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# HIGH RECOVERY DESALTING OF BRACKISH WATER BY ELECTRODIALYSIS

## FIELD TESTS AT YUMA DESALTING TEST FACILITY & AT LA VERKIN SPRINGS

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16. ABSTRACT

An ED (electrodialysis) pilot plant achieved high desalting recoveries of nearly 95 percent at the YDTF (Yuma Desalting Test Facility, Arizona) and 92 percent at LVS (La Verkin Springs, Utah) during over 4000 hours of operation. Brine TDS (total dissolved solids) concentrations of nearly 100 000 g/m$^3$ were obtained at LVS, which is a greater brine concentration than is possible using RO (reverse osmosis). The LVS required ED energy (while producing a product TDS concentration of about 1000 g/m$^3$) is estimated to be about one-third the energy requirements of a commercially available distillation brine concentrator. Lowering product TDS concentration by ED requires increased equipment size and energy consumption. Special modifications of a standard ED design by its manufacturer were required for the pilot plant to achieve the high brine concentrations through a minimization of both the wastage of water and the dilution of brine that usually occurs with polarity reversal. During initial ED operation (at the YDTF) about 60 000 g/m$^3$ brine TDS concentration caused the bronze brine-recirculation pump to erode and lose its required capacity and contributed to electrical shorting at the stack electrodes in nonflow areas. Subsequent replacement of the pump by one of plastic and the electrodes by ones specially encapsulated with plastic for higher electrical insulation allowed the pilot plant to operate for over 2000 hours producing high brine concentrations without additional equipment problems. The ED process has been shown to be highly feasible technically for achieving very high brine concentrations and desalting recoveries, which are particularly important to inland-desalting applications where brine-disposal volumes need to be minimized because of the high brine-disposal costs.

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## FIELD TESTS AT YUMA DESALTING TEST FACILITY AND LA VERKIN SPRINGS

by

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December 1984

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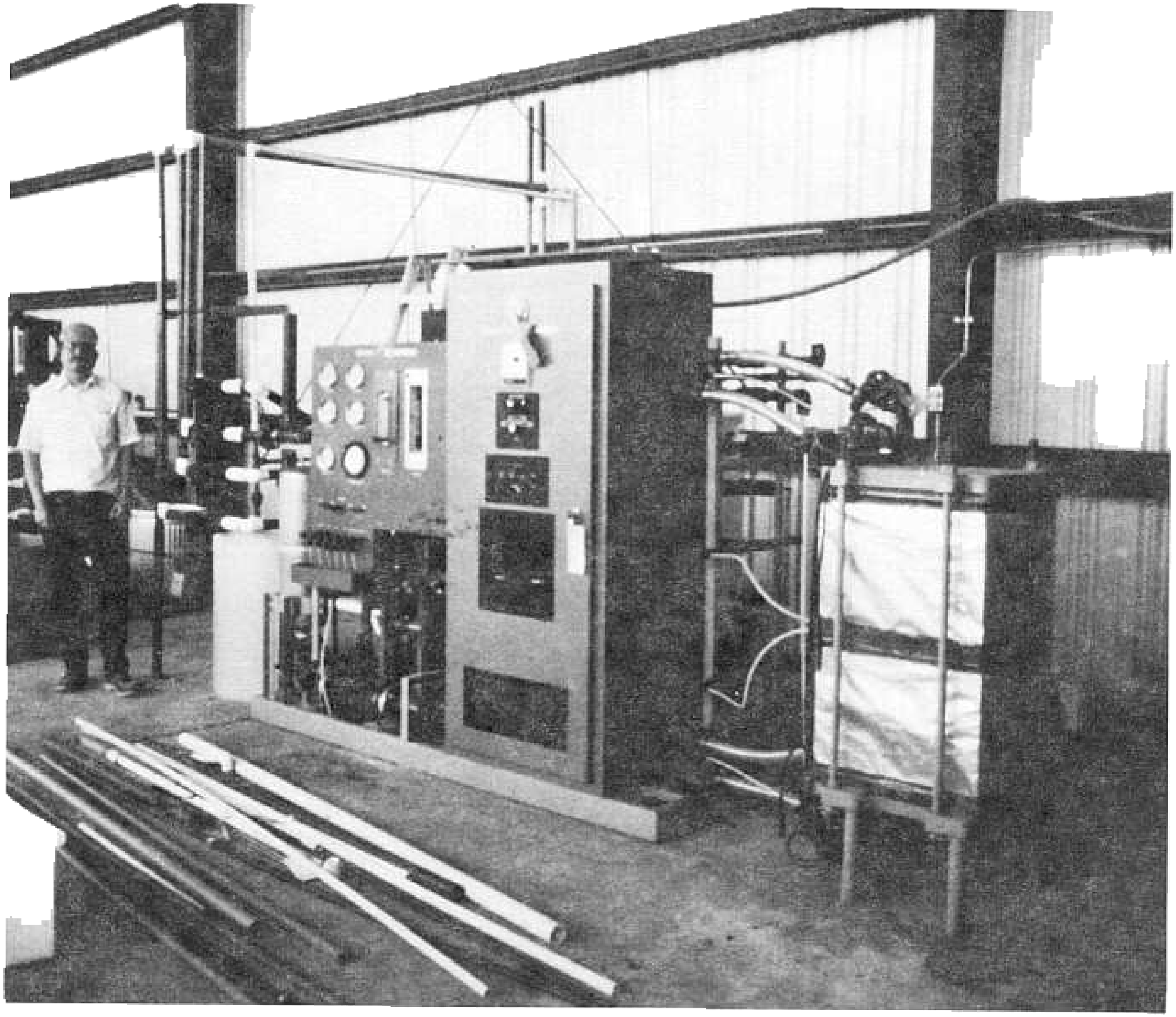

Frontispiece. – *Yuma Desalting Test Facility. Author standing in front of electrodialysis pilot plant as installed in early 1979. P801-D-80827*

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# GLOSSARY

| | |
|---|---|
| **Anion exchange membrane –** | Anion exchange material in the shape of a sheet having positively charged fixed functional groups capable of exchanging and passing anions. |
| **Cation exchange membrane –** | Cation exchange material in the shape of a sheet having negatively charged fixed functional groups capable of exchanging and passing cations. |
| **Cell pair –** | A set consisting of an anion membrane, a cation membrane, and two spacers to contain a dilute and a concentrate stream. |
| **Concentrate stream –** | The flow stream through an ED stack into which ions are concentrated to exit as the reject brine. |
| **Current density –** | Current passing through an ion-exchange membrane pair divided by the effective membrane area. |
| **Current efficiency –** | The number of chemical equivalents of ions effectively transferred divided by the number of electrical equivalents passed through membrane pairs. |
| **Dilute stream –** | The flow stream through an ED stack where feed water is desalted and exits as product. |
| **ED –** | Electrodialysis, electrodialyzer. |
| **Effective membrane area –** | The net area of an ion-exchange membrane through which ions are transferred by passage of electrical current. |
| **Electrode –** | Inert metal sheets at each end of an electrical stage which deliver electrical potential and direct current to cell pairs to drive cations toward one electrode and anions toward the opposite electrode. |
| **Electrode rinse –** | Water fed to an electrode compartment to remove products of chemical reactions at the electrodes. |
| **Faraday's law –** | Defines the relation between the rate of transfer of electrolyte through the membranes and the magnitude of the direct current flowing through the membranes. |
| **Ion exchange membrane –** | Either a cation or anion exchange membrane. |
| **LVS –** | La Verkin Springs test site in Utah. |
| **MOV –** | Motor-operated valve. |
| **Ohm's law –** | Energy consumption related to any two of the following: voltage, current, and resistance. |
| **Osmotic pressure –** | The differential pressure resulting from the ionic concentration difference (more precisely the chemical potential difference) between two solutions separated by a semipermeable membrane. |
| **Plugging factor –** | A measurement of the purity of water according to the rate of decrease in flow of the test water passed through a membrane filter under fixed applied pressure. |
| **Polarity reversal –** | The change in sign of applied voltage across the stack and change in identity of the dilute and concentrate streams, which are done to prevent an accumulation of scale on membrane surfaces or to eliminate the need for addition of acid to remove calcium carbonate scale. |
| **Polarization –** | A characteristic of ED operation where there is a sharp rise in electrical resistance in the dilute compartment as current density is increased to where the transfer of hydrogen and hydroxyl ions is appreciable due to dissociation of water. This occurs as electrodialysis separation is limited by the diffusion rate of ions to the membrane surfaces. |
| **Reverse osmosis –** | RO: A desalting process where water is forced by a net applied pressure greater than the net osmotic pressure through a semipermeable membrane with rejection of salt. |
| **YDTF –** | Bureau of Reclamation's Yuma Desalting Test Facility near Yuma, Arizona. |

# LETTER SYMBOLS AND QUANTITIES

| *Symbol* | *Quantity* | *Units* |
|---|---|---|
| $A$ | effective membrane area | $m^2$ |
| $C$ | ionic concentration | $eq/m^3$ |
| $C'$ | total dissolved solids concentration | $g/m^3$ |
| $E$ | stack energy consumption per volume of product water | $kWh/m^3$ |
| $e$ | current efficiency | dimensionless |
| $F$ | faraday's constant, 96,500 | coulombs/eq |
| $f$ | temperature correction factor to 25 °C | dimensionless |
| $I$ | electrical current | amperes |
| $n$ | number of cell pairs per electrical stage | – |
| $Q$ | flow of solution | $m^3/s$ |
| $R'$ | desalting recovery | dimensionless |
| $R$ | cell-pair resistance | $ohm \cdot m^2$ |
| $R_g$ | gas law constant | kWh/(mole °C) |
| $R_1$ | cell-pair resistance of first electrical stage | $ohm \cdot m^2$ |
| $t$ | temperature | degrees Celcius |
| $T$ | absolute temperature | degrees Kelvin |
| $T_o$ | operating time | hours |
| $V$ | voltage | volts |

| *Subscript* | |
|---|---|
| *a* | average |
| *ave* | average |
| *b* | reject brine |
| *c* | concentrate |
| *d* | dilute |
| *dave* | average dilute |
| *e* | electrode compartment |
| *f* | feed |
| *p* | product |
| *t* | thermodynamic |
| 1 | first stage |
| 2 | second stage |

# INTRODUCTION

Recovery of a maximum volume of desalted product water from a saline feed water source is a goal in desalting where there is a scarcity of feed water or where the disposal of the reject brine volume is difficult. In many instances of inland desalting of brackish water [i.e.; less than 10 g/L of TDS (total dissolved solids)], brine disposal by such methods as deep well injection or evaporation in ponds are a dominant cost. Thus, by minimizing the brine disposal volume and maximizing the product water volume, high recovery can make desalting more economically feasible. In addition, a minimum brine volume lowers the environmental impacts of brine disposal.

