# Compression Evaporators

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*ABSTRACT*

*The paper discusses the integration of thermal and mechanical compression evaporation systems with existing salt plant evaporation equipment. The compression evaporators offer increased production capability along with improved economy of operation. The paper also discusses improvement of operating costs and methods for integration.*

*Different kinds of mechanical compression devices both those which are presently available or will be available in the future are introduced, and the economics for the use of these evaporators compared to conventional steam driven evaporation systems is presented.*

## INTRODUCTION

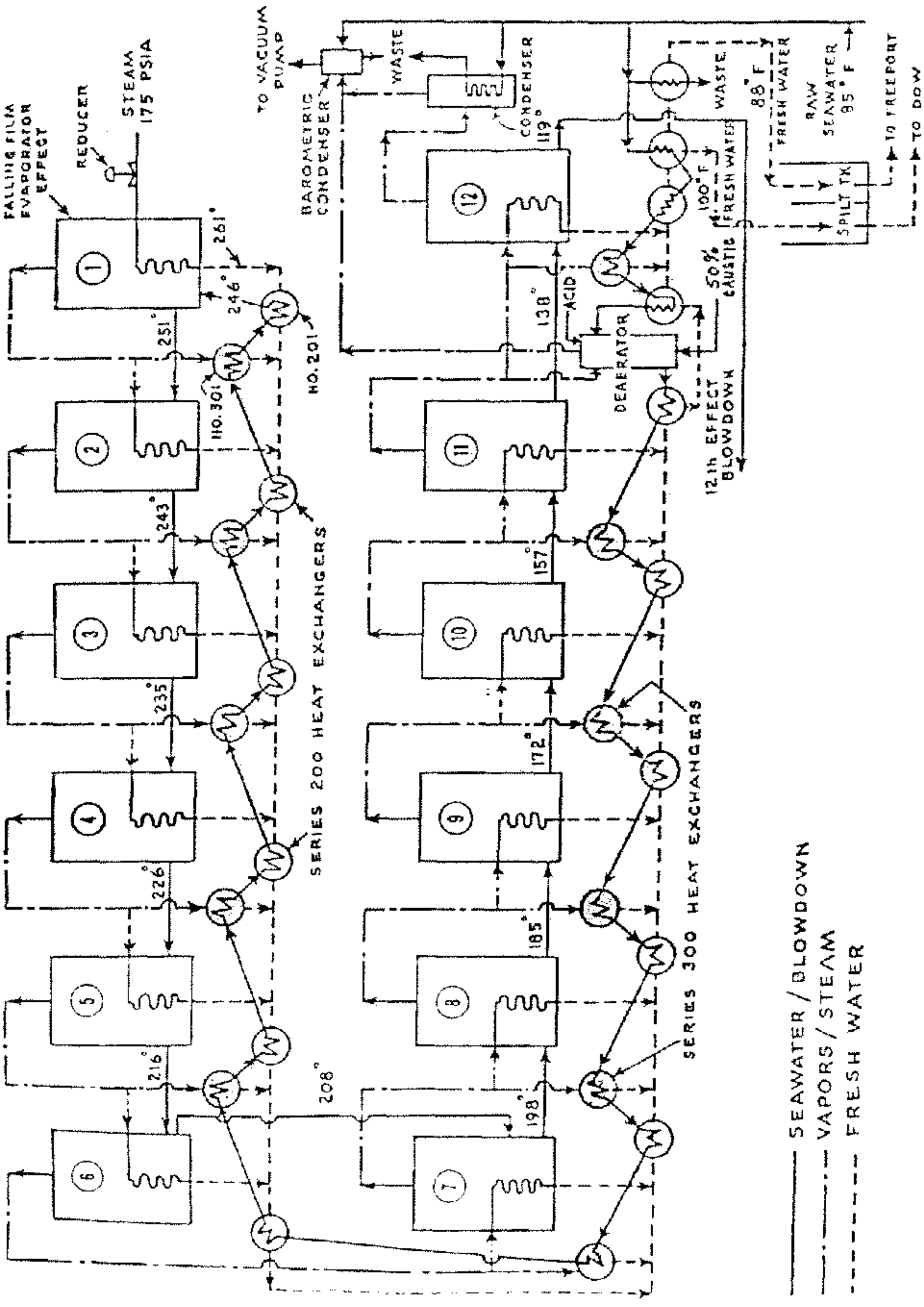
Shortage of energy is a new ailment for our industry, because North American salt plants are notoriously old installations. Equipment, in the evaporative area especially, dates from the turn of the century, with some modernization from the 1940s through the late 1970s. Very little of the modernization, however, was directed toward energy conservation; thus, the plants are running at rather low efficiencies. Salt producers are just now starting to think about improving the efficiency of their plants in the evaporative salt area, and these improvements are still modest in comparison to other industries.

Here it might be well to put these improvements in perspective; that is, to compare the salt industry with other industries in their performance (Figure 1). Saline water conversion plants operate with about a 14-effect economy; the pulp and paper industry, which is by far the biggest user of evaporation equipment in North America, is seriously considering switching from its current sextuple effect arrangements to an 8-effect evaporation system with a steam economy in excess of seven pounds of evaporation per steam pound. It may be compared to that of the typical salt system economy of 2.2 to 3.2 pounds of evaporation per pound of steam. In other words, the economy of these new

ECONOMY OF STEAM-DRIVEN EVAPORATORS

| INDUSTRY | NUMBER OF EFFECTS | STEAM ECONOMY # EVAPORATION/# STEAM | BPR(°F) |
|---|---|---|---|
| SALINE WATER CONVERSION PLANT | 12 FOR EVAP. MULTI-FLASH: 30-40 STAGES | ECO.:OVER 12 | 0.5 - 1 |
| PULP & PAPER INDUSTRY (PRESENT SYSTEMS) | 5-6 | 4.5 - 5.5 | 2 - 17 |
| PULP & PAPER INDUSTRY (FUTURE SYSTEMS) | 7-8 | 6.5 - 8.0 | 2 - 17 |
| SALT INDUSTRY (PRESENT SYSTEMS) | 3-4 | 2.0 - 3.5 | 15 - 24 |

**Figure 1.**




PROCESS FLOW SHEET, pH CONTROL

**Figure 1.** *(continued)*

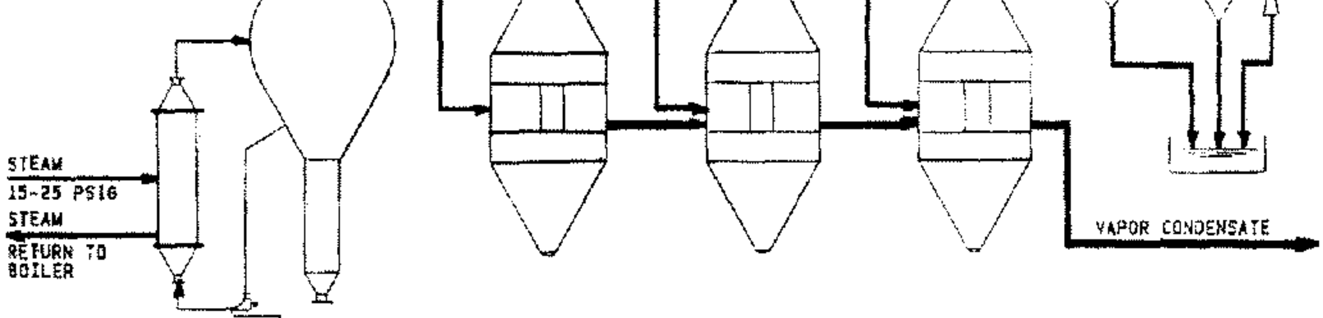
pulp mill systems is about triple that of salt production plants; however, there are some obvious problems where we could not achieve such economy in a steam-driven salt plant.

