covers metal, separates oxides, transports fine solids, and promotes droplet coalescence. Its performance depends on liquidus temperature, viscosity, density, oxide capacity, entrained-solid fraction, and interfacial behavior. A flux that melts late in the cycle cannot protect or separate effectively; a flux that is chemically effective but excessively viscous after oxide pickup may still trap metal (Gyarmati et al., 2025; Kulikov et al., 2025; Milani & Timelli, 2023; Milani et al., 2023; Moodispaw et al., 2024; Peterson, 2020).

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Fluorides such as cryolite, NaF, KF, or CaF_2 can increase activity toward oxide films and improve inclusion removal, but their benefit must be evaluated against refractory attack, fluoride emissions, residual fluoride in salt slag, and complexity of regenerated-salt quality. Studies of cryolite content, fluoride determination, recycled-alloy properties, and flux design confirm that "fluoride addition" is not a single variable; chemical form, concentration, and interaction with the base chloride mixture matter (Cai et al., 2024; Milani et al., 2023; Shi & Li, 2023; Wan, Li, Liu, et al., 2020; Wan, Li, Sun, et al., 2020; J.-F. Wang et al., 2026; G. Zhang et al., 2023).

7.2. Salt dosage and the need for a consistent basis

Salt consumption is frequently reported as a percentage of total charge, even though the total charge can consist of very different fractions of metallic aluminum and oxide. Comparisons should therefore report salt per total feed, salt per estimated oxide/non-metal fraction, and fresh salt per tonne of saleable alloy. The following proposed heuristic indicators standardize the bookkeeping but are not validated optimization metrics.

$$SF_{ox} = m_{salt} / m_{oxide\text{-}rich\ fraction} \quad (2)$$

$$CSF = m_{fresh\ salt\ makeup} / m_{saleable\ alloy} \quad (3)$$

SF_{ox} isolates the separative duty associated with oxide-rich material, while CSF measures the fresh-salt burden after regeneration. Both require explicit dry/as-received bases, salt assay, purge definition, and saleable-product boundary. No universal target value is proposed.

Simple NaCl can improve recovery for some drosses, while commercial or multicomponent fluxes may improve fluidity or refining. The correct formulation is therefore feed- and objective-specific. A high-performance refining flux for clean melt treatment is not automatically the best bulk separator for oxide-rich dross, and a salt optimized for recovery may be costly to regenerate (Becker & Friedrich, 2021; Illés & Kékesi, 2023; Kulikov et al., 2025; Milani & Timelli, 2023).

Table 6. Quantitative flux and separation evidence

Study	System	Flux composition/basis	Key conditions	Reported response	Direct rotary evidence?	Main limitation
Milani et al. (2023).	NaCl–KCl flux-property and	0–3 wt% cryolite in salt	Controlled thermal/coalescence testing	Increasing cryolite lowered liquidus	No—controlled flux study	No complete furnace mass,

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Study	System	Flux composition/basis	Key conditions	Reported response	Direct rotary evidence?	Main limitation
	coalescence tests			and increased coalescence efficiency		energy, or emission balance
Illés & Kékesi (2023)	Al dross in rotary converter	Simple NaCl; exact comparable mass basis NR	Rotary melting; detailed common conditions NR	9% metal-yield increase; less secondary dross	Yes, controlled rotary study	Short duration and incomplete reporting
Santos et al. (2025).	Sized Al dross	15 wt% salt/feed for best reported case	Particles >7.5 mm	73.99% recovery	No/unspecified laboratory furnace	Feed assay and uncertainty not on common basis
Sun et al. (2025).	Dispersed chips + supergravity	Reduced salt; exact ratio NR	Intensified separation	High recovery and molten-salt reuse reported	No	Laboratory route; industrial energy not closed
Wang et al. (2023).	Dross size fractions + supergravity	NR	G = 900; 5 min	97.14% recovery; 99.17 wt% purity	No	High-intensity laboratory equipment
Sahoo et al. (2025).	Al chips, liquid-state route	0 salt	Laboratory	>90% recovery	No	Prepared chips only; industrial validation required

Note. The table separates direct rotary evidence from mechanistically relevant studies in other equipment. NR = not reported on a common basis. Reported maxima are not directly comparable.

7.3. Low-salt and salt-free alternatives

Low-salt operation should be understood as feed-specific process intensification rather than simple reagent reduction. It requires a cleaner and denser feed, a stable liquid heel, controlled charging, rapid submergence, enough—but not excessive—mixing, and a slag that remains separable and tappable. Salt-free chip routes can be credible when oxidation is

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suppressed through preparation, liquid-state processing, or rapid collection and when dispersed droplets are efficiently separated (Sahoo et al., 2025; Sun et al., 2024; Sun et al., 2025). Their environmental benefit depends on energy use, metal loss, oxide-residue treatment, and product qualification. These strategies are not universally transferable to oxidized, contaminated, dross-rich, or high-surface-area feeds without matched repeated industrial validation; avoiding salt is not beneficial if the associated recovery loss increases primary-aluminum demand or creates an unusable residue.

8. Heat Transfer, Melting Kinetics, and Furnace Modeling

8.1. Energy balance and heat-transfer mechanisms

The gross furnace energy balance accounts for sensible heating of feed, salt, refractory, and retained bath; latent heat of melting; moisture evaporation; heating and reaction of organics; heat from oxidation or combustion; sensible and chemical energy in off-gas; shell and cooling losses; and energy in metal and slag at tapping. The useful denominator should be saleable alloy, not total charged mass. Heating oxide, salt, and moisture is a penalty unless it results in enough metal recovery to offset it.

Radiation from flame and hot refractory dominates high-temperature zones, while gas convection, wall conduction, contact with liquid metal, and transport through the salt/slag layer govern local heating. Rotation exposes and buries solids, changing view factors and contact conduction. Preheating with CO_2 flue gas and heat recovery can reduce fuel demand but must control oxidation, emissions, and dust (Diop et al., 2021; Oyelami et al., 2021). Figure 5 illustrates these pathways.