The Bureau of Reclamation has been investigating high recovery desalting for possible application in the arid southwestern United States. Besides being a source of freshwater, desalting brackish water and properly disposing of the reject can decrease the total flow of dissolved solids entering a river system. Natural and anthropogenic salinity sources to the Colorado River are causing detrimental effects on irrigation and other uses of Colorado River water [1].*

This report describes ED (electrodialysis) pilot-plant experiments for high recovery desalination of pretreated brackish waters at two field test sites. At the first site, the YDTF (Yuma Desalting Test Facility) near Yuma, Arizona, the ED test unit desalted irrigation return flow having a TDS concentration of about 3300 g/m$^3$ at recoveries up to 94 percent. At the second site, the ED desalted well water from LVS (LaVerkin Springs) in Utah having a TDS concentration of about 9200 g/m$^3$ at recoveries up to 92 percent, which required the reject brine concentrations of nearly 100 000 g/m$^3$ of TDS.

This report contains a description and discussion of the ED equipment and performance at YDTF and LVS. These data and results of further calculations demonstrate the technical feasibility and some advantages of high recovery desalination using the ED process.

The primary purpose for the high recovery experimentation at the YDTF and LVS was to study a cation-exchange pretreatment process for removing calcium from the desalting feed to prevent gypsum scale from forming in the desalting equipment. The ED was used to produce reject brine of fixed concentrations to regenerate the cation exchanger. Details of the cation exchange experiments are in the final reports from the work at the YDTF [2] and LVS [3]. The present report contains a unified presentation and discussion of the ED portion of the testing. In the preparation of this report, the author assumed that the reader would have a basic understanding of the ED process [4, 5].

# SUMMARY AND CONCLUSIONS

The field experiments at the YDTF and LVS substantiate that ED is applicable for achieving high product water recoveries above 90 percent and brine concentrations of up to at least 100 000 g/m$^3$ of TDS. Such high brine concentrations are not possible with the competing membrane-desalting process of RO. While such high recoveries and brine concentrations are possible with distillation brine concentrators, commercially available distillation units incur much more energy to operate than an ED – three times more in a process comparison assuming LVS feed-water composition – and generally are more expensive to purchase initially. The ED also has the advantage of usually not requiring pretreatment silica removal because ED does not concentrate un-ionized silica in the feed water as do RO and distillation processes.

Because raw saline waters usually contain sulfate and divalent cations such as calcium, strontium, and barium, pretreatment removal of some constituents are necessary to prevent scaling by sparingly soluble salts in the highly concentrated reject brine. Cation exchange provides an ideal process for removing calcium, strontium, and barium because the waste reject from the ED can be used as the regenerant for the cation exchanger. However, cation exchange does not remove silica, which may be required for RO. Thus, cation exchange and ED provide an ideal pretreatment-desalting process combination for many inland saline water compositions where high product-water recovery is required.

Success of ED in the present work shows that ED could help at inland saline water sites as:

1. To achieve 90 percent or greater product-water-recovery desalting rates while providing as a biproduct a concentrated reject brine useable to regenerate an ion-exchange pretreatment step prior to the ED.

2. To minimize the sizes and costs of the waste brine streams from desalting and the evaporation ponds needed for brine disposal.

3. To reduce pretreatment costs for silica removal relative to other desalting processes that concentrate silica.

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* Numbers in brackets refer to the Bibliography.

4. To facilitate the operation of solar salt-gradient ponds by creating high concentration brines at rates much faster than natural evaporation.

Depending upon the desalting application, a disadvantage of ED is that it requires increasingly more equipment and/or operating energy to achieve relatively low product salinities, therefore ED is increasingly more costly, as required product salinity is lowered, particularly if high brine concentrations and recoveries are achieved simultaneously.

An attractive possibility for more optimum high recovery desalting overall is to couple ED and RO such that ED is used to achieve the high concentration brines – but moderate product salinities – plus RO to desalt the ED product to a lower final salinity. This combination could make the best uses of both the RO and ED process by operating each process over a salinity range determined by the overall optimum of the coupled process.

Estimation of the purely theoretical thermodynamic energy requirements of the ED process (at YDTF and at LVS) yield values that are less than 10 percent of the experimentally measured stack energy consumption. This fact illustrates how ED units are designed presently to operate at sufficiently high current densities where overcoming the ohmic resistances of the stack membranes, concentrate streams, and especially the dilute streams are the greatest usages of energy in desalting with ED. While equipment modifications such as much larger ED membrane area can result in significantly lower energy consumption, the increased amortized equipment cost may exceed the savings in energy costs, particularly if the ED design has been optimized to balance incremental equipment and energy costs. The ED energy efficiency is unlikely to improve dramatically in the future as equipment costs will probably keep pace with or may even exceed rises in energy costs.

Three equipment modifications were included by the ED manufacturer in the ED pilot-plant as delivered to the YDTF, which helped achieve the very high recoveries and brine concentrations:

1. Timer relays to delay activation of the motor-operated valves at the stack outlet following activation of the inlet motor-operated valves such that the mixing of dilute and concentrate streams were minimized as a result of polarity reversal.

2. An inline conductivity electrode and monitor with set-point controller to divert by motor-operated valve the reject brine that had a TDS concentration below the set point from flowing to the brine storage tank. (Recycling this intermittent lower conductivity brine stream to the ED feed raises the overall water recovery of the system.)

3. At LVS, ion-exchange membranes having relatively high ionic selectivities were required to reach brine concentrations up to 100 000 g/m$^3$ of TDS. At the YDTF, standard selectivity membranes were adequate to achieve brine concentrations of 60 000 g/m$^3$ of TDS, but current and energy efficiencies would have been higher with more selective membranes.

ED equipment failures occurred during operation at very high brine concentrations and required two additional equipment modifications of the YDTF.

1. The brine-recirculation-pump bronze impeller eroded and failed to produce rated flow capacity. It required replacement of the pump by one with an impeller and pump casing of plastic.

2. The standard stack electrodes were replaced with ones having special plastic encapsulation at nonflow areas to prevent the shorting and stack damage that occurred with the standard electrode insulation in contact with the very low resistivity brine.

After these required modifications were made the ED unit operated with minimal equipment problems for over 2000 hours at YDTF and LVS. The detection and solution of such equipment problems are a justification for field testing beyond the collection of performance data. The success of ED operation at high brine concentrations also indicates how a standard ED unit – designed originally to operate at moderate brine concentrations and recoveries – can be modified successfully to achieve very high brine concentrations and recoveries.

## BACKGROUND

### High Recovery Membrane Desalting Processes

The two membrane processes (ED and RO) are the most economical commercial processes for desalting brackish water [6]. Distillation processes have been used for desalting seawater and as brine concentrators to achieve zero brine discharge in inland desalting of brackish water, but distillation is not used often for desalting brackish water because of its greater cost and energy consumption relative to RO and ED. Although RO has become more popular than ED in recent years, there are at least two specific process advantages for ED compared to RO which make ED technically preferable in some situations.

One of the advantages of ED over RO for high recovery desalting is that the pretreatment removal of silica can be avoided generally with ED but not with RO. When the RO process concentrates silica above its solubility (about 100 mg/L of $SiO_2$ at 20 °C, depending on the amorphous or crystalline form [7]) silica can scale the RO membranes. This results in a severe loss in desalting capacity that cannot be reversed generally by membrane cleaning, which means that the membranes must be replaced. Removal of silica from the RO feed water in a chemical pretreatment step may be necessary to avoid silica scaling of RO membranes. However, because silica is generally un-ionized in neutral and acidic solutions and because the ED process acts only on ions, the un-ionized silica is not concentrated in the reject stream of an ED unit. (Neither is un-ionized silica removed from the ED dilute stream, which also can be a disadvantage if a low silica product is required, for example, for steam boiler makeup water.) For many product water uses such as for drinking and irrigation, silica removal may be unnecessary. Thus, the complication and expense of a pretreatment step, for example, a solids-contact reactor in which lime is added to achieve a pH above 11 to remove silica from the desalting feed water, can be avoided in most cases when ED is used as the desalting process.

The other advantage of ED over RO stems from the greater limitation of RO to achieve very high brine concentrations. The net driving force for RO desalination is the pressure applied to the feed side of the RO membrane minus the gauge pressure on the product side minus the difference in osmotic pressure across the membrane [8]. Depending on the water temperature and type of RO element, the maximum allowable feed pressure without materials failure in existing seawater-type commercial RO elements is 5.5 to 6.9 MPa. The RO materials failure can cause excessive loss in product water capacity due to membrane compaction and collapse of product-water channels. The osmotic pressure is approximately proportioned to TDS concentration. At 25 °C solutions of 1.0, 3.45, and 10-mass-percent concentration of sea salt (mostly NaCl) have osmotic pressures of 0.72, 2.5, and 8.5 MPa, respectively [8]. Moreover, the osmotic pressure of a sea-salt solution exceeds the maximum applied pressure of 5.5 MPa when the sea-salt concentration exceeds about 7 percent or 73 500 mg/L of TDS. The practical maximum reject TDS concentration – when a practical amount of permeate flow is driven through the RO membrane at the maximum allowable feed pressure – is presently between 5 and 6 percent at most. Thus, RO has limited applicability when used as the sole brakish water desalting process for very high recovery applications. Sometimes RO is used as an economical first stage for desalting where the reject is fed to a different brine concentration process such as ED or distillation to achieve high recovery.

Proper design allows very high brine concentrations using ED. The general principles and design of ED are available in the literature [4, 5]. Some basic design equations are included in this report. Under contracts with the Office of Saline Water (U.S. Department of the Interior) Dow Chemical Company did a specific study on design and pilot plant testing of ED for brine concentrations above 20 percent of TDS [9]. Dow's work applied existing technology, namely Asahi Chemical Company ED equipment developed for the Japanese salt-production industry, which uses ED to concentrate seawater to over 20 percent of TDS in the commercial production of NaCl. Such equipment is not like more common ED equipment because this NaCl concentrating equipment was not designed to produce a usable low salinity product. Dow's report recommended coupling ED to produce a concentrated brine with RO to produce a low salinity product from the relatively high salinity ED product. Coupling ED and RO would not be necessary because of technical limitations of ED, but was recommended by Dow to lower overall costs by taking advantage of the different optimum feed salinity ranges of ED and RO. In the present tests, ED alone achieved brine TDS concentrations at LVS of nearly 10 percent while producing water at a salinity of about 1200 g/m$^3$ of TDS.

### Field Test Sites

The first Bureau test site was the Yuma Desalting Test Facility near Yuma, Arizona. The U.S. Government developed the YDTF for the purposes of evaluating pretreatment and desalting processes for obtaining design data for the prototype YDP (Yuma Desalting Plant) [10]. Presently, the YDP is under construction. It will be the world's largest membrane desalination plant with a design capacity of 3.2 cubic meters per second of product water. The design product-water recovery of the YDP is 70 percent of the feed flow. An 82-km-long canal conveys the waste reject brine to the Gulf of California. In a competitive bidding procedure that gave equal weight to cost and technical design, two manufacturers of spiral wound RO equipment were selected over other manufacturers of RO and ED equipment to provide the desalting units for the YDP. Part of the congressional authorization for the YDP provided for studying various means of replacing the reject brine system (30 percent of the YDP feed flow) which is lost for beneficial use [11]. One of the methods studied was to increase the recovery of the YDP through charges in pretreatment and desalting equipment [12, 13]. Ion exchange pretreatment and ED desalting were tested in a pilot plant at the YDTF to obtain feasibility design data for achieving higher water recoveries. The ED tests are the main subject of this report.

