ENGINEERING DESIGN OF THE ROSWELL WATER CONVERSION PLANT

Edward H. Lebeis, Jr.[1/]

This paper describes the saline water conversion plant located at Roswell, New Mexico. This plant, with an output capacity of one million gallons of fresh water per day, is the fourth of the demonstration plants authorized by the Office of Saline Water of the U. S. Department of the Interior, under Public Law 85-883. The selection of Roswell as the plant site was made by a board empaneled by the Office of Saline Water (OSW), and the OSW had stipulated that this plant employ a forced circulation vapor compression distillation process.

Catalytic Construction Company was engaged by the OSW as the engineering design contractor late in 1960. Under this contract, Catalytic's primary responsibilities were to establish the conceptual process design and to prepare definitive drawings and specifications as a basis for competitive bidding for the plant construction contract. The final design drawings and specifications were issued by the OSW in the fall of 1961, and the construction contract was awarded in the spring of 1962.

While the vapor compression process is not new, relatively few large scale plants have been built incorporating this feature and none with a capacity as large as one million gallons per day. This is the first high capacity plant to couple series staging of evaporators with vapor compression. Another distinctive feature of this plant is that it is designed for a brackish water feed which is probably the most difficult to handle of any water ever to be fed to a conversion plant. The concentration of the calcium sulfate (gypsum) can reach very high levels. The natural tendency is for much of this gypsum to deposit on the heated surfaces. In the Roswell installation, the problem of fouling of heat exchange surface with calcium sulfate scale is avoided by ion exchange pretreatment of the feed brine. This represents the first large-scale adaptation of this technique to this problem. An alternative scale prevention technique is also incorporated--recycling of calcium sulfate crystals, generally referred to as the sludge recycle technique.

In the following sections the major design problems are discussed, with particular emphasis on those problems arising from the water composition and from the fact that this is an inland

1/ Process Designer, Catalytic Construction Company, Philadelphia, Pennsylvania.

installation. Following this, the process is described and the reasons are given for the selection of various features of the design. Lastly, the efficiency of this process is treated.

DESIGN PROBLEMS

Feed Brine Composition

The feed to the vapor compression plant is drawn from a well near the eastern edge of the plant site. Emerging at the well head, it has the current analysis shown in Table I. The total dissolved salts content is 16,000 parts per million (1.6 weight per cent). While common salt, sodium chloride, is the major constituent, accounting for about 80% of the total salinity, the bulk of the remainder consists of calcium and magnesium sulfates. Calcium and magnesium bicarbonates (alkalinity) represent minor constituents; nevertheless, almost all of this can decompose thermally to form a scale of calcium carbonate and magnesium hydroxide on heat transfer surfaces.

At the time that the engineering design work was in progress, the supply well had not yet been drilled. Based upon the analyses of test wells available then, the plant design was set up to handle water with total concentrations up to 24,000 parts per million of total salts. Thus, a considerable increase in salt content can be tolerated without prejudicing the operation of the conversion plant. The design analysis is also shown in Table I.

The brackish water feed analyses, both design and current, are compared with normal sea water in Table II. Although Roswell water has only one-half to two-thirds the salinity of sea water, it is richer in scale formers. According to the current analysis the calcium content is 35% higher than that of sea water, sulfate is 43% lower, and bicarbonate is 75% higher. Although sea water has a very much higher magnesium content, this is of minor significance since magnesium sulfate is very soluble.

Should the total salinity reach the value on which the plant design is based, the calcium content would be more than twice that of sea water, and the sulfate content about 20% higher than that of sea water. This water is essentially saturated with respect to calcium sulfate, so that scaling could take place upon evaporation of only a small amount of water.

When operating at a concentration factor of 4 (75% potable water yield) the scaling potential of Roswell brine is about 5 tons per day based on the current feed analysis. The corresponding figure is 10 tons per day based on the design feed analysis. This is the quantity of calcium sulfate, calcium carbonate and

TABLE I

ANALYSIS OF ROSWELL BRINE

(Units: Parts Per Million)

	Design	Current
Total hardness (as $CaCO_3$)	3,262	2,145
Calcium hardness (as $CaCO_3$)	2,340	1,370
Magnesium hardness (as $CaCO_3$)	922	775
Alkalinity (as $CaCO_3$)	155	202
Chlorides (as Cl)	11,820	8,064
Sulfate (as SO_4)	3,200	1,528
Iron (as Fe)	0.38	Tr.
Silica (as SiO_2)	15	Tr.
Calcium (as Ca)	936	549
Magnesium (as Mg)	224	303
Sodium (as Na), by difference	7,780	5,000
Total dissolved solids	24,470	15,860
pH	7.1	7.4