Part of the economy of the salt plant lies in the reduction of the steam through turbine generators which exhaust to a low pressure for maximum electrical generation. The pulp and paper industry does not use such low back pressure turbines and, thus, recovers somewhat less electricity, making a higher pressure steam available for its evaporation plants. Even with the steam pressure available, as used by the back pressure turbines in the pulp and paper plants, we could not drive an economical and affordable multiple effect, steam-driven evaporation system for salt production larger than a quintuple effect. This is because of the higher boiling point of the salt solution compared to that of the pulp mill liquors. Using the normal back pressure steam from turbines in salt plants, i.e., 10 to 20 PSIG, the largest feasible installation is about a quadruple effect system giving an economy of approximately 3.2 pounds of evaporation per pound of steam. Obviously, with this efficiency, we are far off the mark of what the rest of the industry requires today in terms of energy efficiency.

A further complicating problem faced by the salt industry is the cost of the equipment. Having gone through the exercise a number of times, we know it is difficult to justify the expansion of an existing salt plant with equipment that is constructed of high alloy materials, such as monel, incoloy or inconel, and obtain a reasonable return. Even if the economy would justify such an expansion and even if we could provide a higher steam pressure, or if equipment could be built for lower driving forces, the expenditure on the part of the salt producer would be very high and the recovery period excessively long. Further complication is the use of existing equipment in the design of, for example, a quintuple effect system, because the larger the number of effects in a train, the more surface area is required for each effect to drive it with a lower driving force, or $\Delta T$, and attain the same production capacity of quadruple effect.

To circumvent some of these problems, in the past few years the industry adopted a device commonly known as a "topping pan." Topping pans have been added to existing systems, usually calandria evaporators, which acted as steam reducing stations. The "topping pan" receives the full available steam pressure and, in turn, supplies the reduced pressure to the existing double or triple effect system. By the use of this method, the existing evaporators maintained, by and large, their previous capacity, while the topping pan was able to bring the capacity up to, or even exceed, that of the formal set and give an overall steam economy of a quadruple effect system (Figure 2). This method allowed the industry to convert to a quadruple effect economy for a moderate cost for the additional unit. Again, as we are falling short of the mark, other methods need to be examined for the future in order to keep the industry competitive at times of rising energy costs.

The solution to the problem presented here, is the use of compression evaporators. The two methods used in indus-




CONVERTS EXISTING TRIPLE EFFECT SYSTEM TO QUADRUPLE EFFECT WITH INCREASED SALT PRODUCTION.

ECONOMY 3.0-3.2 # EVAP./# *STEAM*

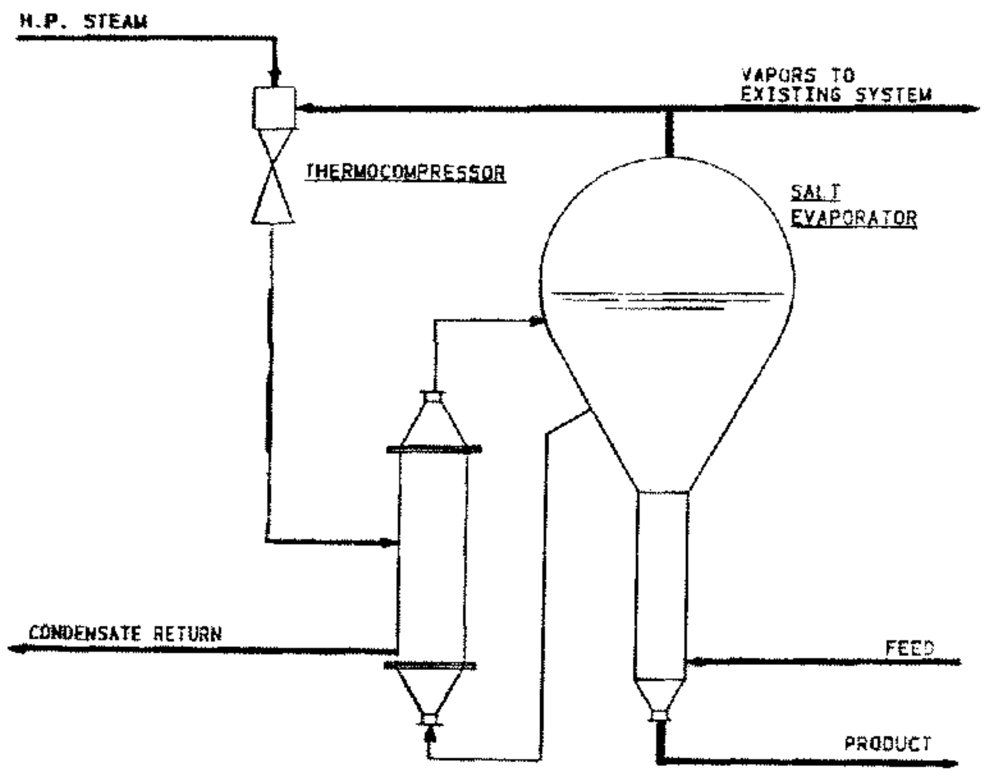
**Figure 2.**

try for vapor compression are thermo and mechanical. Both of these utilize the principle that vapor generated by a unit can be compressed to a higher pressure with a lower amount of energy than that required for evaporation, because the vapor is already in the gaseous state. Therefore, the energy required to convert from the liquid to the vapor state does not need to be added to the system; only the energy that is required to compress the vapors from a lower to a higher pressure is needed. The unit generates the vapor at a lower pressure, and with the thermo or mechanical energy this vapor is compressed to the pressure required for condensation by the evaporator heat exchanger. The thermocompression systems use high pressure steam to achieve the compression, while the mechanical compressors use mechanical energy, usually in the form of electrical energy, to achieve the same end result.

## THERMOCOMPRESSION EVAPORATORS

These units, as described above, use high pressure steam to compress the vapor generated in the evaporator from the lower to the higher pressure. In the process, because higher steam pressure is used, excess vapor is available in the uncompressed state from the evaporator (Figure 3). Vapor can also be bled from the discharge side of the thermocompressor (Figure 4), making this vapor available at the discharge pressure of the compressor. The lower, medium pressure vapor is utilized in other systems and could then be used to drive existing multiple effect evaporators. The overall thermocompression system then acts as a high-economy "topping pan" type unit.

A flowsheet of an arrangement where all of the vapor from the evaporator is recompressed from 14 PSIG pressure of the evaporator to 36 PSIG pressure discharging from the thermocompressor is illustrated in Figure 4. In this particular configuration, the unit acts as a steam pressure reducing station for 65% of the high pressure steam when it exits the system, at 36 PSIG, and is then made available at the existing quadruple effects. Steam required for production at this station is, then, 35% of total, giving an economy of 3.4 pounds evaporation/pound steam. These energy figures are based on the single effect opera-



