

Industrial Extraction and Purification of Sodium Chloride: A Comprehensive Analysis of Brine Processing and Crystallization Technologies

Introduction

Sodium chloride (NaCl) represents a foundational pillar of the global inorganic chemical industry. While universally recognized as an essential dietary mineral, its primary industrial utility lies as a highly purified feedstock for the chlor-alkali sector. Through the electrolysis of saturated sodium chloride brines, industrial facilities generate chlorine gas, sodium hydroxide (caustic soda), and hydrogen—precursors to thousands of downstream chemical syntheses ranging from polyvinyl chloride to advanced pharmaceuticals. Beyond electrolysis, sodium chloride is vital for water softening, de-icing operations, and the production of sodium sulfate and hydrochloric acid via secondary reactions¹.

The isolation of high-purity sodium chloride is a complex chemical engineering challenge due to the multicomponent nature of its source materials. Extracted from the solar evaporation of seawater, the processing of subterranean brine springs, or the mining of ancient geological halite deposits, the raw brine invariably contains high concentrations of competing alkaline earth metals, sulfates, and trace halogens. Consequently, modern industrial salt production demands a rigorous integration of fractional crystallization, advanced electromembrane pre-concentration, sophisticated thermodynamic modeling, and high-performance metallurgy. This report exhaustively documents the mechanisms, risks, and innovations defining the contemporary extraction and purification of sodium chloride.

Primary Extraction Methodologies

Solar Evaporation of Seawater and Surface Brines

The solar evaporation of seawater and hypersaline surface brines represents the oldest and most energy-efficient method of salt production. By leveraging solar insolation and prevailing winds, immense volumes of water are vaporized, progressively driving the brine toward supersaturation. Standard seawater contains approximately 3.5% dissolved solids (35 g/L), representing a complex matrix containing over 70 elements in dissolved states².

The progression of brine concentration in a solar saltworks is historically and practically

monitored using the Baumé scale ($^{\circ}\text{Bé}$), an empirical hydrometer scale developed by the French pharmacist Antoine Baumé in 1768⁴. The Baumé scale comprises two distinct, non-overlapping formulas depending on whether the fluid is lighter or heavier than water⁶. For

brines, which are heavier than water, 0°Bé corresponds to pure water, while 15°Bé

originally corresponded to a 15% NaCl solution by mass⁵. The relationship between specific gravity (SG) at 60 °F (15.5 °C) and degrees Baumé for dense liquids is expressed as:

$$SG = \frac{145}{145 - ^\circ \text{Bé}}$$

The evaporation sequence unfolds across distinct thermodynamic stages in a series of shallow, interconnected ponds designed to achieve sequential fractional crystallization⁸:

1. **Carbonate Stage:** In the initial "cold ponds," seawater concentrates from approximately 3.5 °Bé to 12 °Bé (salinity of 35‰ to 140–200‰)⁴. The least soluble compounds, primarily calcium carbonate (CaCO_3) and iron oxides, precipitate out of solution⁴.
2. **Sulfate Stage:** As density increases from 12 °Bé to 25 °Bé (salinity > 200‰), calcium sulfate precipitates as gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$). Initially forming fine grains, the gypsum crystals progressively coarsen into larger "selenite" structures exceeding 2 mm in size⁴. Removing gypsum before the brine enters the main crystallizers is critical to ensuring halite purity⁴.
3. **Halite Stage:** Between 25 °Bé and 29.5 °Bé (salinity 290–325‰), the brine reaches the stability field of sodium chloride, which crystallizes as halite. Harvesting within this narrow density window maximizes NaCl yield while preventing the co-precipitation of highly soluble magnesium and potassium salts⁴.
4. **Bitterns Stage:** The residual liquor, known as "bittern," exceeds 29.5 °Bé and is highly enriched in magnesium, potassium, sulfate, and bromide ions¹². If evaporation continues to the eutonic point, complex evaporite minerals such as epsomite ($\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$), carnallite ($\text{KMgCl}_3 \cdot 6\text{H}_2\text{O}$), and bischofite ($\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$) precipitate⁴.

Optimizing yield requires not only physical chemistry but also biological management. The presence of halophilic organisms, particularly the brine shrimp *Artemia*, plays a critical role in solar salt ponds⁸. *Artemia* graze on microscopic algae, preventing massive algal blooms that would otherwise increase brine viscosity, inhibit evaporation, and embed organic impurities into the halite crystal lattice⁸.

Evaporation Stage	Density Range (°Bé)	Approximate Salinity (‰)	Primary Precipitate	Chemical Formula
Carbonate	3.5 – 12.0	35 – 140	Calcite /	CaCO_3

			Aragonite	
Sulfate	12.0 – 25.0	140 – 290	Gypsum	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$
Halite	25.0 – 29.5	290 – 325	Halite (Sodium Chloride)	NaCl
Bitterns	> 29.5	> 325	Epsomite, Carnallite, Bischofite	MgSO_4 , KMgCl_3 , MgCl_2 salts

Solution Mining of Underground Halite Deposits

Where geological conditions permit, subterranean halite deposits—such as salt domes or bedded salt formations—are exploited via solution mining. This process involves drilling boreholes into the evaporite deposit and injecting fresh water or unsaturated brine to dissolve the halite in situ, forming a subterranean cavern¹³. The resulting fully saturated brine is subsequently pumped to the surface for purification and thermal crystallization.

Solution mining heavily relies on the fluid dynamics of double-well convection or single-well injection/extraction mechanisms¹⁵. To control the dissolution geometry and prevent excessive, uncontrolled leaching of the cavern roof, a "blanket pad" of lighter, immiscible fluid—such as diesel oil or nitrogen gas—is injected at the cavern apex¹⁶. The dissolution kinetics are influenced by the salt boundary layer, concentration gradients, and the flow field established by the injection pressure¹³.

Geomechanical Risks and Subsidence

The creation of large, unsupported underground cavities introduces severe geomechanical risks. Salt caverns exist in a state of stress where the internal hydrostatic pressure of the brine is generally lower than the surrounding geostatic rock pressure¹⁵. This differential induces continuous, time-dependent visco-plastic deformation, known as creep, in the surrounding rock salt. Elevated temperatures at depth can induce strain softening, which decreases the deformation modulus and accelerates primary creep and fatigue deformation¹⁵.

If the cavern span becomes excessive, or if the roof strata are insufficiently competent, catastrophic geomechanical failure can occur. Failure modes include progressive subsidence—where the surface slowly deforms—or sudden sinkhole collapse, threatening operational sustainability and public safety¹⁴.

Historical incidents underscore the criticality of rigorous geological characterization. A notable failure occurred at Lake Peigneur, Louisiana, in November 1980. A Texaco oil drilling rig, misplaced by approximately 400 feet, inadvertently breached the 14-inch roof of the active

Diamond Crystal Salt Mine located directly beneath the shallow freshwater lake¹⁷. The influx of unsaturated lake water into the mine rapidly accelerated dissolution, triggering a massive vortex a quarter-mile wide¹⁹. This vortex drained 3.5 billion gallons of water, reversed the flow of the Delcambre Canal to pull in saltwater from the Gulf of Mexico, and devoured the drilling platform, eleven barges, and 58 acres of botanical gardens, permanently transforming the freshwater lake into a deep saltwater crater¹⁷.