TABLE II

COMPARISON OF ROSWELL WATER AND SEA WATER

(Units: Equivalents Per Million)

	Sea Water	Roswell Design	Roswell Current
CATIONS			
Sodium & Potassium	478	339	214
Magnesium	106	18	25
Calcium	20	47	28
Total	604	404	267
ANIONS			
Chloride	545	334	227
Bicarbonate	2.3	3.1	4.0
Sulfate	56	67	32
Total	603.3	404.1	263

magnesium hydroxide which could precipitate on heat exchange surfaces if adequate preventive measures were not incorporated in the design.

Although this brackish water is more difficult to process than sea water, there are several reasons to justify a conversion plant based on this type of feed.

First, heavily mineralized waters of this type occur widely, not only in the arid regions of the Southwest, but also in a broad belt extending up into the Dakotas. With the ever-increasing demand for water, it becomes more and more necessary to utilize this kind of water.

Second, these saline ground waters are encroaching upon fresh water supplies. At Roswell, two artesian aquifers oppose each other (1). Municipal water is drawn from a relatively pure aquifer flowing from the west. With increasing consumption, more saline water flowing underground from the east is entering the city supply. When the Roswell site was picked by the independent selection board, it was noted that a conversion plant located here would be of benefit in two ways. On one hand, the consumption from the municipal supply would be decreased by one million gallons a day, thereby increasing the hydrostatic head in the fresh aquifer. On the other hand, the withdrawal of saline water for feed to the conversion plant would decrease the head in the brackish aquifer.

A final reason for this selection may be found in the comments of several water experts to the effect that if this water can be converted successfully, then almost any water can be handled in a distillation, or evaporation, plant.

Inland Plant Location

Almost all of the saline water conversion plants in existence operate on a sea water feed. A notable exception is the OSW demonstration plant in operation at Webster, S. D. This is an electrodialysis plant of lower capacity with a feed of much lower salinity.

It does not take the designer of an inland plant long to encounter a somewhat distressing fact--there is no extraneous cooling water. While a sea water plant has available an unlimited supply of cooling water at a low temperature, an inland plant has only its feed water.

It will be seen that the favorable economics of the vapor compression cycle depends in large measure upon efficient exchange of heat between the hot products and the cold feed. Nevertheless, there are times when it would be desirable to have an outside source of cooling water, such as when one is considering a condensing steam turbine drive for the vapor compressor.

While the sea is a convenient repository for the concentrated brine blowdown from a sea water conversion plant, an inland site has no sea. At Roswell, the blowdown is pumped to evaporating ponds for disposal. It is obvious that the smaller the quantity of blowdown, the less the disposal problem.

The volume of blowdown brine is an inverse function of the concentration factor. This is the ratio of the weight of feed brine to that of the blowdown. It is also the ratio of the concentration of salts in the blowdown to that in the feed.

With a brine feed rich in salts, an upper limit on concentration factor is imposed by boiling point elevation. This represents a thermodynamic inefficiency which makes increasing amounts of the energy supplied to the process unavailable as the final salt concentration rises.

The maximum concentration factor is dictated not only by boiling point elevation, but even more by scaling considerations. Although scale formation can be prevented by the use of ion exchange up to a concentration factor of 4, there is a concentration factor limit past which this technique will not be effective.

PROCESS DESCRIPTION

The vapor compression plant is designed to operate with either of two methods of scale prevention. The process will be described for both methods. A simplified process flowsheet is shown in Figure 1 appended.

Ion Exchange Process

In the first step of this process the feed brine exchanges a major portion of its calcium for sodium in an ion exchange unit. This operation is identical to the well-known softening of water with zeolites. The brine is then warmed to about 145°F by heat exchange with product water and blowdown, followed by acidification to break down bicarbonates. Carbon dioxide and dissolved gases are removed under vacuum in the degasifier. The effluent brine is then neutralized and further heated by exchange with product water and blowdown.

Having reached a temperature at which the evaporator system can operate at thermal equilibrium, the feed brine is introduced into the first evaporator. In each evaporator about 90,000 gallons of water per minute is constantly recirculated by an axial-flow pump. The flow is from the vapor body down to the pump and then up through the tubes of the evaporator heat exchanger, emerging again in the vapor body. A high liquid level is maintained in the vapor body. This imposes sufficient hydrostatic head on the liquid that boiling cannot occur in the tubes. Boiling can, and does, occur as the hot liquid rises up into the vapor body.