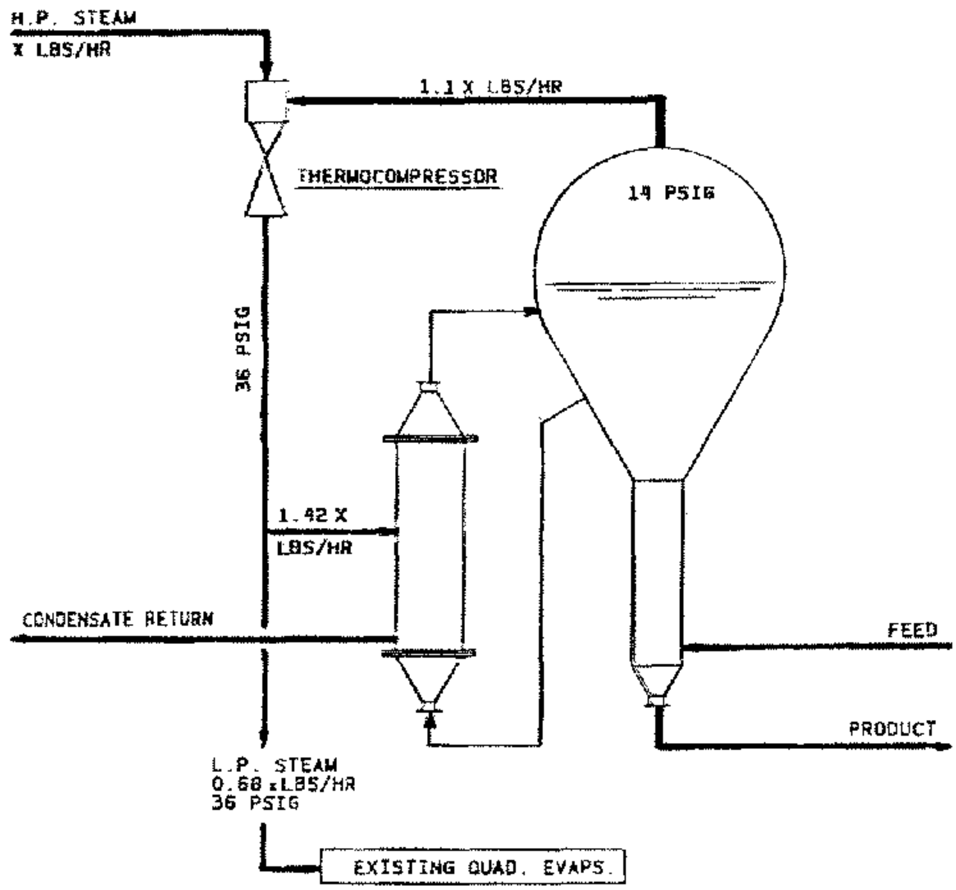

BALANCE LOSS OF POWER GENERATION AGAINST REDUCED STEAM GENERATION.

OPTIMUM: STEAM GENERATION = POWER REQUIREMENTS IN PLANT

THERMO-COMPRESSION CAN BE ECONOMICALLY USED WHEN STEAM GENERATION MUST EXCEED POWER GENERATION.

**Figure 3.**

THERMO-COMPRESSION EVAPORATION




ECONOMY OF SINGLE EFFECT BASED ON DIFFERENTIAL STEAM CONSUMPTION.

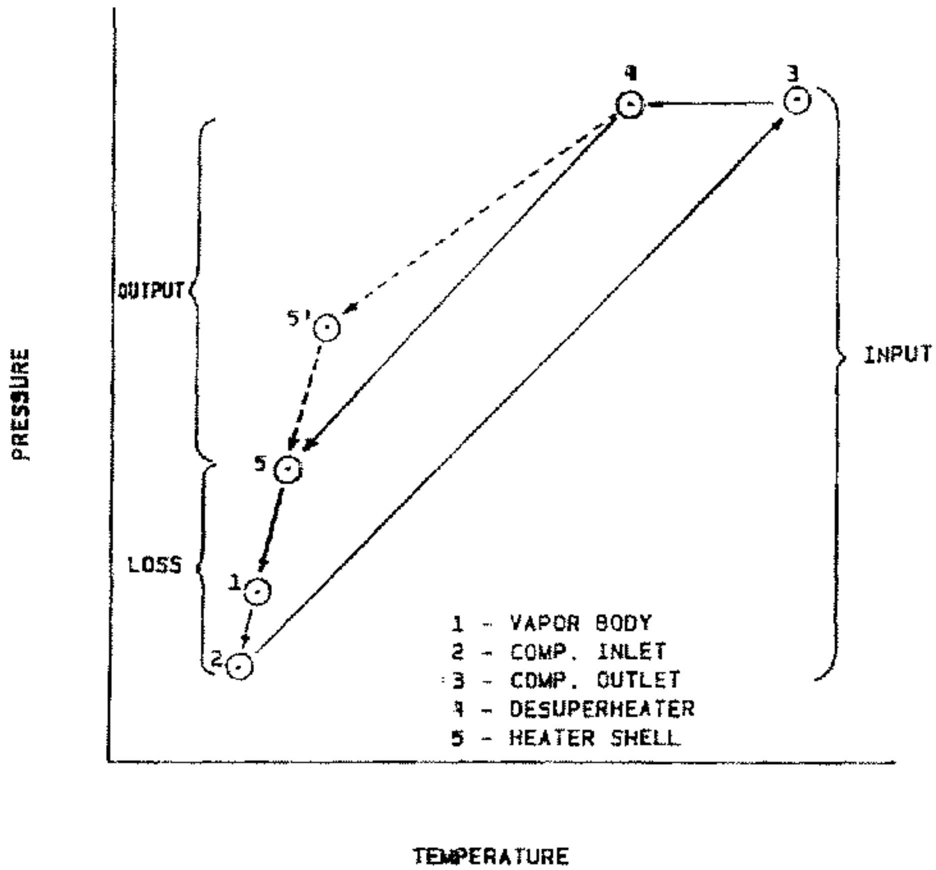
3.4 # EVAP./# STEAM

**Figure 4.**

tion, that is, taking the differential steam usage for evaporation and salt production for the unit. It is obvious that this performance is an excellent one for a single evaporator effect since it is equal to that of a quadruple effect system. The drawback, however, is that it utilizes high steam pressure and the plant is deprived of the electrical generating capability of this steam. Therefore, this solution can only be adopted, as it was in our case, for a plant where steam generation is in excess of electrical demand or where the economies of steam and electrical costs will show this to be a more favorable use of the energy available from the high pressure steam source.

## MECHANICAL VAPOR COMPRESSION

The mechanical vapor recompression scheme presents a refinement in the thermodynamics of an evaporator in that we continuously reuse the heat that we have generated in the evaporator. To those familiar with work cycle plots (such as Carnot, Sterling and Otto cycles), the work cycle of vapor recompression is shown in Figure 5. This cycle begins at point 1 in the vapor body of a salt pan where water vapor has been generated. The cycle progresses to point 2, suffering some losses through the vapor piping. The vapor enters the compressor at point 2 and enough energy is added to raise the pressure to point 3. During this compression, the vapor is also superheated. This superheat is removed in the "de-superheater," dropping from point 3 to point 4. The difference in temperature between points 4 and 5 represents the driving force for heat transfer in the evaporator. This driving force depends on both the compression provided in going to point 4 and on the boiling point elevation as represented by the dotted lines to point 5. Progressing from point 5 back again to point 1 represents the boiling point elevation loss in our system.




SCHEMATIC VIEW OF VAPOR RECOMPRESSION WORK CYCLE.