Similar mechanisms drove the 2012 Bayou Corne sinkhole in Louisiana, resulting from the collapse of a poorly designed solution mining cavern that led to uncontrolled brine and hydrocarbon migration¹⁴. In 2006, excessive mining well density and prolonged extraction at the Dingyuan Salt Mine in Anhui, China, triggered massive surface subsidence¹⁵. To mitigate these risks, modern operations utilize 3D sonar cavern profiling, microseismic monitoring, and dynamic backfilling with alkaline slag or other inert materials to provide structural support and limit creep shrinkage¹³.

Conventional Room and Pillar Mining

In shallower bedded salt formations, conventional dry mining is employed using the room and pillar method. This involves extracting salt in a grid pattern, leaving solid pillars of halite to support the overburden. The stability of the exploitation system is evaluated using analytical geomechanical methods to determine the optimal extraction ratio, ensuring that the stress concentrated on the pillars does not exceed the compressive strength of the rock salt²⁰. Roof bolting is frequently utilized to reinforce the strata spanning the rooms, preventing localized roof falls and ensuring long-term mine stability²⁰.

Electromembrane Pre-Concentration and ZLD Systems

Advancements in electromembrane technologies have introduced novel methodologies for brine pre-concentration, particularly crucial for industrial Zero Liquid Discharge (ZLD) systems and the valorization of seawater reverse osmosis (SWRO) reject streams.

Electrodialysis (ED) and Electrodialysis Reversal (EDR)

Electrodialysis utilizes an applied direct current to drive ions through alternating cation- and anion-exchange membranes²¹. Electrodialysis Reversal (EDR) represents a significant operational improvement by periodically reversing the electrical polarity and hydraulic flow²¹. This reversal effectively dissolves incipient scale formation (such as calcium carbonate or calcium sulfate) and minimizes organic fouling without the need for intensive chemical dosing²¹. Unlike conventional Reverse Osmosis (RO), which relies on hydraulic pressure and is severely limited by osmotic pressure ceilings—typically capping at 80,000 to 130,000 mg/L total dissolved solids (TDS)—EDR is decoupled from osmotic limitations²². By applying voltage rather than pressure, EDR systems can concentrate brines up to 180,000 to 300,000 mg/L TDS²¹. Innovative systems coupling Closed-Circuit Reverse Osmosis (CCRO) with EDR can further optimize the pre-concentration phase, reducing the volume and mass load on energy-intensive downstream thermal evaporators by up to 6.5 times²².

Monovalent-Selective Ion-Exchange Membranes

To obtain a high-purity sodium chloride feedstock directly from complex brines, selective electrodialysis (S-ED) is employed using monovalent-selective anion and cation exchange membranes (MSAEMs)²⁴. These specialized membranes rely on steric hindrance and specific charge-density engineering to preferentially transport monovalent ions (Na^+ , Cl^-) while rejecting multivalent ions (Ca^{2+} , Mg^{2+} , SO_4^{2-})²⁵.

This technology effectively separates sodium chloride from competing sulfate and hardness ions, generating a purified concentrate²⁵. However, operational parameters must be strictly controlled to prevent "uphill transport," a phenomenon where multivalent ions are dragged against their concentration gradients due to the overwhelming flux of monovalent ions across the membrane²⁶. The permselectivity of these membranes decreases at excessively high current densities; for instance, laboratory scale studies indicate that limiting currents (e.g., 0.89 A) must be respected to prevent severe concentration polarization and loss of separation efficiency²³.

Reverse Electrodialysis (RED) and Bipolar Membranes (EDBM)

The salinity gradient between concentrated brines and fresh water represents a massive reservoir of renewable energy. Reverse Electrodialysis (RED) captures this energy by placing alternating ion-exchange membranes between high-salinity feeds and low-salinity feeds²⁶. The spontaneous diffusion of ions across the membranes generates an open-circuit voltage (OCV). The presence of multivalent ions significantly reduces the achievable power density in RED systems due to increased membrane resistance and uphill transport effects, further underscoring the necessity of monovalent-selective membranes in these advanced energy recovery systems²⁶.

Furthermore, concentrated brines can be upgraded using Bipolar Membrane Electrodialysis (EDBM). Bipolar membranes force the dissociation of water into H^+ and OH^- ions at rates millions of times faster than spontaneous aqueous dissociation²⁹. When integrated with standard ED, EDBM converts the sodium chloride brine directly into highly valuable hydrochloric acid (HCl) and sodium hydroxide (NaOH) up to 2 M concentrations, representing the ultimate valorization of waste brine streams²⁵.

Brine Purification Strategies

Raw brines extracted via solution mining or solar evaporation are inherently contaminated with alkaline earth metals (calcium and magnesium), sulfates, and trace heavy metals. For the production of technical and food-grade salt, and particularly for feedstock destined for chlor-alkali electrolysis, comprehensive chemical purification is mandatory.

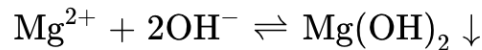
The chlor-alkali industry relies predominantly on membrane cell electrolysis, an advanced technology that is extraordinarily sensitive to brine impurities. Divalent cations such as calcium and magnesium can precipitate as hydroxides inside the perfluorinated ion-exchange membranes, causing irreversible mechanical damage, increased cell voltage, and a

catastrophic drop in current efficiency². Consequently, the brine must undergo multi-stage purification.

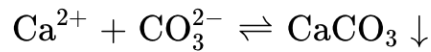
Primary Purification: The Lime-Soda Process

The foundational step in brine treatment is primary purification, universally executed via a modified lime-soda precipitation process³². The sequential addition of alkaline reagents forces the precipitation of interfering ions.

1. **Magnesium Removal:** Milk of lime, $\text{Ca}(\text{OH})_2$, or sodium hydroxide, NaOH , is introduced to raise the pH and precipitate magnesium ions as magnesium hydroxide, a highly insoluble, flocculant solid³².



2. **Calcium Removal:** Sodium carbonate (soda ash, Na_2CO_3) is subsequently added to precipitate the naturally occurring calcium, as well as the excess calcium introduced during the first step, as calcium carbonate³².



3. **Co-precipitation and Flocculation:** Trace metals (e.g., iron, aluminum, nickel) co-precipitate as hydroxides. The magnesium hydroxide flakes incorporate the finer calcium carbonate crystals, aiding in overall sedimentation³⁶.

The thermodynamics of these deposition reactions are highly pH-dependent. Operating at an elevated pH (e.g., 11.6) enhances precipitation kinetics, achieving removal efficiencies of 98.5% for calcium and 99.6% for magnesium³⁵. The efficiency of this process is continuously monitored using analytical techniques such as EDTA (ethylenediaminetetraacetic acid) titration with Cal Red indicators and triethanolamine (TEA) masking agents to precisely determine residual alkaline earth concentrations³².

The resulting brine mud (sludge) is separated via clarifiers³⁷. To manage the Sludge Volume Index (SVI), coagulants are often utilized³⁶. Effective thickeners and decanters can reduce the waste volume by up to 89-90%, ultimately producing a solid filter cake suitable for environmentally safe disposal or secondary byproduct recovery, drastically lowering haulage costs³.