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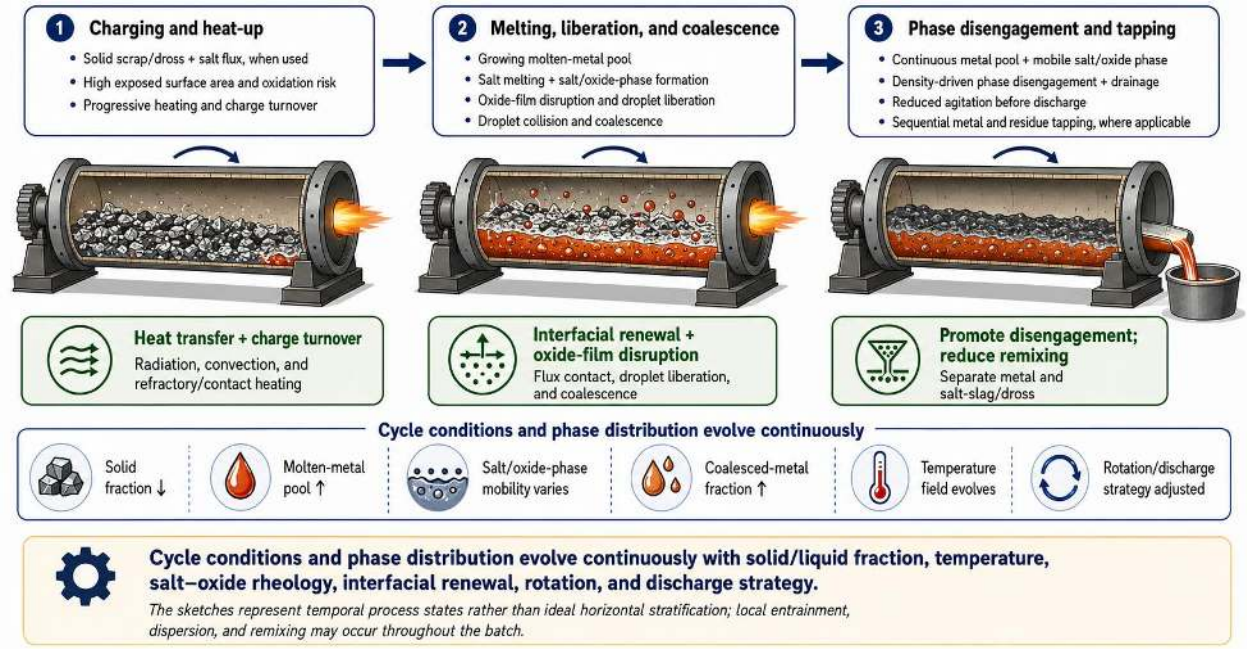

Figure 5. Dynamic phase evolution and heat/mass-transfer functions during a rotary-furnace batch
Note. Author-developed conceptual synthesis informed by Anderson et al. (2022), Crego et al. (2024), Flores Saldívar et al. (2021), and Rimár et al. (2020). The panels are temporal states, not permanent stratified layers.

The cycle representation avoids implying permanent stratification. The relative amounts and locations of solids, molten salt/oxide slurry, dispersed droplets, and metal pool evolve with charging, liquid fraction, rheology, rotation, and tilt; local entrainment and remixing can occur throughout the batch.

8.2. Melting kinetics, bed motion, and modeling requirements

Melting kinetics depend on particle thickness, characteristic length, compaction, preheat, immersion, liquid fraction, oxide envelope, and local heat flux. Rolling, slumping, cascading, or more energetic bed motion changes contact renewal and entrainment. These regimes are often inferred from geometry and rotational speed, but industrial feeds change friction and rheology throughout the cycle. A model calibrated on a dry granular bed may therefore fail after salt melts, metal pools, and oxides form a cohesive slag.

Recent furnace and process models range from high-resolution nonferrous-furnace simulation reviews to transient rotary-furnace calculations, combustion models, thermodynamic process simulation, and hybrid digital-twin concepts (Anderson et al., 2022; Bartie et al., 2024;

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Crego et al., 2024; Dahiya, 2022; Flores Saldívar et al., 2021; Mayr & Chasparis, 2026; Moodispaw et al., 2024; Rimár et al., 2020). Their main limitations are simplified multiphase behavior, uncertain feed properties, limited validation, and inadequate representation of the moving furnace geometry during tilting operations. Validation should include gas and metal temperature histories, melt time, fuel and oxidant use, tapping mass, slag mass and composition, alloy chemistry, and uncertainty—not just a single temperature trace.

Table 7. Industrial, pilot, and field evidence relevant to rotary-furnace operation

Study	Feed/application	Configuration and scale	Quantitative variables reported	Recovery/quality outcome	Energy/emissions	Balance closure	Dominant limitation
Bazhin et al. (2025).	Motor scrap to Al-alloy ingot	Industrial-context campaign	Feed and alloy application; detailed common furnace variables NR	Thixotropic ingot production reported	NR	Partial	Regional/specific application; full balance unavailable
Bhaskar et al. (2022).	Al chips in die-casting foundry	Foundry-scale remelting study	Preparation and remelting outcomes	Chip recycling demonstrated	NR	Partial	Furnace and salt bases not fully comparable
Dzurňák et al. (2020)	Secondary melting	Rotary tilting furnace / industrially relevant	Air infiltration and combustion response	Metal recovery not primary endpoint	Combustion and gas effects reported	No Al–salt closure	Single process dimension
Dzurňák et al. (2021).	Al melting with oxygen enhancement	Industrial/field-relevant furnace	Combustion and gaseous emissions	Product-quality detail limited	Emission formation studied	No full material balance	Recovery and salt not jointly reported
Lawrence et al. (2020).	Tilt rotary furnace	Industrial digital-twin report	Performance and yield improvement discussed	Quantitative raw campaign dataset unavailable	Control-focused	Proprietary/partial	Short trade-technical report
Makw	Secondary	Industrial	Operation	Performance	Combustion	Partial	Conference

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Study	Feed/application	Configuration and scale	Quantitative variables reported	Recovery/quality outcome	Energy/emissions	Balance closure	Dominant limitation
ana et al. (2026).	melting furnaces	smart-combustion/process advisor	al implementation	improvement claimed	control		chapter; detailed uncertainty absent
Rostamian & Berthe rat (2025).	Solid/liquid loading optimization	Industrial technology application	Loading times and process control	Efficiency improvement discussed	NR	Partial	Vendor/technology context
Kheirkhah et al. (2025).	Hydrogen-containing oxy-fuel	Secondary-melting study	Fuel mode and melt-quality response	Melt-quality implications measured/discussed	Fuel/emission implications	Partial	Alternative-fuel transferability requires campaigns

Note. None of the listed studies simultaneously closes feed composition, metallic-Al assay, salt, fuel, tapped metal, saleable alloy, off-gas, slag composition, and uncertainty over repeated industrial campaigns. NR = not reported in a comparable form.

9. Operating Variables, Process Control, and Metal Yield

9.1. Temperature, time, rotation, burner, and atmosphere

Temperature must be reported by location and phase. Flame, gas, wall, solid feed, salt, metal bath, and tapping temperatures are not interchangeable. Higher thermal severity can shorten incomplete-melting periods, but excessive superheat accelerates oxidation, volatilization, refractory attack, and off-gas heat loss. Residence time has the same dual character: it permits melting and coalescence but reduces productivity and increases exposure. Rotation improves heat and mass transfer until entrainment, droplet dispersion, abrasion, or atmosphere renewal become dominant penalties.

Burner operation determines both heat flux and chemical environment. Air–fuel ratio, oxygen enrichment, flame length, burner angle, and furnace pressure interact with infiltration and post-combustion. Oxygen-enhanced combustion can reduce flue-gas volume and change heat transfer, but its effect on NO_x, oxidation, and melt quality depends on actual mixing and leakage (Dzurňák et al., 2020; Dzurňák et al., 2021; Kheirkhah et al., 2025; Rimár et al., 2020).

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Hydrogen-containing combustion changes water-vapor concentration and may alter oxide or hydrogen-related melt-quality risks, so full product measurements are needed rather than fuel-only carbon calculations (Kheirkhah et al., 2025; Tichy, 2025).