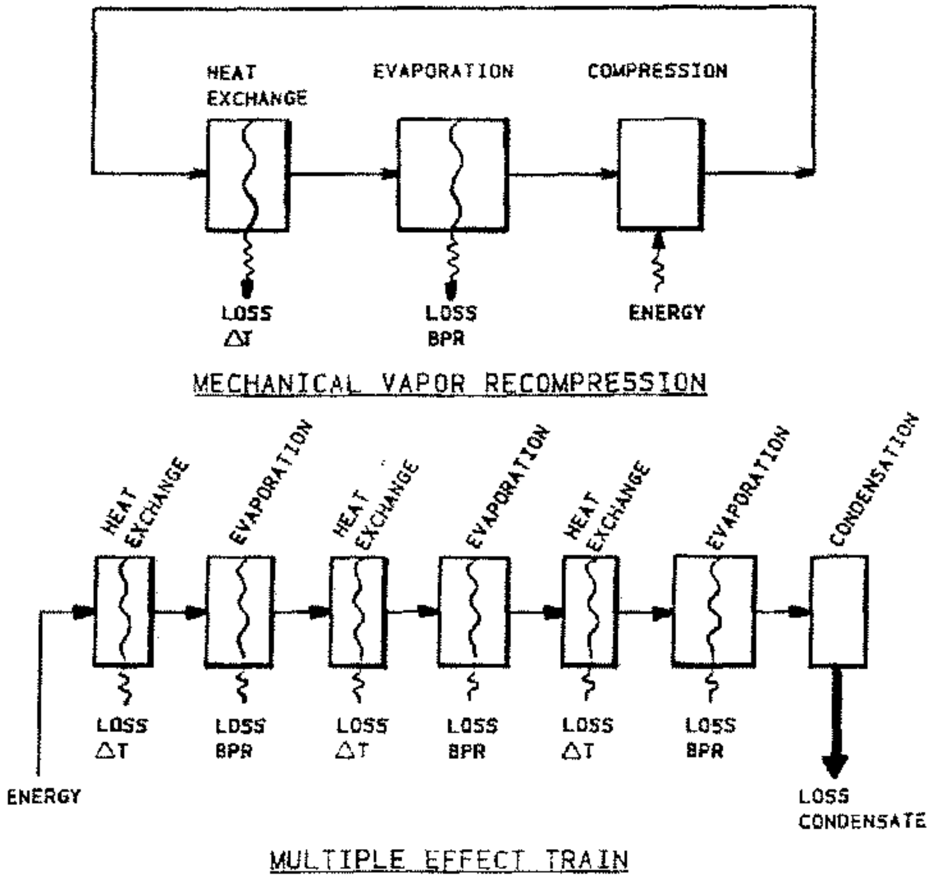
**Figure 5.**

In evaporation without vapor recompression, energy is added to the front end, used once, twice, or perhaps three or four times (as in common salt pan installations) and then thrown away. In the work cycle of the mechanical vapor recompression, energy is added to the compressor and reused continuously, replacing only as needed to make up for the energy forcibly taken by system losses.

A review of the block diagram presentation of both the MVR and a multiple effect scheme results in some apparent differences shown in Figure 6. In the MVR scheme, the energy put into the compressor is cycled around the system and encounters some losses in the heat exchange equipment (known as temperature driving force, or $\Delta T$) and in the evaporator (known as boiling point elevation). These losses are small, however, compared to the main energy contained in the vapor stream, and this heat is returned to the compressor. We thus have a simple, closed cycle engine that does work with minimnum equipment and little waste.

For comparison, the conventional multiple effect common in the salt industry has some very significant differences. First, the same $\Delta T$ losses are present; however, since there are three or four effects, that is three to four times the loss encountered in an MVR system. Likewise, there is three to four times the loss due to boiling point elevation of the combined effects. In addition, the largest waste of energy is the amount of heat that is rejected from the system condenser and thrown away in a cooling system. In both systems, the same amount of net work is produced; however, the energy input that is required by the open cycle of the multiple effect is much larger than that of the mechanical vapor recompression system.

A mechanical vapor recompression is shown in a more familiar representation in Figure 7. The forced circulation




COMPARISON OF ENERGY USE AND EFFICIENCY FOR MVR AND ME EVAPORATION.

**Figure 6.**

evaporator crystallizer itself is virtually identical to those now used in salt plants and comprises:

- a forced circulation heat exchanger
- a vapor body/crystallizer vessel
- a salt elutriation leg.

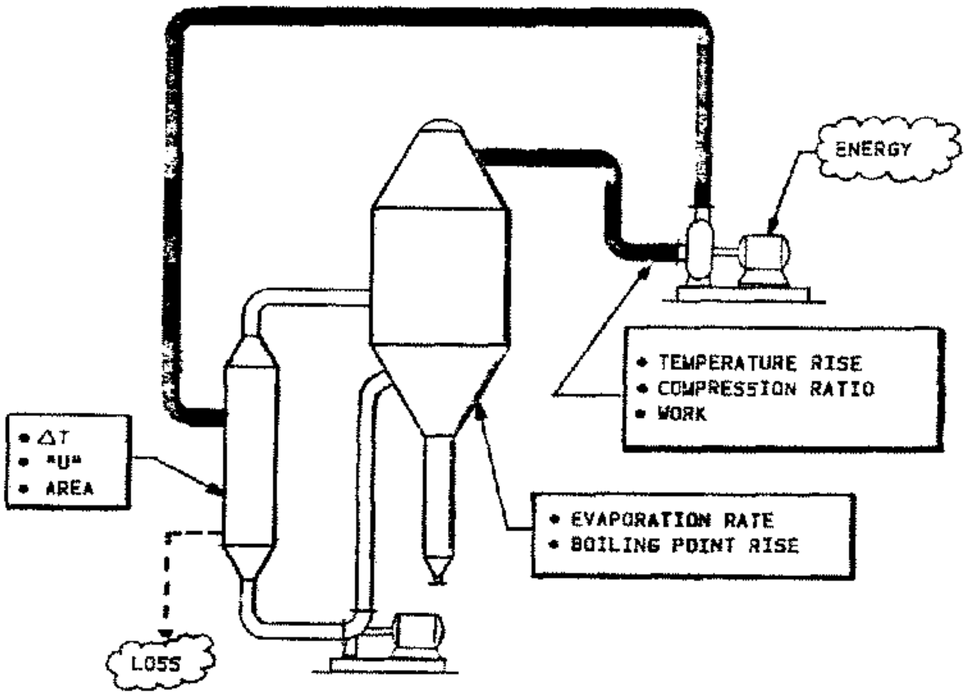
The only but nevertheless important differences are in the details of the equipment design:

- the heater temperature driving force
- the average heat transfer coefficient
- surface area
- recirculation flow
- compressor temperature rise
- compression ratio
- power requirements.

Just as a conventional multiple effect train requires a balance of all of the variables involved to provide proper design, a mechanical vapor recompression system also needs a balance of these elements. It is in this balancing of the design elements that the system designer earns his keep. We do pay for the closed cycle efficiency of the MVR system in the time spent evaluating and designing the equipment. The closed cycle results in a process feedback that requires proper knowledge of the system to provide correct design.

This brings up the key element in design of an MVR system: the selection of the compressor compression ratio and the trade off between this compression ratio and the heating surface required in the evaporator. This trade off is the principle control of the economic value of mechanical vapor recompression. The relationship between required compression ratio and the saturation temperature rise across the compressor is shown in Figure 8.

This data shows nothing really new, as it is just another way of representing data from steam tables. In use, the compression ratio required is determined by adding the system boiling point elevation and the desired heat exchanger temperature difference that is desired, and reading from this chart the compression ratio that is required



