

Thermal Fractional Ore Processing System

Terrestrial Application — Detailed System Description

Executive Summary

The Thermal Fractional Ore Processing System (TFOPS) is a zero-waste ore processing architecture that replaces conventional single-target extraction with staged thermal separation, capturing every mineralogical fraction as a characterized, marketable product. The system eliminates the two largest cost and liability centers of conventional mining: energy-intensive comminution and long-term tailings management. Every output — from primary refined metal to residue stone blocks — carries embedded provenance data and has a defined market. True waste approaches zero.

Stage 1 — Feed Preparation

Ore is crushed only to the coarse size required to feed the thermal train — not to mineral liberation size as required by conventional flotation. This single change eliminates the majority of conventional processing energy. A coarse crush sufficient to feed the apparatus requires a fraction of the energy consumed by the ball mills, SAG mills, and multi-stage crushing circuits of a conventional plant.

LIBS (Laser-Induced Breakdown Spectroscopy) sensors characterize incoming feed material in real time, providing elemental composition data that initializes bay temperature calibration before material enters the system. The ore body is continuously mapped as it is processed, generating geological data as a byproduct of production.

Stage 2 — Thermal Cascade

Sequential thermal bays, each sealed and independently managed, step through the melting thresholds of the ore body's mineral inventory. Material enters bay one already characterized. It is never returned to ambient temperature between stages — sensible heat is paid once at bay one and only the delta temperature is added at each subsequent bay. This cascading thermal efficiency is the system's primary energy advantage.

Representative Bay Sequence

- Bay 1 — ~840°C: Calcite decomposition. CO captured for downstream reduction chemistry. Calcium oxide (CaO) collected as flux feedstock for viscosity management in later bays.
- Bay 2 — ~1,100°C: Low-end feldspar and silicate fractions begin melting and draining.
- Bay 3 — ~1,500°C: Remaining feldspar and mid-range silicate fractions collected.
- Bay 4 — ~1,650°C: Quartz and high silicate fractions melt and drain.
- Bay 5 — Reducing atmosphere: Iron reduction and collection. CO from Bay 1 serves as reducing agent feedstock.
- Additional bays configured per ore body geology as indicated by geological survey and LIBS characterization.

Each bay operates as a sealed vessel with its own off-gas capture line feeding a central gas processing system. Drain geometry is engineered per bay for passive gravity-driven melt flow. CaO flux from bay one is fed forward to manage silicate melt viscosity passively, eliminating the need for external reagents.

Stage 3 — Per-Bay Separation Modules

Each bay contains a separation module selected at installation based on geological survey data and the expected melt density profiles for that bay's temperature range. The module

interface is standardized — the thermal infrastructure, LIBS monitoring, and plumbing connections are identical at every bay. Only the separation mechanism changes.

Module selection follows a strict hierarchy that minimizes external inputs:

- Passive density stratification — quiescent melt pool, drain from top and bottom, mechanically simplest
- Magnetically suspended centrifuge vessel — for streams where density differences require enhancement
- Electromagnetic separation — for magnetically responsive fractions
- Electrolytic cell — for conductive metal fractions, no external reagents, electrode products are the separated materials
- Vacuum distillation module — optional, early-stage, for ore bodies containing volatile metals
- Dedicated reactive stage — isolated from main train, only where no other method works, only where reactant is itself a recovered product

Vacuum Distillation Module — Optional Early-Stage

For ore bodies containing economically significant concentrations of volatile metals — zinc, lead, cadmium, arsenic, antimony, mercury — a vacuum distillation module may be inserted between bay one and bay two. This is the optimal placement because volatile metals mobilize at relatively low temperatures and are the first fractions to become available in the thermal cascade. Capturing them before the silicate melt stages begin prevents contamination of downstream product streams and improves overall purity throughout the train.

The module operates as a sealed chamber receiving partially heated material from bay one, already at $\sim 840^{\circ}\text{C}$. A vacuum pump reduces internal pressure to the point where target volatile metals evaporate freely at the existing material

temperature — well below their atmospheric boiling points. Evaporated material travels in straight lines to cooled condenser surfaces positioned downstream within the chamber. Multiple condenser surfaces at staged temperatures collect different vapor pressure fractions sequentially, each acting as a collection plate for a specific volatile element.

Vacuum Distillation Target Metals

- Zinc — boils at 907°C at atmospheric pressure, evaporates at substantially lower temperatures in vacuum. Conventional zinc smelting is energy intensive precisely because it works against atmospheric pressure. Vacuum zinc distillation is established industrial practice.
- Lead — low vapor pressure enables vacuum separation well below its 1,749°C atmospheric boiling point.
- Cadmium, arsenic, antimony, mercury — all have usable vapor pressures at temperatures already present in the bay one residue stream.

Trigger condition: geological survey showing volatile metal concentrations exceeding the economic recovery threshold for the specific ore body. If not present in sufficient concentration, the bay interface accepts an alternative module without modification.