Raw feed water (for the YDTF and YDP) is irrigation return flow pumped from wells in the Wellton-Mohawk Irrigation District where 30 000 hectares are irrigated with Colorado River water containing 860 mg/L of TDS. The return flow contains 3000 mg/L of TDS (table 1). The increase in TDS during irrigation is because of evapotranspiration during irrigation and leaching of solutes from the irrigated soils. Conveyance of the irrigation return flow in an open canal results in windblown dust, aquatic weeds, and algae in the raw saline water [14]. Lime pretreatment in a solids-contact reactor followed by filtration partially softened and clarified the raw water by removing suspended particulates such as clays and diatoms prior to membrane desalting. Partial lime treatment in the present YDP design at a pH of about 9.5 is adequate to avoid membrane scaling by calcium salts and silica at 70 percent recovery [10].

To avoid membrane scaling in the YDP with recoveries much greater than 70 percent would require additional removal of calcium for RO and ED and greater removal of silica for RO [12]. Calculations using methods developed by Marshall and Slusher [15] indicate that calcium concentrations need to be reduced to less than about 35 mg/L at 90 percent recovery and 17 mg/L at 95 percent recovery to avoid gypsum precipitation in the reject for the YDTF feed-water composition. Given in table 1 is a typical ED feed water composition at the YDTF after lime-treated water was passed through cation exchange. An alternative pretreatment possibility to avoid gypsum precipitation would be to remove sulfate with anion exchange, but this approach was judged less feasible than cation exchange removal of calcium with the Yuma water compositions. Some more recent ED experiments have shown that accumulation of gypsum scale in the membrane stack by supersaturated calcium sulfate can be avoided with polarity reversal, but precipitation in the concentrate recirculation pump – which is in constant contact with the supersaturated solution – occurred unless SHMP (sodium hexametaphosphate) scale inhibitor was added to the concentrate [16]. Lime softening at a pH of 10.4 or more results in substantial silica removal necessary for high recovery using RO, but such silica removal is unnecessary for ED. Lime treatment at a pH of 10.4 was used in the IX-ED experiments of the YDTF because the IX experimental results were to apply to a single pretreated water composition range, which would be suitable for RO as well as ED. A feasibility study by the Bureau's Division of Design concluded that installing additional RO equipment for desalting recoveries up to 90 percent in the YDP would be more economical than tail-end ED in the case where only RO would be used in the YDP [12]. However, recoveries above 90 percent by RO would not be technically feasible. The final IX report [2] and a previous paper [17] describe the YDTF IX experiments in detail.

Table 1. – Typical raw water compositions at YDTF and LVS.

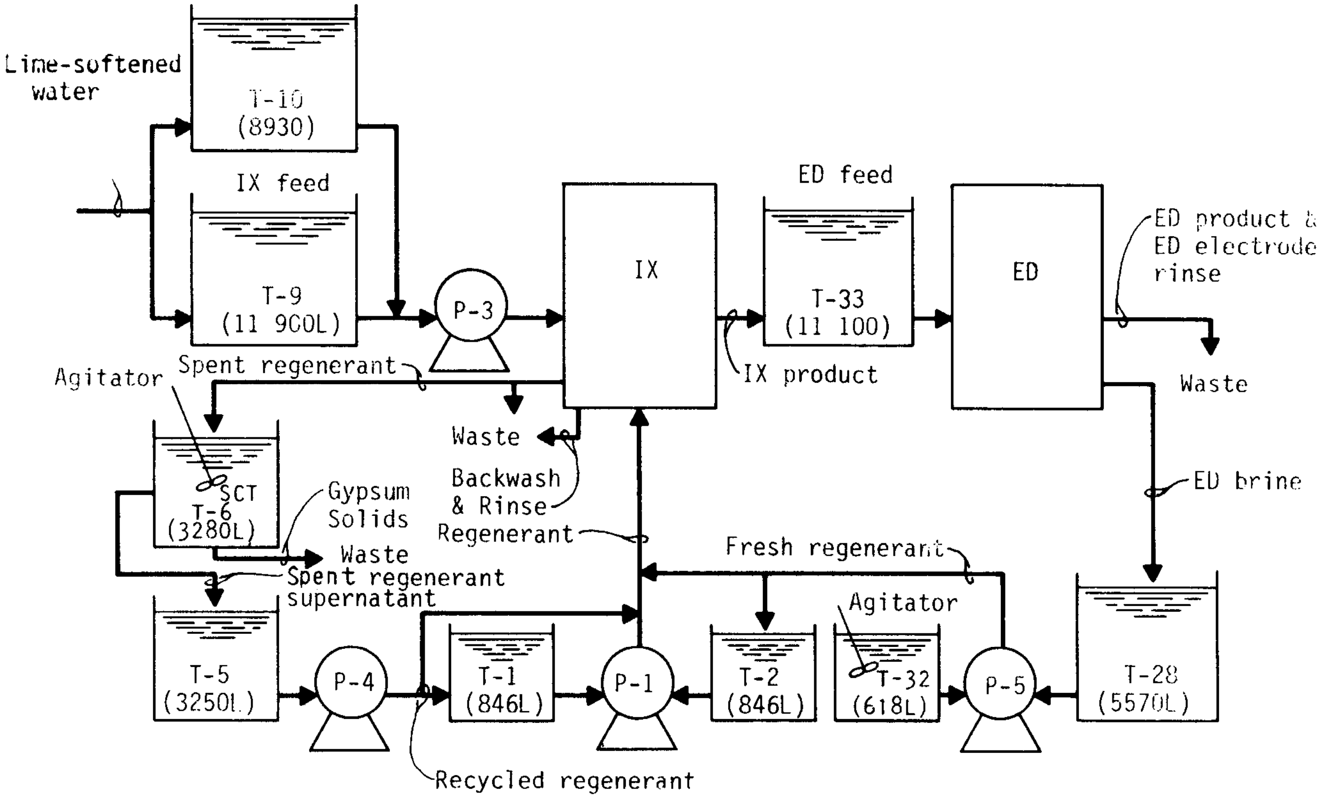
| Component g/m³ | YDTF Raw canal | YDTF ED feed | LVS Raw well | LVS ED feed |
|---|---|---|---|---|
| pH units | 7.8 | 7.0 | 6.0 | 7.6 |
| Silica | 29 | 4.0 | 30 | 14 |
| Calcium | 228 | 10 | 790 | 43 |
| Magnesium | 94 | 20 | 160 | 53 |
| Sodium | 916 | 1180 | 2300 | 3110 |
| Potassium | 9 | 11 | 210 | 176 |
| Iron | 0.3 | 0 | 0.09 | 0 |
| Strontium | 3.7 | 0.6 | 12.0 | 1.5 |
| Bicarbonate | 417 | 18 | 1270 | 47 |
| Sulfate | 904 | 960 | 1980 | 2040 |
| Chloride | 1160 | 1200 | 3480 | 3660 |
| Free carbon dioxide | 0 | 0 | 800 | 0 |
| TDS | 3750 | 3404 | 9430 | 9145 |

The other site where the IX and ED pilot plants were tested was the La Verkin Springs (located in southwestern Utah) adjacent to the Virgin River which flows into the Colorado River. The typical raw and ED feed water compositions at LVS are given in table 1. The springs have a water temperature of about 40 °C. As carbon dioxide effervesces from the spring water at ambient pressure, calcite precipitates naturally. Tests at LVS were for the purpose of obtaining pretreatment and desalting data for feasibility estimates. The Bureau has been studying alternative methods for preventing the LVS dissolved solids from increasing the salinity of the Colorado River. High desalting recovery would be important at LVS because onsite reject brine disposal would probably be part of any desalting project there. In addition to ED, ion exchange, partial lime softening, lime-soda softening, dual media filtration, and RO also were tested at LVS [18]. The ion exchange experiments done at LVS are detailed in another report [3]. Only the YDTF and LVS ED experiments are described here.

## EXPERIMENTAL METHODOLOGY

### Equipment

A simplified process flow diagram of the ion-exchange pretreatment and ED equipment used for the high recovery experiments at YDTF is shown on figure 1. A grit basin removed large suspended particles from the canal water at the YDTF. A basin was not needed at LVS because the well water was relatively particle free. At LVS, the raw water was aerated to remove effervescent carbon dioxide gas and some calcium carbonate. High lime-softened (up to about a pH of 10.4) clarified water was provided to the ion exchanger by a solids-contact internal-solids-recirculation reactor-clarifier at the YDTF [17] and by an inline reactor, flocculator, clarifier system with external solids recycle at LVS [18]. The clarifier effluent



Pumps

| | |
|---|---|
| P-1 | Regenerant |
| P-3 | IX feed |
| P-4 | Recycled regenerant transfer |
| P-5 | Fresh regenerant transfer |

Processes

| | |
|---|---|
| IX | Ion exchanger |
| ED | Electrodialyzer |
| SCT | Solids contact tank (T-6) (Calcium sulfate precipitator **for recycling regenerant)** |

Tanks

| | |
|---|---|
| T-1 | Recycled regenerant (metering) |
| T-2 | Fresh regenerant (metering) |
| T-5 | Recycled regenerant |
| T-9 | IX feed |
| T-10 | IX feed |
| T-28 | ED brine |
| T-32 | Sodium chloride solutioning |
| T-33 | IX product/ED feed |

Figure 1. – Pilot plant flow diagram.

at each site was filtered through dual media beds of granular anthracite coal over silica sand. Sulfuric acid was added to the filter influent to maintain a pH of about 7 in the filter effluent to prevent calcium carbonate precipitation. Gaseous chlorine at the YDTF and sodium hypochlorite solution at LVS were added to the raw water to maintain a chlorine residual of over 1.0 g/m$^3$ through the lime treatment and filtration. Dechlorination with sodium sulfite solution was applied just prior to the ion-exchange pretreatment step to protect the cation-exchange resin beads and subsequently the ion-exchange ED membranes from chlorine attack. Further chlorination of the IX product and dechlorination of the ED feed was practiced at LVS but not at the YDTF. The ion exchanger removed additional calcium not removed by the partial lime treatment. Once cyclical operation was established the ion exchange resin was regenerated solely by reject brine from the ED [2, 3].

The ED pilot plant was an Ionics, Inc. Aquamite V model with a single Mark II stack (fig. 2). The Aquamite V skid contained the pumps, flow control devices, variable voltage transformer, rectifier, and associated monitoring and control devices. The stack contained the following components at each site.

| | *YDTF* | *LVS* |
|---|---|---|
| Electrical stages | 2 | 2 |
| No. of electrodes | 4 | 4 |
| Total hydraulic stages | 4 | 6 |
| Cell pairs per stage | 75-50-50-75 | 45-45-40-40-45-45 |
| Total cell pairs | 250 | 260 |
| Cation membrane model No. | CR61 AZL183 | CR61 CZL183 |
| Anion membrane model No. | AR103 PZL183 | AR204 SXZL183 |

Each cell pair in the ED stack consisted of one anion membrane, one cation membrane, and a tortuous path spacer between each membrane. Each stack component measured 508 by 457 mm, overall. Taking into account the portions of a membrane in contact with spacers and flow path the effective area of each membrane was 0.144 m$^2$. Electrodes were made of platinum-coated titanium. The product TDS concentration at LVS was allowed to be relatively high at about 1 g/L to simplify the design. Lower product TDS at LVS would have required additional ED stages.