Approximately, 250 pounds of water is recirculated for every pound vaporized. The water temperature rises 4°F as it passes through the heater tubes. After leaving the tubes, the excess heat represented by the 4°F temperature rise is absorbed by the boiling operation, with the unvaporized liquid returning to the original temperature before starting upon another recirculation through the pump and heater.

Reduced to essentials, the heat required to vaporize one pound of water is supplied by cooling 250 pounds of water 4°F. The 250 pounds is then reheated 4°F by pumping it through the evaporator heater.

The heat taken up by the water is obtained from the condensation of steam on the outside of the tubes in the evaporator heater. The steam condenses at a temperature slightly higher than the temperature of the water in the tubes.

The steam produced in the first evaporator is separated from the unvaporized water in the vapor body, which is a large chamber designed to effect the separation with a minimum of entrainment of liquid in the steam.

From the vapor body of the first effect, the generated steam flows to the steam chest of the heater of the second effect evaporator. Here it condenses on the outside of the tubes in that heater, transferring its heat to the water circulating through the tubes. The heating and boiling operation in the second effect is identical to that described for the first effect, except that the temperatures and pressures are lower.

In order to recover the major portion of the heat energy of the steam generated in the second effect, the steam temperature and pressure must be raised. This is the function of the vapor compressor. This machine compresses 75,000 cubic feet per minute of steam from 2 pounds per square inch gauge to 8.5 pounds per square inch gauge. The higher pressure steam discharged by the compressor condenses in the first effect evaporator heater, furnishing the heat for evaporation in that effect.

Partly concentrated brine is withdrawn at a regulated rate from the recirculating stream in the first effect evaporator and added to the recirculating stream in the second effect. These two rates and the rate of admission of preheated feed are set so as to maintain a constant liquid level in the evaporator bodies.

The hot concentrated brine leaving the evaporation system is termed blowdown. Its sensible heat content is recuperated in large measure by heat exchange with a portion of the feed brine, the feed brine becoming heated and the blowdown becoming cooled. The cool blowdown is used to regenerate the ion exchange resin after which it is pumped to the disposal pond.

The other hot stream leaving the evaporators is the essentially pure water resulting from the condensation of steam in the steam chests of the two evaporators. The heat content of this condensate is also largely recuperated by exchange with another portion of the feed brine. Leaving the heat exchangers, the cooled condensate becomes the potable product water. According to the plant specifications, this product water must contain less than 50 parts per million of solids.

Sludge Recycle Process (Alternate Method of Scale Prevention)

When the sludge recycle system is in operation, the feed brine bypasses the ion exchange system. With the sludge recycle technique, calcium sulfate crystals are maintained in suspension in the brine at all points of the system where supersaturation with respect to calcium sulfate can be encountered.

The crystal suspension, or "sludge," is introduced downstream of the degasifier. A sludge concentration of about 1% by weight is maintained in the first evaporator effect. Leaving the second effect, the blowdown contains about 4% sludge. After exchange of heat between the blowdown and the feed brine, about 80% of the crystals are recovered. Following grinding to bring the particle size distribution within the desired range, the crystals are returned to the preheat and evaporation system. The unrecovered crystals flow to the disposal pond along with the blowdown.

DISCUSSION OF MAJOR OPERATIONS

Ion Exchange

The amount of calcium that must be removed is a function both of the concentration factor and of the temperature in the final effect of evaporation where the calcium content is highest. At a concentration factor of 4 (4 parts feed to 1 part blowdown) up to 75% of the calcium in the feed brine must be replaced by sodium to avoid precipitation of calcium sulfate. At a factor of 3, the corresponding value is about 65%.

The most interesting feature of the ion exchange system is the use of the evaporator blowdown for regeneration of the ion exchange resin. At first glance this would appear impossible because the blowdown contains exactly the same quantity of chemical constituents as the "softened" brine leaving the ion exchange system. The only difference is that about 3/4 of the water has been removed so that the concentration of each chemical in the blowdown is four times as great as in the "softened" ion exchange effluent.

The equilibrium relationship between calcium and sodium ions in the brine and calcium and sodium ions held by the resin is markedly affected by total salt concentration. It is this factor which makes it possible to regenerate with the concentrated blowdown.