Desulfation via Nanofiltration

Sulfate ions (SO_4^{2-}) accumulate in closed-loop brine circuits, severely depressing anodic current efficiency in chlor-alkali cells and accelerating anode coating wear⁴⁰. Historically, sulfate was removed by precipitation with toxic barium salts (forming insoluble BaSO_4) or by the

addition of calcium chloride to precipitate gypsum¹¹.

Modern facilities increasingly rely on nanofiltration (NF) for desulfation. NF membranes operate based on steric hindrance and the Donnan exclusion effect, exhibiting a high rejection rate for divalent sulfate ions ($\geq 95\%$) while allowing the passage of monovalent sodium and chloride ions⁴⁰.

The implementation of NF depends heavily on the specific brine stream being treated:

- **Primary Brine (~300 g/L NaCl):** Serves as a guard duty before electrolysis. The high osmotic pressure demands robust membranes to maintain sulfate rejection at saturation⁴⁰.
- **Dilute Brine (~200 g/L NaCl):** The return stream after electrolysis is the primary point for desulfation. This stream operates at ~80 °C with free chlorine and high pH (9–11). Pretreatment is critical here: the brine must be dechlorinated with sodium sulfite, cooled to ≤ 40 °C, and pH-adjusted (5.5–7.5) to protect the NF polyamide membrane layer from oxidative and thermal degradation⁴⁰.
- **Saturated Brine (~310 g/L NaCl):** Requires the highest pressure ratings and often side-stream dilution to prevent severe hardness scaling on the membrane⁴⁰.

The sulfate-rich NF reject stream can subsequently undergo fractional freezing to recover sodium sulfate (Glauber's salt)³⁵.

Secondary Purification: Chelating Ion Exchange

To achieve the stringent purity requirements of membrane cell electrolyzers, the clarified primary brine is subjected to secondary purification using chelating ion-exchange resins³⁰. These macroporous resins, functionalized with iminodiacetic acid or aminophosphonic acid groups, exhibit exceptionally high selectivity for alkaline earth metals over sodium⁴².

The brine percolates through fixed-bed columns where residual Ca^{2+} and Mg^{2+} are exchanged for Na^+ , driving their concentrations down to less than 20 parts per billion (ppb)³⁰. Because chelating resins are highly susceptible to oxidative degradation, the feed brine must be thoroughly dechlorinated. This is achieved via dosing with sodium sulfite or passing the brine through activated carbon beds, which effectively adsorb and reduce damaging chlorates and free chlorine before they enter the ion-exchange unit³⁸.

Solvent Extraction for Trace Element Recovery

In instances where the brine or subsequent biterns contain valuable trace metals or highly specific impurities, solvent extraction (liquid-liquid extraction) is employed. This process contacts the aqueous brine with an immiscible organic phase containing specialized extractants. Extractants such as Aliquat 336 (a quaternary amine salt) and acidic organophosphorus compounds like D2EHPA or Cyanex 272 demonstrate high affinities for transition metals and other trace elements³⁵.

The efficacy and safety of solvent extraction heavily depend on the selection of the organic diluent. While highly aromatic diluents were historically used, modern operations favor safer, high-flash-point aliphatic or less volatile aromatic diluents, such as 1,4-di-tert-pentylbenzene or

p-Cymene, which provide excellent phase disengagement and reduce the risk of fire or toxic vapor emissions during continuous operation⁴⁵.

Extractant	Example Diluents	Target Metals	Mechanism
Aliquat 336	1,4-di-tert-pentylbenzene, p-Cymene	Al, Cd, Co, Cu, Zn	Anion exchange (chloride complexes)
Cyanex 272	HVO100, TBB	Co, Zn, Mn, Rare Earths	Cation exchange (phosphinic acid)
D2EHPA	HVO100, 1-methyl-4-(tert-pentyl)benzene	Al, Cd, Ni, Zn	Cation exchange (phosphoric acid)

Thermodynamic Modeling of Hypersaline Systems

The design of the evaporation sequence, the optimization of desulfation parameters, and the prediction of scale formation are fundamentally reliant on precise thermodynamic modeling. Standard thermodynamic models (e.g., Debye-Hückel theory or Davies equations), which assume dilute conditions where ion-ion interactions are negligible, fail catastrophically in

hypersaline environments. In crystallizing brines (ionic strength $I > 5$ mol/kg), electrostatic interactions, short-range forces, and complex ion pairing heavily depress the activity of water and the activity coefficients of dissolved salts⁴⁶.

The Pitzer Model and Activity Coefficients

To accurately predict phase equilibria and saturation states in these extreme environments, chemical engineers rely on the semi-empirical equations developed by Kenneth Pitzer⁴⁶. The

Pitzer model calculates the mean ionic activity coefficient ($\gamma_{\pm}$) using a virial expansion approach that accounts for binary (ion-ion) and ternary (ion-ion-ion) specific interactions⁴⁷.

The excess Gibbs free energy of the solution is defined by a long-range Debye-Hückel term (accounting for electrostatic shielding) combined with short-range interaction

parameters—specifically $\beta^{(0)}$, $\beta^{(1)}$, and C^{ϕ} —which must be empirically fitted for specific ion combinations at given temperatures⁴⁶. Without these empirically derived parameters, thermodynamic models become unstable beyond 0.1 M concentrations⁴⁷.

By inputting brine composition into geochemical codes utilizing Pitzer databases (such as PHREEQC), engineers calculate the Saturation Index (SI) of potential mineral phases:

$$SI = \log \left(\frac{IAP}{K_{sp}} \right)$$

where IAP is the Ion Activity Product and K_{sp} is the thermodynamic solubility product constant⁴⁶. If $SI > 0$, the brine is supersaturated, and crystallization will proceed⁵⁰.

Phase Equilibria and Saturation Indices

This thermodynamic modeling is critical for managing the multicomponent quaternary system ($\text{Na}^+, \text{Mg}^{2+}, \text{Ca}^{2+} // \text{Cl}^- - \text{H}_2\text{O}$). Studies utilizing the Pitzer model and Jänecke quinary diagrams demonstrate that phase boundaries shift dramatically with temperature⁴⁸. For instance, at 348.2 K and 363.2 K, the crystallization regions correspond to single salts (NaCl , $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$, $\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$) and the double salt $2\text{MgCl}_2 \cdot \text{CaCl}_2 \cdot 12\text{H}_2\text{O}$ ⁵². As the temperature increases to 383.2 K, the regions of NaCl and $\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$ contract, and a new double salt, $2\text{CaCl}_2 \cdot \text{MgCl}_2 \cdot 6\text{H}_2\text{O}$, forms⁵². These predictive models dictate the precise temperature and density setpoints required to isolate high-purity halite while avoiding the co-precipitation of these highly complex, contaminating double salts⁵³.

Evaporative Crystallization Technologies

Once purified, the brine is subjected to evaporative crystallization to recover solid sodium chloride. Unlike solar evaporation, which is reliant on environmental variables, industrial thermal crystallization allows for precise control over supersaturation, crystal growth kinetics, and particle size distribution.