The ED membranes used at the YDTF were Ionics, Inc.'s standard brackish water types, also their most common type. The membrane types used at LVS were specially selected for higher current efficiencies, which is important for demineralizing high brine concentrations. Both membrane types at the YDTF and the cation membrane at LVS were comprised of cross-linked coplymers of vinyl monomers. The anion membrane type used at LVS was made from acrylic material. Appendix D contains copies of Ionics, Inc. data sheets of the membranes used.

Water flowed through the ED unit as shown on figure 2. Feed water was split between the dilute stream (diluate), which flowed once through the stack, and the makeup to the concentrate stream. The concentrate was recirculated to equalize the flow rates and pressure drop in the tortuous flow paths on each side of a membrane. Desalting recovery and brine concentration were easily set by adjusting the makeup flow of feed water to the recirculating concentrate stream. The portion of concentrate not recirculated became the reject brine at the outlet of the stack. Part of the feed water provided the electrode rinse at the YDTF. At LVS, lime-softening water provides the electrode rinse as shown on figure 2, which was done to avoid wasting IX-softened product for the electrode rinse and to maintain the correct ratio of reject brine regenerant volume to IX product volume as required for the IX experiments.

Timers in the ED unit reversed the polarity of the electrode once every 15 minutes at the YDTF and every 30 minutes at LVS. When polarity reversal occurs, the dilute and concentrate streams exchange identity in the stack such that the dilute stream becomes the concentrate stream and the concentrate stream becomes the dilute stream. Four MOV's (motor-operated valves) at the inlets (MOV-2 and MOV-3) and outlets (MOV-4 and MOV-5) of the stack shown on figure 2 caused the X and Y streams to be alternately concentrate or diluate according to the valve positions corresponding to electrode polarities. To minimize the mixing of the diluate and concentrate in the stack following polarity reversal, the ED unit had special timer relays controlling the two outlet MOV's, not a standard Ionics, Inc. feature, which delayed the outlet valve activations relative to the inlet valve activations by a duration approximately equal to the residence time of the diluate and concentrate in the stack. Immediately following polarity reversal, because the new dilute stream contains concentrate from the previous polarity, the diluate leaving the stack is initially diverted by MOV-6 to waste. Then when the inline measured conductivity of the new dilute stream effluent decreases to a set-point value specified for the product, MOV-6 is activated to send the diluate flow to the product-water storage tank. Similarly, to maximize brine concentrations for the purpose of the IX pretreatment experiments the ED system contained a special modification to divert the initially low TDS concentrate flow to waste following

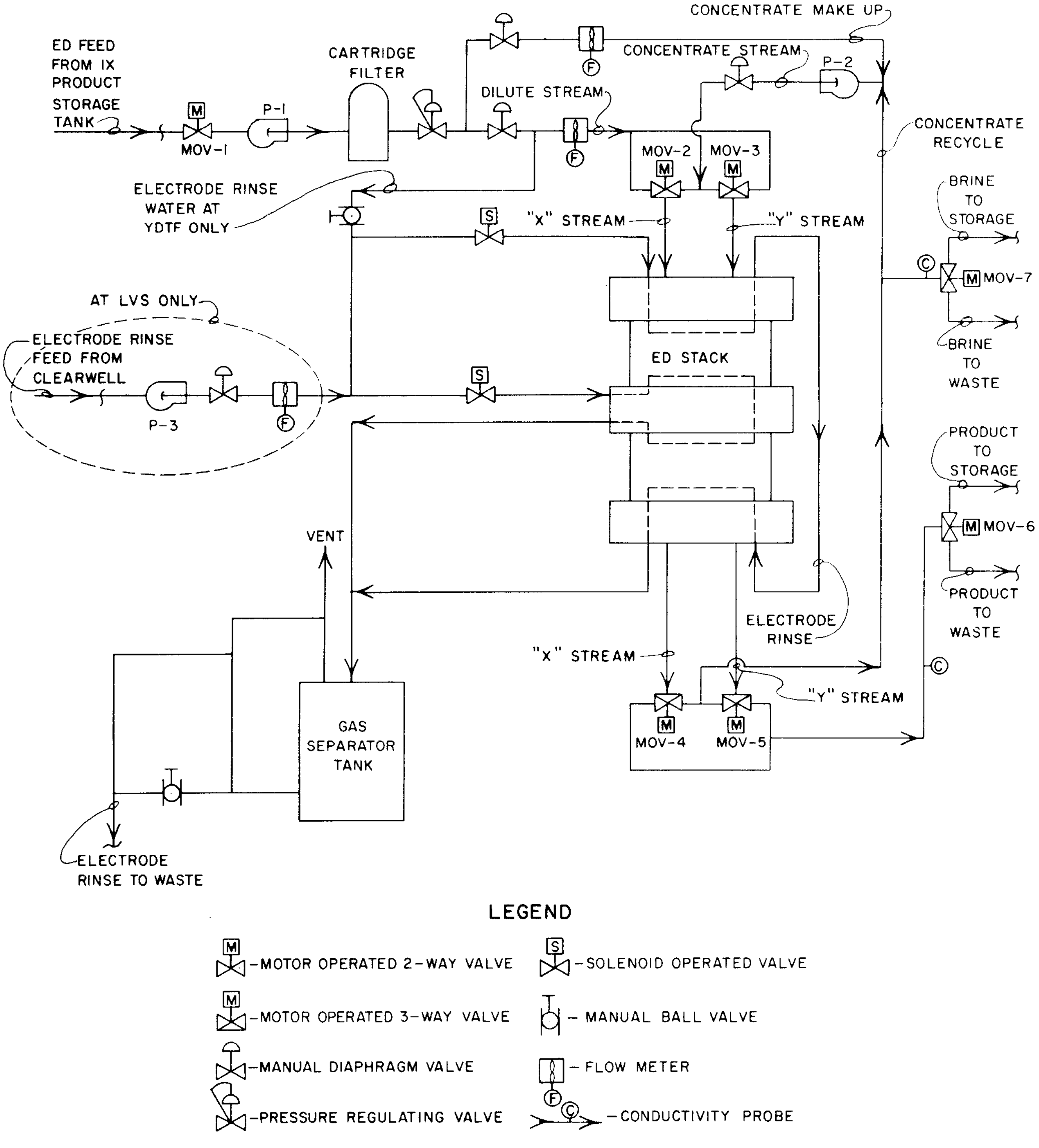


Figure 2. – Flow diagram of ED unit.

polarity reversal until a set-point brine conductivity was reached, which then automatically caused MOV-7 to divert the brine to the IX fresh regenerant storage tank (T-28 on fig. 1). Although unimportant for normal ED operation, such a modification should be considered in applications where very high recoveries are desired, because the concentrate of lower-than-set-point conductivity could be recycled to the ED feed to avoid its loss – which loss would lower overall desalting recovery.

### Procedures

Operators on duty 24-hours per day measured and set flow rates; measured tank volumes; did chemical analyses as necessary for operational control; made numerous other measurements, process adjustments, readings, and observations, which were recorded on data sheets and in a log; and collected samples for analysis in a chemical laboratory. Chemical analyses of samples collected for ED process calculations were made using atomic absorption spectroscopy and other standard analytical techniques.

During ED unit operation, ED performance data were collected at least daily after steady state had been achieved or at least 10 minutes following polarity reversal as indicated by the relative constancy of dilute and concentrate conductivities measured inline. Data collection included:

Accumulated operating time,
Feed temperature,
Flow rates of dilute inlet, brine makeup, product, and reject brine,
Brine pH,
Conductivities of the feed, product, and brine,
Currents of electrical stages 1 and 2, and
Voltages of electrical stages 1 and 2.

The voltage drop across each electrode compartment was measured using a voltmeter attached to two probes inserted into the sides of the stack at the top and bottom of the electrode compartment. This method also was used occasionally along the entire stack profile to check the performance of individual sections of cell pairs. For example, during initial start up at the YDTF, it was found that the order of installation of a cation and an anion membrane were mistakenly reversed resulting in a high voltage drop at that location, which was remedied easily by correctly reinstalling the two membranes.

Operators collected samples for chemical analyses of ions in the ED feed, product, and brine at selected operating times during the test program. Special runs at LVS also included sampling of the dilute and concentrate flows between the two electrical stages. Chemical analyses of samples were by standard chemical methods in the Bureau chemical laboratories at the YDTF, the Lower Colorado Region office in Boulder City, Nev., and the E&R Center in Denver. The chemical analyses, as judged by comparisons and a summation of ions TDS concentrations, evaporative TDS concentrations, and conductivities, and between summations of anions and cations, were consistently of high quality for the YDTF and regional laboratories. All chemical analyses contained in this report were judged accurate by the preceding criteria.

Desalting recoveries were calculated from the TDS concentrations of the inlet and outlet streams by:

$$R = \frac{C'_b - C'_f}{C'_b - C'_p} \qquad (1)$$

where

$R$ = desalting recovery as a dimensionless fraction,
$C'_b$ = TDS concentration of the ED reject brine (concentrate outlet) g/m$^3$,
$C'_f$ = TDS concentration of the ED feed (diluate inlet) g/m$^3$, and
$C'_p$ = TDS concentration of the ED product (diluate outlet) g/m$^3$.

Equation (1) is derived from mass balances of water, TDS, and the normal definition of recovery (product flow divided by feed flow). Recoveries were calculated from salinity measurements alone using equation (1) – not from flow rate measurements – because flow rates generally are subject to greater experimental error than TDS concentrations and because the ED electrode rinse caused a loss of feed water at the YDTF. At the YDTF, brine TDS concentrations were determined operationally by evaporation at 103 °C in the chemistry laboratory, usually daily because more than a week was required to obtain summation-of-ions data for TDS. The TDS measured by both methods were in agreement. Using this procedure [including equation (1)], reject-brine TDS concentrations of 20, 35, and 50 g/L correspond to calculated recoveries of 85.5, 91.8, and 94.3 percent, respectively, when the feed TDS concentration is 3.3 g/L and the product TDS concentration is 0.427 g/L, the approximate values at YDTF. At LVS, the TDS concentrations of the ED reject were 40 g/L and 92 g/L corresponding to 80 and 92 percent recoveries for an ED feed TDS concentration of 8.7 g/L and a product concentration of 1.0 g/L of TDS.

The ED was operated on IX softened water primarily to supply reject brine regenerant for the IX experiments. Thus, the recoveries and brine concentrations were determined by the IX experimental design [2], and the ED unit was operated intermittently as needed to provide brine for IX regenerant to conduct the IX experiments. The ED was operated such that the product TDS concentration was kept nearly constant at each site. Thus, the brine concentration or desalting recovery was the primary parameter varied.