9.2. Yield definitions and mass-balance closure

Reported "yield" is often ambiguous. Gross yield, metallic recovery, and saleable-alloy yield answer different questions and should be reported together with a declared system boundary. Net circular recovery may additionally credit metal recovered during slag retreatment, but must assign the associated energy, salt, water, and emissions.

$$Y_g = m_{tapped\ metal} / m_{total\ feed} \quad (4)$$

$$R_m = m_{recovered\ metal} / (m_{feed} \times x_{metallic\ Al}) \quad (5)$$

$$Y_s = m_{saleable\ alloy} / m_{total\ feed} \quad (6)$$

Yg penalizes oxide-rich feed; Rm requires a representative metallic-Al assay; and Ys includes chemistry, holding-furnace dross, filtration, and off-specification losses. Uncertainty in feed assay and all mass measurements must accompany the calculated values.

Figure 6 distinguishes chemical loss from physical non-recovery and downstream commercial loss, clarifying why tapped-metal mass is not equivalent to saleable-alloy yield.

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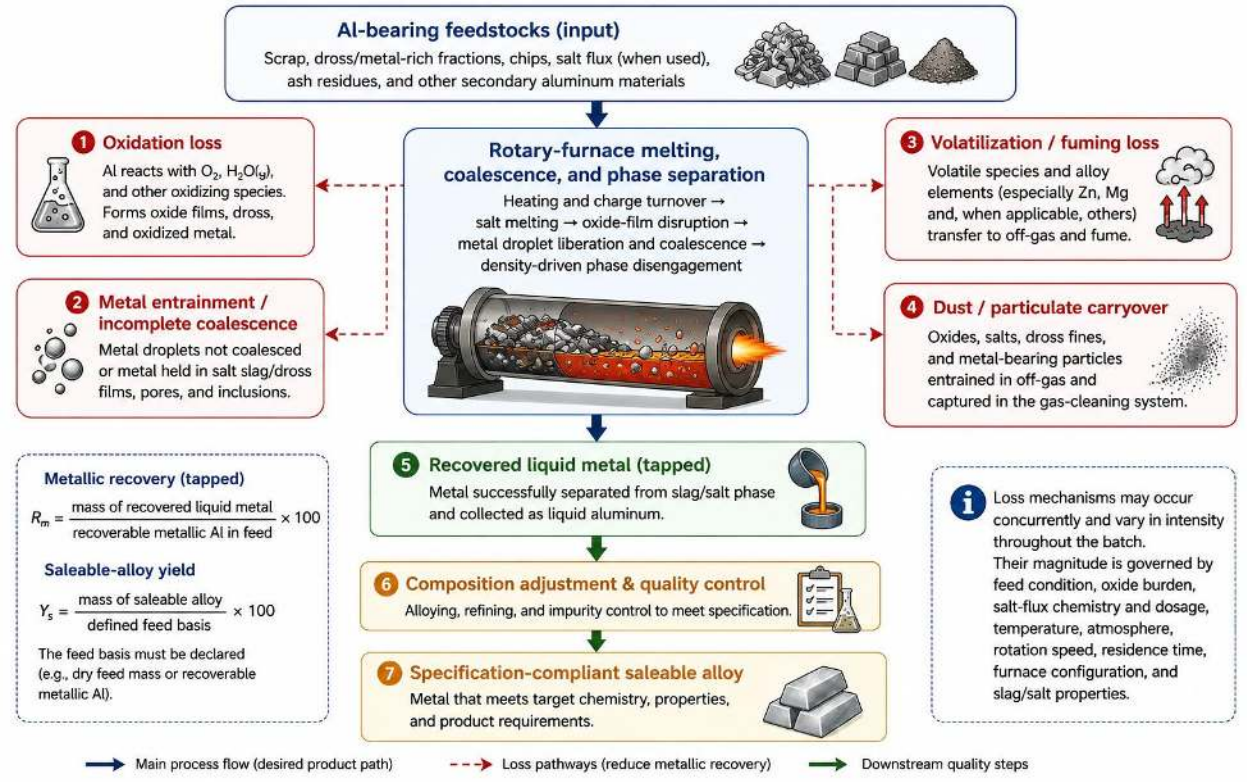

Figure 6. Mechanisms separating aluminum input from tapped and saleable metal
Note. Author-developed conceptual synthesis informed by (Gökelma et al., 2021; Huang et al., 2023; Li et al., 2023; Liao et al., 2022; Sinha et al., 2025; Sitaramu et al., 2023; Solem et al., 2023; Yamamoto et al., 2020).

The figure shows why high tapped mass does not guarantee high saleable yield. Chemistry drift, inclusions, or retreatment can convert nominally recovered metal into a lower-value or non-saleable stream.

Table 8. Status, calculation basis, and validation requirements for established metrics and proposed indicators

Indicator	Definition	Status	Required basis	Validation / control requirement
Gross metal yield (Yg)	Tapped metal / total feed	Established accounting metric	As-received and dry feed mass	Declared boundary, calibrated mass measurement, and uncertainty; not a technology-ranking metric by itself.
Metallic recovery (Rm)	Recovered metal / metallic Al in feed	Established accounting metric	Representative metallic-Al assay	Representative feed sampling/assay and uncertainty propagation.
Saleable-alloy yield (Ys)	Qualified alloy / total feed	Established accounting metric	Product disposition and downstream losses	Traceable product qualification plus reject/downgrade accounting and uncertainty.

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Indicator	Definition	Status	Required basis	Validation / control requirement
Feedstock recyclability indicator (FRI)	Normalized metallic-Al and bulk-density benefit divided by feed penalties	Proposed heuristic indicator	Normalized feed descriptors and site-specific coefficients	Repeated plant lots with feed assays, product disposition, residue mass, calibration, and out-of-sample testing; no universal threshold.
Salt factor on oxide-rich fraction (SF_{ox})	Salt / oxide-rich non-metal fraction	Proposed heuristic indicator	Dry/as-received feed phases and salt assay	Repeated plant lots with explicit oxide/non-metal assay, salt balance, recovery, residue, and uncertainty; plant-specific calibration.
Circular salt factor (CSF)	Fresh salt makeup / saleable alloy	Proposed heuristic indicator	Fresh makeup, recovered salt, purge, and saleable product	Closed salt balance over repeated campaigns, regenerated-salt quality, purge, product yield, residue, and uncertainty.
Specific energy	Total melting-cell energy / saleable alloy	Established engineering KPI; boundary-dependent	Fuel, oxygen, electricity, pretreatment, auxiliaries	Metered energy carriers, heat-recovery credit, matched product basis, and uncertainty.
Residue intensity	Dry salt slag + dust / saleable alloy	Established accounting/operational KPI	All collected solids and moisture basis	Complete solids accounting, moisture correction, and declared disposition route.
Mass-balance closure	Accounted input–output / total input	Established data-quality metric	Al, salts, solids, liquids, gases	Prospective element/phase closure criteria, uncertainty, and reconciliation rules.
Carbon intensity	Scope-defined CO_2e / saleable alloy	Established LCA/accounting metric; method-dependent	Fuel, electricity, oxidants, pretreatment, transport, credits	Declared scope, electricity mix, allocation/system expansion, avoided-product assumptions, and sensitivity analysis.

