SODIUM CHLORIDE

1. Introduction

The electrolyte, sodium chloride [7647-14-5], NaCl, is commonly known as salt, a readily available, inexpensive commodity. A basic requirement for all life, it is found throughout the earth in natural underground deposits as the mineral halite and as mixed evaporates in saline lakes. Salt is the largest component of dissolved solids found in seawater. Although the percent composition varies from lower values near the north and south poles to higher values closer to the earth's equator, the composition averages 2.6% by weight. One cubic kilometer of seawater contains nearly 458×10^6 t of sodium chloride, 66×10^6 t of magnesium chloride, and 30×10^6 of calcium sulfate (1). Table 1 gives the composition of seawater.

Producers of salt classify their output by the three methods used for its production: mechanical evaporation of solution-mined brine, such as evaporated-granulated salt; underground mining of halite deposits, ie, rock salt; and solar evaporation of seawater, natural brine, or solution-mined brine, such as solar salt. Salt in solution as salt brine is a fourth classification, ie, solution-mined brine typically used as a feedstock for chemical production and often produced by the end-user.

2. Salt Deposits

Underground salt deposits are found throughout the world and their depositions span many geologic eras. This article will focus on the North American salt deposits and Figure 1 displays the principal salt deposits overlaid by the locations of current salt production sites. Salt deposition occurred from the Precambrian through the Quaternary periods. In the Western hemisphere, there are 10 principal salt basins (2): (*1*) the Maritime provinces of eastern Canada; (*2*) Appalachian (New York, Ohio, and Ontario); (*3*) Michigan (Michigan and Ontario); (*4*) Williston (North and South Dakota, Montana, and Saskatchewan); (*5*) Alberta (northern and eastern Alberta); (*6*) Mackenzie (Northwest Territories); (*7*) Permian (west Texas, New Mexico, Oklahoma, and Kansas); (*8*) Paradox (southeast Utah and southwest Colorado); (*9*) Supai (New Mexico and Arizona); and (*10*) the Gulf region (southern United States, eastern Mexico, and Cuba).

Salt formations exist in basically two types. Bedded deposits are the most prevalent in the United States, where the salt is layered in a fairly horizontal pattern. This type of formation can be deformed by tectonic forces or exist relatively undisturbed. These bedded deposits are found with layers of halite separated by layers of anhydrite ($CaSO_4$). Other mineral impurities that have been identified in salt formations include shale, iron pyrites, and silica.

The second type of salt formation is known as a salt dome or diapir. These domes are formed from bedded salt deposits that have been stressed by isostatic salt movements (2). An anticline is another name for a diapir. The planes in diapers approach verticality due to upward salt movements. Over the ages, the horizontally bedded salt deposits were slowly covered by layers of sediment and were buried deep within the earth's crust. The overlying strata exhibited a greater density than the salt layers below. Confined salt has the capacity to deform plastically under pressure, becoming a mobile plastic at depths of 7600 m and temperatures $>200°C$ (3). The salt was forced by the unequal pressures to flow upward through weaker overlying strata. The resulting formations took on a vertically elongated plume or teardrop shape of relatively pure sodium chloride.

3. History of U.S. Salt Production

The date of the earliest production of salt is unknown, because it has been identified as probably the second chemical compound (after water) that was identified by humans and the only stone eaten by humans (4). Maurus Jokai, nineteenth century Hungarian novelist and poet, referred to sodium chloride as “the Edible Gem”. The first colony at Jamestown had a saltworks (5). In 1641, the first patent issued in America was for a salt-making process. The patent was issued by the Colony of the Massachusetts Bay to Samuel Winslow, but the New England climate being unfavorable for such production, the venture failed.

The earliest recorded date for any type of salt production in the United States was 1656, when the French Jesuit priest, Father Simon LeMoyne, produced the first salt from springs on Onondaga Lake, near what is now known as Syracuse, N.Y. The Onondaga Indians were taught by LeMoyne to use the salt springs as a source of salt, and produced the salt by boiling.

The first salt mine was dug in Saltville, Smyth County, Va. in 1799, but the first commercial rock salt mine was established in Avery Island, La. in a salt dome in 1862, and continues to be an efficient, high capacity, working mine today. From 1788 through the early 1900s, salt was produced commercially by open air boiling of brine from salt springs and salt wells using iron kettles or pans.

In 1661, an Amsterdam merchant was granted Coney Island by the Dutch government to produce salt along the shore. As early as 1770, solar evaporation of seawater, bay water, or natural brine was performed in various areas. Around 1833 and continuing through the twentieth century, brine was evaporated in open grainer pans and later by multiple-effect vacuum pans. Salt has played a vital role throughout world history, but in the United States, it was during the Civil War when U.S. salt production became vital to the outcome of U.S. history. Many battles were fought over seizing and controlling salt, for an army without salt could not sustain its troops.

In Kanawha, West Virginia, Native Americans made salt from springs for their own use by open boiling before 1755 (6). The first deep-well drilling for salt took place in the Kanawha, WV salines, establishing the King Mine for solution mining. Commercial salt production was underway by 1797, and the Kanawha Valley also supplied the Confederacy with salt during the Civil War. Production in this region peaked during the 1860s, and by early in the twentieth century, only one plant survived.

The increased growth of salt production was due in part to the industrial revolution, creating new uses for salt as a raw material for many industries. Population growth also affected the increase in salt production. Commencing in the 1820s, commercial solar salt production was brought indoors using covered sheds to protect the salt from dilution by the elements. Evaporated salt technology advanced significantly in 1833 when multiple-effect, open grainer pans were invented. The technology included additions of reservoirs and settling vats that clarified the brine and produced clean, white salt. The grainer process was further refined at Silver Springs, New York, during the nineteenth century and ultimately led to the development of steam-heated vacuum pans. Solar salt-making began on San Francisco Bay, Calif. in 1770 and at Salt Lake City, Utah, on the Great Salt Lake in 1847. During the 1830s, there were 442 salt works producing salt on Cape Cod, Mass. (7). Between 1790 and 1860, evaporating furnaces operated in Ohio, Michigan, Pennsylvania, Kentucky, Indiana, Illinois, and Missouri. In the mid-1800s, salt was produced from salt springs at Saginaw and St. Clair, Michigan where waste wood products from the lumber industry were used as an inexpensive fuel source. In 1882, rock salt was discovered at St. Clair, Mich. by drilling. Solution mining of rock salt deposits grew rapidly thereafter in Kansas, Louisiana, Michigan, New York, Ohio, and Texas. Conventional underground mining of rock salt began in Kansas, Louisiana, Michigan, and New York between 1880 and 1887.

4. Salt Properties

Sodium chloride exists naturally in cubic, crystalline form. In its pure state, it is colorless and consists of 60.663 wt% Cl, atomic wt 35.4527 (8), and 39.337 wt% Na, atomic wt 22.989768 (9). Sodium chloride that has been produced commercially can exist as discrete crystals in various size ranges, fine granules of powder, and compressed pellets or blocks. When observed using magnification, all forms of sodium chloride are crystalline. Depending on gradation and commercial form, salt can be white, gray, reddish, or even brownish. The color can be attributed to impurities present, either occluded or on the surface of the crystals. Large crystals of apparently recrystallized halite found in some salt mines are colorless and transparent, clearly showing the mineral's characteristic cubic cleavage. Pure sodium chloride is transparent in the near- and mid-infrared (ir) regions. Table 2 shows the physical properties of sodium chloride. Salt is soluble in polar solvents, insoluble in nonpolar types. Solubility of pure sodium chloride in water and other solvents is given in Table 3. An aqueous solution of pure sodium chloride has a pH 7.

The phase diagram for the sodium chloride—water system is shown in Figure 2. The composition of the eutectic mixture, 23.31 wt% NaCl, may also be expressed as 37.68 wt% $NaCl{\cdot}2H_2O$ and 62.32 wt% water. At low temperatures, brines more concentrated than 23.31 wt% NaCl deposit large, transparent crystals of monoclinic sodium chloride dihydrate [23724-87-0]. These crystals, although similar to ice in appearance, are birefringent and account for freezing of moist highway deicing salt stockpiles during storage in cold weather. A good sourcebook on sodium chloride properties is available (4).