Operational criteria for the ED as operated at LVS are given in table 2 to illustrate how the ED unit was adjusted. Operating criteria used at the YDTF were similar. Note that pressure differentials were adjusted such that concentrate stream pressure was slightly higher than the dilute stream pressure in order that any stack leakage of water between the streams would be from the concentrate to the diluate. This was done because a converse leakage from the dilute to the concentrate would lower the brine TDS concentration and maximizing the brine concentration was a primary objective during ED operation. Note that the brine makeup flow was approaching zero during highest recovery operation because most of the outlet brine flow resulted from electro-osmotic water (water associated with hydrated ions) transported through the membranes and other leakage from the dilute stream to the concentrate stream. Voltages applied to the stack were adjusted to the values given in table 2 which resulted in the currents listed in table 2 according to the stack resistance and Ohm's law. Stage 1 voltage settings were kept low enough to avoid shorting of electrical current along concentrate manifold channels, which would occur at higher voltage settings and cause severe damage to the stack due to heat generation. This voltage limitation was a reason that the LVS product TDS concentration was not lower for the required capacity and the given configuration of the stack.

Table 2. – Operating conditions of the LVS ED pilot plant

| Parameter | Units | Value |
|---|---|---|
| Diluate flow | L/s | 0.37 |
| Brine makeup flow | L/s | 0.067 at 80% recovery<br>$0.006 \times 10^{6}$ at 92% recovery |
| [1]Stack pressure drop | kPa | 300 |
| [2]Stack differential pressure | kPa | 0.98 to 2.94 |
| Outlet | kPa | 0 to 1.96 |
| Stage 1 potential | Volts | 109 |
| Stage 2 potential | Volts | 104 |
| [3]Stage 1 current | Amperes | 23.4 at 80% recovery<br>27.7 at 92% recovery |
| [3]Stage 2 current | Amperes | 15.3 at 80% recovery<br>17.6 at 92% recovery |
| Product conductivity | µS/cm | 2200 to 3000 |
| Electrode rinse | | |
| Pressure | kPa | 275 |
| Flow | L/s | 0.047 |

[1]Stack inlet pressure minus stack outlet pressure approximately equal for both dilute and concentrate streams.

[2]Inlet concentrate pressure minus inlet diluate pressure.

[3]Current increased when feed-water temperature and brine-stream concentration increased.

## ED Performance Calculations

The ED performance is described by:

Current efficiency,
Cell pair resistance, and
Energy consumption.

A theoretical energy consumption estimate called *exergy* is calculated also for comparison.

*Current efficiency* of an ED stack is a measure of the ability of the membranes to transfer ions but not water, and includes effects of water transport by osmosis and electro-osmosis, and ion transport by diffusion in the direction opposite to current flow. Current efficiency is defined empirically for a single electrical stage as the following ratio [5]:

$$e = \frac{\text{number of chemical equivalents of ions effectively transferred}}{\text{number of electrical equivalents passed through membrane pairs}}$$

$$e = \frac{FQ_d\,(C_f - C_p)}{nI} \tag{2}$$

where

$C_f$ = feed ionic concentration, eq/L
$C_p$ = product ionic concentration, eq/L
$e$ = current efficiency
$F$ = Faraday's constant, 96 500 coulombs per equivalent
$I$ = electrical current passing through each cell pair, ampere
$n$ = cell pairs number,
$Q_d$ = inlet dilute flow, L/s

Generally, the inlet dilute flow does not match the outlet dilute (product) flow exactly because of water transport through the membranes and some leakage between the concentrate and dilute streams in the manifold. The concentrate stream was adjusted to a 1- to 3-kPa higher pressure than the dilute stream to prevent diluate leakage from lowering the brine TDS concentration. Because the dilute outlet had about 5 percent less flow than the dilute inlet, the error caused by assuming these two flows equal was less than 1 percent in equation (2), which is negligible. For the present case of two serial electrical stages, 1 and 2, with $n$ cell pairs per stage ($n$ = 125 at the YDTF and $n$ = 130 at LVS) a composite current efficiency for both electrical stages of the stack was calculated from:

$$e = \frac{FQ_d\,(C_f - C_p)}{n\,(I_1 + I_2)} \tag{3}$$

The *cell-pair resistance of stage 1* corrected to 25 °C was calculated using

$$R_1 = \frac{A_f(V_1 - V_e)}{I_n} \qquad (4)$$

where

$A$ = effective area of a membrane (0.144 $m^2$ in the present experiments)
$V_e$ = voltage drop across both first stage electrode compartments (about 10 V in the present experiments),
$f$ = $(0.605)(1.020)^t$, an empirical temperature-correction factor to 25 °C supplied by Ionics, Inc., (t is temperature, °C)
$I_1$ = current passing through the electrical stage, amperes
$n$ = cell pairs, number
$R$ = first stage specific cell pair resistance, ohm·$m^2$
$V_1$ = voltage drop across the first electrical stage, V

Note that $R_1$ – by equation (4) – changes with variations in feed salinity, product salinity, diluate flow, and recovery. Because the diluate flow, feed salinity, and product salinity were relatively fixed during the YDTF and LVS experiments, differences in $R_1$ at each site should be primarily a function of desalting recovery or brine concentration, although membrane fouling probably increased $R_1$ with time gradually at the YDTF (see Results and Discussion sec.). The cell pair resistance of the second electrical stage was not calculated in the present work because it is not independent but directly follows from the fractional demineralization achieved by the first electrical stage, which determines the resistivity of the dilute stream, the largest component of stack resistance in the second stage.

The *energy consumption* per volume of product water (corrected to 25 °C) used by the rectifier to supply direct current to the stack for demineralization was calculated from the ED pilot-plant performance data using

$$E = \frac{f(V_1 I_1 + V_2 I_2)}{Q_p\,(0.94)\,0.90} \qquad (5)$$

where

$E$ = direct current energy consumption of the stack supplied by the rectifier per volume of product kWh/$m^3$
$f$ = see equation (4)
$I_1$ = current passing through the 1st electrical stage, A
$I_2$ = current passing through the 2nd electrical stage, A
$Q_p$ = product-water flow, $m^3$/s
$V_1$ = voltage drop across the first electrical stage, V
$V_2$ = voltage drop across the second electrical stage, V
0.94 = estimated rectifier energy efficiency
0.90 = fraction of time producing product water following from the approximately 10-percent loss of operating time during off-specification (high salinity) product water which is initially recycled following polarity reversal

Note that because $V_1$ and $V_2$ include $V_e$, the voltage drops of the electrode compartments, equation (5) is total energy consumption of the stack including that at the electrodes.

Although equation (5) was used to calculate stack energy consumption from the ED performance, equation (5) does not indicate clearly how changes in ED operating conditions affect energy consumption. Thus, equation (6) is introduced to show how operating variables (flow rate and concentrations of the feed and product), equipment size (membrane area), and performance parameters (current efficiency and cell pair resistance) affect energy requirements [20, 21].

$$E = \frac{F^2 Q_p}{n\,A}\,(C_f - C_p)\;\ln\,\frac{C_f}{C_p}\left(\frac{R\,C_{dave}}{e^2}\right) \qquad (6)$$

where

$A$ = effective membrane area, $m^2$
$C_{dave}$ = average dilute stream (i.e., feed and product) ionic concentration, eq/$m^3$
$C_f$ = feed ionic concentration, eq/$m^3$
$C_p$ = product ionic concentration, eq/$m^3$
$e$ = current efficiency
$E$ = stack energy consumption per volume of product water, J/$m^3$
$F$ = Faraday's constant, 96 500 coulombs per equivalent
$n$ = cell pairs, number
$Q_p$ = product water flow rate, $m^3$/s
$R$ = electrical resistance of the dilute stream of 1 $m^2$ area of one cell pair, ohm·$m^2$

Because the electrical resistance of an ionic solution is approximately inversely proportional to its ionic concentration, $R\ C_{dave}$ is nearly constant along he path length of the dilute compartment in the stack. The term $RC_{dave}/e^2$ is a unit operation parameter, which is a function of water composition and membrane type. Assumptions [20] used in deriving equation (6) include:

1. Polarization potential (membrane potential plus concentration potentials arising from concentration gradients in the solutions between the membranes) is negligible compared to the ohmic loss.

2. Resistances of the membranes are negligible compared to the resistance of the dilute stream.

3. Resistance of the concentrate stream is negligible compared to the resistance of the dilute stream.

4. Water transfer across the membrane is negligible.

Note that an equation essentially the same as equation (6) could be derived by rearranging equation (4) in terms of voltage and equation (2) in terms of current and by substituting these rearranged expressions for the voltages and currents in equation (5).

While equation (5) is more usable for calculating energy consumption from the ED performance data, equation (6) clarifies which are the most important variables affecting ED energy consumption. According to equation (6), stack energy consumption increases as:

1. Equipment size decreased ($A$ decreases for the same $Q_p$)
2. Feed ionic concentration, $C_f$, increases
3. Product ionic concentration, $C_p$, decreases
4. Brine ionic concentration increases, (causing $e$ to decrease)

Although more equipment results in a lower energy consumption, it also results in greater amortized equipment cost. Thus, the incremental amortized equipment cost should match incremental energy costs with respect to plant capacity at the optimum plant size assuming that other costs change negligibly with plant size.

There are other uses of electrical energy by ED besides stack energy consumption. These include energy to pump water through the stack and piping, intermittent energy to the motor-operated valves, and energy to operate the measurement and control instrumentation. Neither the pumping nor the total ED energy consumption was measured in these tests, which could have been done by a kilowatt-hour meter in the electrical lines powering the ED unit and pumps. As a point of comparison, about 2 kW per stack are needed for fluid pumping in a small ED plant [4] which usually amounts to 20 percent of the total ED energy consumption. Electrical energy the ED used for instrumentation and electrically operated valves would be negligible comparatively.

The *thermodynamically minimum* amount of energy required for a process is called its *exergy* [19]. Exergy values compared to actual energy consumption indicate the departure of the process energy consumption from ideality, which is also the maximum potential for lowering energy consumption. The actual energy consumption of desalting processes is generally several times the exergy for practical requirements such as the need to recirculate water and for economic reasons to lower equipment size and amortized equipment cost. That is, it is less expensive overall to speed the process rate somewhat at further departure from thermodynamic equilibrium, which increases energy consumption, than it is to provide the additional equipment capacity needed to operate at a slower rate closer to equilibrium conditions.