The vacuum pump infrastructure integrates naturally with the existing off-gas capture architecture. The bays are already sealed vessels with managed atmospheres and gas handling lines. Adding vacuum capability to a bay that is already sealed and gas-managed is a smaller engineering step than it would be in a conventional open processing system. Condenser surfaces, once loaded, are removed and replaced as a maintenance operation, with collected material cast into standard stamped output forms.

The energy cost of pulling and maintaining vacuum on a single sealed bay is modest relative to the value of volatile metal fractions recovered and the downstream purity improvement across the full train. The decision to include this module is

made at installation based on geological survey data and is not revisable during operations — it is a design-time choice, not a runtime one.

Centrifuge Vessel Design

The centrifuge vessel is the system's most sophisticated module. It is magnetically suspended, eliminating mechanical bearing contact, lubrication requirements, and heat-related bearing degradation. Resistive or inductive heating elements embedded in the vessel walls maintain melt temperature throughout the spin cycle. Power and data are transmitted via radial slip ring using carbon-graphite brushes rated for the operating environment.

Feed and drain connections use an overlapping pipe geometry — mechanically disconnected during spin but thermally proximate, maintaining melt temperature by radiation during the separation cycle. Multiple drain points at different vertical positions correspond to density bands: densest fraction at the bottom drain, lightest at the top. The vessel operates in batch cycles: receive charge, seal, spin, stratify, drain layers sequentially, repeat.

Where LIBS analysis of incoming ore confirms that density separation will not cleanly resolve a given mineral pair — determined in advance from geological survey data — the centrifuge module is replaced with an alternative apparatus suited to that ore body without modifying the surrounding bay infrastructure.

Stage 4 — Process Control

LIBS sensors are positioned at every bay drain point, providing real-time elemental composition of each output stream. Automated valves at each drain point route material to either the primary product mold or a catch basin based on LIBS readings. Bay temperatures are adjusted dynamically in response to composition feedback, continuously chasing the purity threshold.

When LIBS identifies co-draining minerals forming a eutectic composition suited to glass or ceramic production, that stream is routed to a dedicated eutectic collection rather than treated as contamination. When LIBS identifies a mixed melt that resists separation, it is routed to a catch basin for later reprocessing or downgrade sale. The system manages its own exceptions without stopping.

All readings, valve positions, temperature adjustments, and routing decisions are logged continuously with timestamps, building a complete operational data record from first pour.

Stage 5 — Off-Gas Recovery

Each bay operates under independent atmospheric management. Off-gas from each bay is captured in a dedicated line feeding a central gas processing system, preventing cross-contamination between oxidizing and reducing zones. Gas streams are separated chemically downstream.

- Sulfur dioxide from sulfide minerals — converted to sulfuric acid via contact process, sold as industrial chemical
- CO from bay one calcite decomposition — fed to iron reduction bay as reducing chemistry feedstock, closing the loop
- Arsenic trioxide, mercury vapor, fluorine compounds — captured and processed or safely contained per regulatory requirements

The atmosphere composition within each bay can be tuned to the ore body — inert blanket to prevent oxidation of product streams, reducing conditions throughout the train for high-oxide ore bodies, or oxidizing conditions to convert sulfide minerals cleanly before they reach downstream bays.

Stage 6 — Output Casting and Provenance Stamping

Every drain point feeds either a primary product mold or a catch basin mold. Both are engineered for the specific product form — ingot geometry for metals, tile or block for silicates, standard industrial forms for chemical feedstocks. Catch basin molds use standard geometry: uniform, stackable, shippable by standard freight without specialized handling.

At the appropriate point in the cooling curve — still impressionable but dimensionally stable — a stamp or die presses identifying information into the surface of every output unit. This includes a human-readable alphanumeric identifier and a machine-readable data matrix, both linking to the complete LIBS data record for that pour: elemental composition, bay of origin, temperature at drain, timestamp, pass number, and reroute reason if applicable.

The information is physically part of the material. It cannot fall off, be misapplied, or be separated from the unit during outdoor storage, rough handling, or shipping. Every party downstream has complete provenance data before the material arrives.

Stage 7 — Thermal Shock and Second Pass

Residue from the main train that did not melt at any stage is passed into a water quench pool. Cold water contact produces rapid thermal shock — differential expansion and contraction stresses crack grain boundaries preferentially along mineral interfaces, liberating associations that survived the first pass. The thermally stressed material emerges smaller, better liberated, and more receptive to the second pass.

The water system is fully closed. Steam generated by the quench is captured, passed through a small turbine generating electricity before condensing, and returned to the pool by gravity. Evaporative losses are minimal. No continuous water input is required in steady state beyond initial fill and minor top-off. No pumps are needed for water return — the

condensate collection point is positioned above the quench pool elevation by design.

Water Quality Monitoring

A LIBS sensor pointed at the steam capture area provides continuous water composition monitoring. Periodic batch boiling of a water sample concentrates any trace dissolved material, and LIBS analysis of the evaporite residue provides enhanced-sensitivity confirmatory testing. Simple mechanical filtration — settling clarifier plus media filter — removes suspended particulate. Filter solids are characterized by LIBS and returned to second-pass feed if valuable. The permit application for this water system is supported by a complete automated data record from day one of operations.