5. Processing

Salt production includes three production types: (*1*) solution mining, the production of dry, crystalline sodium chloride by solution extraction of salt from underground deposits using water, followed by evaporation of the brine, (*2*) the dry mining method of extracting the mineral halite from beneath the ground, and (*3*) solar salt harvesting.

When solution-mined salt is dissolved in water, the resultant brine is considered an intermediate product that is further processed into evaporated-granulated salt or used to produce other chemical products. Brine characteristics vary and are dependent on the source formation, and the physical and chemical treatment applied, if any, prior to further processing. Since all salt deposits originated from either current or ancient seas, all natural salt is a form of seasalt.

5.1. Solution Mining Followed by Mechanical Evaporation. An underground salt deposit may be solution-mined by drilling wells into halite [14762-57-7] veins, injecting fresh or recycled water through the well casings to dissolve the salt, and leaving a residence time long enough for the brine solution to reach saturation with sodium chloride. Solution mines, called Class III wells, can vary in depth from 150 to 1500 m and they can operate with a single well or with a linkage of several wells in a brine field. Brine is produced from a single well by injecting water into the salt deposit through tubing, then extracting brine through a concentric annulus between the tubing and the well casing. Water injected into one well in a multiple-well brine field dissolves salt. The resulting brine is extracted through other wells in the same brine field or gallery. Insoluble impurities, such as anhydrite (calcium sulfate) settle out in the underground gallery, while the saturated sodium chloride brine, called green brine (untreated or refined), is pumped to holding tanks on the surface. Solution-mining technology provides control over the size and shape of the caverns and minimizes the potential for surface subsidence. State-of-the-art drilling and operating techniques, well and cavern logging instruments, and other devices provide precise control over salt cavern development and use. Green brine is pumped from the underground cavern and transported via pipeline to the nearby salt refinery for processing into evaporated-granulated salt or is used as a feedstock for chloralkali production.

The typical characteristics of evaporated-granulated table salt produced in vacuum pan evaporators are colorless to white, cubic crystals, some with rounded corners. Nearly all food-grade salt sold or used in the United States is currently produced by vacuum pan evaporation of saturated brine. Prior to the evaporation process, the brine may be chemically treated to remove hardness minerals that adversely affect salt purity, but also can cause scaling in the evaporators. The treatment reduces levels of dissolved calcium, magnesium, and sometimes sulfate, depending on the type of treatment. Typical chemicals used to treat the green brine are calcium hydroxide, $Ca(OH)_2$; sodium carbonate, Na_2CO_3; sodium hydroxide, NaOH; calcium chloride, $CaCl_2$; flocculating agents; and stack gas, CO_2. Sulfuric acid treatment or chlorination may be used to remove hydrogen sulfide, and hydrochloric acid neutralizes brine used in diaphragm cell production of chlorine and caustic soda. Brine purification has become increasingly important for production of high purity salt for use in chlor-alkali production, particularly in Europe where dry salt is used extensively for this purpose.

Water is evaporated from purified brine using multiple-effect or vapor recompression evaporators (Figs. 3 and 4). Multiple-effect systems typically contain three or four forced-circulation evaporating vessels (Fig. 4) connected together in a series. Heat is supplied by steam from boilers and this steam is fed from one evaporator to the next to increase energy efficiency in the multiple-effect system.

Vapor-recompression forced-circulation evaporators consist of a crystallizer, a compressor, and a vapor scrubber. Feed brine enters the crystallizer vessel, where salt is precipitated. Vapor is withdrawn, scrubbed, and compressed for reuse in the heater. Ultimately, weak brine from the process is recycled to the solution-mined cavern. Crystallized salt is removed from the elutriation leg as a slurry. Recompression evaporators are more energy-efficient than multiple-effect evaporators, but require higher cost electrical power for energy input. The development of single-stage compressors has significantly reduced costs. During the twentieth century, salt producers made significant advances in lowering energy consumption and in reducing salting and scaling in evaporators. The salt slurry from either type of evaporator is dewatered first by centrifuging or vacuum drying, followed by rotary kiln or fluidized-bed drying. The moisture content of the final product is 0.05% or less.

Grainer Salt. A lesser utilized method of producing evaporated salt is via the addition of heat in open pans. The process creates salt flakes instead of cubic crystals. The flakes form on the surface of the brine and are supported by surface tension. As the flake salt continues solution mining to increase in size, the flakes sink to the pan bottom as incomplete cubes or hopper-shaped crystals. The product is gathered by a mechanical rake, and dried in a similar manner as vacuum pan salt. The process is affected by many variables that can impact production quality, such as ambient temperature, humidity, and purity of the feed brine. The market for flake salt is in food applications where a coarser, flake salt product is desired.

Since the grainer process is energy-inefficient, it was modified to make it less costly to produce. One such variation still in use is the Alberger process, a radically modified grainer method that produces a combination of salt flakes and cubic salt crystals. Alberger salt is less dense than evaporated-granulated salt and is used where coarser salt crystals are desired. Kosher salt can be made using the Alberger process.

Dendritic salt, a snowflake configuration, is made by altering the crystal lattice with yellow prussiate of soda (YPS) (sodium hexacyanoferrate) to the brine. Dendritic crystals have a lower density when compared to cubic evaporated-granulated salt and are friable. Purified salt can be produced via the recrystallizer process, but is no longer widely used in the United States for economic reasons. Brine made by dissolving halite, rock salt or solar salt is purified and then fed to vacuum pan evaporators to produce high purity evaporated-granulated salt.

5.2. Conventional Underground Mining. Rock salt is mined from underground deposits by drilling and blasting. Deposits are reached through a circular shaft, typically ∼6-m diameter and as deep as 700 m, depending on the depth and location of the salt deposit. Shafts are lined with concrete, at least through the overburden and into the top of the salt deposit, and often all the way to the shaft bottom. Mining methods depend on whether the salt deposit is relatively horizontal or a more vertical salt dome. The differences in mining methods depend on the thickness and structure of the salt deposit. Bedded or layered deposits are mined using the room and pillar mining method, as horizontal rooms or entries of ∼3–8 m high and 15 m wide. Openings or cross-cuts are created perpendicular to the length of the rooms to connect the rooms at planned intervals. Salt pillars are left in place to provide structural support for the overlying roof and other layers. Experienced mine engineers rely on the principles of rock mechanics to accurately size the rooms and pillars to assure worker safety and mine opening stability. Most of the room-and-pillar operations recover ∼45–65% of the salt available, with the remainder left behind as pillar supports, ceiling, and floor margins. When salt is confined and under high stress, it deforms, resulting in a plastic flow or salt creep. Mined out areas will, after long periods of time, begin to show convergence of the mine floor and roof. When rock mechanics principles are applied properly, convergence is allowed to occur without failure of the salt floor or the roof.

Typically, salt is mined using large, diesel-powered equipment designed for undercutting, drilling, blasting, loading, and transporting the blasted salt. To prepare the face for advance mining, an undercutter with tungsten carbide blade prepares a horizontal cut 15 cm high along the salt floor to a depth of 4–6 m. A drill team then prepares a series of drill holes the same horizontal depth as the undercut. The holes are loaded with ANFO, explosives consisting of a mixture of fertilizer-grade ammonium nitrate and 5% No. 2 fuel oil. An igniter and primer are inserted into the drill hole, while the ANFO blasting mixture is pneumatically blown into the hole over the primer. Once the room is safely wired and the mine evacuated, a single blast in one room can bring down 350–900 t of rock salt. It is normal practice to blast several rooms at a time to provide enough salt to meet daily production requirements. Once cleared of the blasted rock salt, the blasted areas are inspected for loose pieces of salt in the roof and pillars. Any loose salt is removed with handheld scaling tools or with mechanized roof-scaling equipment as a safety precaution.