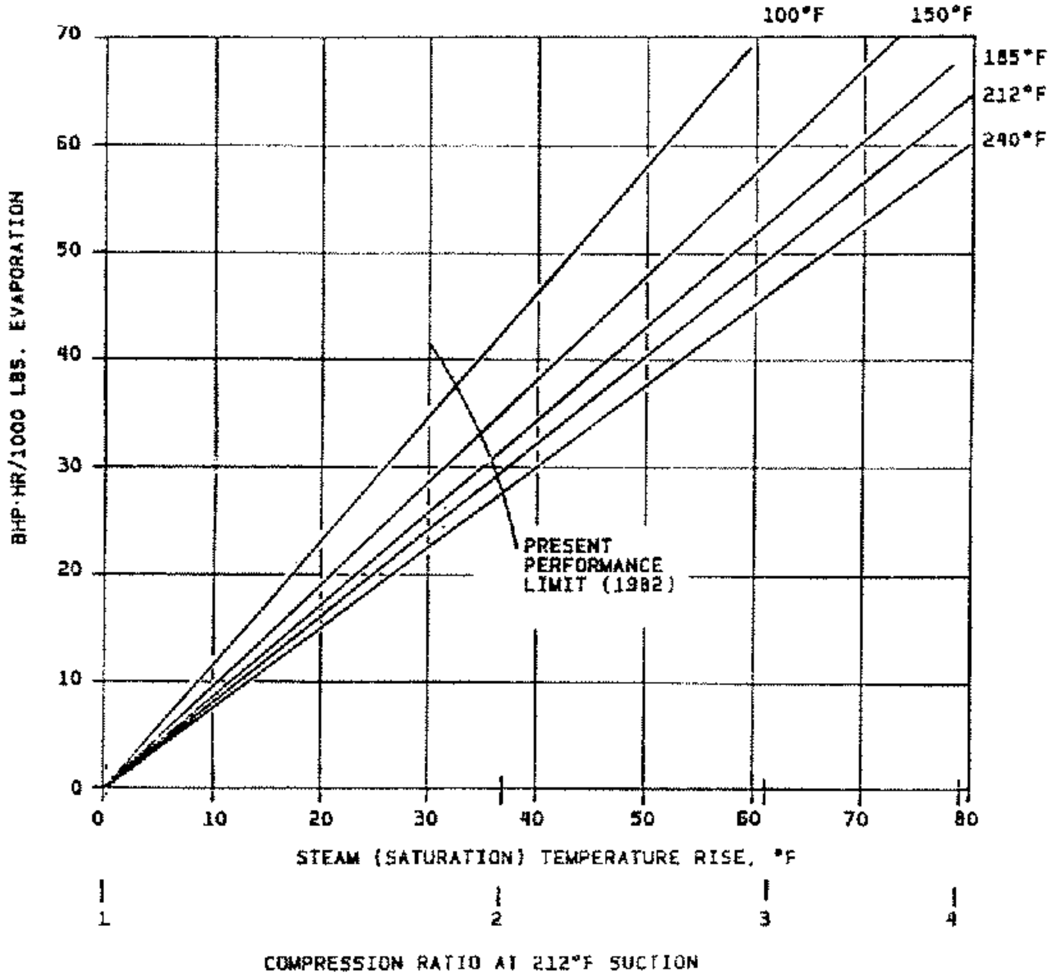

MECHANICAL VAPOR RECOMPRESSION SALT PAN.

**Figure 7.**

to achieve this total temperature rise. Here is exactly where the first complexities come in. The next chart, Figure 9, shows a comparison of the boiling point elevations and compression ratio requirements for five different materials, (1) a water stream, such as would be obtained from a cooling tower blowdown, (2) a waste water more or less typical of chemical operation, (3) a sodium chloride brine, (4) an impure potassium chloride brine and (5) caustic soda. These five different solutions span the range of what is normally encountered or can be handled in MVR systems (Figure 9). We have shown in this chart a constant compression ratio of 2.2, which is the limit in performance of equipment that has seen reasonable commercial use to date. The chart shows the energy waste that would be encountered if a single compression ratio were to be used for all solutions. For caustic soda, of course, this compression ratio will not allow the MVR system to work. The chart also demonstrates the relationship between the compression ratio (outlet pressure over inlet pressure) and the temperature rise available between the vapor body and heater shell. Subtracting the boiling point rise from this total difference gives the net driving force available for heat transfer. Selection of this net driving force is then based on the economic balance between the driving force and the heating area required. For water, we would balance this compression ratio at approximately 1.45. For sodium chloride brine, this balance increases to approximately 1.95 to 1.98. For caustic soda we would require 4.2 or more.

The next item of MVR evaluation is the performance and characteristics of compression machinery. For a given compression machine, this data is presented as a performance curve in Figure 10 relating the vapor flow rate, the pressure rise and the power consumption of the machine. The data as shown in this chart appears very similar to the performance curves seen for a very common centrifugal machine pump. Also shown in this set of curves are the compressor characteristics that provide system turn down. Each curve represents a given setting of the inlet guide vanes, which are used to control compressor capacity. Continuing the analogy to centrifugal pumps, the boiling point rise represents a static head and the heat exchanger temperature difference represents a dynamic head. A system head curve can, therefore, be superimposed on the performance curves. Inlet guide vanes typically provide turn down operation to 75% of rated flow. Additional turn down is provided by vapor recycle around the compressor. The inlet guide vanes provide an advantage of reduced power consumption at reduced capacity. Control valves provide the same turn down but not at a commensurate power reduction. Depending upon the compression ratio selected, the type of mechanical machinery is selected.

This type of machinery can be divided into three categories (as shown in Figure 11), the low-lift, medium-lift and high-lift compressors. A low-lift compressor is capable of compression ratios up to approximately 1.3 and this machinery is uncommon in evaporator use. The medium-lift



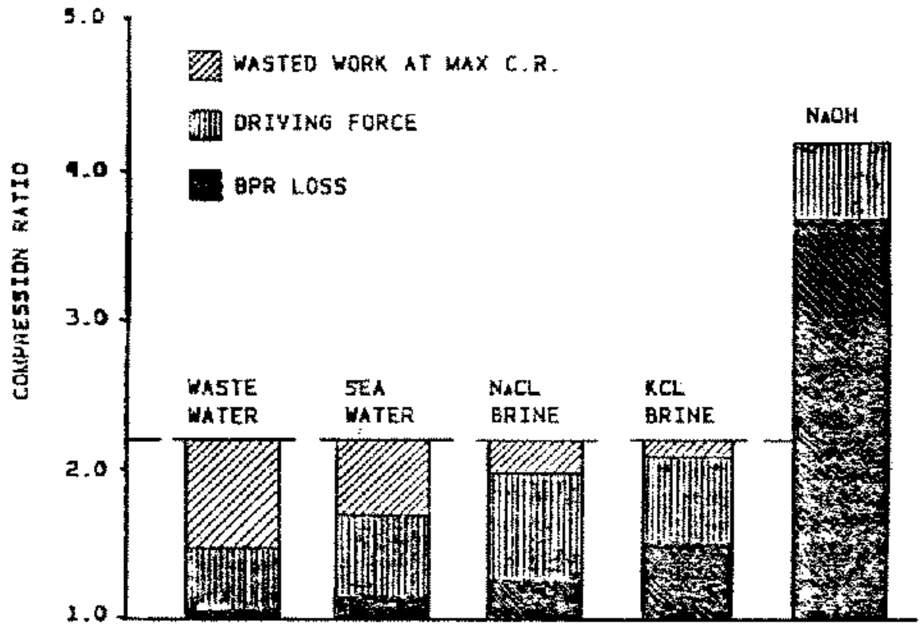

COMPRESSOR POWER VS. VAPOR TEMPERATURE RISE.

**Figure 8.**

equipment is capable of compression ratios up to about 1.7 and is typified by standard centrifugal compressors such as Elliot or Allis Chalmers and by the lobe type blowers such as Dresser Roots. Higher compression ratios, up to 2.2, are provided by high-speed centrifugal machines such as the Atlas Copco Turbonetics overhung shaft centrifugal compressor. This compressor is not a new machine but has seen extensive and varied service, including more conventional air compression requirements and evaporation service. This type of equipment is what is required for problems such as salt brine evaporation. When other problems, such as caustic soda, are encountered, even higher compression ratios are necessary and this type of equipment is typified either by special high-speed compressors or by screw compressors. Screw compressors are extremely expensive in the capacities typical of evaporation plants and are not likely to be used extensively. Machines are under development by companies such as Airesearch that will provide the high compression ratios using technologies that have been used in aircraft engines. When using high- or very high-lift compressors, mechanical design features require special care in evaluation. These features include aerodynamic design stability of the compressor wheel, rotor dynamics, vibration, bearing designs, bearing life, gear designs, gear life, gear speeds and materials of construction. Corrosive attack on high-speed machines is more serious than in the low-speed machines.