This ion exchange technique had been studied by the Dow Chemical Company in connection with sea water distillation, under contract with the OSW. Because this technique could be so advantageous at Roswell, additional studies using Roswell brine were authorized by the OSW. These studies (2) proved the feasibility of ion exchange pretreatment on both laboratory and pilot plant scale. In the pilot plant, 20,000 gallons of Roswell water were fed to a vapor compression still. No calcium sulfate scale formed, and regeneration with blowdown brine was successful.

Sludge Recycle

The sludge recycle technique was studied experimentally by W. L. Badger and Associates under contract to the OSW. This work was performed in a forced circulation pilot plant. The results (3) showed that calcium sulfate scale would not form at the design conditions for the Roswell plant provided the slurry concentration in the first effect is maintained at or above one per cent by weight when the particle size distribution is maintained in the proper range.

Since only 80% of the solids must be recovered from the blowdown for recycle, the separation system is set up to recover the coarsest fraction, which is easiest to recover. The recovered solids are then reduced to the proper size by grinding.

Evaporation

In the distillation system, the evaporators are arranged in series with forced circulation within each effect, and forward flow of brine from the first to second effect.

Series staging in multiple effects has two advantages. One, it reduces mixing of feed and blowdown and, therefore, permits evaporation of a large part of the water from more dilute solution, resulting in a lower expenditure of work (4). Second, for each pound of steam handled by the compressor and entering the first effect heater, the number of pounds of distilled water produced is approximately equal to the number of effects.

The design specifications permitted a choice between a two-effect and a three-effect system. It was realized that a two-effect system would pose a difficult, but challenging, design problem because of the physical size of the evaporators required. The construction contractor, Chicago Bridge & Iron Co., successfully met that challenge and installed a two-effect system.

An interesting feature of the evaporators is the specification that the effective temperature difference between the condensing steam and the brine in the tubes be in the range 4.5°F to 5.5°F. This is considerably below the range of temperature differences normally employed in evaporators. Since this temperature difference is created by the vapor compressor, specifying a low value minimizes the power consumption of the compressor. The range noted above was determined in an optimizing study involving electronic computation which was made as part of the engineering design effort. The results were in substantial agreement with those of an earlier study for the OSW (5).

Another advantage of the low temperature difference is that it minimizes the possibility of scale formation. It follows that the vapor compression process is a very good choice when heavily mineralized feed must be treated.

VAPOR COMPRESSION AND EFFICIENCY

If the evaporators were rated as boilers, the rating would be 1,320,000 horsepower. The power consumption of the vapor compressor is of the order of 2300 horsepower, which represents less than 2% of the work accomplished in the evaporation system. This gives some idea of the very high efficiency which can be achieved in a vapor compression plant.

Looked at another way, about 1000 BTU's are required to vaporize a pound of water. In the Roswell plant, this is accomplished by the consumption of only 17 BTU's at the shaft of the compressor. A conventional multiple-effect evaporator would require more than 25 effects in series to equal this economy, based on the heat content of the steam consumed.

There are a number of pumps in the plant which also consume power; however, the compressor accounts for about 75% of the total power consumption.

In order to achieve this high degree of efficiency, it is necessary to preheat the brine feed to a temperature close to that in the first effect evaporator. This, in turn, requires very efficient heat exchange between the cold feed and the hot condensate and blowdown. This is achieved by utilization of true counterflow heat exchangers.

SUMMARY

The Roswell forced circulation vapor compression evaporation plant has been designed to produce one million gallons per day of high purity potable water. The brine feed to this plant may well be the most difficult to convert of any because of its high concentration of calcium sulfate. This can form scale on heat transfer surfaces to an extent that the plant could become inoperable.

Two alternate methods of prevention of scaling are incorporated in the design. One is the removal of part of the calcium by ion exchange, using the concentrated blowdown to regenerate the ion exchange resin. The other is the recycling of calcium sulfate crystals to the evaporators.

The Roswell conversion plant represents a synthesis of a number of proven operations into a novel combination characterized by very high efficiency of energy conversion. Several of these operations are being conducted on a size or capacity scale never before achieved.