In diapers, the mining is advanced by the room and pillar method until sufficient area has been opened up. Then the salt floor is bench-mined by drilling a series of vertical holes downward and blasting to a depth of up to 23 m. Benching yields several thousand tons of salt in a single blast, increasing operating efficiency.

Continuous Mining. Since the late 1950s the use of continuous mining machines has increased in salt mines. These “continuous miners” have movable, rotating heads with carbide-tipped cutting bits. The mining machines bore into the salt, eliminating the need for undercutting, drilling, and blasting steps; however, excessive fines production initially caused problems, but the newer equipment has reduced fines production to an acceptable level. Use of trucks or shuttle cars to haul the crushed salt for further crushing is still implemented. The diesel hauling trucks (LHDs) have oversized, off-road tires and a load capacity of up to 65 t. The LHDs can load, haul, and dump the broken rock salt to the primary crusher where the particle size is reduced on the larger salt pieces; alternatively, an end loader with 9–14-t capacity buckets is employed instead of the LHD. The crushed salt is transported from the primary crusher via conveyor belt to second- and third-stage crushers, and then to screening stations for separation into standard product grades established for specific end uses. Locations of screening stations can be totally underground, totally on the surface, or a combination of the two. Extremely fine salt fractions tend to be troublesome in handling on the surface due to their inherent ability to cake when exposed to moisture or humidity cycles. Small particles exhibit increased surface area and thus are able to adsorb more moisture. With underground screening, dust is contained more easily. Less desirable sieve cuts are utilized within the mine to construct or repair roads and provide brattice between rooms for ventilation control. Grades of salt are either stockpiled underground or hoisted to the surface in large capacity, rectangular skips varying in size dependent on the shaft size; however, most skips can achieve 18–20-t capacity. Hoisting rates can reach 900 t/h at large mines.

Solar Salt Production. Commercial solar salt is produced by natural evaporation of seawater or brine in large, diked, earthen ponds called condensers. Evaporation is carried out by solar radiation and wind action, producing concentrated brine containing dissolved mineral salts. The process for separation of crystal types is known as fractional crystallization. Calcium carbonate, which is less soluble in concentrated brine, is the first to crystallize. The relatively simple process of commercial solar evaporation requires large areas of flat land, low rainfall rates, abundant sunshine, and some wind to supply optimum yields. Location near a brine source, such as the coast or brine lake, is ideal. It is also helpful to have access to inexpensive means of transporting the final product, once produced. If the production site is located on or near a seacoast, a deep water site for bulk loading ships is an economic advantage.

The concentration of dissolved solids in seawater, although variable by location and depth, averages 3.5 wt% (3.6° Bé) and 77% of the total dissolved solids, ie, 2.7 wt% of seawater (see Table 1), is sodium chloride. Seawater must be reduced in volume by ∼90% before sodium chloride begins to crystallize at a concentration of 25.8 wt% NaCl (25.4° Bé). The most favorable sodium chloride precipitation occurs between 26° Bé and 29 or 30° Bé. Above 30° Bé, high levels of magnesium reduce the evaporation rate to unacceptable levels. At 29° Bé, 72% of the NaCl has precipitated; at 30° Bé, 79% has precipitated. The remaining solution is highly concentrated magnesium brine, referred to as bitterns due to its bitter taste. The bitterns are either discharged or collected for additional product crystallization.

Additional newly concentrated salt brine is added to the crystallized sodium chloride in the crystallizer pond and the crystallization process continues. A solar salt works producing 400,000 t/year of sodium chloride may have an area of 4000 ha or more, depending on climatic conditions. Proper brine control during concentration and crystallization results in salt of purity >99.7% NaCl on a dry basis.

Solar salt production begins as the brine source, usually seawater, enters the solar pond system and moves in turn from one pond to the next either by pumping or by gravity. The quantity of flow is controlled with mechanical gates to maintain target brine densities and pond levels. Iron, calcium, and magnesium carbonates are crystallized when the concentration of brine is 3.5–13° Bé. About 85% of the calcium sulfate is crystallized as gypsum and then as anhydrite at brine concentrations from 13 to 25.4° Bé. When the brine reaches the crystallizers, it contains dissolved calcium sulfate, magnesium sulfate, magnesium chloride, and small amounts of potassium chloride, plus trace amounts of other elements that are present in seawater. The saturated brine at a specific gravity of 25.4° Bé is fed into shallow, level, rectangular crystallizing ponds to maintain a brine depth of 30 cm or less. Sodium chloride precipitates with continuing evaporation, forming a salt layer 10–25-cm thick. Often the first salt crop deposited remains on the crystallizer bottom as a salt floor to prevent soil contamination and weak brine intrusion, and to increase the crystallizer-bottom strength, enabling it to support heavy harvesting vehicles. When the crystallizer brine reaches 25–30° Bé, the bittern is drained. Most magnesium sulfate, magnesium chloride, and potassium chlorides remain in the bitterns.

It takes up to 2 years to produce salt from the time seawater is introduced into the salt pond system. In the Western hemisphere, the new salt crop is harvested using heavy equipment and very little human resources. Typically, salt harvesters, elevating scrapers, or large end loaders are utilized. The harvested salt is loaded into trucks and transported to a wash plant, where the salt is washed with clean, nearly saturated brine to remove particulate matter and to replace magnesium-laden brine clinging to the salt crystals. Wash brine, made by dissolving fine salt in a settling pond, is free of magnesium and sulfate impurities. The wash brine is recycled by adding seawater that dissolves the fine salt collected during washing. Weak brine or seawater is sometimes used as a final salt wash; however, production losses by dissolution are increased. After washing, the salt is stockpiled and allowed to drain. Rinsing action supplied by limited rainfall is expected to improve salt quality. Prior to shipment, the stockpiled solar salt will drain, with time, to a moisture level of ~3.5%.

Further processing is similar to processing mined rock salt. Solar salt may be crushed, screened and separated into various grades, and often kiln or fluidized-bed dried. Coarse solar salt is a premium product because of high purity and relatively large crystal size, making it quite suitable for use to regenerate cation-exchange water softener resins.

Electrodialytic Membrane Process Technology. Used extensively in Japan to produce evaporated-granulated salt, filtered seawater is concentrated by membrane electrodialysis and evaporated in multiple-effect evaporators. Seawater is effectively concentrated to a product brine concentration of 200 g/L with a power consumption of 150 kWh/t of NaCl (10). Table salt is currently produced at reasonable energy costs due to improvements in electrodialytic membrane technology. However, industrial-grade salt, which is marketed at much lower prices, cannot economically with low cost-high purity solar salt imported into Japan from Australia and Mexico.

6. Salt Standards and Specifications

Since there are many grades of salt available for purchase and purity levels for these grades vary from a low of 95% for some rock salts to a high purity of 99.99%

for purified evaporated-granulated treated salt, it has been necessary to establish standards for particular salt uses (Table 4).

6.1. Additives. Sodium chloride is hygroscopic at >75.3% at 20°C relative humidity (critical humidity). Individual salt crystals, especially smaller crystals with higher surface area, can adsorb enough moisture during storage to result in formation of brine on crystal surfaces. With a subsequent drop in relative humidity, evaporation takes place, causing surface recrystallization. This phenomenon often creates strong bonds between crystals, thus causing bridging and caking.

Free-flow agents or anticaking agents are often added to salt to lessen the likelihood of caking and to prevent handling problems. Free-flow agents coat the salt crystals, blocking opportunities for bond formation between salt crystals. These agents also adsorb moisture, provide a slippery surface over the crystals that permit salt crystals to flow freely without hanging up in the container or vessel. Most free-flow agents are water insoluble, small particles, and finely divided. Some typical free-flow agents used in salt are calcium silicate, magnesium carbonate, silicon dioxide, sodium silicoaluminate, and tricalcium phosphate. All of the above are approved for use in food grade salt. Typically, concentrations between 0.5 and 2% are added to table salt and some industrial salt grades, which is the permissible amount established by the U.S. Food and Drug Administration (FDA).

