Application of Intelligent Three-Ring Kiln Activation Calcination Technology in the Harmless Disposal of Aluminum Ash and its Low-Carbon, High-Value Circular Economy in the Middle East

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The Middle East, as a core region of the global electrolytic aluminum industry, generates a large amount of secondary aluminum ash during the production of electrolytic alumina. In particular, high-fluorine aluminum ash, with a fluorine content generally exceeding 5%, has become a key environmental bottleneck restricting the industry's green, low-carbon, and sustainable development. Traditional landfill or simple treatment methods not only fail to eradicate the long-term environmental pollution risks posed by the contained fluorides and nitrides but also waste valuable resources such as aluminum and fluorine.

Based on the large-scale patented "Intelligent Three-Ring Kiln" equipment with independent intellectual property rights from Shandong Hening Shun Kiln Industry Co., Ltd., and its tailor-made "four-step closed-loop" high-value utilization process plan, this innovative path of "aluminum ash briquetting for enhanced pretreatment → intelligent three-ring kiln for gradient calcination activation → sulfuric acid system for selective leaching separation → co-production and purification of alumina/cryolite" aims to "exhaustively utilize" the hazardous solid waste of secondary aluminum ash. It efficiently co-produces strategic new materials such as 4N-grade (99.99%) high-purity alumina and industrial-grade high-purity cryolite. This technology not only provides a technically feasible, economically superior, and environmentally friendly complete industrialized solution for the thorough harmless disposal of high-fluorine aluminum ash in the Middle East but also constructs a new paradigm of a circular economy with extraordinary profitability and excellent environmental benefits. It offers highly competitive strategic support for Middle Eastern aluminum enterprises in the face of global low-carbon transformation and challenges from new trade regulations like the EU carbon tariff.

1. Dilemma and Opportunity: Technical Bottlenecks and Strategic Breakthroughs in Middle East High-Fluorine Aluminum Ash Disposal

1.1 The Severe Challenge of High-Fluorine Aluminum Ash in the Middle East

The electrolytic aluminum industry in the Middle East holds a pivotal position globally, but its by-product, secondary aluminum ash, is generally characterized by "high fluorine," with fluorine content typically exceeding 5%. This type of aluminum ash is explicitly listed as hazardous waste, and its environmental hazards are mainly reflected in:

Chemical Toxicity and Environmental Hazards: Aluminum nitride (AlN) contained in the ash undergoes hydrolysis upon contact with water or moisture in the air, producing toxic ammonia gas (NH_3) with a pungent odor. At the same time, the salts present, such as fluorides and chlorides, have strong leaching toxicity. If traditional landfill methods are used, these pollutants will seep with rainwater, posing a serious and long-term threat to the region's precious groundwater resources and soil.

Limitations of Traditional Disposal Methods: Currently, the common disposal methods in the industry have obvious technical bottlenecks. Off-site transportation and anti-seepage landfilling are not only costly and occupy a large amount of land resources but also represent a hidden environmental hazard with a huge risk of leakage, failing to eradicate the pollution. Some resource utilization attempts, such as traditional wet processes (hydrolysis), have a denitrogenation rate of only 30-40%, which is inefficient, and the tail gas is difficult to meet standards. The use of traditional pyrometallurgical equipment such as rotary kilns for treatment generally suffers from a series of technical pain points, including low thermal efficiency, uneven heating of materials tumbling in the kiln (which can easily lead to "under-burning" or "over-burning"), and the difficulty of effectively controlling and recovering pollutant gases such as fluorine.

Increasingly Severe Pressure from Global Low-Carbon Development: Against the backdrop of increasingly strict environmental regulations and the deep-rooted concept of "waste-free cities," especially with the advancement of the global greenhouse gas emission reduction goals of the Paris Agreement and the approaching full implementation of the EU's Carbon Border Adjustment Mechanism (CBAM, or "carbon tariff") in 2026, the global industrial, economic, and trade landscape is undergoing

profound changes. For the aluminum industry in the Middle East, this not only means that its aluminum products exported to markets such as the EU will be subject to high tariffs due to their carbon footprint in the production process, but it also places higher demands on the energy consumption and carbon emissions of its back-end links such as solid waste treatment. Therefore, finding an advanced low-carbon technology for the Middle East that can fundamentally stabilize or remove harmful elements, completely eliminate environmental risks, and simultaneously achieve high-value recovery of all resource components has become an urgent strategic need for the sustainable development of the region's aluminum industry.