Note. FRI, SF_{ox}, and CSF are proposed heuristic indicators and require plant-specific calibration; Yg, Rm, and Ys are accounting metrics whose usefulness still depends on declared boundaries, representative measurements, and uncertainty. Author-developed synthesis informed by (Hannula et al., 2020; Lawrence et al., 2020; Makwana et al., 2026; Rostamian & Bertherat, 2025; Santos et al., 2025; Solem et al., 2023; Vallejo-Olivares et al., 2024; J. Wang et al., 2025; Y. Zhang et al., 2023).

9.3. Operating-window control

The optimal cycle is a moving, feed-dependent window rather than one set point. Figure 7 is deliberately heuristic: it contains no calibrated numerical boundary. A wet, oily, low-density feed shifts operation toward slower controlled charging and greater pretreatment; oxide-rich dross requires enough liquid flux and residence time for liberation; and clean dense returns favor lower salt and shorter exposure. The location and width of every region must be fitted from plant campaigns that include product quality, energy, emissions, refractory response, residue generation, and uncertainty.

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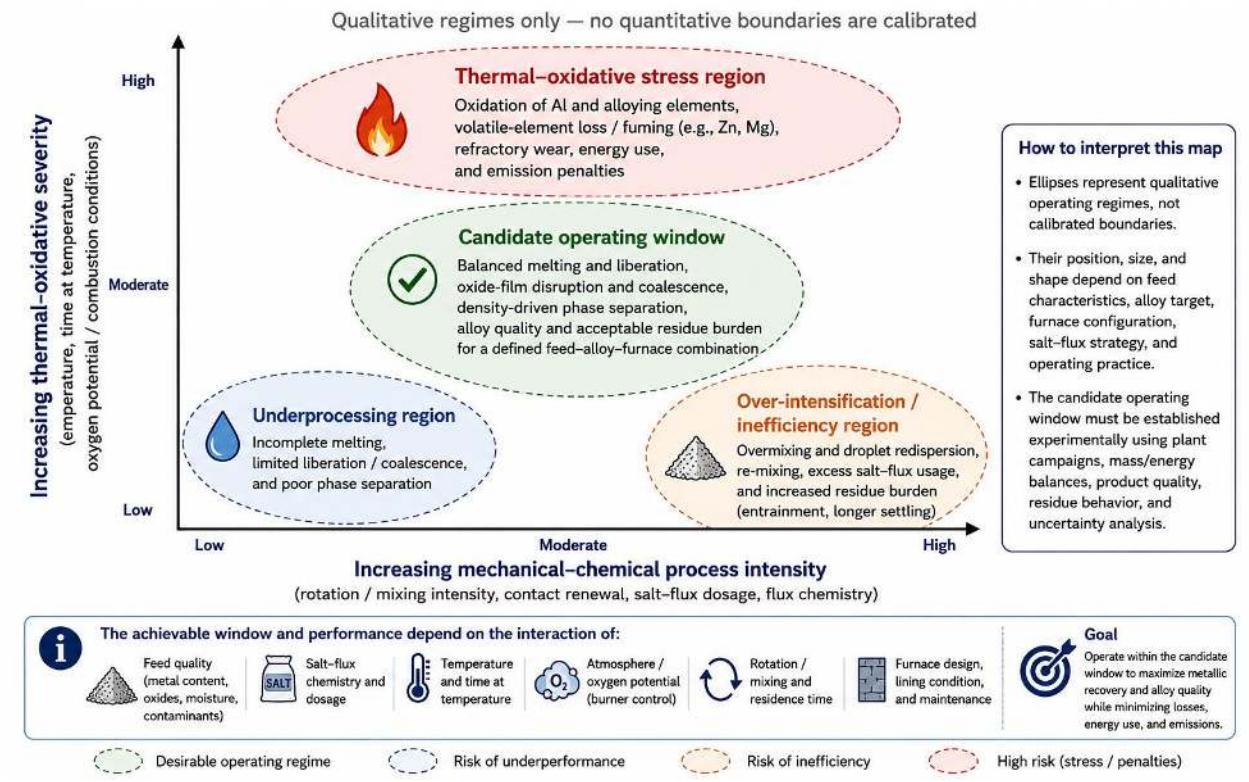

Figure 7. Qualitative operating-window map for rotary-furnace melting
Note. Author-developed conceptual synthesis informed by the cited operating and mechanism studies. The zones are qualitative hypotheses for local calibration and must not be interpreted as validated numerical limits.

A plant should populate this map with campaign data and uncertainty. The desired region is the one that maximizes qualified alloy while meeting energy, emission, refractory, and residue constraints—not the region with the highest instantaneous melt rate.

10. Alloy Chemistry, Melt Quality, and Product Qualification

10.1. Element recovery and residual-element control

Scrap composition should be translated into predicted tapped-metal chemistry using element-specific recovery factors. Silicon, copper, manganese, iron, nickel, chromium, and titanium are comparatively persistent under many remelting conditions, whereas magnesium, zinc, sodium, strontium, and other reactive or volatile elements may show greater loss or variability. These factors depend on temperature, atmosphere, salt chemistry, time, and physical form. A charge model that assumes 100% recovery for every element can satisfy an input calculation while missing the final alloy specification.

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Residual-element control is often more restrictive than total aluminum recovery. Mixed scrap can accumulate Fe, Pb, Sn, Bi, Cr, Ni, V, or other elements that are difficult to remove after melting. Thermodynamic and experimental approaches to iron control, alternative fluxes for impurity removal, and alloy-specific scrap applications show that treatment may be possible but can create intermetallic losses, additive demand, or a narrower product route (Bazhin et al., 2025; Kudyba et al., 2021b; Sinha et al., 2025; Srinath et al., 2025). Product-oriented recycling therefore favors upstream sorting and appropriate alloy families before corrective metallurgy.

10.2. Inclusions, bifilms, salts, and hydrogen

Rotary melting can transfer oxide films, carbides, salts, refractory fragments, and other particles to the tapped metal. Foundational aluminum melt-processing practice treats hydrogen control, oxidation, fluxing, and filtration as linked elements of metal quality, while recent salt-flux remelting and inclusion studies confirm that recovered mass must be paired with cleanliness assessment (ASM International, 1993; Çapkın & Gökelma, 2023; Gökelma et al., 2021; Li et al., 2023; J.-F. Wang et al., 2026; Yang et al., 2025). Depending on the intended product, qualification may include optical-emission or equivalent chemical analysis, hydrogen measurement, reduced-pressure testing, filtration-based inclusion assessment such as PoDFA/Prefil-type methods or validated plant equivalents, metallography, mechanical testing, and corrosion-sensitive testing. Acceptance limits must be tied to the declared alloy/customer specification and internal control plan rather than assumed to be universal. A process that raises recovered mass but increases inclusions, porosity risk, or chemistry drift can lower downstream yield or force product downgrading.