One type of anticaking agent is a water-soluble crystal modifier, YPS (sodium hexacyanoferrate decahydrate). Another agent is ferric ammonium citrate. Both of these additives have been approved by the FDA for use in food grade salt. The YPS and Prussian Blue (ferric ferrocyanide), are typical agents applied to a rock salt grade used for deicing highways. Approved concentrations vary between states and even districts or municipalities, but falls within the range of 20 to 100 ppm. Humectants such as propylene glycol, glycerol, sorbitol, or calcium chloride can be helpful in preventing caking and drying.

7. Economic Aspects

Salt deposits were unevenly distributed globally, but universally sought. Since the beginning of recorded time, salt trade has been part of the world economy, to the point that wars were fought to obtain it. In 2002, world salt production was 210,000,000 metric tons (11). The leading salt-producing countries are listed in Table 5.

Total U.S. salt production decreased by ~10% in 2002 to 40.3 million metric tons compared with that of 2001. Diminished chlorine production, the largest single use of salt as a raw material and brought about by environmental pressure, has resulted in a leveling off of salt production. Highway deicing, the second largest use of salt has remained fairly consistent, despite fluctuations in winter weather patterns. The past 10 years has seen an increase in the use of liquid brine for prewetting salt, deicing roads, and antiicing prior to a snow/ice event (see Highway section for further information.).

Salt sales for ion-exchange water softener regeneration has grown steadily over the past few years, particularly in terms of revenues, but it remains to be seen whether this area will continue to grow. The salt industry in the United States is mature and sales are not likely to increase rapidly without the advent of new uses for salt. The United States and Canadian salt companies have undergone consolidation with closures of some inefficient facilities during the past 15 years to the point that in 2002, according to the USGS, <29 salt companies operated in the United States, where there were >50 companies in the late 1970s.

The amount of salt sold or used in the United States in 2002 by product type is (12) listed in Table 6. The five leading U.S. states for total salt sold or used in 2002 were Louisiana, 32%; Texas, 24%; New York, 12%; Kansas, 7%; and Utah, 6%. Six additional eastern states (Alabama, Michigan, Ohio, Tennessee, and West Virginia) accounted for 16% of the U.S. total, and four western states represented 3% of the total salt sold or used (Arizona, California, Nevada, New Mexico, and Oklahoma).

8. Analytical Methods

Methods for determining the purity of sodium chloride have been dependent on indirect methodology for many years. Although methods of determining direct levels of sodium chloride in a substance existed, most of these methods were developed for determining low levels of chloride or sodium in a liquid or semisolid sample. Assays for levels of sodium or chloride >85% required large dilutions to obtain a manageable sample. These dilutions brought with it a high probability of error and were therefore not recommended for those reasons. Calculations for chloride by difference, based upon the assays for other known components has been the accepted method for many years.

The most common impurities, depending on the origin of the salt, are calcium sulfate, calcium chloride, magnesium chloride or magnesium sulfate, sodium sulfate, and water-insoluble materials consisting of calcium sulfate, ferric iron compounds, and trace amounts of other elements. Surface moisture is determined by drying, water insoluble matter by weighing, and calcium and magnesium ions by various methods that include called ethylenediaminetetraacetic acid (EDTA) titration, flame photometry, and ion chromatography; however, the plant laboratories mainly utilize EDTA titration due to its simplicity and low cost. Sulfate is typically assayed gravimetrically or by ion chromatography (Table 7).

9. Health and Safety Factors

Sodium chloride is essential to life for all animals, including human. A fifth century Goth administrator was cited by Tannahill in Moses' monograph as stating: "It may well be that some seek not gold, but there lives not a man who does not need salt (14)." Sodium is the principal cation in blood plasma, body cells, and all bodily fluids. It is ingested by every living organism and excreted in the urine, feces, and sweat. Sodium regulation within the body maintains osmotic pressure, acid–base balance, and volume of circulating body fluids (15). Extracellular fluid volume is maintained by the total body sodium content. Total body sodium content is dependent on a balance between intake and excretion. The human body contains ~1840 mg (80 mEq) of sodium per kilogram of body weight, half of which is exchangeable (16). The sodium concentration of blood and other body fluids is maintained by a complex mechanism involving the kidneys and the adrenal glands. A wide range of sodium intakes can be accommodated by renal excretion of sodium. Sodium is conserved when intake is low, and excreted, mainly in the urine, when intake is high. Chloride is necessary as well for good health. It preserves acid–base balance in the body, aids potassium absorption, supplies digestive stomach acid, and aids the blood's ability to carry carbon dioxide to the lungs from body cells during respiration. Not only is salt essential for health, it also improves the taste of food, and was one of the first methods of preserving food.

9.1. Sodium Intake. Under readily available conditions, most of the world's population chooses to consume ~6000–11,000 mg of salt or sodium chloride a day. The average daily sodium intake from all sources is 3450 mg (8770 mg NaCl) (17). The GRAS review of the FDA publishes the amount of naturally occurring sodium in the American diet as 1000–1500 mg/day, equivalent to the amount of sodium in ~2500–3800 mg NaCl. Consequently, the average daily intake of NaCl from food grade salt used in food processing (qv) and from salt added in cooking and at the table is from 4960–6230 mg NaCl. The requirement for salt in the diet has not been precisely established, but the safe and adequate intake for adults is reported as 1875–5625 mg (18).

The National Academies recommends that Americans consume a minimum of 500 mg/day of sodium to maintain good health. Individual requirements vary widely depending on genetic make-up and the way they live their lives, but most individuals have no trouble meeting the minimum recommended requirement. Most Americans consume sufficient amounts of sodium. The kidneys excrete any excess sodium over what is required for proper bodily function. Experimentally, most people tolerate a wide range of sodium intakes, from ~250 mg/day to over 30,000 mg/day. However, the actual range is much narrower. Americans consume ~3500 mg/d of sodium, with men consuming more and women less.

9.2. Sodium Restriction. The World Health Organization (WHO) and the International Society of Hypertension estimated 10–15% of the adult population is hypertensive (15), meaning that the blood pressure is elevated from what is considered normal. For the past 20 years, Americans have been advised to monitor their sodium intake if they have been diagnosed to be "salt sensitive", meaning a population that exhibits a decrease in blood pressure when there is a corresponding decrease in sodium intake. Salt sensitivity is being better understood as induced by poor quality diets, particularly diets with insufficient calcium, potassium, and magnesium. It appears that this imbalance of dietary electrolytes is what makes some individuals "salt sensitive". Scientific literature is not in agreement with what should be the recommended intake for salt in the American diet. Also, they are not in agreement with what variables impact blood pressure, widely accepted as an indicator of risk in heart disease and stroke. But blood pressure is not the only risk factor for cardiovascular disease.

The DASH study (19) sponsored by the National Heart, Lung, and Blood Institute (NHLBI), with sodium intake held constant, ensured adequate intakes of fruits and vegetables. The result produced a lowering of systolic blood pressure

2–3 times greater than would have been achieved by salt reduction (DASH-Sodium Study) (20). When dairy products were added to that diet, the blood pressure benefit doubled (21). The 2004 Dietary Guidelines Advisory Committee, in their recommendation to the USDA and FDA, advised that the dietary sodium level should be reduced for all people, including normo-tensives. The Cochrane Collaboration has advised that blood pressure for the non-salt sensitive population is not improved by restricting salt levels in the diet (22). They stated, "It is unclear what effects a low sodium diet has on cardiovascular events and mortality. Lowering sodium intake may have adverse effects…". Other evidence-based public health groups have found insufficient scientific support to recommend reducing dietary sodium chloride to lower cardiovascular risk, such as the Canadian Hypertension Society and the Canadian Coalition for High Blood Pressure Prevention and Control (23).