We do not want to leave the wrong impression that because of these additional mechanical requirements the compressors and mechanical vapor recompression systems are not reliable. Evaluation of commercial performance of these high-lift compressors have shown greater than 99.8% on-stream time over a span of more than three million hours of operation. These compressors and gear box arrangements provide over 14 years of mean time between failures. It is unlikely that much other equipment in salt service can provide such reliability.

Throughout our discussion of selection of the compres-




COMPARISON OF WORK REQUIREMENTS AND COMPRESSION RATIO SELECTION FOR VARIOUS BRINE COMPOSITIONS.

**Figure 9.**

sor and compression ratio we must not lose sight of the fact that the only reason for installing a mechanical vapor recompression evaporator is to reduce energy consumption and, thus, reduce the cost of producing salt. A summary of typical cost categories is shown in Figure 12. The cost of producing salt includes the capital expenditure for equipment, installation costs, maintenance costs and the energy and operating cost. The selection of the compression ratio and the design of the equipment is essential to balancing the capital equipment and energy cost. This is not the only evaluation that must be made by the designer in selecting mechanical vapor recompression systems rather than equipment. The elements included in capital cost are major equipment, which includes the salt pans, compressor and the compressor drive, and the power source, which can be a boiler with a condensing turbine, a non-condensing turbine or electrical, which will include the capital cost for power distribution.

The operating costs for the multiple effect system include the cost of steam and the cost of the electric drives on the pumps. The thermocompression system includes the cost of steam, the cost of boiler feed water makeup and, again, the cost of electric drive on the pumps. The MVR system presents many more options for energy source than the multiple effect or thermocompression systems. The compressor drive can use purchased electrical power, steam from the boiler by expanding it through a condensing or noncondensing turbine or even by expanding it through a turbine for electrical generation and subsequent electric drive on the compressor. Also possible is direct natural gas or oil firing of a gas turbine drive. Gas turbine drives are somewhat expensive; however, they may be economically attractive if the exhaust gas can be used for drying the product salt.

This paper will not attempt to completely examine all of these alternatives; it does examine the comparison between the turbine drive versus direct electric drive.

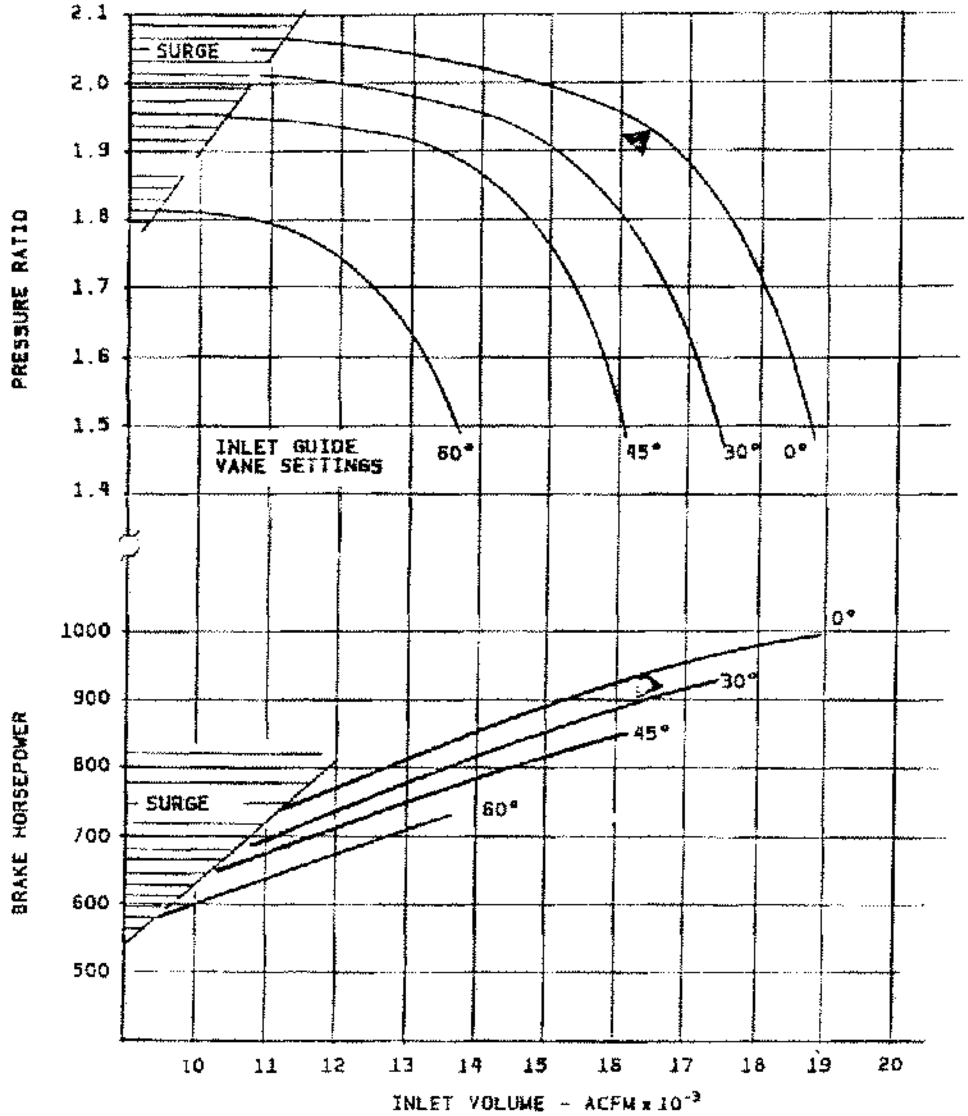
Note that the use of mechanical vapor recompression presents many more options for improving salt plant economics than does the multiple effect or thermocompression designs. The full evaluation of the schemes available must be made on a plant-to-plant basis, because a general solution is not available. For example, a salt plant in Ontario has very low-cost electrical energy available. In the middle of Saskatchewan, however, the cost of bringing electricity to the plant alone may be a serious detriment to the economics of the MVR.

## HYBRID SYSTEM

We may consider retrofitting an existing installation in a manner to preserve time, or all of the electrical generating capability of the existing plant. In this configuration, the turbine exhaust from the electrical generators is fed to the multiple effect evaporators (Figure 13).

The MVR evaporator can be driven in any of three ways (Figure 14):

1. Electricity generated in plant. This method will increase the low pressure steam to the multiple effects




TYPICAL COMPRESSOR PERFORMANCE.

**Figure 10.**

and increase the salt production at this location. The disadvantage of the scheme is reduced efficiency due to the two-step approach—electrical generation and electrical drive.

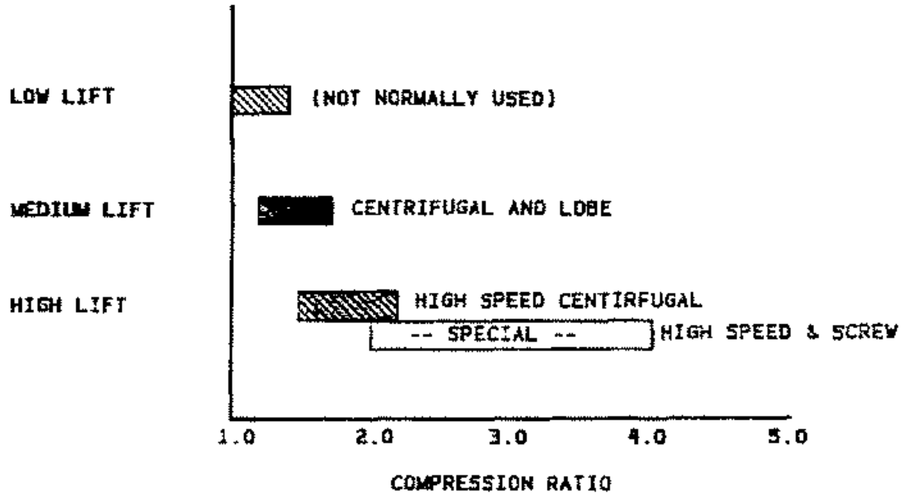
2. Use of high pressure steam at the MVR turbine drive. This approach will also increase salt production at the multiple effects as the turbine exhaust is sent to the multiple effects.
3. Use of purchased power to drive the MVR.