REFERENCES

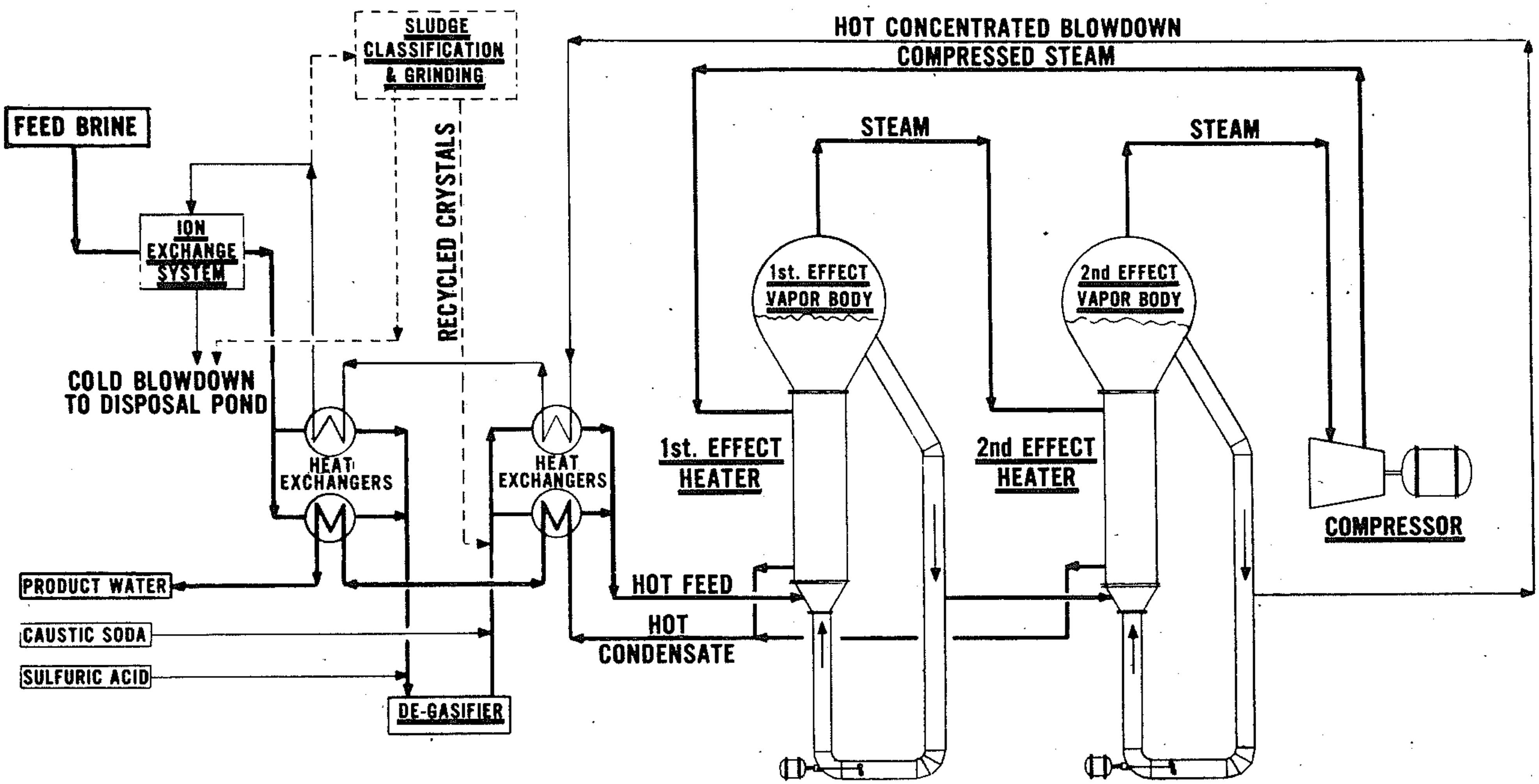
1. J. W. Hood, R. W. Mower, and M. J. Gorgin, "The Occurrence of Saline Ground Water Near Roswell, Chaves County, New Mexico," Technical Report No. 17, New Mexico State Engineer, Santa Fe, New Mexico, 1960.

2. Office of Saline Water, U. S. Department of the Interior, Specifications No. 224, Appendix B.

3. Ibid, Appendix C.

4. J. T. Chambers and P. S. Larsen, "Series of Staging of Vapor Compression Distillation," University of California, Institute of Engineering Research, Berkeley, California, Series 75, Issue No. 20, May 13, 1960.

5. B. F. Dodge and A. M. Eshaya, "Economic Evaluation Study of Distillation of Saline Water by Means of Forced-Circulation Vapor-Compression Distillation Equipment," Office of Saline Water R & D Progress Report No. 21, U. S. Department of the Interior.



SIMPLIFIED FLOW DIAGRAM