9.3. Toxicity. The U.S. Food and Drug Administration regards common salt, ie, NaCl, as GRAS for its intended use as a food additive. Oral toxicity for mammals is reported in mg/kg (24): for humans, TD_{LO}: 12,357; 23D-C (daily-continuous) for mice, LD_{50}: 4000; for rats, LD_{50}: 3000; and for rabbits, LD_{LO}: 8000. TD_{LO} and LD_{LO} are lowest level toxic and lethal dosages, respectively.

Aquatic toxicity is reported in mg/L: for *Pimephales promealas* (fathead minnow), 69-h LC_{50}: 7650 (25); for *Daphnia magna* (water flea), 48-h EC_{50}: 3310 (26); for *Myriophyllum spicatum* (water milfoil), phytotoxicity (EC_{50} for growth): 5962 (27); and for *Rana breviceps* (frog), no observed effect concentration (NOEC): 400 (28). LC_{50} and EC_{50} are lethal and effect concentrations, respectively, for 50% of the subjects tested.

9.4. Environment and Infrastructure. Both ions that make up the electrolyte, sodium chloride, are present in the environment naturally. Ecosystems supporting aquatic species, biota and vegetation, including roadside grasses, trees, shrubs, and food crops, can tolerate various concentrations of sodium and chloride. The U.S. Department of Agriculture (USDA) classifies irrigation water according to conductivity and salinity hazard. Conductivity range can be converted to approximate milligram per liter (mg/L) dissolved solids. Salinity hazard ratings in milligram per liter are low, 70–175; medium, 176–525; high, 526–1575; and very high, >1575 (29).

Environmental effects of elevated salinity levels resulting from use of salt are highly site-specific. Other site characteristics must be considered also, such as soil texture, permeability, drainage, amount of water applied, dilution factors, and tolerance of particular crops or vegetation to salt levels. Deicing salt can be used to ensure traffic safety and mobility without causing environmental harm by implementing sensible salting techniques and recommending the planting of salt-tolerant trees, grasses, and shrubs along the roadside immediate to the roadway. Typically, vegetation at more of a distance from the road shoulders has not been adversely impacted when sensible salting procedures are implemented. Automobile manufacturers have improved vehicle construction and materials, such as using more plastics, to such a degree that car warranties for corrosion perforation in 2000 model year automobiles sold in the United States ranged from 4 up to 12 years (30), with the average warranty at 5.8 years.

Highway and bridge structures are lasting longer due to improved construction design and materials, such as epoxy-coated reinforced steel concrete and use of high quality air-entrained concrete. States and municipalities have been offering new training techniques to public works crews to advise the most effective and prudent use levels of deicing salts needed to clear highways, bridges, and city streets. Other chemical deicers available are far more costly and less effective than sodium chloride as a general deicer. Abrasives such as sand, cinders, or ash do not function as deicers. Some communities use them for enhanced traction on packed snow and ice. These abrasives, although less costly initially than salt, prove to be much more expensive when clean up costs to remove dust and residues from roads, gutters and drains, and the environmental and vehicular damage caused are factored in. Abrasives also lack the ability to ensure the same level of wintertime highway safety.

10. Uses

Over 14,000 different uses for salt have been identified. However, the salt industry generally classifies salt uses by the five principal use categories and then lumps the remaining uses in the miscellaneous classification: (*1*) food use and processing, (*2*) agriculture, (*3*) highway, (*4*) water conditioning, (*5*) chemical, and (*6*) miscellaneous.

10.1. Foods and Food Processing. All living animals have an inherent taste for salt. When added to food, salt enhances the flavor and makes bland tasting foods more palatable. The estimated amount of salt consumed in food products, cooking and at the table in the United States has remained fairly constant for years and most increases can be attributed to population increases. Total sales of food-grade salt in the United States during 2003 were 1,520,000 t (31). This number includes salt used during food processing that is ultimately disposed of with cooking water and not ingested.

Sodium chloride not only flavors food during cooking and food processing, it also performs as a food preservative, a color developer, a binding agent, texturizer, and as a fermentation-control agent. Salt aids in color development in processed meats, such as ham, hot dogs, sausage, and sauerkraut. Salt provides binding strength for processed meats by extracting myofibrillar proteins, which helps bind water. Stable emulsions are formed by salt-soluble protein solutions as they coat finely formed fat globules to produce a binding gel consisting of meat, fat, and moisture.

In cheese manufacture, salt is used to control fermentation and to control texture and flavor. Depending on the type of cheese, salt is used in various methods. About 2–3 lb of salt/100 lb of curd are added directly to the curd in curd salting. Cheddar cheeses are salted in this manner. Salt brine immersions are used to produce Swiss, Edam, and brick cheeses. Dry-salting or rubbing dry salt on the surface of the cheese over a varying period of time is one type of salt use in cheese manufacture and dependent on the salt level desired in a particular cheese. Blue cheese and Roquefort cheeses are dry salted in this manner. Most U.S. cheese is curd salted.

Salt provides a hostile environment for certain microorganisms. In foods, salt brine dehydrates bacterial cells, alters osmotic pressure, and inhibits bacterial growth and food spoilage. Salt and brine have been used in different food curing processes. Pickles, are preserved in strong brine prior to final processing. In butter manufacturing, salt acts bacteriologically and chemically to influence the keeping quality and flavor of butter. At refrigerated temperatures, the growth of molds, yeasts, and bacteria shows a decided increase in unsalted butter. In salted butter, the growth of yeast and bacteria is greatly decreased, while the growth of mold is markedly reduced. At room temperature, the keeping qualities and flavor retention of salted butter are superior to those of unsalted butter.

Salt acts as a texture aid in bread and pastries by strengthening gluten in bread dough, providing uniform grain, texture, and dough strength. Then gluten is able to hold more water and carbon dioxide, allowing the dough to expand easily. Salt also provides a smooth, firm texture to processed meats. Salt develops a characteristic rind hardness in cheese and aids in producing cheese's even consistency, as well as working similarly in sauerkraut.

In baked goods, salt controls fermentation (qv) by slowing down yeast activity, preventing uncontrolled fermentation, and is important in making a uniform end product. In pickling, salt brine concentration is often increased to reduce the fermentation rate as the process proceeds to completion.

10.2. Iodized Salt. In 1924, the Michigan State Medical Society and salt producers collaborated to iodize table salt in Michigan as a means of providing supplemental iodine in the diet (32). Iodine deficiency disorders (IDD) were prevalent in certain regions of the United States at that time. This cooperative, voluntary effort of salt iodization led to the virtual eradication in the United States of iodine deficiencies, such as preventable mental retardation and impaired psychomotor development in young children, a risk factor in stillbirth and miscarriage for pregnant women, cretinism, goiter, impaired mental growth and development, reduced intellectual ability, squint, and impaired work performance. More than 50% of the table salt sold in the United States is iodized. Iodine is added as potassium iodide in table salt at levels of 0.006–0.01% KI. Potassium iodide is one of two sources of iodine permissible by the FDA. The other supplement, cuprous iodide, is not used by U. S. salt producers, probably due to its increased cost when compared to potassium iodide. Animal feeds are enriched with iodine in the form of potassium iodate. Countries other than the United States also use the more stable compound, potassium iodate, for table salt iodization. Use of potassium iodate in the United States is not approved for human consumption. The FDA permits iodine levels in salt to provide daily intake levels not to exceed 225 μg micrograms for adults and children >4 years of age. Potassium iodide is unstable under conditions of extreme moisture and temperature, particularly in an acid environment. Sodium carbonate or sodium bicarbonate is added to increase alkalinity, and sodium thiosulfate or dextrose is added to stabilize potassium iodide. Without a stabilizer, potassium iodide is oxidized to iodine and lost by volatilization from the product.

Today, iodine deficiency is still a serious concern on a global level. Many less developed countries do not iodize their salt or, if they do, the amount may not be at sufficient or consistent levels. Another problem is the lack of understanding about the nature of IDD disorders and how to prevent them. Many underdeveloped countries continue to buy locally produced salt because of tradition and convenience, not knowing that these products might not provide any iodine protection. Even in more industrialized countries, there is an increase once again in the levels of reported immune deficiency disorders. This may be due, in part, to the increased dependence on processed foods that may or may not contain iodized salt. The International Council for Control of Immune Deficiency Disorders (ICCIDD) works in conjunction with UNICEF and the Salt Institute (the U.S. association of global salt producers) to promote global iodization to eradicate this easily eradicated deficiency disorder.