Table 9. Product-class qualification tests, rejection triggers, and disposition tracking

Product class / intended route	Chemical and melt-quality qualification	Property / service-sensitive tests	Typical rejection criterion	Disposition and feedback
Remelt ingot / secondary foundry feed	OES/XRF or equivalent against declared purchase/alloy chemistry; residual-element trend; hydrogen/RPT where relevant; visible/inclusion/salt/refractory assessment.	As required by receiving foundry/customer.	Chemistry outside purchase specification; abnormal hydrogen/cleanliness; entrained salt or refractory above internal limit.	Accept, blend, retreat, downgrade, or reject; retain feed lot and furnace campaign traceability.

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Product class / intended route	Chemical and melt-quality qualification	Property / service-sensitive tests	Typical rejection criterion	Disposition and feedback
General casting alloy	Final chemistry after correction (including Fe, Cu, Mg, Zn, Si and specified modifiers); hydrogen; RPT; inclusion/filtration assessment such as PoDFA/Prefil-type or validated plant equivalent; metallography as needed.	Tensile, hardness, or casting validation according to product specification.	Chemistry, cleanliness/hydrogen control, or mechanical verification outside specification/control plan.	Quantify yield loss from correction, filtration, dross, rejects, and downgrade.
Pressure-tight / structural casting	Tight chemistry/residual-element control; hydrogen + RPT; inclusion assessment; porosity/metallography or radiographic/NDT route where specified.	Mechanical testing and pressure/leak or fatigue verification when required.	Failed RPT/density-index control, porosity/NDT criterion, mechanical property, or chemistry requirement.	Record reject/retreat route and link outcome to feed, flux, furnace, transfer, and holding conditions.
Wrought-feed / composition-sensitive billet or slab feed	Narrow chemistry and residual/trace-element window; hydrogen and inclusion cleanliness before transfer/casting; filtration performance.	Downstream homogenization, extrusion, rolling, or surface-quality indicators as specified.	Residual elements, inclusions, or unstable corrected chemistry inconsistent with downstream wrought quality.	Downgrade to compatible alloy family or retreat; track dilution and metal loss.
Corrosion- or surface-sensitive product route	Chemistry including corrosion/finishing-sensitive elements; contamination and salt carryover; cleanliness; hydrogen/porosity control.	Corrosion, coating/finishing adhesion, or surface-quality test required by customer specification.	Failed corrosion/surface requirement, salt inclusion, chemistry drift, or porosity criterion.	Distinguish true circular substitution from downgrade to a less demanding use.
Any product after corrective retreatment or blending	Re-analysis after each correction/blend; element-specific recovery factors; repeat relevant cleanliness/hydrogen tests after treatment.	Repeat tests affected by retreatment or required by final product class.	Failure to meet final declared product specification or internal control plan.	Record correction additions, metal loss, energy/consumables, reject mass, and final saleable destination in Ys.

Note. Test selection and rejection limits must be tied to the declared alloy, customer, and product specification; no universal numerical acceptance limits are proposed. Author-developed conceptual synthesis informed by foundational melt-processing practice and recent melt-quality evidence (ASM International, 1993; Cai et al., 2024; Çapkın & Gökelma, 2023; Gökelma et al., 2021; Gyarmati et al., 2025; Kheirkhah et al., 2025; Kudyba et al., 2021b; Li et al., 2023; Sinha et al., 2025; Srinath et al., 2025; J.-F. Wang et al., 2026; Yang et al., 2025).

10.3. Downstream melt treatment and the saleable product

Rotary-furnace metal normally enters a holding or refining stage for skimming, chemistry correction, degassing, filtration, modification, grain refinement, and casting. These operations should not be treated as an invisible fixed loss. Their metal loss, energy, consumables, and quality rejects belong in the saleable-alloy balance. The best rotary cycle is thus the one that

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minimizes total cost and impact for qualified product, even when its tapped-metal mass is slightly lower than a more aggressive cycle.

11. Energy Use, Off-Gas Emissions, Refractory, and Operational Integrity

11.1. Energy and decarbonization pathways

Energy reduction begins with avoiding unnecessary mass and water. Cleaner, drier, denser feed requires less heat and often less residence time. Preheating, recuperation, improved insulation, pressure control, and endpoint prediction reduce stack and shell losses. Fuel switching, oxygen enrichment, electrical assistance, and hydrogen can reduce direct fossil carbon, but their merit depends on upstream energy, oxygen production, gas leakage, metal oxidation, and product quality (Deng et al., 2022; Diop et al., 2021; Kheirkhah et al., 2025; Makwana et al., 2024; Oyelami et al., 2021; Tichy, 2025). A decarbonization claim should use total melting-cell energy per tonne of qualified alloy and should report the fate of recovered heat.

11.2. Off-gas formation and treatment

The off-gas can contain CO_2, CO, NO_x, particulate matter, condensed salts, metal-bearing dust, organic products, HCl, HF, and—when halogenated organics and a suitable thermal history coexist—persistent organic pollutants. Source reduction through dry, well-characterized feed and controlled combustion is preferable to relying only on end-of-pipe treatment. A typical train combines post-combustion, rapid cooling where required, coarse-particle removal, fabric or ceramic filtration, alkaline sorbent, activated carbon for selected contaminants, and continuous or campaign-based monitoring. Ceramic-filter practice illustrates the importance of temperature, dust properties, and maintenance in high-temperature gas cleaning (Krasnyi et al., 2024).

11.3. Refractory and operational integrity

Refractory degradation results from thermal cycling, abrasion, metal infiltration, chemical attack by chlorides and fluorides, and local flame impingement. Salt reduction may lower chemical burden but could increase mechanical or thermal stress if the process relies on stronger agitation or higher temperature. Refractory life should therefore be normalized to tonnes of qualified alloy and linked to feed and flux campaigns. Operational integrity also includes

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seals, drives, tilt mechanisms, burner safeguards, pressure control, tapping reliability, and safe slag cooling.

Table 10. Quantitative salt-slag metal recovery, salt removal, and detoxification evidence

Study/feed	Route and scale	Initial basis reported	Key conditions	Reported outcome	Energy/emissions boundary	Product or residue	Critical comparability limitation
Kudyba et al. (2021a), white dross	Mechanical activation + remelting, laboratory	Real dross; size fraction basis	Milling 3 h at 35 rpm; >1 mm; remelt at 900 °C	Coarse fraction ~80% metallic Al; remelted matrix >96 at.% Al	No normalized energy or off-gas balance	Al-rich metal + fine residue	Feed-specific batch and no salt-loop closure
Wang et al. (2023), Al dross	Mechanical activation + supergravity, laboratory	Three size classes	G = 900; 5 min	97.14% recovery; 99.17 wt% purity	High-intensity separation energy NR	High-purity Al + non-metallic residue	Not an industrial rotary-furnace campaign
Teixeira et al. (2022), salt slag	Water leaching optimization, laboratory	Chloride-bearing salt slag	Optimized leaching variables; common values NR here	Chloride extraction optimized	Evaporation/crystallization and gas capture not fully included	Brine + desalted solid	Leaching step only; no full regeneration energy
Gao et al. (2021), secondary dross	Alkali leaching, laboratory	Fluoride-bearing dross	Controlled alkali treatment	Defluorination demonstrated	Aqueous effluent generated	Fluoride-depleted residue	Upstream metal recovery and salt regeneration not integrated
Xie et al. (2023). high-/low-salt SAD	Roasting, laboratory	Initial salt and AlN differ by feed	800 °C, 120 min high-salt; 1000 °C low-salt	95.8% AlN removal high-salt; 69.47% low-salt	Thermal penalty and volatile capture not normalized	Detoxified oxide/salt residue	Strong feed-assay dependence
Wang et al.	Pyrometallurgical AlN	Real dross	Controlled	AlN removal	Thermal/emission closure	Treated dross	No upstream