Thermal Concentration Kinetics

The phase transition of water from liquid to vapor requires a massive latent heat input. To optimize thermal efficiency, industrial salt plants employ multi-stage or vapor-recovery architectures.

Multiple Effect Evaporation (MEE): The MEE system connects several evaporator bodies (effects) in series. High-pressure steam is fed into the heat exchanger of the first effect. The primary vapor generated from the boiling brine in the first effect is subsequently utilized as the heating medium for the second effect, which operates at a lower pressure (and thus a lower boiling point) maintained by a vacuum system⁵⁵. This cascading of latent heat drastically improves the steam economy. A typical double-effect system can evaporate approximately 1.8 to 2.0 kg of water per kg of live steam consumed⁵⁶. The physical limitation of MEE is the Boiling Point Elevation (BPE) of the concentrated brine, which requires careful temperature difference distribution across the effects to prevent scaling and ensure adequate heat transfer⁵⁶.

Mechanical Vapor Recompression (MVR): MVR technology represents the zenith of energy

efficiency. Instead of condensing the secondary vapor generated by the boiling brine, the vapor is routed to a mechanical compressor⁵⁷. The adiabatic compression elevates both the pressure and temperature of the vapor, upgrading its thermal grade so that it can be recycled back into the heat exchanger of the same evaporator body as the primary heating medium⁵⁷. Operating essentially as an open-cycle heat pump, MVR systems recover nearly all the latent heat of vaporization, reducing specific energy consumption to a third of that required by standard MEE systems⁵⁷. Typical MVR evaporation temperatures run between 70 °C and 90 °C, offering a highly stable, low-temperature concentration environment that mitigates scaling risks⁶⁰.

Crystallizer Architectures and Fluid Dynamics

The structural design and internal flow field of the crystallizer vessel directly determine the multiphase flow behavior, separation efficiency, and the morphological properties of the crystalline product⁵⁷.

Forced Circulation (FC) Crystallizer

The Forced Circulation crystallizer is the workhorse of the salt industry, favored for its robust handling of high-scaling, viscous, or high-solid-content slurries⁵⁷. Driven by a high-capacity external axial pump, the crystal slurry flows through a shell-and-tube heat exchanger at high velocities, suppressing boiling at the heat transfer surface⁵⁷. The heated slurry enters the main flash chamber, where the hydrostatic pressure drops, causing rapid solvent flashing⁵⁷. This violent flashing generates high localized supersaturation, which is relieved by both crystal growth and vigorous secondary nucleation. Consequently, FC crystallizers produce a fine, highly uniform crystal size distribution⁶². While ideal for high-throughput commodity salt and ZLD applications, the intense mechanical agitation can lead to crystal attrition and a higher proportion of fines⁶².

Draft Tube Baffled (DTB) Crystallizer

The DTB crystallizer is engineered to produce larger, coarser crystals with a narrow size distribution⁵⁷. The vessel features an internal draft tube centered over a slow-moving, low-shear impeller. The slurry circulates internally—up the draft tube into the vaporizer section and down the annular space—promoting homogeneous mixing and controlled suspension⁶⁴.

A critical feature is the annular settling zone (baffle area) at the periphery of the vessel. The upward velocity of the mother liquor in this zone is carefully controlled to allow large product crystals to settle, while fine, undersized nuclei are swept out with the overflow⁵⁷. This overflow is routed through an external heat exchanger where the fines are actively dissolved (fines destruction), subsequently returning the clear, supersaturated liquor to the growth zone⁶². By artificially suppressing the population of nuclei, supersaturation is channeled almost entirely into the growth of the existing crystals, yielding coarse, high-purity salt with rounded edges due to controlled attrition⁶².

Oslo (Fluidized Bed) Crystallizer

The Oslo crystallizer completely decouples the supersaturation generation zone from the crystal growth zone⁵⁷. The mother liquor is withdrawn, heated, and flashed in an upper vaporization chamber. The resulting supersaturated liquid is pumped down a central downcomer and injected into the bottom of the crystallizer, flowing upward through a dense, fluidized bed of suspended

salt crystals⁶¹.

Because mechanical agitation is absent in the growth zone, secondary nucleation via crystal-impeller collisions is virtually eliminated⁵⁷. The supersaturation is relieved gently via diffusion onto the massive surface area of the fluidized bed.

To harvest the product, Oslo crystallizers frequently employ an **elutriation leg** at the base of the vessel⁶¹. The elutriation leg is a cylindrical column through which a counter-current flow of fresh feed brine or mother liquor is pumped upward. The downward flow of slurry is deflected radially by a target member to prevent disruption of the fluidized bed⁶⁶. The upward fluid velocity acts as a strict hydraulic classifier: fine crystals with a low terminal settling velocity are swept back up into the bed to continue growing, while only the largest, heaviest crystals overcome the upward drag and discharge from the bottom⁵⁷. This continuous classification ensures a superior, exceptionally coarse crystal size distribution (1–5 mm) and effectively washes the discharging crystals, displacing impure body liquor⁶⁶.

Crystallizer Type	Circulation Mechanism	Supersaturation Relief	Typical Crystal Size	Primary Application
Forced Circulation (FC)	External axial pump	Flash evaporation (violent)	Fine to Medium	High-volume commodity salt, ZLD streams
Draft Tube Baffled (DTB)	Internal impeller	Gentle boiling, fines destruction	Medium to Coarse	Pharmaceutical grade, controlled PSD
Oslo (Fluidized Bed)	External pump (liquor only)	Fluidized bed deposition	Coarse (1-5 mm)	High-purity coarse salt, low attrition
Cerny Direct Contact	Immiscible coolant drops	Direct heat transfer	Variable	Specialized low-temperature cooling

The Alberger Process and Flake Salt

While standard vacuum pan evaporation produces dense, cubic salt crystals, specific culinary and industrial applications demand salt with rapid dissolution rates, low bulk density, and high surface area. The **Alberger Process**, developed in the late 19th century, satisfies these requirements by yielding hollow, pyramid-shaped (hopper) flake salt⁶⁸.

Unlike the enclosed, rapidly boiling conditions of vacuum pans, the Alberger process operates

via open-pan evaporation. Brine is heated under pressure and introduced into large, circular, open-air shallow pans. Evaporation occurs at the quiescent surface of the brine, where supersaturation is highest⁶⁸. Crystal nucleation begins at the air-liquid interface; because the edges of a forming cubic face possess higher growth kinetics than the center, the crystal grows preferentially outward along the edges, forming a hollow, stepped pyramid that floats on the surface tension until it becomes heavy enough to sink⁶⁸.

This unique flake structure possesses a profoundly higher surface-area-to-mass ratio compared to standard granulated salt. This translates into rapid solubility, excellent blendability, and superior adherence to surfaces, making Alberger salt highly prized in food manufacturing⁷¹.

Crystal Modification and Post-Processing

Crystal Habit Modifiers

Sodium chloride naturally crystallizes in the cubic $\{100\}$ habit. However, the introduction of specific trace impurities into the brine can fundamentally alter the crystal morphology by selectively adsorbing onto different crystallographic faces, altering their relative growth kinetics. The addition of crystal habit modifiers such as urea, formamide, or barbituric acid retards the growth of the $\{111\}$ faces relative to the $\{100\}$ faces, resulting in the formation of complex octahedral crystals rather than cubes⁷⁴. While historically significant for theoretical crystallography, the industrial manipulation of crystal habit is reserved for specialized applications where altered flowability or bulk density is required⁷⁵.