1.2 Strategic Opportunity: The Breakthrough of Intelligent Three-Ring Kiln Technology

The urgent needs of the market provide huge development opportunities for disruptive technologies. The intelligent three-ring kiln activation calcination technology, a large-scale patented equipment with independent intellectual property rights developed by Shandong Hening Shun Kiln Industry Co., Ltd. in China, and its supporting customized process for the high-value utilization of secondary aluminum ash in the Middle East, provide a new way of thinking and an industrialized path to solve the above problems. The core advantage of this technical solution lies in the systematic transformation of hazardous solid waste into high-value-added industrial raw materials through a series of precise physical and chemical processes, achieving an "alchemical" leap in value. This complete industrialized solution is technically rigorous and feasible, economically rewarding, and environmentally friendly and thorough, perfectly matching the dual demands of the Middle East for environmental protection and economic development.

2. Core Technology Platform: The Disruptive Advantages of the Intelligent Three-Ring Kiln

The fundamental reason why the Intelligent Three-Ring Kiln has become the preferred large-scale patented equipment for treating complex hazardous solid wastes

like secondary aluminum ash is its systematic subversion and innovation of traditional kilns in terms of design philosophy and technical implementation, overcoming a series of core pain points in the high-temperature activation and calcination of lump materials.

Disruptive Direct Firing of Lump Material and Precise Activation Technology: This kiln can directly calcine and activate pre-treated and pressed aluminum ash spheres of Φ30-50mm, simplifying the process flow. Its interior is innovatively designed with three major temperature zones: a **Preheating Zone** (400–600°C), a **Decomposition Zone** (650–850°C), and an **Activation Zone** (900–1100°C). The material moves slowly from top to bottom in the kiln, passing through different temperature zones in sequence, achieving gradient heating and precise activation, completely overcoming the industry problem of uneven heating caused by material tumbling in traditional rotary kilns. What is particularly crucial is the **24 to 36-hour "smoldering homogenization" slow cooling section** at the bottom of the kiln. In this stage, the lump material is kept at a high temperature for insulation, ensuring that the residual reactions inside the material can be fully completed. The final product's loss on ignition can be stably controlled below 1% (traditional processes are usually 3-8%), fundamentally solving the "under-burning" problem and ensuring the high quality and uniformity of the product.

Disruptive Energy Closed-Loop and Ultimate Energy Saving and Consumption Reduction: The core energy-saving mechanism of this technology lies in its unique **four-stage waste heat closed-loop circulation system**. The high-temperature flue gas (about 1200°C) generated from calcination is not directly discharged but is recycled as a heat source to preheat the new material entering the kiln; the cooled medium-temperature waste gas (about 600°C) is then sent to drive a waste heat boiler for power generation; finally, the low-temperature exhaust gas (about 250°C) can also be used for processes such as drying raw materials, with the final exhaust temperature being below 130°C. Through this cascade utilization, the comprehensive thermal efficiency of the kiln can be optimized to **over 85%** in this project plan. Compared with traditional kilns, it can

significantly reduce fuel costs by about **40%**, which means a lower carbon emission intensity per unit of product and is key to achieving low-carbon production.

Full-Process Intelligent Control and Unmanned Operation: The project is equipped with an advanced **AI digital twin control system** that can monitor key parameters such as temperature, pressure, and atmosphere inside the kiln in real time and make intelligent adjustments. The discharge link uses **infrared sensor robots** for adaptive unloading, achieving 24-hour unmanned stable operation. This not only greatly improves production efficiency (processing efficiency is **3–5 times** that of traditional kilns) but also eliminates dust spillage and potential safety risks from manual operations at the source.

3. Customized Process Solution: The Four-Step Closed-Loop Method for "Exhaustively Utilizing" Secondary Aluminum Ash

Targeting the complex component characteristics of high-fluorine secondary aluminum ash in the Middle East, this project adopts a new closed-loop process plan centered on "targeted impurity removal and precise separation." This plan aims to achieve efficient recovery and high-value utilization of all valuable components such as fluorine, aluminum, and sodium through four closely connected steps.