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Study/feed	Route and scale	Initial basis reported	Key conditions	Reported outcome	Energy/emissions boundary	Product or residue	Critical comparability limitation
(2021). SAD	removal, laboratory		thermal treatment	quantified in source	incomplete		furnace or downstream product balance
Xie et al. (2023). SAD	Particle sorting + roasting, laboratory	Particle-size/composition fractions	Sorted feed followed by roasting	Improved F and AlN removal relative to unsorted feed	NR	Treated fractions	Source-dependent composition and no industrial campaign

Note. SAD = secondary aluminum dross; NR = not reported on a comparable basis. Values should not be combined because metal-first recovery, leaching, roasting, and intensified separation have different feed assays and system boundaries.

The critical point is that environmental control should not be separated from recovery optimization. A cycle that increases oxide dust or salt carryover may raise apparent furnace recovery while transferring aluminum and contaminants to the gas-cleaning residue. Complete balances across metal, slag, dust, and gas are therefore required.

12. Salt-Slag Management, Circularity, Economics, and Research Agenda

12.1. Salt-slag characterization and metal-first recovery

Salt slag is a heterogeneous process residue whose composition depends on feed, flux, oxidation, refractory wear, and tapping. Foundational reviews established the importance of residual metallic aluminum, soluble chlorides, nitrides/carbides, oxides, and the environmental consequences of water-reactive phases; recent work adds more detailed routes for metal recovery, salt regeneration, detoxification, and valorization (Tsakiridis, 2012; Mahinroosta & Allahverdi, 2018; Padamata et al., 2021; Wu et al., 2025; Zou et al., 2026). It may contain NaCl, KCl, fluorides, metallic aluminum, alumina, AlN, Al_4C_3, MgO, spinels, silica, refractory fragments, and trace metals. The first decision is whether enough metallic aluminum remains to justify physical or thermal recovery before hydrometallurgical treatment (Kudyba et al., 2021a; Kulikov et al., 2026; Lan et al., 2026; Santos et al., 2025; Sun et al., 2024; Sun et al., 2025; Z. Wang, Gao, Lan, & Guo, 2023; Wang et al., 2024; Z. Wang, Gao, Lan, Feng, et al., 2023).

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Metal-first is not universally optimal. Its value depends on residual metallic content, particle-size distribution, oxidation during cooling, electricity and fuel costs, product quality, and the ability to return the recovered metal to a compatible alloy. Dross valorization with copper to produce Al–Cu alloy, for example, deliberately changes the product route rather than returning pure aluminum (Kudyba et al., 2021b). The decision should therefore compare net recovered value, not only metal percentage.

12.2. Salt recovery, reactive-phase treatment, and non-metallic products

Aqueous salt recovery typically involves water leaching, solid–liquid separation, solution purification, evaporation, and crystallization. Chloride extraction can be high, but process performance is governed by liquid-to-solid ratio, temperature, time, particle size, washing, evaporation energy, impurity accumulation, and the required NaCl–KCl product specification. Hot treatment and optimized water leaching show routes for salt recovery, while multistage schemes integrate metal extraction and flux regeneration (Hegedüs et al., 2023; Kulikov et al., 2026; Teixeira et al., 2022).

Water contact also activates AlN and Al_4C_3, producing gas and alkaline conditions. Thermal, alkaline-roasting, fluoride-assisted, particle-sorting, and other routes have been studied to remove nitrogen, fluorides, or both (Gao et al., 2021; Li et al., 2024; Li et al., 2026; Li et al., 2021; Lv et al., 2022; Ni et al., 2022; Wang et al., 2021; Wei et al., 2023; Xie, Guo, Xu, & Zhang, 2023; Xie, Guo, Xu, Zhang, et al., 2023). These studies demonstrate that “detoxification” has multiple endpoints: reduced gas evolution, reduced soluble salts, fluoride stabilization, or conversion to a phase suitable for a product. No single treatment should be described as harmless without specifying the test, residual contaminants, effluent, gas capture, and product-use boundary.

The non-metallic fraction has been proposed for cementitious materials, calcium aluminate, alumina recovery, adsorbents, ceramics, and other products (Harmaji et al., 2024; Modalavalasa & Ayyagari, 2024; Muñoz-Vélez et al., 2023; Polat et al., 2022; Yuan et al., 2023; P. Zhang et al., 2023; Zhu et al., 2020; Zuo et al., 2021). Product claims require more than just compressive strength or laboratory extraction. They require compliance with impurity and

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leaching limits, variability control, market capacity, substitution credit, and evidence that processing does not consume more reagents or energy than the avoided product.

12.3. Circularity validity, environmental assessment, and economics

Life-cycle and environmental-economic studies show that conclusions depend strongly on avoided products, electricity mix, recovered-metal credit, transport, residue disposal, salt-regeneration energy, and system expansion (Hannula et al., 2020; Ji et al., 2025; Vallejo-Olivares et al., 2024; J. Wang et al., 2025; Xiao et al., 2023; P. Zhang et al., 2023; Y. Zhang et al., 2023; Zhu & Jin, 2021; Zhu et al., 2020). Salt-slag valorization can improve the result of rotary-furnace recycling, but it does not erase the upstream incentive to minimize salt and oxidation. Conversely, a low-salt furnace should not receive an automatic circularity advantage if lower recovery increases primary-metal demand or produces an unusable oxide residue.

12.3.1. Technical recovery, regulatory acceptability, and market-displacing circular use

Three levels of circularity validity should be distinguished. Technical recovery means that a material can be recovered to a defined composition or functional state with explicit mass, water, gas, and residue balances. Regulatory acceptability requires that the recovered product and all residual streams satisfy the applicable product, waste, leaching, emissions, occupational, transport, and permitting requirements in the jurisdiction of use. Market-displacing circular use requires evidence that the recovered output is accepted at meaningful scale and actually substitutes a virgin or incumbent market product without hidden downgrading, stock accumulation, or an unaccounted secondary waste burden. Technical closure alone therefore does not demonstrate circularity; a closed-loop claim should identify which of these three levels has been demonstrated and which remains conditional.

Economic assessment should include feed price or gate fee, preparation, fuel, oxygen, electricity, salt makeup, refractory, labor, maintenance, off-gas treatment, water, residue transport, treatment/disposal, metal revenue, quality discount, and coproduct credit. Multiobjective assessment is particularly appropriate because the lowest direct cost may have higher safety or environmental risk (J. Wang et al., 2025). Market-value analyses also show that residue utilization is sensitive to regional product prices and carbon benefits (Ji et al., 2025).