Anti-Caking Agents

Because sodium chloride is highly hygroscopic, variations in ambient humidity cause trace moisture condensation on the crystal surfaces. As this moisture evaporates, solid crystalline bridges form between adjacent particles, leading to severe caking and agglomeration during storage.

To preserve flowability, anti-caking agents are injected into the crystal mass post-centrifugation. The most universally applied agent is **Yellow Prussiate of Soda (YPS)**, chemically known as

sodium ferrocyanide decahydrate ($\text{Na}_4\text{Fe}(\text{CN})_6 \cdot 10\text{H}_2\text{O}$)⁶⁹. YPS acts as a crystal habit modifier on a microscopic scale; it strongly adsorbs onto the faces of nascent microscopic salt crystals formed during moisture evaporation, preventing them from forming robust, macroscopic solid bridges between the bulk crystals⁷⁹.

Due to its high efficacy, YPS is required only in minute concentrations. Regulatory limits govern its usage; authorities generally approve its addition at levels between 10 and 250 parts per million (ppm), depending on whether the salt is destined for road de-icing or human consumption⁶⁹. At these trace levels, the ferrocyanide complex is exceptionally stable and exhibits no toxicity⁸¹.

Dewatering, Drying, and Iodization

Following crystallization, the slurry is discharged to continuous centrifuges (pusher or peeler types) to dewater the crystal cake to approximately 2-5% moisture⁶⁷. The remaining surface

moisture is eradicated in thermal dryers, predominantly vibrating fluid-bed dryers, where hot air fluidizes the salt bed, achieving a final moisture content of $\leq 0.1\%$ ⁶⁷. The dried salt is then screened for size classification and magnetically separated to remove trace metallic wear particles⁶⁷.

For human consumption, iodine deficiency is globally addressed through the fortification of table salt. Potassium iodate (KIO_3) is the preferred fortificant due to its superior stability over potassium iodide in warm and humid climates. The iodization process involves uniformly spraying a concentrated potassium iodate solution onto the dry salt mass in continuous mixers to achieve a target dosage of approximately 40 ppm⁸⁵.

Microplastics and Product Purity

In the modern context of environmental contamination, the origin of the raw brine significantly impacts the final purity profile of the salt, specifically regarding microplastics. Studies assessing the microplastic content in commercial salts reveal that minimally processed, unrefined sea salt extracted from coastal solar pans contains significantly higher concentrations of microplastic particles per kilogram compared to vacuum salt or mined rock salt⁸⁶.

The vacuum pan process—drawing upon deep subterranean brine deposits that predate synthetic polymers, combined with rigorous filtration and closed-loop crystallization—effectively eliminates microplastic contamination, rendering vacuum salt superior for high-purity food and pharmaceutical applications⁸⁸.

Materials Engineering in Brine Processing

The evaporation and crystallization of hot, concentrated sodium chloride brines constitute one of the most aggressively corrosive environments in chemical engineering. The combination of high chloride ion concentrations, elevated temperatures (often exceeding 100 °C), low pH fluctuations, and the physical erosion caused by dense crystal slurries demands exceptional metallurgical integrity⁹¹.

The primary failure mode for standard austenitic stainless steels (such as 304 or 316L) in these environments is highly localized pitting corrosion and chloride-induced stress corrosion cracking (SCC)⁹³. Pitting initiates when the protective passive oxide film on the metal surface is breached by chloride ions⁹³. The localized pit acts as a small anode, while the vast surrounding passive surface acts as the cathode, driving a massive current density that rapidly perforates the metal structure⁹³. At 60 °C and 100,000 ppm chloride, standard 316L can fail catastrophically within weeks⁹³.

The Pitting Resistance Equivalent Number (PREN)

To predict and classify the resistance of stainless steel alloys to localized pitting, metallurgists utilize the Pitting Resistance Equivalent Number (PREN)⁹⁵. PREN is an empirical formulation based on the mass percentage of critical alloying elements—primarily chromium, molybdenum, and nitrogen—which stabilize the passive film and resist chloride attack⁹⁴. The standard equation is:

$$\text{PREN} = \%Cr + 3.3 \times \%Mo + 16 \times \%N$$

Higher PREN values correlate directly with superior resistance to pitting⁹³. For demanding brine environments, material selection centers exclusively on high-PREN alloys.

Advanced Alloys: Duplex Stainless Steel and Titanium

Modern salt plants rely on advanced duplex stainless steels and titanium alloys to ensure operational longevity⁵⁸.

Duplex Stainless Steels (DSS): Alloys such as Grade 2205 (PREN 32-36) feature a biphasic microstructure containing approximately equal proportions of austenite and ferrite⁹¹. This dual-phase structure provides significantly higher mechanical yield strength and vastly superior resistance to chloride SCC compared to standard austenitic steels⁹¹.

Super Duplex Stainless Steels (SDSS): For extreme conditions, such as high-salinity crystallizer bodies and brine intake pumps, Super Duplex Grade 2507 (PREN > 42) is the material of choice⁹³. The high chromium (~25%), molybdenum (~3.8%), and nitrogen (~0.28%) content ensures robust passivation⁹³. However, the thermal processing of SDSS requires rigorous control; improper welding or heat treatment can precipitate brittle intermetallic phases (such as the sigma phase) at grain boundaries, which locally deplete chromium and severely degrade both toughness and localized corrosion resistance⁹⁵.

Titanium: In the most extreme environments—such as the first effect of a high-temperature evaporator, anolyte circulation pumps with acidic pH (2 to 4) and dissolved chlorine, or brines containing severe pitting agents like calcium chloride—Grade 2 Titanium is utilized⁶⁰. Titanium

forms a highly stable, self-healing titanium dioxide (TiO_2) passive film that is practically immune to chloride pitting and SCC, ensuring decades of reliable service despite a substantially higher initial capital cost⁹¹.

Material Grade	Microstructure	Typical PREN	Application Profile
316L	Austenitic	~24	Unsuitable for hot concentrated brines
2205	Duplex	32–36	Moderate brines up to 100 °C
2507	Super Duplex	> 42	High-salinity RO reject, crystallizers
Titanium Gr. 2	Hexagonal Close-Packed	N/A	Acidic, high-chloride environments

Valorization of Bitterns

The residual liquor generated after the extraction of sodium chloride, whether from solar ponds or thermal crystallizers, is known as bittern. Bitterns are highly concentrated solutions of the remaining soluble ions and represent a valuable secondary resource, transforming a waste disposal problem into an economic opportunity.

Bromine Extraction

Seawater naturally contains low levels of bromide. As sodium chloride crystallizes, bromide ions do not form their own crystalline phases; instead, a fraction substitutes into the halite lattice by isomorphic replacement of chloride ions, while the majority concentrates in the residual bittern⁴.

By allowing the bittern to evaporate to 34.5–35.0 °Bé, bromide concentrations can be enhanced up to 8.4 g/L without significant losses to solid precipitates¹².