Step 1: Enhanced Pretreatment of Aluminum Ash by Briquetting

The goal of this step is to improve the reactivity of the aluminum ash and to make chemical preparations for the subsequent targeted defluorination in the kiln. An exclusive optimized formula of "secondary aluminum ash + calcium aluminate cement (as a binder) + aluminum sulfate (as a fluorine-fixing and activating agent)" is used for mixing and briquetting. The ingenuity of this formula lies in the addition of aluminum sulfate ($Al_2(SO_4)_3$). During the subsequent high-temperature calcination process, aluminum sulfate will decompose to produce highly active alumina (Al_2O_3). At the same time, it can react with fluorides such as sodium fluoride (NaF) in the aluminum ash, promoting the

temporary fixation of the fluorine element in the form of aluminum fluoride (AlF_3), which is more easily volatilized under specific conditions, laying the foundation for the targeted gasification and separation in the second step.

Step 2: Gradient Calcination and Activation in the Intelligent Three-Ring Kiln

The pre-treated aluminum ash spheres are sent to the Intelligent Three-Ring Kiln for gradient calcination under precisely controlled temperature and atmosphere to achieve targeted separation and activation of each component. Through gradient control of the **Dehydration Zone (300-600°C)**, **Targeted Defluorination Zone (900°C)**, and **Deep Crystallization Zone (1200°C)**, fluorine is precisely volatilized in the form of gaseous aluminum fluoride (AlF), achieving a defluorination rate of over 98%, and sodium is deeply removed to finally obtain a high-purity alumina-based clinker.

Step 3: Selective Leaching and Separation in a Sulfuric Acid System

A unique "controlled-acid leaching" method is used to leach the calcined clinker in dilute sulfuric acid with the pH strictly controlled at 1.5-2.0. Under this condition, the dissolution rate of the target product α-alumina (α-Al_2O_3) is extremely low (less than 3%), while impurities are effectively dissolved, thereby obtaining a high-purity α-alumina filter residue with a purity greater than 99.2% and a filtrate rich in valuable ions.

Step 4: Product Co-production and Purification System

High-Purity Cryolite Synthesis: The pH of the filtrate, rich in various ions, is adjusted to synthesize cryolite (Na_3AlF_6) with a purity of over 98%, which can be directly returned to the electrolytic aluminum process as a high-quality flux for recycling.

4N-Grade High-Purity Alumina Refining: The high-purity alumina filter residue is further purified to finally obtain an ultrafine high-purity alumina powder product with a purity of up to 99.99% (4N grade).

4. "Zero Waste Emission" Full-System Closed-Loop and Circular Economy Chain Construction

The advanced nature of this solution is not only reflected in its high-value product output but also in its thorough resource utilization of all materials throughout the production process, ultimately constructing a true "zero waste emission" closed-loop system.

Efficient Utilization of All Components: Through the above four-step method, the key valuable components in the aluminum ash are recovered to the greatest extent, with the conversion and utilization rates of fluorine (F), sodium (Na), aluminum (Al), and silicon (Si) reaching as high as 99.7%, 99.5%, 98.9%, and 100%, respectively.

Closed-Loop Utilization of Waste Gas: A small amount of combustible waste gas containing hydrogen, methane, etc., generated during the production process can be directly sent back to the kiln as supplementary fuel for combustion, achieving internal energy circulation. The most critical fluorine-containing calcination tail gas in the system will enter a specially equipped "Venturi scrubber + two-stage alkaline washing tower" high-efficiency purification system, with a removal rate of up to 99.9%. The absorbed liquid then enters the cryolite synthesis unit in the fourth step, achieving the "transformation of waste into treasure."

Closed-Loop Utilization of Wastewater: The wastewater generated during the production process is recycled within the system. After saturation, industrial-grade sodium sulfate and other by-products can be crystallized and sold, achieving zero discharge and resource utilization of wastewater.

Closed-Loop Utilization of Waste Slag: The small amount of inert vitreous slag remaining at the end can be used as high-quality building materials or road base materials, achieving self-consumption of all solid waste.

Through the above measures, the entire production process forms a complete circular economy industrial chain from the input of hazardous solid waste to the output of high-value products and commercialized by-products, perfectly interpreting the design concept of "exhaustive utilization."

5. Techno-Economic Analysis and Investment Value in the Middle East

This technical solution is not only disruptive at the level of low-carbon environmental protection and activation calcination technology, but its excellent economic benefits and strong investment return capabilities also make it extraordinarily attractive commercially.