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Figure 8 extends the closed-loop boundary to water and gas as well as salt and metal, making purge requirements and secondary-stream obligations explicit.

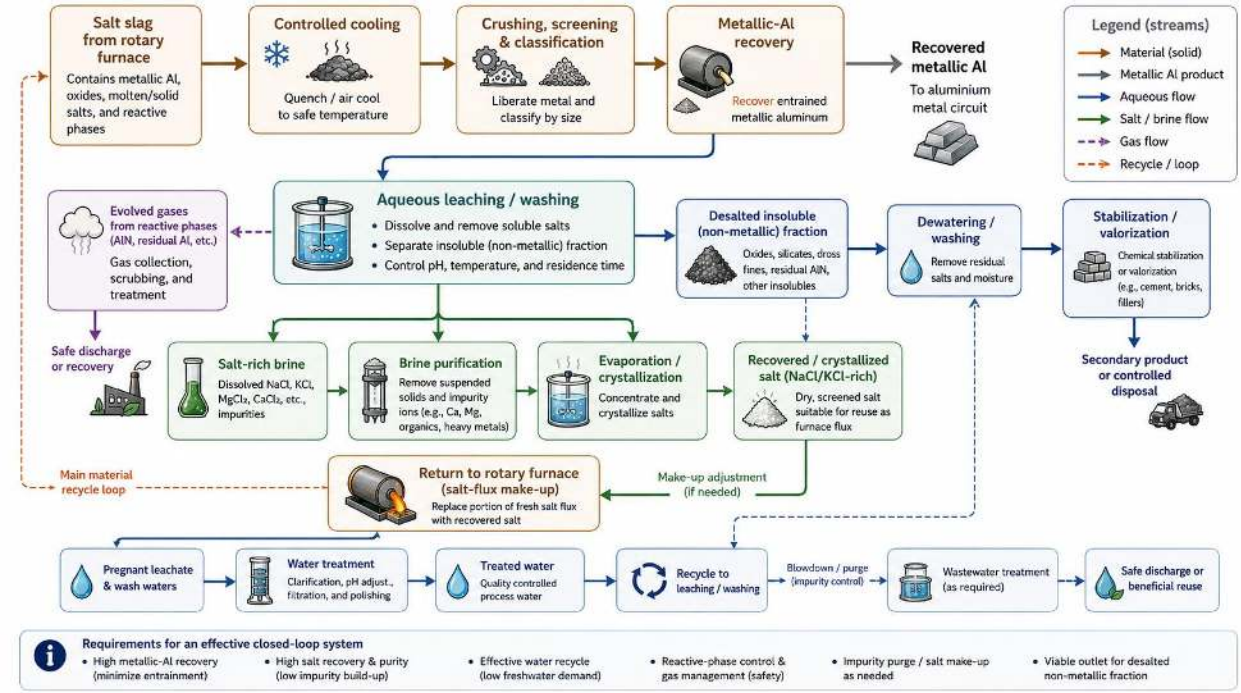

Figure 8. Closed-loop salt-slag management and conditional recycle
Note. Author-developed conceptual synthesis informed by (Gao et al., 2021; Hegedüs et al., 2023; Kulikov et al., 2026; Li et al., 2024; Modalavalasa & Ayyagari, 2024; Padilla et al., 2022; Teixeira et al., 2022; Wan, Li, Sun, et al., 2020; Z. Wang, Gao, Lan, & Guo, 2023; Wu et al., 2025; Xiao et al., 2023; Yuan et al., 2023; Zou et al., 2026).

The loop must include purges and quality limits. Without impurity control, repeated salt recycling can accumulate fluorides, oxides, fine solids, or trace metals, eventually impairing flux performance or creating more concentrated waste.

12.4. Digitalization and process control

Digitalization is most valuable when it reduces uncertainty in variable feed. The required architecture links lot identity, weighing, feed assays, temperature, gas analysis, pressure, burner and oxidant flow, rotation, tilt, time, metal and slag mass, product chemistry, and maintenance history. Soft sensors can estimate melt state or endpoint, while hybrid models combine physical constraints with statistical learning. Reports on digital twins, smart combustion, process advisors, and smart loading indicate substantial practical interest (Aly, 2026; Lawrence et al., 2020; Makwana et al., 2026; Mayr & Chasparis, 2026; Rostamian & Bertherat, 2025). However, a

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model trained on furnace signals without reliable feed labels can learn campaign identity rather than causal process behavior.

Figure 9 visualizes the nine gates and their reject, reroute, retreat, and feedback logic. Digital sensing and operator-advisor functions support the gates but do not replace feed identity or product verification.

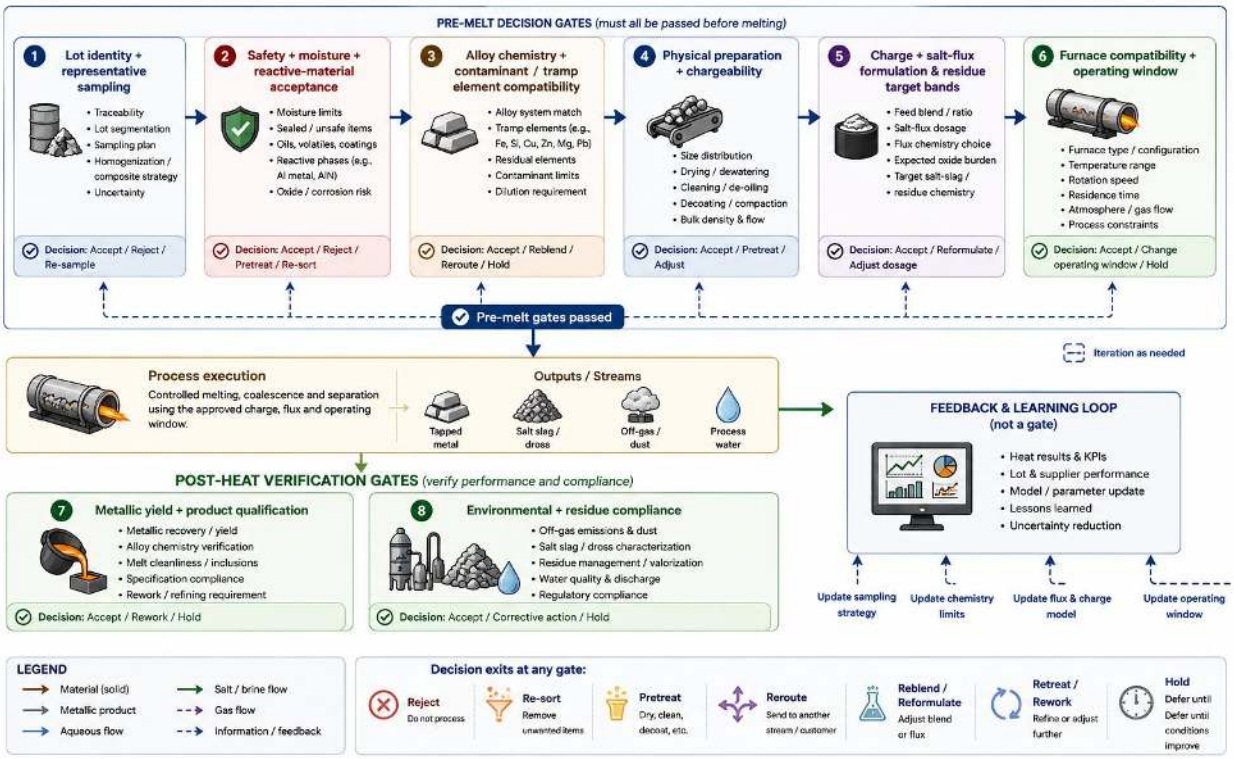

Figure 9. Nine-gate Feedstock–Flux–Furnace–Residue decision framework
Note. Author-developed conceptual synthesis informed by the evidence reviewed in Sections 3–12. The framework is proposed and requires prospective industrial validation.