Bromine is subsequently extracted by bubbling chlorine gas through the acidified bittern, oxidizing the bromide ions into elemental bromine, which is then stripped via air or steam and collected for use in flame retardants, pharmaceuticals, and agricultural chemicals.

Magnesium and Potassium Recovery

Bitterns are exceptionally rich in magnesium. The integration of magnesium recovery involves a reactive crystallization process, typically precipitating magnesium hydroxide ($\text{Mg}(\text{OH})_2$) through the addition of alkaline agents such as ammonia or hydrated lime¹². If optimized properly, such as using an ammonium hydroxide to magnesium molar ratio of 6, high-purity magnesium hydroxide (93.5%) is achieved, which can be further calcined at 500 °C to yield highly reactive magnesium oxide (MgO) with a large specific surface area¹².

Potassium is recovered sequentially from the bittern as carnallite ($\text{KMgCl}_3 \cdot 6\text{H}_2\text{O}$). To maximize yield, the bittern is often desulfated with calcium chloride (produced by reacting the magnesium chloride within the decomposed carnallite liquor with lime) to force the precipitation of carnallite free from sulfate contamination¹². These integrated recovery frameworks embody the ultimate industrial goal of complete resource utilization from saline matrices.

Conclusion

The industrial extraction and purification of sodium chloride is a deeply mature, yet relentlessly evolving discipline of chemical engineering. Driven by the dual imperatives of the chlor-alkali industry's demand for ultra-pure feedstocks and the global shift toward energy-efficient, Zero Liquid Discharge (ZLD) operations, the technological landscape has shifted significantly. Modern salt production seamlessly integrates empirical legacies—such as the 18th-century Baumé scale and the 19th-century Alberger process—with highly sophisticated, closed-loop process engineering. Solution mining operations now apply complex analytical geomechanics, 3D sonar profiling, and dynamic backfilling to prevent catastrophic subsidence, mitigating the severe risks inherent in massive subterranean fluid extraction. In parallel, advancements in

electrodialysis and monovalent-selective ion-exchange membranes have revolutionized the ability to pre-concentrate brines and fractionate ions before they reach a thermal threshold, massively reducing the energetic penalty of solvent evaporation.

When thermal separation is required, the transition from Multiple Effect Evaporators to Mechanical Vapor Recompression signifies a paradigm shift in energy recovery, effectively recycling the latent heat of vaporization through adiabatic compression. The specific morphology of the final crystal—whether a fine cubic structure from a Forced Circulation unit, a precisely classified coarse crystal from a Draft-Tube Baffled or Oslo fluid-bed crystallizer, or a hollow pyramid from an open pan—is dictated strictly by fluid dynamics and supersaturation control.

Ultimately, the stability of these aggressive thermal processes rests entirely upon rigorous thermodynamic predictions via Pitzer interaction models and the deployment of advanced metallurgy. By utilizing Super Duplex stainless steels and Titanium to withstand catastrophic chloride pitting, modern crystallizers are engineered for decades of continuous operation. The synthesis of these physical, chemical, and mechanical disciplines ensures that sodium chloride remains an abundant, highly pure, and economically viable cornerstone of the global chemical industry.

Works cited

1. Ullmann's Enc. of Industrial Chemistry | PDF | Sulfuric Acid - Scribd, <https://www.scribd.com/document/73692538/Ullmann-s-Enc-of-Industrial-Chemistry>
2. Production of high purity salt with reduced levels of impurities, <https://patents.google.com/patent/CN104203825A/en>
3. Handbook of Chemical Technology and Pollution Control - Madar, https://madar-ju.com/storage/images/files/file_1738773299SISCn.pdf
4. Mineralogical Characterization of the Trapani–Paceco Saltworks, <https://www.mdpi.com/2075-163X/16/7/681>
5. Baumé scale - Wikipedia, https://en.wikipedia.org/wiki/Baum%C3%A9_scale
6. The MSDS HyperGlossary: Baume scale, <https://www.ilpi.com/msds/ref/baumescale.html>
7. What is a degree Baumé Scale? - Camlab, <https://www.camlab.co.uk/blog/what-is-a-degree-baume-scale>
8. Manual on Artemia production and use - UGent personal websites, <https://users.ugent.be/~psorgelo/A4BreportClosingMayJune2024/FAO%20Artemia%20Manual%202024.pdf>
9. South Bay Salt Pond Restoration - NERRS Science Collaborative, https://nerrssciencecollaborative.org/media/files/South%20Bay%20Salt%20Pond%20Feasibility%20Study_2002.pdf
10. VEE GEE - Nova-Tech International, <https://www.novatech-usa.com/pdf/VEE%20GEE%20Hydrometers%20Brochure.pdf>
11. Recovery of sodium chloride and other salts from brine,

- <https://patents.google.com/patent/JP2010222242A/en>
12. Enrichment of Bromine in Sea-Bittern with Recovery of Other Marine,
https://www.researchgate.net/publication/231372249_Enrichment_of_Bromine_in_Sea-Bittern_with_Recovery_of_Other_Marine_Chemicals
 13. Simulation of Flow Field of Solution Mining Salt Cavities for,
<https://asmedigitalcollection.asme.org/energyresources/article/145/2/022001/1141949/Simulation-of-Flow-Field-of-Solution-Mining-Salt>
 14. Global Accidents in Solution Mining - IKR Publishers,
<https://ikrpublishers.com/wp-content/uploads/2026/03/IKRJET37281-2026.pdf>
 15. Solution mining with double-well convection - ResearchGate,
https://www.researchgate.net/figure/Solution-mining-with-double-well-convection_fig1_327158314
 16. Delft University of Technology Document Version Final published,
https://research.tudelft.nl/files/159825950/1_s2.0_S2352152X23023101_main.pdf
 17. What do you consider the most interesting engineering disaster?,
https://www.reddit.com/r/engineering/comments/3v6bt8/what_do_you_consider_the_most_interesting/
 18. The pistol shrimp snaps its claw so fast it creates a collapsing,
<https://spacedaily.com/d-the-pistol-shrimp-snaps-its-claw-so-fast-it-creates-a-collapsing-cavitation-bubble-nearly-as-hot-as-the-suns-surface-and-kills-with-the-shock-wave-not-the-claw/>
 19. Author Spotlight: Allan Wolf - From The Mixed Up Files,
<https://fromthemixedupfiles.com/author-spotlight-allan-wolf/>
 20. Stability Analysis of the Exploitation System with Room and Pillar by,
https://www.researchgate.net/publication/378445919_Stability_Analysis_of_the_Exploitation_System_with_Room_and_Pillar_by_Analytical_Methods
 21. Understand the Basics of Electrodialysis Reversal (EDR) - DESALT,
<https://www.desalt-iex.com/post/understand-the-basics-of-electrodialysis-reversal-edr-a-complete-guide>
 22. What Is Electrodialysis Reversal and What Are its New Innovations?,
<https://www.saltworkstech.com/articles/what-is-electrodialysis-reversal-and-its-new-innovations/>
 23. Electrodialysis Reversal for Industrial Reverse Osmosis Brine,
https://www.researchgate.net/publication/329883515_Electrodialysis_Reversal_for_Industrial_Reverse_Osmosis_Brine_Treatment
 24. Prefractionation of LiCl from concentrated seawater/salt lake brines,
https://www.researchgate.net/publication/325066719_Prefractionation_of_LiCl_from_concentrated_seawatersalt_lake_brines_by_electrodialysis_with_monovalent_selective_ion_exchange_membranes
 25. In-Situ Combination of Bipolar Membrane Electrodialysis with ... - PMC,
<https://pmc.ncbi.nlm.nih.gov/articles/PMC7345200/>
 26. Power Generation Performance of a Pilot-Scale Reverse ... - MDPI,
<https://www.mdpi.com/2077-0375/11/1/27>
 27. Continuous Selective Reverse Electrodialysis Process Based on,
<https://pubs.acs.org/iecred/article/63/39/16935/862422/Continuous-Selective-Rev>