For ED, the exergy is the minimum possible work requirement by a hypothetical completely reversible process which would begin with a volume of water of feed composition in one reservoir and end with that volume separated into two separate reservoirs, one having the product composition and the other having the reject brine composition. All three reservoirs are assumed here to be at 25 °C. For such a process, Spiegler [20] gives the equation:

$$E_t = 2R_gT\,(C_f - C_p)\left[\frac{\ln(C_f/C_b)}{(C_f/C_b) - 1} - \frac{\ln(C_f/C_p)}{(C_f/C_p) - 1}\right] \qquad (7)$$

where

$C_b$ = ionic concentration of the brine, eq/m$^3$

$C_f$ = ionic concentration of the feed, eq/m$^3$

$C_p$ = ionic concentration of the product, eq/m$^3$

$E_t$ = thermodynamic minimum energy requirement or exergy, kWh/m$^3$

$R_gT$ = universal gas law constant times absolute temperature = $0.689 \times 10^{-3}$ kWh/mole at 25 °C

Equation (7) is subject to the following assumptions [20]:

1. Salt is a soluble completely dissociated electrolyte consisting of monovalent cations and anions. In the present calculations, solutions of NaCl with the same total normality as the actual, multicomponent solutions were assumed.

2. Activity of each solution is approximated by the equivalent fraction of water in that solution, which implies ideality and complete validity only for infinitely dilute solutions.

3. There is no water transfer across the membranes.

Although the conditions of these assumptions were only approximated in the YDTF and LVS tests, the values calculated using equation (7) were such a small fraction of the actual energy consumption, that more accurate, rigorous calculations of *exergy* would be unimportant for purposes here.

## RESULTS AND DISCUSSION

Two major ED equipment problems had to be resolved at the YDTF before the ED operated successfully. Both problems can be attributed to effects of the unusually high brine concentrations on the standard Ionics, Inc., ED design. This design had seldom, if ever, been used previously to make such high concentration brine. This is in contrast to the experience of Japanese companies who make NaCl concentrators. Fortunately, both ED problems were solved by equipment modifications.

1. The first was rapid erosion of the bronze impeller of the brine recirculation pump during highest recovery operation, when the brine concentration reached about 60 g/L of TDS and the pH dropped. Substitution of the brine pump supplied by Ionics, Inc., with one having a CPVC (chlorinated polyvinyl chloride) impeller and case and a Hastelloy shaft completely solved the pump failure problem.

2. The second problem was electrical shorting through insulation on the stack electrodes. Ionics, Inc., replaced the standard electrodes originally supplied with ones specially encapsulated with plastic for better electrical insulation in critical stagnant flow areas where the shorting had occurred.

Following these two equipment modifications, there were minimal ED operational and maintenance problems during the remainder of testing at the YDTF and LVS.

High plugging factors (similar to silt density index used primarily as a predictor of reverse-osmosis membrane fouling), including many values of over 90 percent, were measured in the IX product water at the YDTF and are shown on figure 3. Simultaneously, the IX feed water had consistently very low plugging factors. Steps were not taken to lower the high plugging factors in the IX product because the high plugging factors had no immediately apparent effect on ED performance. Later analysis of ED data did reveal a gradual increase in *cell pair resistance* at the YDTF, as presented in the following section. Scanning electron microscopy and chemical analyses of amino acids and polysaccharides indicated the presence of microbiological growth [22] on surfaces of the cation exchange resin of the pretreatment and in the ED feed water but not in the IX feed water. These findings are consistent with the plugging factor measurements. This microbiological growth was attributed to dechlorination of the IX feed water that was necessary to prevent gradual oxidation and deterioration by chlorine of the cation exchange resin and the ED membranes. In response to these YDTF findings, at LVS the ED feed water (IX product) was rechlorinated prior to its storage and dechlorinated again just prior to entrance into the ED. Apparently, as a result of this rechlorination, ED feed water plugging factors were consistently low at LVS, and other microbiological growth affecting ED at LVS were not evident.

Typical ED performance levels for each different control brine concentration tested are given in table 3. The values are means of data collected during positive and negative polarities. Chemical analyses results of corresponding feed, product, and brine samples are listed in table 4. Complete tabulations of raw and the reduced data for all observations are contained in appendixes A and B. Statistical analyses (including curve fitting of ED performance data) were by multiple regression using the partial F test with 95 percent confidence limits [23]. Computer printouts document these statistical analyses in appendix C. Results of those statistical analyses are discussed in the following sections.

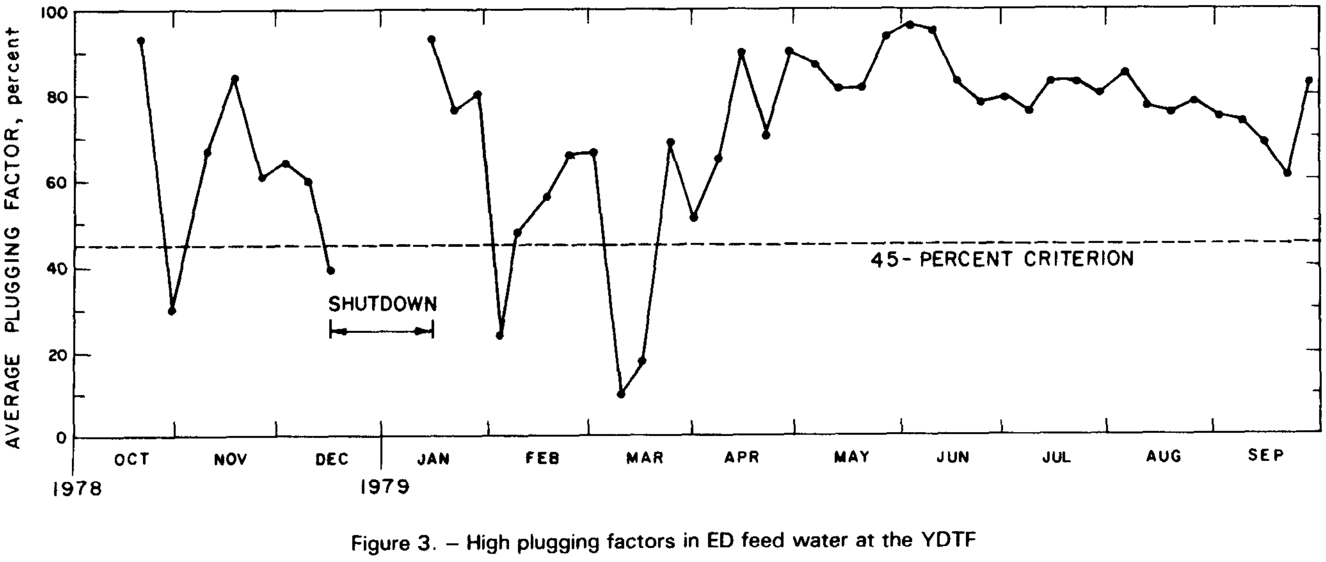


Figure 3. – High plugging factors in ED feed water at the YDTF

Table 3. – Typical Ed performance with different recoveries at YDTF and LVS

| Site date | YDTF – 1979 | | | LVS – 1980 | |
|---|---|---|---|---|---|
| | May 7 | June 4 | June 18 | Feb. 11 | March 10 |
| Operating time, hours | 7902.8 | 8219.3 | 8376.8 | 9786.5 | 10 210.7 |
| Brine concentration g/m³ | 51 680 | 33 361 | 19 406 | 41 600 | 96 500 |
| Feed temperature, °C | 25.0 | 29.5 | 27.0 | 23.8 | 25.1 |
| Dilute flow rate, L/min | 34.0 | 34.0 | 34.0 | 22.0 | 21.9 |
| Brine makeup flow rate, L/min | 0 | 1.35 | 4.4 | 3.7 | 0.2 |
| Product flow rate, L/min | 32.7 | 33.0 | 32.0 | 20.0 | 20.7 |
| Brine flow rate, L/min | 1.65 | 3.2 | 5.88 | 4.3 | 1.6 |
| Brine pH, units | 4.54 | 5.24 | 6.45 | 6.3 | 5.5 |
| Electrical stage 1 | | | | | |
| Current, amperes | 23.6 | 24.0 | 21.6 | 26.2 | 31.9 |
| Voltage, volts | 153 | 154 | 155 | 109 | 104 |
| Specific cell pair resistance, ohm·mm² | 6980 | 7570 | 8050 | 4090 | 3270 |
| Electrical stage 2 | | | | | |
| Current, amperes | 9.6 | 8.6 | 7.4 | 15.6 | 18.1 |
| Voltage, volts | 122 | 123 | 124 | 104 | 98 |
| Specific cell pair resistance, ohm·mm² | 13 440 | 16 570 | 18 470 | 6520 | 5400 |
| Feed cationic concentration, eq/m³ | 51.3 | 55.3 | 55.1 | 147.2 | 148.9 |
| Product cationic concentration, eq/m³ | 7.73 | 6.06 | 6.25 | 18.2 | 20.5 |
| Current efficiency, percent | 57.4 | 66.1 | 73.7 | 84.0 | 69.5 |
| Rectifier | | | | | |
| Energy consumption, kWh/m³ | 2.88 | 3.11 | 2.73 | 4.31 | 4.86 |
| Exergy, kWh/m³ | 0.158 | 0.152 | 0.123 | 0.292 | 0.402 |
| Exergy/energy consumption, percent | 5.5 | 4.9 | 4.5 | 6.8 | 8.3 |

## Cell Pair Resistance

The importance of cell pair resistance is that its increase causes an increase in voltage drop to maintain a given current needed for demineralization, and thus, an increase in power consumption according to equation (5). Cell pair resistance $R_1$ for the first stage corrected to 25 °C was calculated using equation (4). Note that 10 V was subtracted from each value of the stage voltage to account for electrode compartment voltage drop measured by a voltage probe of the ED stack.

Multiple regression analysis of the data yielded for the ED first stage cell pair resistance at the YDTF:

$$R_1 = 0.812\ T_o - 25.3\ C'_b + 6734$$

where

$R_1$ = first stage cell pair resistance, ohm·m$^2$
$T_o$ = operating time, hours
$C'_b$ = dissolved solids concentration in the brine, kg/m$^3$

For the LVS data the regression analysis yielded

$$R_1 = 4560 - 12.6\ C'_b \tag{9}$$

Statistically, there was insignificant relation between $R_1$ and $C'_p$ at either site and between $R_1$ and $T_o$ at LVS. The $R_1$ should increase with lower $C'_p$, but it was not observed in the data from YDTF or LVS because $C'_p$ was not varied sufficiently at either site to indicate a relationship between $R_1$ and $C'_p$.

Figure 4 shows $R_1$ decreasing with brine concentration; it is expected because solution and membrane electrical resistances *each* decrease with increasing ionic concentration. Figure 4 curves were plotted by using equation (8) with $T_o$ = 2342 hours (the mean) for YDTF and equation (9) for LVS.

The $R_1$ at LVS was less than $R_1$ at YDTF because of the higher feed-water and product-water (dilute stream) TDS concentrations at LVS, which had less resistivity. The scatter (fig. 4) of the YDTF $R_1$ data at a 35-g/L TDS brine concentration results from the variation of $R_1$ with another independent variable – operating time – as in equation (8).