12.4.1. Validation status of the proposed framework

The nine-gate framework is a proposed, testable decision architecture; it is not a validated control algorithm, standard, or universal operating model. Its apparent completeness in Figure 9 should not be interpreted as evidence of predictive validity. Prospective validation requires repeated industrial campaigns with defined feed lots and independent closure of feed assays, salt use, fuel and oxidant demand, tapped and saleable metal, product chemistry and quality, residue mass, emissions, and uncertainty. Validation should also test gate decisions against subsequent product disposition and environmental routing, with calibration and out-of-sample assessment

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where digital models are used. Until such evidence is available, the framework should be used to structure data collection, reporting, and pilot decisions rather than to prescribe universal operating limits.

12.5. Research priorities and proposed integrated framework

The strongest research need is not another isolated maximum recovery. It is an industrial dataset that closes aluminum, alloying-element, salt, solid, liquid, gas, energy, and uncertainty balances for defined feed lots over repeated campaigns. Matched comparisons of fixed-axis and tilting furnaces, conventional and low-salt operation, and alternative fuels should hold feed quality and product specification constant. Models should couple combustion, radiation, bed motion, melting, slag rheology, thermodynamics, and control at a level justified by validation data. Refractory wear and off-gas solids should be included as metal and cost pathways rather than maintenance footnotes.

The proposed Feedstock–Flux–Furnace–Residue Framework uses nine gates: (1) lot identity and representative sampling; (2) safety and moisture acceptance; (3) alloy and contaminant compatibility; (4) physical preparation; (5) charge and flux formulation on oxide and saleable-metal bases; (6) operation within a calibrated thermal–mixing window; (7) tapped-metal and downstream product qualification; (8) full off-gas and salt-slag routing; and (9) feedback to supplier, lot, and process models. A batch is successful only when it passes all gates. This prevents high gross recovery from masking excessive salt, energy, off-specification metal, emissions, or an unmanageable residue.

Technology maturity is uneven and was interpreted jointly with evidence transferability. Conventional rotary salt melting and standard gas cleaning are mature but still lack publicly available A-level full balances. Feed preparation, heat recovery, and basic digital monitoring are deployable but site-specific. Low-salt operation has meaningful industrial potential but requires transparent long campaigns. Salt-free chip processing, supergravity, plasma or hydrogen integration, advanced hybrid twins, and near-zero-waste residue products remain feed- and scale-dependent. The available evidence supports targeted pilots with complete balances rather than universal replacement claims (Lan et al., 2026; Makwana et al., 2026; Sahoo et al., 2025; Sun et

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al., 2024; Sun et al., 2025; Tichy, 2025; Z. Wang, Gao, Lan, & Guo, 2023; Z. Wang, Gao, Lan, Feng, et al., 2023).

12.6. Limitations of the evidence base and review process

The principal evidence limitation is the absence of repeated industrial studies that jointly report representative feed assays, salt use on explicit bases, fuel and oxidant demand, tapped and saleable metal, alloy chemistry and melt quality, emissions, slag composition, and uncertainty. Laboratory maxima frequently arise from prepared feeds, narrow particle classes, short tests, or intensified equipment and cannot be transferred without qualification. The review is auditable from the final 106-record coding stage onward, but the discovery-stage corpus cannot be independently reconstructed. In addition, one reviewer performed all retrospective coding without independent duplicate coding; A–E levels are therefore interpretive transferability judgments rather than reliability-tested evidence categories. The synthesis consequently identifies conditional relationships and reporting requirements rather than pooled effect sizes, universal rankings, or universal operating limits.

13. Conclusions

Rotary furnaces remain strategically important for aluminum-bearing feeds whose oxidation, coatings, low bulk density, contamination, or entrained droplets make conventional bath melting difficult. Their advantage arises from the coupling among heat transfer, rotation, liquid metal, flux, and slag behavior; the same coupling can also generate oxidation, salt-bearing residue, emissions, refractory wear, and alloy-quality loss. The evidence therefore indicates that feedstock qualification is the first process-control gate, not an auxiliary purchasing activity.

Fixed-axis and tilting furnaces should be compared only for matched feed, bath inventory, salt basis, product specification, and auxiliary-system boundary. Salt is a functional separation medium whose minimum effective dosage depends on oxide burden, slag rheology, coalescence duty, and regeneration capability. Low-salt and salt-free routes appear credible for selected prepared feeds, particularly chips, but require repeated industrial validation before extension to the full range of difficult materials.

Metal yield alone remains an incomplete performance measure. Industrial reporting should combine gross yield, metallic recovery, saleable-alloy yield, salt and residue intensity,

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total melting-cell energy, emissions, refractory consumption, and mass-balance closure. Product chemistry, inclusions, hydrogen, and downstream treatment determine whether the recovered mass qualifies as alloy. Salt-slag treatment can improve circularity, but its net benefit depends on water, gas, energy, impurities, market capacity, and assumptions about avoided products.

The proposed Feedstock–Flux–Furnace–Residue Framework integrates receiving, preparation, charge and flux formulation, calibrated operation, product qualification, off-gas treatment, residue routing, and feedback through nine gates. It should be regarded as a testable decision architecture rather than a validated universal metric or control model. The review is auditable from the final 106-record coding stage onward, but the discovery-stage corpus cannot be independently reconstructed; furthermore, the retrospective A–E classification is a single-reviewer transferability judgment. The available evidence suggests that cleaner and denser feed, minimally sufficient functional fluxing, heat recovery, calibrated sensing, product-oriented yield, and site-specific residue treatment constitute a credible pathway within the evaluated system boundary. Low-salt and salt-free routes remain feed-specific, and prospective industrial campaigns with transparent uncertainty quantification are required before broader transfer or validation of the framework.

Declarations

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Conflict of interest: The author declares no conflict of interest.

Data availability: Supplementary Table S1 accompanies the resubmission and contains the complete 106-record evidence matrix, including full citation, DOI and DOI URL fields, primary evidence category, direct/contextual class, A–E industrial-transferability judgment, feedstock, process/furnace configuration, scale, pretreatment, flux/additive composition, operating variables, recovery and product-quality fields, energy, emissions, residue outcome, reported uncertainty, principal limitation, and the reviewer coding note. The discovery-stage exports and screening counts are not recoverable and are not reconstructed.

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