erse-Electrodialysis

28. Influence of multivalent ions on renewable energy generation in,
<https://pubs.rsc.org/ee/article/7/4/1434/402066/Influence-of-multivalent-ions-on-renewable-energy>
29. integration of monopolar and bipolar electrodialysis for valorization,
<https://upcommons.upc.edu/bitstreams/f62a36ae-14e0-4799-ba9a-1252486179e6/download>
30. DCM Chlor-Alkali Training Report | PDF | Ion Exchange - Scribd,
<https://www.scribd.com/document/804985791/DCM-Shriram-Report-file>
31. Handbook of Chlor-Alkali Technology Vol 1 - studylib.net,
<https://studylib.net/doc/26233305/handbook-of-chlor-alkali-technology>
32. Technoeconomic Analysis of a Brine Purification Process Combined,
<https://pubs.acs.org/doi/10.1021/acs.iecr.2c00353>
33. Industrial Water Softener Waste Brine Reclamation - epa nepis,
<https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockkey=9101F807.TXT>
34. Sustainable brine management: Unlocking magnesium and calcium,
https://www.researchgate.net/publication/381663992_Sustainable_brine_management_Unlocking_magnesium_and_calcium_for_improved_carbonation_in_the_modified_Solvay_process
35. Optimization of NaOH–Na₂CO₃ brine purification method,
[https://www.researchgate.net/publication/361080173_Optimization_of_NaOH-Na₂CO₃ brine purification method From laboratory experiments to industrial application](https://www.researchgate.net/publication/361080173_Optimization_of_NaOH-Na2CO3_brine_purification_method_From_laboratory_experiments_to_industrial_application)
36. Process for the purification of raw sodium chloride brines,
<https://patents.google.com/patent/US3816592A/en>
37. Chlor-Alkali Industry - eere.energy.gov,
https://www1.eere.energy.gov/manufacturing/resources/chemicals/pdfs/profile_chap6.pdf
38. Chlor Alkali | PDF | Sodium Hydroxide | Physical Sciences - Scribd,
<https://www.scribd.com/document/198149775/Chlor-Alkali>
39. Environment Engineering - Physics Wallah,
https://static.pw.live/5eb393ee95fab7468a79d189/GLOBAL_CMS_BLOGS/a6525ae5-0247-42cd-8f03-a4894adec409.pdf
40. Choosing NF Membranes for Brine Sulfate Removal,
<https://www.jiuwumembrane.com/choosing-nf-membranes-for-brine-sulfate-removal-primary-brine-dilute-brine--saturated-brine.html>
41. Hydrometallurgical process and method for recovering metals,
<https://patents.google.com/patent/US8936770B2/en>
42. Request for Proposal (RFP) for Operation & Maintenance of 800,
http://gnal.co.in/writereaddata/Portal/Tender/6_1/1_Master_GNAL_OM_CSP.pdf
43. Chlor-Alkali Production Overview | PDF | Sodium Chloride - Scribd,
<https://www.scribd.com/document/515274988/step-2>
44. REDUCING THE RELEASE OF CHLORATE FROM CHLOR-ALKALI,
https://www.researchgate.net/profile/Shyam_Lakshmanan/publication/320414295_REDUCING_THE_RELEASE_OF_CHLORATE_FROM_CHLOR-ALKALI_PLANT

[_BRINE_STREAM/links/5e2c3de692851c3aadd98d31/REDUCING-THE-RELEASE-OF-CHLORATE-FROM-CHLOR-ALKALI-PLANT-BRINE-STREAM.pdf](#)

45. Safer aromatic process diluents for solvent extraction of critical,
<https://pubs.rsc.org/su/article/4/7/2978/1225255/Safer-aromatic-process-diluents-for-solvent>
46. (PDF) The activity Coefficients and Equilibrium Constants of,
https://www.researchgate.net/publication/260191047_The_activity_Coefficients_and_Equilibrium_Constants_of_Commercial_Potash_at_temperatures_from_25_to_70oC
47. Aqueous solution database and modelling using the Pitzer,
https://gtt-technologies.de/wp-content/uploads/2019/02/Pajarre_2018.pdf
48. (PDF) Thermodynamic study of magnesium sulfate crystallization,
https://www.researchgate.net/publication/282281053_Thermodynamic_study_of_magnesium_sulfate_crystallization_application_of_Pitzer_model_and_quinary_diagrams
49. Hydrogeochemical Studies of the Rustler Formation and Related,
<https://inis.iaea.org/records/rgvrq-9aa61/files/23021673.pdf?download=1>
50. Salar de Atacama Lithium and Potassium Productive Process - MDPI,
<https://www.mdpi.com/2075-4701/14/10/1095>
51. calculation of activity coefficients for organic-inorganic mixtures,
<https://acp.copernicus.org/articles/11/9155/2011/acp-11-9155-2011.pdf>
52. Solid–Liquid Equilibria of the Quaternary Water–Salt System Na⁺,
<https://pubs.acs.org/doi/10.1021/acs.jced.3c00560>
53. (PDF) Seawater solubility phase diagram. Application to an,
https://www.researchgate.net/publication/244742309_Seawater_solubility_phase_diagram_Application_to_an_extractive_process
54. Measurement and Correlation of Phase Equilibria of Ammonium,
<https://pubs.acs.org/doi/10.1021/acs.jced.9b00299>
55. Pharmaceutical Grade Sodium Chloride Production - Salt - Scribd,
<https://id.scribd.com/document/516704339/Technologiesfortheproductionofpharmaceuticalgradesodiumchloride>
56. China Double Effect Evaporator Manufacturers, Suppliers and Factory,
<https://www.encocn.com/double-effect-evaporator/>
57. A review on different structures of crystallizers and internal flow field,
<https://pubs.aip.org/aip/adv/article/16/1/010701/3377848/A-review-on-different-structures-of-crystallizers>
58. MVR Evaporator - 河南名华环保科技有限公司,
<https://www.ecominghua.com/en/mvr-evaporator/>
59. Sodium Chloride Market Size & Share Analysis - Mordor Intelligence,
<https://www.mordorintelligence.com/industry-reports/sodium-chloride-market>
60. Why do 90% of small and medium-sized enterprises waste money,
https://www.wteya.com/industry-news/Why-do-90-of-small-and-medium-sized-enterprises-waste-money-on-wastewater-treatment-This-device-answers_3619.html
61. 61745229-Crystallization_61745229-Crystallization | PPTX,
<https://www.slideshare.net/slideshow/61745229crystallization61745229crystallization>