Salt is also used as a carrier for other nutrients such as fluoride and iron in countries such as Mexico, France, and Switzerland. Fluoride is added for the prevention of dental caries, while iron is added for hemoglobin levels in countries having poor nutritional diets.

10.3. Agriculture. The earliest civilizations were aware that salt is needed by every animal. Farmers and hunters observed animals grazing by salt springs or salt deposits to satisfy their need for salt. Sodium is needed by all animals for normal metabolism. Muscle contraction requires sodium presence. The ion is involved in the transport of organic materials across cell membranes, as well as playing an important role in nerve impulse transmission and maintaining a heart rhythm. Most forages provide insufficient sodium for animal feeding and may lack adequate chloride. Therefore, salt supplementation is a necessary and critical part of a nutritionally balanced diet for animals. A lack of sufficient levels of sodium intake can affect animal health through loss of appetite and weight. Chloride is also required in animals to maintain the acid–base balance in the blood. Because animals naturally crave salt in their diet, salt can be used as a delivery mechanism for additional mineral supplementation, especially for less palatable nutrients. Salt can also be used as a feed limiter. Forage with salt added increases the appetite, and animals having salt available generally gain twice as much weight as animals fed no sodium chloride. Use of salt stations in pasture helps to distribute grazing throughout the area. Lack of sufficient chloride in the diet of chicks has caused poor growth rate, high mortality, nervous symptoms, dehydration, and reduced blood chloride levels.

Either in loose form or in compressed blocks, trace mineral salt can be mixed with feed or fed free-choice to improve animal health and productivity. The intake of salt and trace minerals is animal-specific. Especially with trace mineral salt, it is advisable to consult agricultural nutritionists before feeding. Some of the trace minerals fed as a salt additive are iron oxide, copper, manganese, selenium, cobalt, iodine, zinc, and magnesium. Phosphorous, calcium, sulfur, and some vitamins, such as A and D, are frequently added to salt as well. Also, salt has been used as a carrier to administer drugs like oxytetracycline, ionophores (ie, monensin and lasalocid) or anthelmintics (deworming agents).

10.4. Highway. Rock salt, solar salt, and to some degree, evaporated salt are used to maintain traffic safety and mobility during snow and ice conditions in snowbelt regions worldwide. The use of salt in sunbelt regions is a relatively new but necessary method for maintaining the economic viability and safety for these locales, for there are many communities and roadways that have received devastating winter weather events that bring commerce to a halt and impact the number of traffic accidents. Sodium chloride melts ice at temperatures down to its eutectic point of −21.12°C. Most snowstorms occur when the temperature is near 0°C, where salt is very effective. Salt is used on highways in three ways:

(*1*) deicing by application of dry salt; (*2*) prewetting salt or other deicing materials or abrasives with nearly saturated salt brine; and (*3*) anti-icing prior to the beginning of a winter weather event by spraying nearly saturated brine on the dry pavement. The brine dries leaving sodium chloride on the pavement and its presence prevents a bond from forming between the snow or ice and the pavement when the weather event occurs. More than 40% of dry salt produced in the United States is used for highway deicing.

10.5. Water Conditioning. In different areas of the world, well water and many public drinking water supplies contain elevated levels of calcium, magnesium and other minerals. Calcium and magnesium salts as chlorides and carbonates reduce the sudsing action of soaps and detergents and the water that causes this phenomen is known as hard water. When water is soft, soap lathers freely and immediately. Ample suds are formed with a minimum amount of soap or detergent. The use of such hard water causes a greasy, curd-like deposit when laundering clothes, cleaning, and bathing. The objectionable soap curd is formed when the soluble form of soap, sodium stearate, is converted to insoluble calcium stearate and precipitates. Magnesium ions react in the same manner. Mineral scale builds up in hot water appliances, such as water heaters and coffee pots, and industrial boilers, reducing energy efficiency and shortening appliance and equipment life. The ring found in bathtubs after bathing is formed from curds, scum, and soap in the presence of these hard water cations. The gray cast on white fabrics also is caused by the presence of carbonates of calcium and magnesium. Hardness ions also react chemically to toughen vegetables, injure color shades in textile dyeing, and form a hard scale in boilers of power plants.

The hardness of natural water will vary considerably depending on the source of the water. Rainwater is considered soft water because it contains no minerals attributed to hardness. Once rain soaks into the ground, it begins to dissolve some of these hardness minerals, and eventually these minerals accumulate in underground aquifers. Well water from areas containing limestone ($CaCO_3$) formations will have high hardness due to the gradual solution of the limestone. Magnesium will be dissolved from formations containing magnesite ($MgCO_3$) and dolomite ($MgCO_3.CaCO_3$). Water is softened by removing calcium and magnesium ions from hard water in exchange for sodium ions at sites on cation-exchange resin. Ion exchange involves the reversible interchange of ions between a solid and a liquid. Water softeners frequently use a gel or bead-like polystyrene sulfonate cation-exchange resin for regeneration with salt brine solution (33). Sodium sulfate (NaSO4) and sodium chloride (NaCl), which are water soluble, are formed as by-products in the ion exchange process. If the exchanger material is indicated as X, a typical exchange process can be demonstrated by the equation

$$\mathrm{CaSO4} + 2\mathrm{NaX} \rightarrow \mathrm{Na_2SO_4} + \mathrm{CaX_2}$$

This equation demonstrates that there has been an interchange of sodium and calcium ions. The exchanger material, X (eg, polystyrene sulfonate cation-exchange resin) has absorbed the calcium ions from the water and has exchanged them for sodium ions. The sulfate ions, which remain in the water, are unaffected and are not objectionable from the standpoint of hardness. The role of salt in this process is regeneration of the resin bed. When the sites for sodium exchange are depleted and filled with calcium, magnesium, and other impurities from the untreated water, saturated brine is washed through the resin bed, displacing these impurities and restoring the resin bed to the sodium form. Many types of home water softening equipment exist on the market. Some units have a brine tank as part of the unit where salt is added to produce a saturated brine solution. There are water softener systems available that are serviced by dealers who exchange the spent units with units that have been fully regenerated at the dealership (Table 8).

For home use, a water softener is considered properly functioning if the output has a total hardness level of <17.1 ppm (mg/L) or 1 grain per gallon. The total hardness value is obtained by adding together the calcium and magnesium test levels. For industrial purposes, such as laundries and boiler water, 10 ppm total hardness is considered sufficiently low for economic and operating considerations. Brine system water softeners have been used successfully to remove or reduce the presence of other metals such as iron, manganese, cadmium copper, zinc, and lead. Since each of these ions is usually present in water in the cationic state, they are capable of being exchanged for sodium in the same manner as the hardness ions (35). Typically, a weak carboxylic acid cation exchange resin is utilized when both water softening and iron (and heavy metals) removal is desired. Acid treatment also can be added by using weak acid-treated salt, usually a phosphoric acid.

There are a variety of sodium chloride salt grades capable of resin bed regeneration. These can encompass higher purity rock salt, solar salt, and compressed evaporated salt. Typically, larger grade particle sizes of rock and solar salt are used in water softener brine tanks. These rock and solar grades are less costly than evaporated products, but they may require more frequent cleanouts of the brine tank to remove insoluble sediment naturally present in the salt. Compressed evaporated salt is available in 50-lb blocks and various sized packages of small briquets called pellets, cubes, pellens, etc. Water softening products produced from evaporated salt tend to be higher in cost; however, the purity level is the highest available, requiring less frequent salt brine tank cleanout due to lower insoluble sediments.