The selection of one of these systems will depend on the actual plant conditions and the economics of power generation, fuel cost and equipment cost.

## ECONOMICS

The economics of a thermocompression evaporation system is relatively straightforward. Depending on the configuration, the thermocompression evaporator will give a steam economy base from which the operating cost can be readily evaluated. In this evaluation, an allowance should be made for loss of condensate makeup water to boilers if the condensate has to be provided below 5 ppm dissolved solids.

For the comparison of steam-driven and MVR evaporator set, refer to Figure 15. This figure shows a correlation between steam cost in U.S. dollars per thousand pounds




COMPARISON OF COMPRESSOR CAPABILITIES FOR EVAPORATION SERVICE

**Figure 11.**

<u>CAPITAL</u>

- MAJOR EQUIPMENT
  - SALT PAN (S)
  - COMPRESSOR
  - COMPRESSOR DRIVE
- POWER SOURCE
  - BOILER
  - CONDENSING TURBINE
  - NON-CONDENSING TURBINE
  - POWER DISTRIBUTION

<u>OPERATING COST</u>

BASE: STEAM
ELECTRIC DRIVE PUMPS

TC: STEAM
B.F.W.
ELECTRIC DRIVE PUMPS

MVR: ELECTRICITY (FOR DIRECT ELECTRIC)
STEAM (FOR CONDENSING TURBINE)
STEAM (LESS RECOVERY FOR NON-CONDENSING TURBINE)
NATURAL GAS (LESS RECOVERY FOR GAS TURBINE)

**Figure 12.**

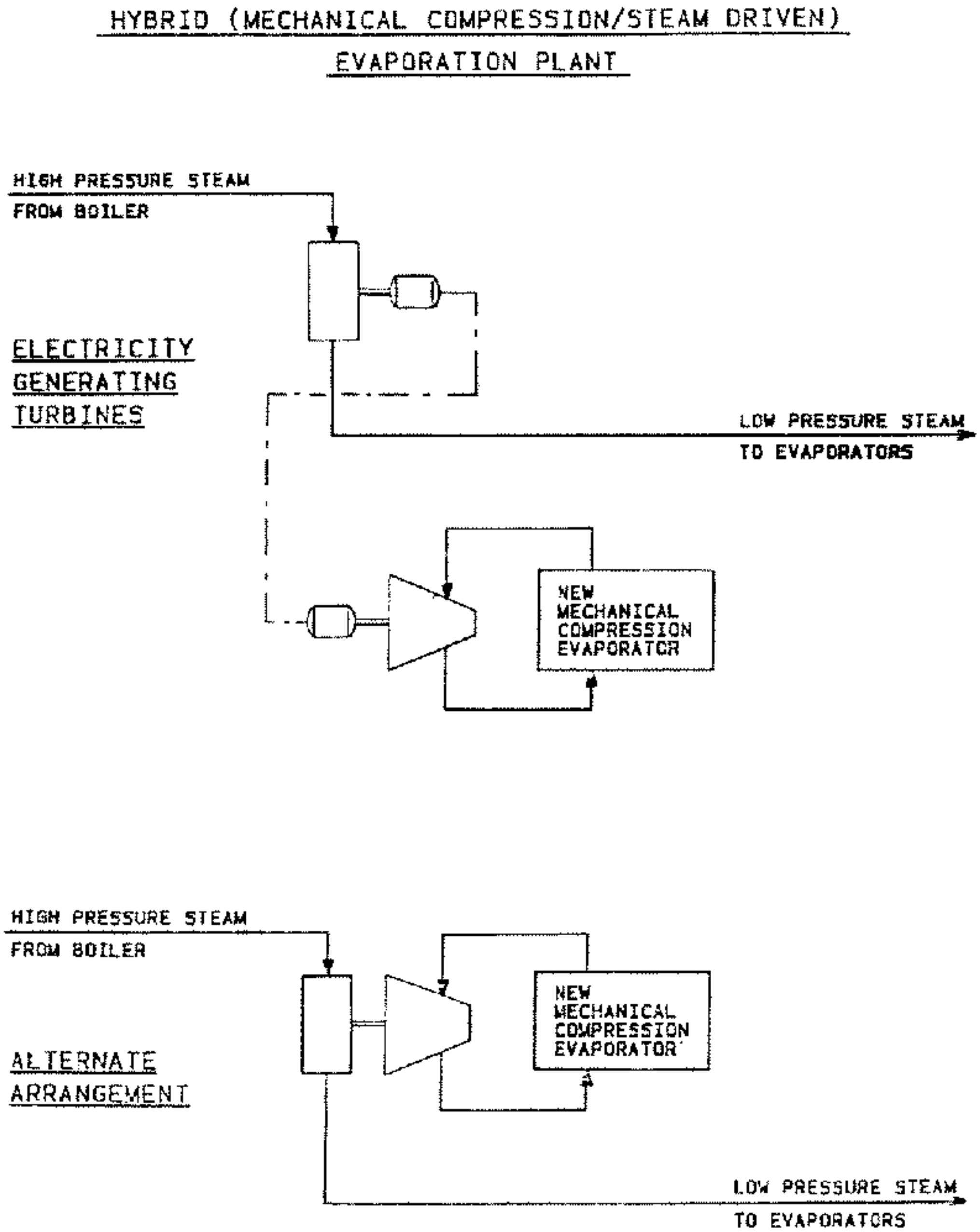

HYBRID (MECHANICAL COMPRESSION/STEAM DRIVEN)
EVAPORATION PLANT
HIGH PRESSURE STEAM
FROM BOILER
ELECTRICITY
GENERATING
TURBINES
LOW PRESSURE STEAM
TO EVAPORATORS
NEW
MECHANICAL
COMPRESSION
EVAPORATOR
HIGH PRESSURE STEAM
FROM BOILER
ALTERNATE
ARRANGEMENT
NEW
MECHANICAL
COMPRESSION
EVAPORATOR
LOW PRESSURE STEAM
TO EVAPORATORS

**Figure 13.**

SALT GENERATION FROM HYBRID SYSTEM

BASIS:

1. PLANT ELECTRICAL CONSUMPTION "A" KWH-CONSTANT.
2. MVR EVAPORATOR ELECTRCIAL USAGE "X" KWH.
3. EXHAUST STEAM FOR ELECTRICAL GENERATION IS UTILIZED AT MULTIPLE EFFECTS.