[on/267134414](#)

62. A Crystal Clear Guide to Crystallization Techniques,
<https://www.scidart.com/blog/a-crystal-clear-guide-to-crystallization-techniques/>
63. (PDF) 51 Industrial Crystallization - ResearchGate,
https://www.researchgate.net/publication/265289791_51_Industrial_Crystallization
64. (PDF) CFD simulation and comparison of industrial crystallizers,
https://www.researchgate.net/publication/265689923_CFD_simulation_and_comparison_of_industrial_crystallizers
65. (PDF) The Steps from Batchwise to Continuous Crystallization for a,
https://www.researchgate.net/publication/342426937_The_Steps_from_Batchwise_to_Continuous_Crystallization_for_a_Fine_Chemical_A_Case_Study
66. US4113552A - Elutriation leg and method - Google Patents,
<https://patents.google.com/patent/US4113552A/en>
67. Drying & Packing Systems for Salt & Crystals | EvapCryst,
<https://evapcryst.com/technologies/drying-packing/>
68. Thought for Food: Salt Crystal Morphology | PPTX - Slideshare,
<https://www.slideshare.net/slideshow/salt-images-rev531final-23160899/23160899>
69. Salt - Wikipedia, <https://en.wikipedia.org/wiki/Salt>
70. US1273208A - Salt manufacture. - Google Patents,
<https://patents.google.com/patent/US1273208A/en>
71. The salt is shaped as advertised : r/mildlyinteresting - Reddit,
https://www.reddit.com/r/mildlyinteresting/comments/1wc7pm8/the_salt_is_shaped_as_advertised/
72. Culinary salt - saltwork consultants pty ltd,
<https://www.saltworkconsultants.com/culinary-salt/>
73. Seasoning and method for seasoning a food product while reducing,
<https://patents.google.com/patent/US7923047B2/en>
74. Crystallization Theory: An In-Depth Study (CHEM 101) - Studocu,
<https://www.studocu.vn/vn/document/truong-dai-hoc-bach-khoa-dai-hoc-quoc-gia-t-hanh-pho-ho-chi-minh/truyen-nhiyet-va-truyen-khoi/crystallization-theory-an-in-dept-h-study-chem-101/150194844>
75. Growth and characteristics of the {111} NaCl crystal surface grown,
https://www.researchgate.net/publication/223569246_Growth_and_characteristics_of_the_111_NaCl_crystal_surface_grown_from_solution
76. Selective Adsorption/Absorption of Formamide in NaCl Crystals,
https://www.researchgate.net/publication/234111565_Selective_AdsorptionAbsorption_of_Formamide_in_NaCl_CrystalsGrowing_from_Solution
77. The Mechanism of Anticaking Agents for Sodium Chloride,
<https://repository.ubn.ru.nl/bitstream/handle/2066/113021/113021.pdf>
78. Technical Information for Highway Grade Deicing Salt,
<https://www.indsalt.com/doccenter/54b8efd7004240e596ab007ddd28df0f>
79. ASTM B117 Salt Purity: Important Facts and Conflicting Claims,
<https://www.finishing.com/406/10.shtml>
80. 12.4.2. Salt - Aquarium Science, <https://aquariumscience.org/12-4-2-salt/>
81. General Specifications Attachment C CORROSION INHIBITOR FOR,

- <https://dot.nebraska.gov/media/r0sn0etw/attachement-c-122984-z5.pdf>
82. Sodium ferrocyanide | C₆FeN₆.4Na | CID 26129 - PubChem - NIH,
<https://pubchem.ncbi.nlm.nih.gov/compound/sodium%20ferrocyanide>
 83. 62 Subpart E—Anticaking Agents - GovInfo,
<https://www.govinfo.gov/link/cfr/21/172?link-type=pdf&ionnum=410&year=mostrecent>
 84. (PDF) 41 Drying of Polymers - ResearchGate,
https://www.researchgate.net/publication/265144952_41_Drying_of_Polymers
 85. Assessment of Iodine Depletion in Food Grade Salt under ... - JOCPR,
<https://www.jocpr.com/articles/assessment-of-iodine-depletion-in-food-grade-salt-under-households-storage-conditions-10031.html>
 86. Sea salt (raw?, organic) | Foundation G+E - diet-health.info,
<https://www.diet-health.info/en/recipes/ingredients/in/ld9162-sea-salt>
 87. MICROPLASTICS IN SALT - PraveBio.cz,
https://www.pravebio.cz/user/related_files/microplastics_statement_unrefined_salt_2021_03_24-12.pdf
 88. Sodium Chloride Food Grade | Food Salt, Brine Salt & Industrial,
<https://foodgradeadditives.com/products/sodium-chloride-food-grade.html>
 89. Iodized Vacuum Salt 25 Kg Bag - Fine Vacuum Salt, Vacuum Salt,
<https://shouldyu.en.made-in-china.com/product/rpHUIPyJhdkq/China-Iodized-Vacuum-Salt-25-Kg-Bag.html>
 90. Pdv Salt Supplier - Pdv Salt, Vacuum Salt | Made-in-China.com,
<https://m.made-in-china.com/amp/product/Pdv-Salt-Supplier-2294860535.html>
 91. Material Selection Considerations for Evaporator Systems in,
<https://enchem.goldsupplier.com/blog/51079.html>
 92. MVR Evaporation Crystallization: A Core Technology For Zero,
<https://www.jmfiltec.com/news/mvr-evaporation-crystallization-a-core-techno-85614847.html>
 93. Centrifugal Pump Selection & Maintenance Guide for Chemical Plants,
<https://www.zgpumpvalve.com/news/centrifugal-pump-selection-and-maintenance-guide-for-chemical-plants.html>
 94. Pitting corrosion of austenitic and duplex stainless steels in dilute,
https://www.researchgate.net/publication/388925733_Pitting_corrosion_of_austenitic_and_duplex_stainless_steels_in_dilute_acids_at_elevated_temperature_effect_of_electrolyte_chemistry_and_material_microstructure
 95. Impact of Ag Coating Thickness on the Electrochemical Behavior of,
<https://www.mdpi.com/2073-4352/15/1/62>
 96. CORROSION RESISTANCE OF DIFFERENT STAINLESS STEEL,
https://iris.unipa.it/retrieve/e3ad8920-cb88-da0e-e053-3705fe0a2b96/Tranchida%20Giada_XXXII%20ciclo.pdf
 97. High-Concentration Saline Wastewater Pump-Zhejiang Jushi Pump,
<https://www.jushipump.com/what-kind-of-pump-should-be-used-for-transporting-high-concentration-saline-wastewater/>
 98. Advanced Stainless Steel—From Making, Shaping, Treating ... - PMC,
<https://pmc.ncbi.nlm.nih.gov/articles/PMC12566239/>

99. Magnesium Recovery from Desalination Brines | PDF - Scribd,
<https://www.scribd.com/document/819607180/Magnesium-recovery-from-seawater-desalination-brines-a-technical-review>
100. Investigation of Magnesium Hydroxide as a Halogen-Free Fire,
<https://www.preprints.org/manuscript/202604.1936>