10.6. Chemical Uses. During 2002, 42% of the total salt distributed by producers in the United States was salt in brine produced and used by chemical manufacturers to produce chlorine and caustic soda (9). Demand for salt in chlor-alkali production has fallen steadily since 1974 from 25,900,000 to 18,300,000 t in 2002 (9). Chlorine and caustic soda (sodium hydroxide) have been used by the pulp (qv) and paper (qv) industry in multistage bleaching; caustic soda has been used in wood fiber processing. Environmental concerns by the pulp and paper industry have reduced use of chlorine, contributing to the decline in U.S. chlor-alkali production. In European countries, chlor-alkali producers depend on nearby dry salt sites, rather than risk potential chlorine-transport hazards. Around the globe, salt is still used by the chloralkali industry to make synthetic soda ash, but this process was discontinued in the United States in 1986.

10.7. Industrial Uses. It would be difficult to list all of the thousands of industries that use salt as a raw material or ingredient. However, the major industries include the textile and dyeing industry where salt is used to fix dyes and to standardize dye batches; metal processing, such as aluminum refining, where salt is used to remove impurities; rubber manufacturing, to separate the rubber from latex; detergent production, where salt is used as a filler; pigment manufacture, as a grinding agent; ceramics manufacture, where salt acts to vitrify heated clays; soap making, where salt separates glycerol from water; oil and gas drilling, where salt is used to produce a drilling mud that prevents widening of bore holes in rock salt strata, inhibits fermentation, and increases mud density; pharmaceuticals, where salt is used for tablet and caplet polishing (36), the production of intraveneous saline solutions and for manufacturing hemodialysis solutions used for kidney machines; and in animal hide processing and leather tanning, where salt is used to cure, preserve, and tan hides.

10.8. Salt Substitutes. For the population who must restrict their sodium intake, many salt producers and several food processors have developed salt substitutes and low sodium alternatives to regular table salt. The most common salt substitute on the market is potassium chloride, which has a bitter, less salty taste than sodium chloride and is more expensive than sodium chloride (table) salt. Among the salt alternatives are several types: (*1*) a mixture of sodium and potassium chlorides that effectively reduces the amount of sodium added at the table and in home cooking is readily available in groceries throughout the United States; (*2*) a modified salt crystal of lower density that provides less salt by volume to cooked dishes and to food at the table; and (*3*) mixtures of herbs, flavorings, and spices that are marketed as a substitute for adding salt seasoning to foods.

10.9. Encapsulated Salt. Sodium chloride can be added in controlled release by encapsulation; a process that coats salt crystals with partially hydrogenated vegetable oil. Encapsulated salt is used primarily in food processing applications. The controlled release feature can be applied to deliver nutrients on a salt carrier. Encapsulation delays or prevents salt particles from dissolving in water until a suitable temperature or pH is attained and thus can protect against undesirable reactions. Coated salt can permit yeast activity, inhibit oxidative rancidity, and control precise water binding when needed in a process. It is used in meat products, baked goods, snack foods, seasoning blends, microwaveable products, and other foods where salt dissolution should be delayed until the product is reheated or digested.

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Fig. 1. Principal salt deposits and dry salt production sites in North America, where ■ represents the salt deposits and □, ×, and ○ correspond to evaporated, rock, and solar production sites, respectively. Sites in Canada, listed by company name (location), are Alberta, □, Canadian (Lindberg); Saskatchewan, □, Sifto/Namsco (Unity) and Canadian (Belle Plaine); Ontario, □ and ×, Sifto/Namsco (Goderich); □, Canadian (Windsor); ×, Canadian (Ojibway); New Brunswick, ×, Potash Corp. of Saskatchewan (Sussex); and Nova Scotia, □ and ×, Canadian (Pugwash) and Mines Seleine (Quebec), and, □, Sifto/Namsco (Amherst). Sites in the United States are Michigan, □, Morton (Manistee), and Akzo Nobel (St. Clair); New York, ×, Cargill (Lansing); □, Akzo Nobel (Watkins Glen), Cargill (Watkins Glen), and Morton (Silver Springs); Ohio: × Morton (Fairport) and Akzo Nobel (Cleveland); □, Akzo Nobel (Akron) and Morton (Rittman); California, ○ and □, Cargill (Newark); □, Morton (Newark); ○, Cargill (Redwood City), Pacific Salt & Chemical (Trona), Cargill (Amboy), Salt Products Co. (Milligan), and Western (Chula Vista); Nevada, ×, Huck (Fallon); Utah, ○, Namsco (Ogden), Akzo Nobel (Timpie), Morton (Grantsville), and Moab (Moab); ×, Redmond Clay & Salt (Redmond); Kansas: ×, Independent (Kanopolis), Lyons (Lyons), and Hutchinson (Hutchinson); □, Namsco (Lyons), Namsco (Hutchinson), Morton (Hutchinson), and Cargill (Hutchinson); Arizona, ○, Southwest/Morton (Glendale); New Mexico, ○, Zuni (Quemado) Don McKibben Trucking (Carlsbad), United (Carlsbad), New Mexico Salt & Minerals (Loving), and Sunwest Salt (Malaga); Oklahoma, ○, Cargill (Freedom); Texas, □ and ×, Morton (Grand Saline); ×, United (Hockley); □, United (Blue Ridge); and Louisiana, □, Cargill (Breaux Bridge); ×, Akzo Nobel (Avery Island) and Namsco (Cote Blanche); and □ and ×, Morton (Weeks Island), Tennessee, Namsco (New Johnsonville). Sites in Mexico are Baja California, ○, Sales de Ometepec (Mexicali); Sonora, ○, Salinas de Lobos (Ciudad Obregòn), Compañia Salinera de Yavaros (Navojoa), and Salinera del Mayo (Navojoa); Coahuila, ○, Salinera Coahuila (Torreòn) and Salinas del Rey (Torreon); Nuevo Leòn, ○, Distribuidora y Envasadora de Productos de Sodio (Monterrey), Empacadora Abelardo Martinez (Monterrey), and Industria del Alcali (Monterrey); Tamaulipas, ○, Salinera la Boladeña (Matamoros) and Salex (Tampico); Baja California Sur, ○, Exportadora de Sal (Guerrero Negro); Sinaloa, ○, Imprenta Mochis (La Mochis), Abelino Lopez Mejia y Socios (Angostura), Salinas de Elota (Culiacàn), Expendio de Sal Herlinda Medina (Culiacàn), Sociedad Cooperativa de Produccion Salinera Montelargo (Culiacàn), Sociedad Cooperative Industrial Salinera (Culiacàn), and Molino de Sal Casa Blanca (Mazatlan). Offshore sites are ○, Morton (Inagua, Bahamas), and Akzo Nobel (Bonaire, Netherlands Antilles). Courtesy of the Salt Institute.

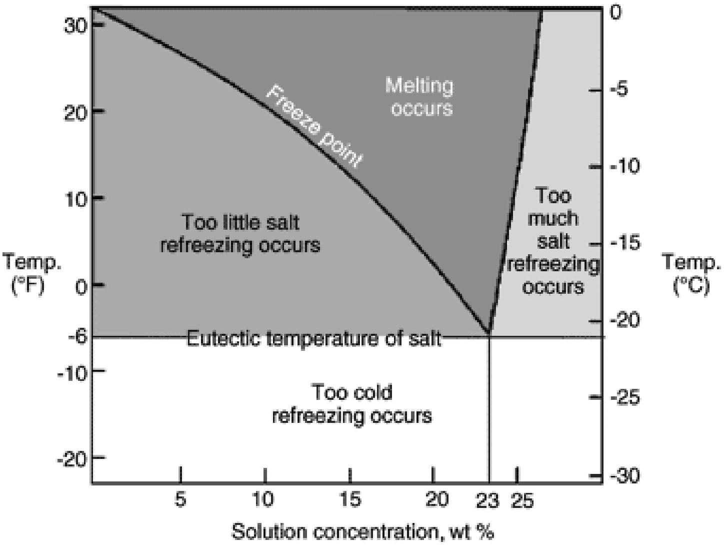

Fig. 2. Phase diagram for salt. The system sodium chloride—water, showing the eutectic temperature, −21.12°C, and composition, 23.31 wt % NaCl.