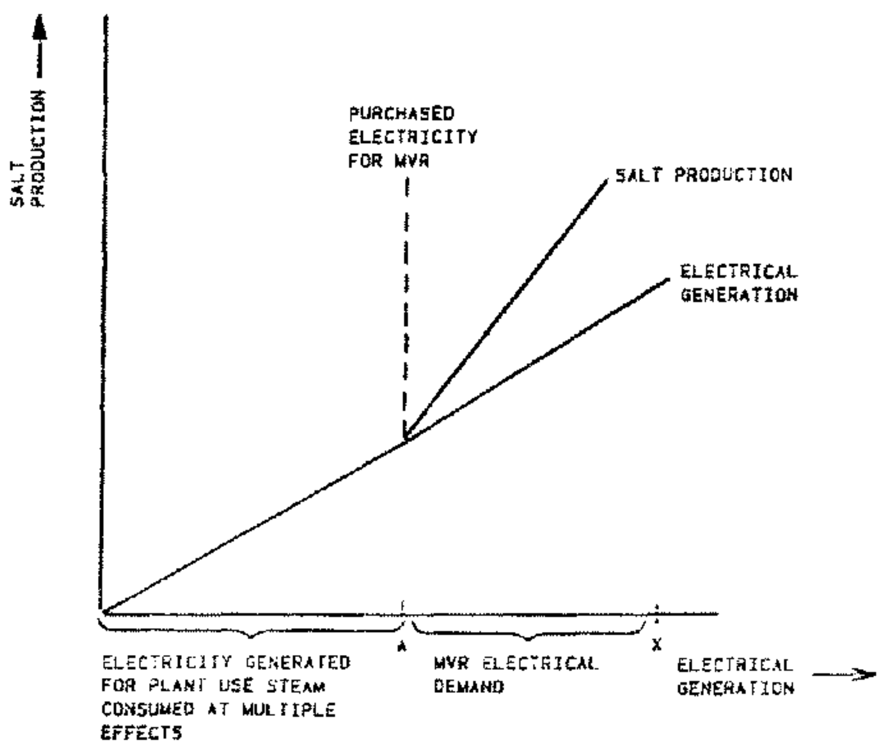



Figure 14.

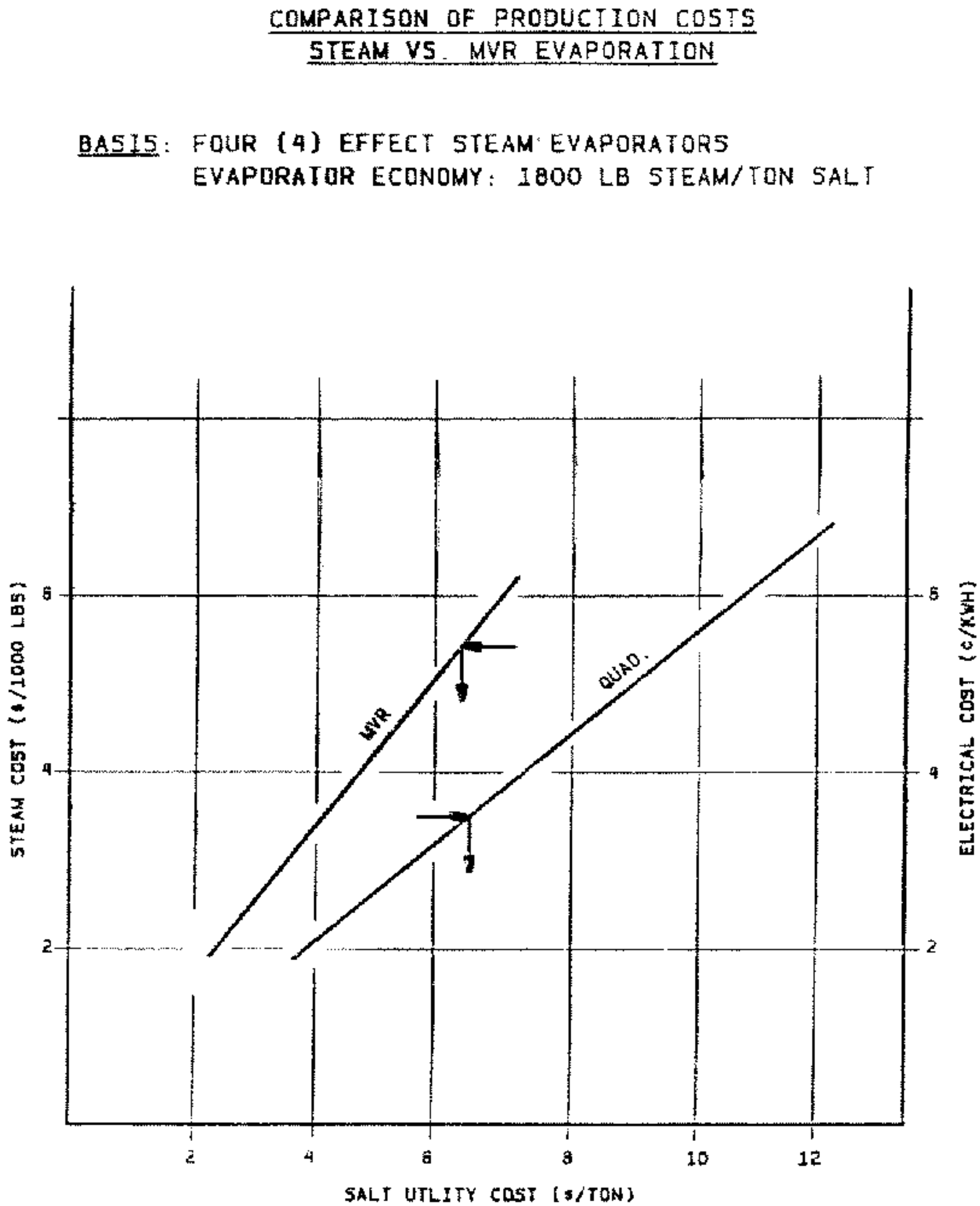



Figure 15.

steam, electrical costs in U.S. cents per kwh versus utility cost for salt production in U.S. dollars per ton of salt. The steam cost is based on a quadruple effect evaporator system with an efficiency of 1,800 pounds of steam per ton of salt. The MVR system is based on single effect MVR efficiency of a conventional, low compression ratio, mechanical compressor. The curves do not allow for credits for electrical generation. This should be allowed within the calculations for the overall system economy. Utilizing these curves, it shows that an MVR system operating cost is somewhat more than 50% of steam driven system operating cost, again allowing no credit for electrical generation. In the case of a hybrid system, the cost will be proportional to a tonnage generated from a steam-driven unit and from the electrically driven MVR system. A 50/50 hybrid would give about 75% of a steam driven unit's utility cost.

Salt production from a hybrid system is shown in Figure 14. The graph of the electrical generation versus salt production shows a certain quantity of salt produced based on electricity generation for plant usage ("A"). The steam is sent to multiple effect evaporators which act as condenser for the low pressure turbine exhaust. If the MVR unit's electrical requirement ("x") is generated within the plant at the electrical turbines or the turbine exhaust from the MVR drive is sent to the steam driven evaporators, the salt production will increase in excess of the electrical generating curve by the amount of salt that is produced by using the excess steam at the steam driven evaporators. If the MVR system is driven with purchased electricity, then salt production will follow the vertical line showing the increase over that of electrical generation.

## SUMMARY

Thermocompression evaporators have but limited use; they apply to situations where high-pressure steam is available without jeopardy to steam generation and where increased salt production is required at a reasonably good economy.

The future for North American salt plants should be in the mechanical compression systems. Presently available compressors will allow installation of energy efficient systems; however, retrofitting of existing installations with the lower compression ratio machines is expensive. The existing systems need rather substantial modifications and addition of evaporator heat transfer areas in order to yield the same production rate as the former steam-driven system gave.

The compressors currently under development with a high-lift capability will allow retrofitting of existing installations, though with some loss of efficiency, for a considerably smaller investment. Even at these somewhat lower efficiences, compared with present compressor designs, the economy of the system will be substantially improved over existing plant efficiencies.

A hybrid arrangement might become the best suited, since it will have the best balance between steam and electrical generation. In these arrangements, the compressor may be driven by high-pressure steam or electricity. Turbine exhaust, either from the electricity generating turbine or from the compressor turbine drive, can exhaust to the steam-driven evaporators.

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