5.1 Innovative "Triple Revenue" Business Model

The project breaks the profit model of traditional industrial projects that rely on single-product profits, building a more diversified and robust value creation system:

Diversified Product Sales Revenue: The main income of the project comes from the sales of two high-value-added products: 4N-grade high-purity alumina and high-purity cryolite. 4N high-purity alumina is an indispensable basic material for the electronics industry and a core raw material for manufacturing LED sapphire substrates, high-end lithium battery separators, specialty ceramics, and other cutting-edge fields, with strong market demand and extremely high value. Molten high-purity cryolite is the main flux in the production of electrolytic aluminum and can be recycled in the production of electrolytic aluminum, greatly reducing the production cost of electrolytic aluminum.

Hazardous Waste Disposal Revenue / Extremely Low Raw Material Cost: As a project for disposing of hazardous solid waste, the acquisition cost of its core raw material, secondary aluminum ash, is extremely low, and it may even receive a certain disposal fee for helping aluminum plants handle hazardous waste, which establishes the project's low-cost advantage from the source.

Potential Policy and Carbon Trading Revenue: This project falls into the category of comprehensive utilization of bulk hazardous solid waste, which is strongly encouraged by the state. In the Middle East, it also aligns with the strategic direction of green development and is expected to receive financial subsidies or tax incentives from the local government. More importantly, with the full implementation of the EU carbon tariff in 2026, the significant energy-saving and emission-reduction effects of this project (a 40% reduction in fuel costs) mean a lower carbon footprint. This can not only help associated aluminum products avoid high carbon taxes when exported, enhancing their international market competitiveness, but the carbon emission reductions generated may also yield considerable additional income in the global carbon trading market in the future, thus opening up a brand new channel for profit.

5.2 Excellent Profitability and Investment Returns

Thanks to extremely low raw material costs and the high efficiency and low energy consumption brought by disruptive technology, the project exhibits extraordinary profitability and strong cash flow generation capabilities. According to the financial evaluation of similar projects:

Gross Profit Margin: The project's gross profit margin is expected to be as high as **70% or more**. This extremely outstanding financial indicator fully demonstrates that the high-value product portfolio produced by this technical solution has strong market competitiveness and pricing power, and also provides a substantial "safety cushion" for the project to withstand market risks.

Static Investment Payback Period: The project's pure static investment payback period is much shorter than that of conventional industrial projects, expected to be completed in about **10 months**. This is an extremely short payback period, fully reflecting the project's strong cash flow generation capability and excellent investment efficiency, which means the investment risk is extremely low.

6. Conclusion: A Benchmark Solution Tailor-Made for the Middle East

The intelligent three-ring kiln activation calcination technology and its supporting "four-step closed-loop" high-value process for secondary aluminum ash have successfully transformed the environmentally hazardous high-fluorine aluminum ash faced by the Middle East into urgently needed high-value-added strategic industrial raw materials through a complete closed-loop system that is technically rigorous and economically rewarding.

This solution fully considers the special needs of the Middle East for high-temperature resistance, water conservation, and dust control, and has made localized consumption designs in the final product planning, such as directly supplying the recovered cryolite to local electrolytic aluminum plants. It transforms the harmful fluorine element into a stable and usable valuable resource in the form of high-purity cryolite through the path of "targeted gasification + efficient capture and recovery," fundamentally solving the risk of secondary pollution.

In the face of the wave of global low-carbon economic transformation and the challenges of new international trade regulations such as the EU carbon tariff, the strategic significance of this solution is particularly prominent. It is not only an environmental protection solution for treating industrial solid waste but also a low-carbon development solution that enhances the overall competitiveness of the industrial chain. By greatly reducing energy consumption and achieving closed-loop resource utilization, it effectively reduces the carbon footprint of the entire aluminum industry chain, providing key technical support for Middle Eastern aluminum products to maintain a competitive advantage in the future international market.

In summary, this solution not only provides a "Chinese solution" for the global high-temperature calcination industry that is both economically excellent, environmentally friendly, and strategic, but it is also a benchmark solution tailor-made for the disposal of high-fluorine aluminum ash in the Middle East, with high technical barriers, a fast

investment return, and a perfect fit with the local low-carbon green development strategy. It is a high-quality industrial project with high investment value and huge commercial potential.