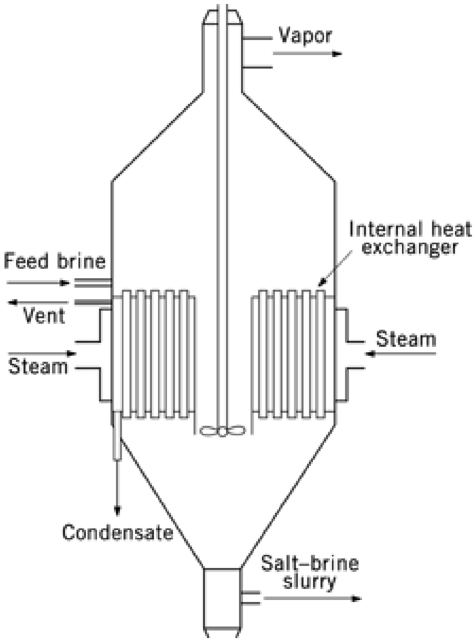

Fig. 3. Calandria evaporator.

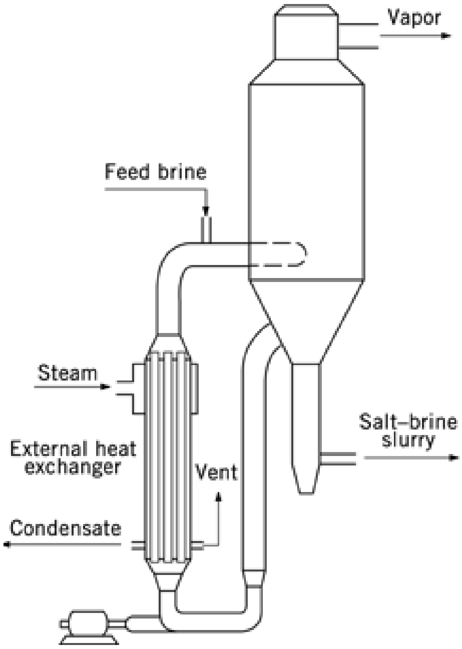

Fig. 4. Forced-circulation evaporator.

Table 1. **Seawater Composition**

Component	Wt %	Component	Wt %
sodium chloride	2.68	potassium chloride	0.07
magnesium chloride	0.32	sodium bromide	0.008
magnesium sulfate	0.22	water	96.582
calcium sulfate	0.12		

Table 2. **Properties of Pure Sodium Chloride**

Property	Value
molecular weight	58.44
crystalline form	cubic
color	clear to white
index of refraction, n_D^{20}	1.5442
density or specific gravity, g/cm^3	2.165
mp, °C	801
bp, °C	1413
hardness, Mohs' scale	2.5
specific heat, J/(gK)[a]	0.853
heat of fusion, J/g[a]	517.1
critical humidity at 20°C, %	75.3
heat of solution, 1 kg H_2O, 25°C, kJ/mol[a]	3.757

[a] To convert J to cal, divide by 4.184.

Table 3. **Solubility of Pure Sodium Chloride**

Solvent	Temperature, °C	NaCl, g/100 g solvent
ethanol	25	0.065
ethylene glycol	25	7.15
formic acid	25	5.21
glycerol	25	10
hydrochloric acid		insol
liquid ammonia	−40	2.15
methanol	25	1.40
monoethanolamine	25	1.86
water	0	35.7
	100	39.12
	120	39.8

Table 4. **Specifications Applying to the Salt Industry**[a]

Type spec.	Title	Designation	Jurisdiction
analysis	*Standard Methods for Chemical Analysis of Sodium Chloride*	ASTM-E-534-98 (2003)	American Society for Testing and Materials (ASTM)
food	*Sodium ChlorideMonograph*	*Food Chemicals Codex* (FCC) 5th ed., 2004	Food and Nutrition Board, Institute of Medicine *of the National Academies*
	Standard for Food-Grade Salt	*Codex Alimentarius*	*Codex Alimentarius* Commission
	Salt	AOAC 925.55, 17th ed., 2003	AOAC International, Official Methods of Analysis
highway use	*Standard Specification for Sodium Chloride*	ASTM-D-632-01	American Society for Testing and Materials
	Standard Specification for Sodium Chloride	AASHTO-M-143-03	American Association of State Highway Transportation Officials
	Handbook of Test Methods for Evaluating Chemical Deicers	SHRP-H-332	Strategic Highway Research Program
medical, pharmaceutical	*Official Monograph on Sodium Chloride*	*United States Pharmacopeia, 26*, 2004	United States Pharmacopeia Convention, Inc.
reagent	*Sodium Chloride*	*Reagent Chemicals*, 9th ed., 2000	American Chemical Society
soil Stabilization	*Standard Test Methods for Water-Soluble Chlorides Present as Admixes in Graded Aggregate Road Mixes*	ASTM-D-1411-04	American Society For Testing and Materials
table salt	*Salt, Table, Iodized*	A-A 20041B	United States Department of Agriculture (USDA)
water	*Federal Specification Commercial Item, Description, Sodium Chloride, Technical (Water Conditioning Grade)*	A-AZ-694	General Services Administration
	AWWA Standard for Sodium Chloride	ANSI/AWWA-B200-03	American Water Works Association

[a] Information courtesy of the Salt Institute website, `www.saltinstitute.org`.

Table 5. **World Salt Production**[a,b]

Country	1998	1999	2000	2001	2002
United States[c]	41,300	45,000	45,600	44,800	40,300
Australia	9,033	9,888	8,778	9,536	9,887
Canada	13,296	12,686	12,164	13,725	12,313
China	22,420	28,124	31,280	34,105	32,835
France	7,000	7,000	7,000	7,000	7,000
Germany	15,700	15,700	15,700	15,700	15,700
India	11,964	14,453	14,453	14,503	14,503
Mexico	8,412	8,236	8,884	8,501	8,500
Netherlands	5,500	5,000	5,000	5,000	5,000
United Kingdom	6,600	5,800	5,800	5,800	5,800
other	58,775	58,113	57,341	58,330	58,162
world totals	*200,000*	*210,000*	*212,000*	*217,000*	*210,000*

[a] Courtesy of U.S. Geological Survey.

[b] $t \times 10^3$ includes salt in brine.

[c] Including Puerto Rico.

Table 6. **Salt Sold or Used in the United States by Product Type and Form in 2002.**[a] **Quantity**[b]

Product type	Vacuum/ open pans	Solar	Rock	Brine	Total
bulk	759	1,460	11,000	19,300	32,500
compressed pellets	1,280	353	[c]	[c]	1,640
packaged	1,840	964	342	[c]	3,150
pressed blocks	185	121	82	[c]	388
grand totals	4,070	2,890	11,400	19,300	37,700

[a] Data courtesy of the U.S. Geological Survey, 2004. See Ref. 13.

[b] $t \times 10^3$.

[c] Not applicable.

Table 7. **Comparative Salt Compositions in the United States**

	Louisiana	New York	Michigan	Ohio	Kansas
NaCl	99.01%	98.24%	98.08%	97.87%	97.27%
$CaSO_4$	0.84	1.48	1.55	1.84	2.22
$CaCO_3$	0.10	0.05	0.11	0.11	
$MgCO_3$	0.01	0.06	0.06	0.06	0.19
SiO_2	0.02	0.11	0.03	0.04	0.23
Fe_2O_3	0.00	0.04	0.01	0.01	0.01
H_20	0.02	0.02	0.16	0.07	0.08

Table 8. **Water Hardness Chart**[a]

Grains/gal	ppm, mg/L	Hardness
<1	<17.0	soft
1–3.5	17.1–60	slightly hard
3.5–7.0	60–120	moderately hard
7.0–10.5	120–180	hard
>10.5	180 and over	very hard water

[a] Ref. 34.