Figure 5 indicates the observed increase in $R_1$ with the operating time at the YDTF, but which did not occur at LVS. Much of the scatter of the YDTF data is because the data for all three brine concentrations are included, which affects $R_1$ according to the multiple regression equation (8). As mentioned earlier in this section, slime-producing microbiological growth occurred at YDTF in the IX resin and IX product water tank when the IX feed was dechlorinated and there was no further disinfection downstream. It is generally known that membrane fouling will cause cell pair resistance to increase. However, upon dismantling the stack for inspection, touch and sight did not indicate any slime on the membrane surfaces of the present ED unit as had been observed during previous YDTF testing of an Ionic's Inc. ED operating at about 70 percent recovery.

Although the rechlorination of the IX product-ED feed at LVS could be the sole reason that $R_1$ did not increase at LVS, as it did at the YDTF, two other factors were different and possibly important in the ED tests at LVS compared to operation at the YDTF. First, the surface water source at the YDTF is rich in biological growth including algae and bacteria prior to pretreatment. Measurements by the U.S. Geological Survey at the YDTF showed that suspended organic material such as algae were removed effectively, but most of the *dissolved* organic matter in the canal (4 g/m$^3$ of organic carbon) penetrated the chlorination and lime

Table 4. – Typical Electrodialysis water compositions

| Site | YDTF | | | | | | | | | LVS | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Date (percent recovery) | May 7, 1979 (94.6) | | | June 4, 1979 (90.9) | | | June 18, 1979 (83.9) | | | February 11, 1980 (80.2) | | | March 10, 1980 (91.7) | | |
| Sample stream | Feed | Product | Brine | Feed | Product | Brine | Feed | Product | Brine | Feed | Product | Brine | Feed | Product | Brine |
| pH (units) | 6.8 | 5.6 | 4.4 | 6.9 | 5.0 | 4.8 | 7.2 | 4.8 | 6.4 | 7.9 | 7.5 | 7.4 | 7.3 | 7.4 | 6.8 |
| TDS (calculated) (g/m³) | 3251 | 494 | 51 680 | 3443 | 435 | 33 361 | 3487 | 431 | 19 406 | 9140 | 1150 | 41 600 | 9180 | 1280 | 96 500 |
| Conductivity at 25 °C (µS/cm) | 5413 | 814 | 62 830 | 5797 | 736 | 43 276 | 5718 | 696 | 27 008 | 1360 | 205 | 5090 | 1370 | 225 | 9670 |
| Silica (g/m³) | 3.5 | 3.6 | 3.5 | 4.0 | 4.2 | 6.5 | 4.6 | 1.8 | 6.5 | 12 | 12 | 17 | 16 | 19 | 26 |
| Calcium (g/m³) | 7.1 | 1.2 | 117 | 9.6 | 0.7 | 109 | 18.5 | 1.7 | 128 | 60 | 2.4 | 310 | 35 | 5.0 | 310 |
| Magnesium (g/m³) | 19.7 | 1.6 | 35.4 | 15.6 | 1.1 | 190 | 30.5 | 2.7 | 210 | 54.9 | 3.9 | 275 | 51.9 | 3.1 | 506 |
| Sodium (g/m³) | 1126 | 158 | 18 140 | 1224 | 136 | 11 500 | 1180 | 136 | 6570 | 3110 | 402 | 13 900 | 3170 | 449 | 33 000 |
| Potassium (g/m³) | 11.2 | 1.6 | 188 | 10.0 | 0.7 | 101 | 12.4 | 1.2 | 68 | 176 | 12.5 | 860 | 196 | 19.6 | 1960 |
| Total iron (g/m³) | <0.10 | <0.10 | <0.10 | <0.10 | <0.10 | <0.10 | <0.10 | <0.10 | <0.10 | 0.06 | 0 | 0.42 | 0.04 | 0 | 0.72 |
| Total manganese (g/m³) | <0.30 | <0.30 | <0.30 | <0.30 | <0.30 | <0.30 | <0.30 | <0.30 | <0.30 | <0.05 | <0.05 | 0.13 | <0.05 | <0.05 | 0.30 |
| Strontium (g/m³) | 0.7 | 0.6 | 2.3 | 0.7 | 0.6 | 1.8 | 0.3 | 0.1 | 1.5 | 1.5 | 0 | 0 | 0.3 | 0 | 2.3 |
| Bicarbonate (g/m³) | 14.6 | 2.4 | 17.1 | 19.5 | 5.9 | 12.2 | 20.5 | 3.9 | 41.5 | 46.5 | 22.0 | 82.4 | 40.3 | 26.2 | 68.9 |
| Carbonate (g/m³) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Sulfate (g/m³) | 970 | 215 | 15 100 | 960 | 205 | 9340 | 1020 | 213 | 5050 | 2040 | 196 | 9620 | 2040 | 190 | 22 900 |
| Chloride (g/m³) | 1114 | 114 | 18 080 | 1200 | 81.2 | 12 100 | 1200 | 71 | 7330 | 3660 | 513 | 16 600 | 3650 | 580 | 37 800 |
| Total anions (eq/m³) | 51.53 | 7.21 | 824.85 | 54.17 | 6.66 | 536.1 | 55.43 | 6.50 | 312.6 | 146.4 | 18.88 | 668.6 | 145.9 | 20.72 | 1545.0 |
| Total cations (eq/m³) | 51.26 | 7.73 | 802.70 | 55.28 | 6.07 | 523.9 | 55.09 | 6.26 | 311.2 | 147.0 | 18.24 | 666.00 | 149.0 | 20.50 | 1542.0 |

pretreatment system [14]. In contrast, LVS water – ground water from a well – is lower in dissolved organic material (about 2 g/m$^3$ of organic carbon), and contains no measurable particulate organic material. Second, there is reason to presume that the aliphatic anion membranes used at LVS may be less sensitive to organic material relative to the more standard anion type used at the YDTF. This presumption is based on the relative insensitivity of aliphatic anion exchange resins to certain anionic organic electrolytes relative to that of more common anion-exchange resins made of aminated styrene-divinyl benzene, which are quite sensitive to many organic anions [24]. Only further experimentation could identify conclusively the variables that caused the increase in $R_1$ at the YDTF and the relative constancy of $R_1$ at LVS.

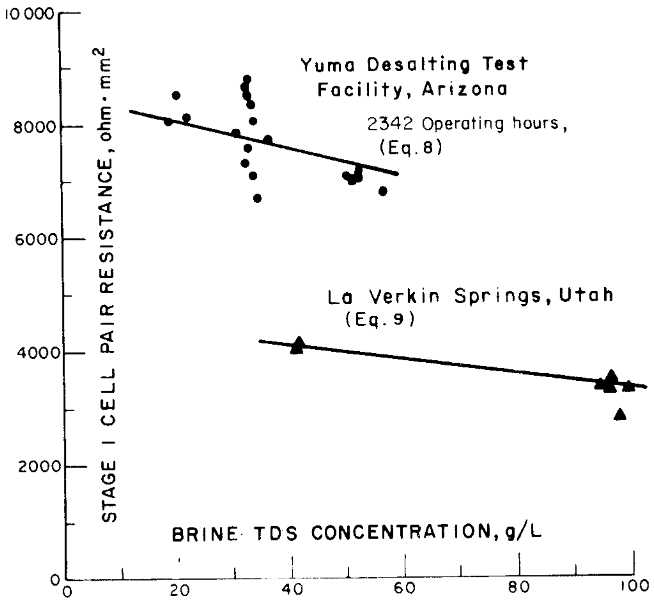


Figure 4. – Stage 1 cell pair resistance 5 °C, ohm·mm² versus g/L brine TDS concentration.

## Current Efficiency

Current efficiencies are shown decreasing with brine concentration on figure 6. The curves represent the regression equations for current efficiency *e:*

at the YDTF

$$e = 0.830 - 0.00505\ C'_b \qquad (10)$$

and at LVS

$$e = 0.893 - 0.000192\ C'_b \qquad (11)$$

The decrease of *e* with $C'_b$ is expected because current efficiency of an ED membrane is largely a function of the ionic concentration difference across a membrane [4]. The higher current efficiency of the relatively more permselective membranes used at LVS is apparent on figure 6. Because required current is inversely proportional to current efficiency, the current efficiency is important as is cell pair resistance (cell pair voltage divided by current) in determining power consumption according to equation (5). Note that the organic fouling, which presumably caused $R_1$ to increase at the YDTF, had no statistically significant effect on current efficiency according to the multiple regression analysis of the data when operating time was included as an independent variable.

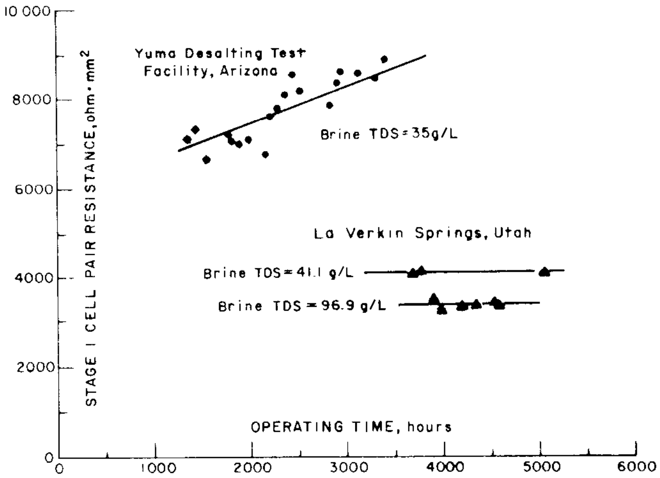


Figure 5. – Stage 1 cell pair resistance 25 °C, ohm·mm² versus hours operating time.

A comparison of current efficiencies of the individual electrical stages further shows the effect of brine

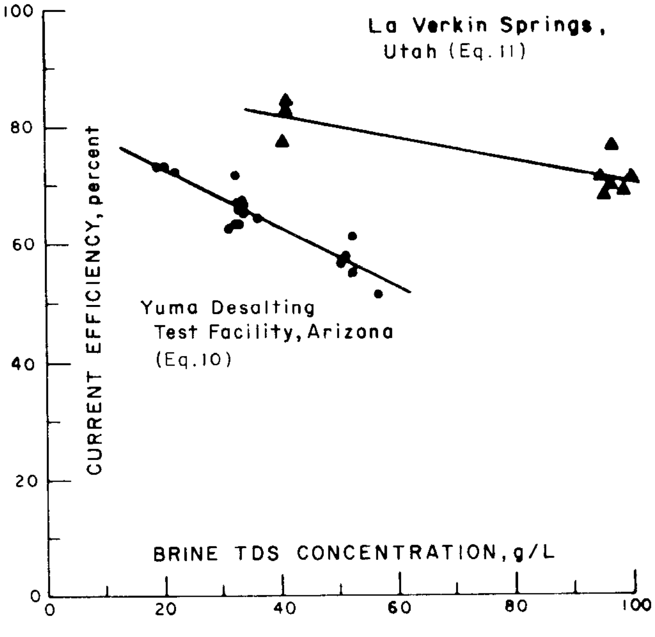


Figure 6. – Current efficiency versus brine TDS concentration.

concentration upon current efficiencies. Interstage water samples for chemical analyses were collected during selected observations at LVS only. Results for three observations follow.

| 1980 Date | Brine concentration, g/m$^3$ | Current efficiency, percent | |
|---|---|---|---|
| | | Stage 1 | Stage 2 |
| April 21 | 40 700 | 77 | 73 |
| March 26 | 98 300 | 71 | 55 |
| March 28 | 94 900 | 71 | 62 |

These data show how current efficiencies were less in the second electrical stage as compared to the first. In stage 2, the brine TDS concentration is higher, the product TDS concentration is less, and thus, the differential TDS concentration and driving force across the membrane is greater – apparently causing the lower current efficiency of stage 2 relative to stage 1. Another cause for lower current efficiencies with higher solution concentrations is the loss in permselectivity that occurs because the quantity of mobile ions in the ion-exchange resin of the membrane with sign opposite to that of the exchange ion increases due to diffusion of ions from the solution into the resin [4].