Thermally shocked material is fed back into bay one of a second pass. Only the high-temperature bays relevant to the remaining composition are run — not the full train. LIBS data from the first pass initializes second-pass calibration. The same separation module logic applies. Outputs are cast and stamped identically to first-pass material.

Stage 8 — Refractory Concentrate

What remains after the second pass and recovery loop is dominated by the highest melting point minerals in the ore body — chromite (~2,180°C), zirconia (~2,715°C), alumina (~2,072°C), tungsten compounds. These materials are high-value refractory and technical ceramics that command serious prices precisely because they are difficult to process.

The system has concentrated this fraction from the original ore mass without requiring specialist high-temperature infrastructure on site. This pre-processed concentrate is cast into standard transportable forms, stamped with full composition data, and transferred offsite to specialist processing facilities. The processing work already done on site is priced into the transfer accordingly.

Stage 9 — Residue Stone

True residue after all recovery stages is poured into molds as a homogeneous melt. The resulting blocks have no internal fractures — they cooled from liquid with no geological stress history. They have no inclusions — composition is uniform throughout the pour. Mechanical properties are predictable and consistent batch to batch from the LIBS composition record. This represents a quality advantage over quarried natural stone, which carries unknown internal fracture networks and variable composition even within a single block.

Optional mineral colorants introduced to the mold feed before pour distribute uniformly throughout the block. Iron oxides produce reds, yellows, and browns. Chromium compounds produce greens. Cobalt produces deep blue. Manganese produces purples and blacks. Copper compounds produce blue-greens. Color survives cutting, chipping, and weathering because it is distributed through the full thickness of the block, not applied to the surface.

If residue composition after the second pass is dominated by high melting point minerals, the resulting block is a functional refractory brick — a material with significant industrial demand that sells for substantially more than landscaping stone. The same pour, the same mold, the same stamp — different market destination based on the LIBS data record.

Operational Models

Dedicated Site Installation

Built and tuned for one specific ore body based on pre-construction geological survey. Modules are fixed at installation. LIBS handles variability within that ore body dynamically, adjusting bay temperatures and routing decisions in real time. The variability envelope is known and bounded from the survey, making operations simpler and more predictable.

Central Processing Facility

Receives ore from multiple customers. Full modular capability — physical bay module swaps between customer runs. Retunes thermally and atmospherically between runs based on incoming feed characterization. Operates as a processing-as-a-service business, serving ore bodies that individually cannot justify dedicated installation capital.

Inventory and Storage

Every output from the system is solid, stable, non-reactive, and homogeneous. Blocks and ingots can be stacked on a flat pad without engineered containment, liner systems, or monitoring infrastructure. Inventory can be built during low demand periods and sold into high demand periods without degradation. The LIBS data embedded in every unit makes inventory searchable by composition without physical re-sampling — the operator knows exactly what is in storage from the production record.

If specific output streams have no immediate local market, they are simply stacked. No disposal problem, no containment cost, no environmental liability. The lowest-value output — residue stone — has a construction aggregate and landscaping market that absorbs essentially unlimited volume at low transport distances.

Site Closure and Post-Mining

Residue blocks used for void backfill are non-reactive, geometrically uniform, structurally competent, and fully characterized. They are better engineered backfill than the conventional waste rock currently used deliberately for this purpose. The volume returned to the ground is less than the volume excavated by exactly the mass sold into product markets — a mass conservation fact, not a system failure.

Toward the end of mine life, custom structural molds produce columns, arches, wall panels, and ceiling support elements

from the residue stream. These are used to engineer excavated voids into usable subsurface space rather than filling them. The complete geological survey accumulated during operations provides every dimension and structural characteristic needed for void engineering design.

Resulting subsurface spaces have natural temperature stability, physical security, and isolation from surface events that make them attractive for data centers, cold storage, controlled environment agriculture, secure document storage, and research facilities requiring isolation from surface vibration or radiation. Signed lease or purchase agreements can be pursued before the last ore is pulled, given the multi-year advance visibility of mine section end-of-life.

Mine Lifecycle Economic Model Comparison

Conventional: Exploration (cost) → Development (cost) → Operations (revenue) → Closure (cost) → Post-closure (liability)

TFOPS: Exploration (cost) → Development (cost) → Operations (multiple revenue streams) → Closure (revenue event) → Post-closure (potential ongoing lease revenue)

Environmental Profile

The regulatory and environmental compliance burden of TFOPS is structurally different from conventional processing. There is no tailings pond, no acid mine drainage potential, no flotation reagent atmospheric emissions, and no perpetual care obligation. The water system is closed loop. Off-gas is fully captured per bay. Residue blocks are non-reactive and require no containment beyond a flat storage pad.

Even the operator who extracts only primary metal and makes no effort to sell secondary product streams still operates a system with no tailings liability, no reactive waste, and no acid

drainage risk. The environmental floor of the TFOPS operating case is above the environmental ceiling of responsible conventional practice in these dimensions. The system does not require sophisticated operation to deliver environmental improvement — it delivers it structurally.