## Energy Consumption

Direct-current energy consumption per volume of product water, $E$ in kWh/m$^3$, versus brine concentration is shown on figure 7. These energy consumption values were calculated by using equation (5). The regression curves on figure 7 are described:

for the YDTF data by

$$E = 0.0110\, C'_b + 2.53 \qquad (12)$$

and for the LVS data by

$$E = 0.00684\, C'_b + 3.96 \qquad (13)$$

The rather poor fit of equation (12) ($R^2 = 0.18$) and the scatter of the YDTF data on figure 7 exist because water temperature affected $E$ more strongly than $C'_b$ according to the regression analyses documented in appendix C, despite the temperature-correction factor $f$ in equation (5) included to calculate $E$. Note that as the brine concentration increases how the decreased current efficiency (equations 10 and 11) have a greater effect than the decreased cell pair resistance (equations 8 and 9) upon energy consumption (equations 12 and 13). This occurs largely because, as shown by equation 6, $E$ drops as the inverse square of $e$, but the effect of $R$ upon $E$ is to the first power.

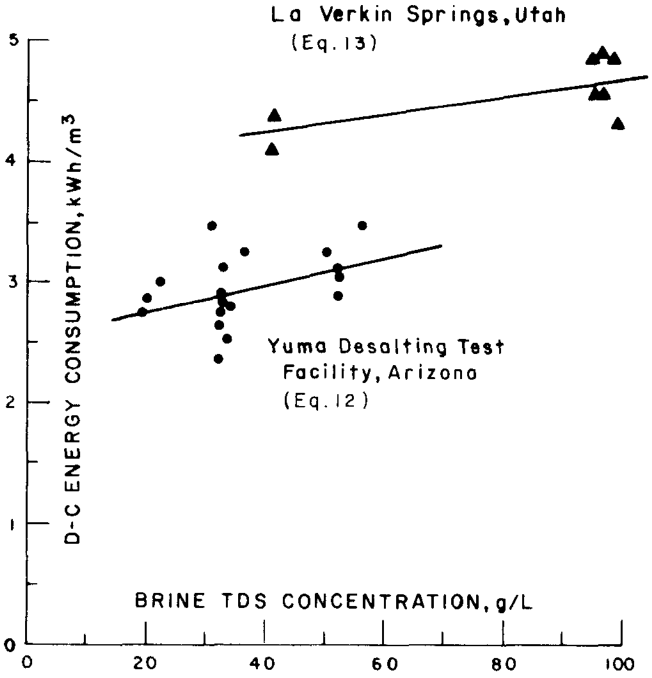


Figure 7. – Direct-current energy consumption (25 °C) versus brine TDS concentration. Product TDS concentration of each site was kept relatively constant.

## Exergy

It is illuminating to compare the actual energy consumption values with an estimate of the theoretical thermodynamic energy or *exergy* that would be required to do the demineralization. *Exergy* calculated from the respective ionic equivalent concentrations using equation (7) are listed in the next to the last row in table 3. The percentage that each of these thermodynamic energies are of the corresponding experimental rectifier energy consumption is in the last row in table 3. The low percentage range of 5.5 to 8.3 percent illustrates how the thermodynamic energy requirements are a minor portion of the requirements of a practical ED process. These percentages would even be lower if the total ED energy consumption, including that for pumping, were used for comparision with *exergy*.

The exergy values calculated from equation (7) neglect the ohmic losses of Joule heating of the water and membranes due to the passage of electrical current through the resistances of the stack. In the dilute water stream – having the lowest electrical conductivity and highest resistance – this ohmic loss, which results in heating the solutions rather than demineralizing, is generally the largest component of ED energy usage in an economically justifiable ED process given present energy and equipment costs [4, 20]. Energy usage can be lowered toward the exergy value (ohmic losses become negligible) by decreasing both the current density (current divided by effective membrane area) and the flow rates through the stack. However, relatively low current densities and flow rates result in a greater increase in amortized equipment costs than the related cost savings in electrical energy. Note also that the electrical energy required for pumping water through the stack at a given flow rate increases as the stack size is increased. There is also an ever present tendency for the salts on the concentrate side to diffuse through the membranes to the dilute side, which requires a continuous expenditure of energy in addition to exergy just to maintain the concentration difference across the membrane. Thus, for economic reasons, ED processes tend to be designed and operated with relatively high current densities and flow rates where the stack energy requirements are far above the theoretical minimum expressed as exergy (equation 7) and the major consumption of energy in the stack is from heating the water and membranes, an inevitable result of passing electrical current through the resistance of the stack, especially the dilute stream.

### Product Concentration Energy Effects

Although product concentration was not varied during the experiments at either the YDTF or LVS, the effect of product concentration can be described approximately by equation (6). From the present LVS data, the cell pair resistance as a function of an average concentration of the concentrate and dilute streams was determined by regression analysis to be approximated by:

$$R = 0.00192 + \frac{0.299}{C_{ave}} \qquad (14)$$

where $C_{ave}$ is the arithmetic mean of the inlet and outlet average normalities, $C_a$, defined by

$$C_a = \frac{2\,C_d\,C_c}{C_d + C_c} \qquad (15)$$

where

$C_d$ = the dilute stream normality, eq/L and

$C_c$ = the concentrate stream normality, eq/L

each measured at the same distance along the flow paths, in the present instance at the inlet or outlet point [4]. (Note that $C_{dave}$ in equation (6) is an average for the dilute stream only and is not the same as $C_{ave}$ in equation 14.) Equations 6, 11, 14, and 15 were combined using an average equivalent weight at LVS of 62.5 g/eq to calculate the curves on figure 8 at two brine ionic concentrations with the following parameters fixed at values for the LVS ED pilot plant:

Number of cell pairs, $n$ = 130

Product flow rate, $Q_p = 3.7 \times 10^{-4}$ m$^3$/s

Effective membrane area, $A$ = 0.144 m$^2$

Figure 8 shows an increase in energy consumption of nearly threefold with lowering the product ionic concentration from 20 eq/m$^3$ to 1 eq/m$^3$ for a given equipment size and flow. Also, according to equation (6), to achieve a 1-eq/m$^3$ product ionic concentration with the same energy consumption used to obtain a 20-eq/m$^3$ product would require nearly three times the membrane area per product flow. Thus, these values show how expensive it is in terms of energy consumption and/or equipment size to obtain increasingly lower product salinities with ED.

### Comparison of ED With Other Desalting Processes

Measured and projected ED energy consumption values were compared with those of a competing process, vapor-compression brine concentrators. The concentrators supplied by Research Conservation Corporation, Inc., use a recirculating seed-crystal slurry to precipitate gypsum and slice in the bulk brine stream to allow brine concentrations of up to 300 000 g/m$^3$ of TDS (corresponding to 99 percent desalting recovery at the YDTF and 97 percent recovery at LVS) without scaling the equipment surfaces. Such a vapor-compression brine concentrator would consume about 25 kWh/m$^3$ of product to desalt a 10 000 g/m$^3$ TDS feed water according to the manufacturer [25], which is at least three times the

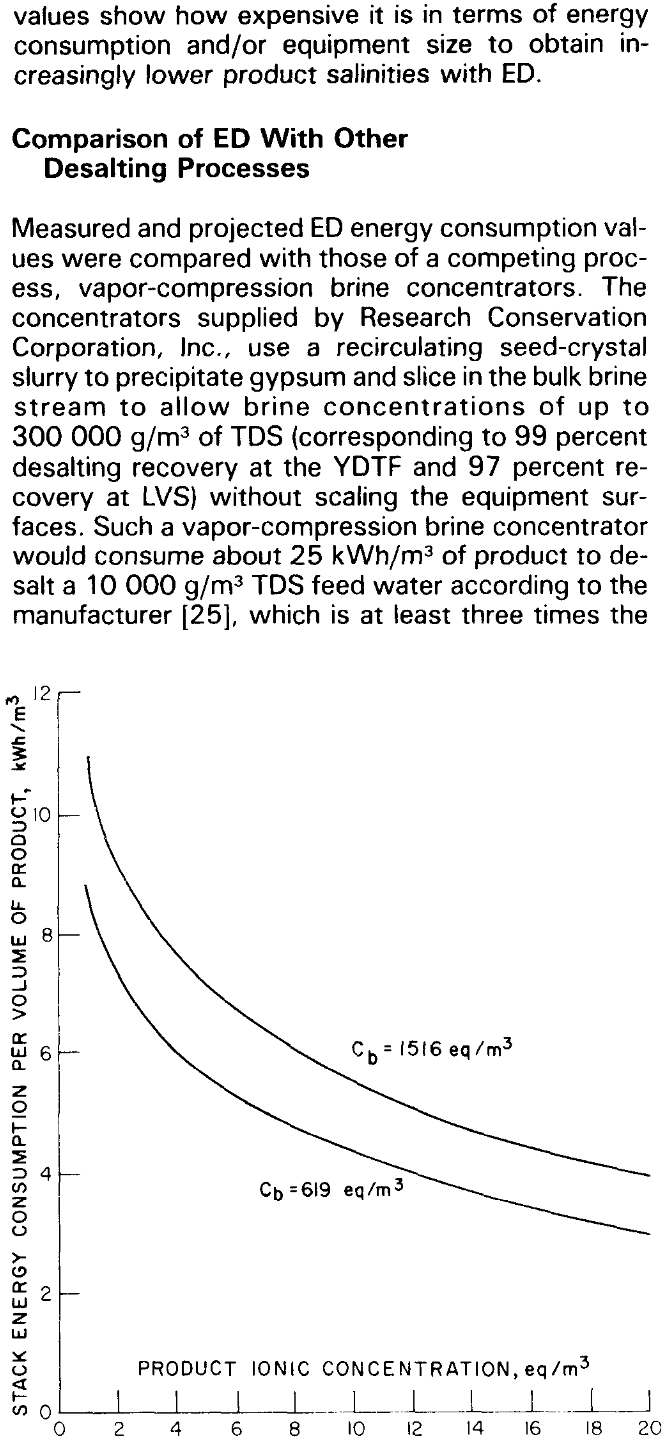


Figure 8. – Projected energy consumption at two brine TDS concentrations versus product ionic concentration at LVS.

total energy consumption of the ED measured in the present experiments (table 3). It is noted that there are certain potential advantages of a vapor compression unit over an ED brine concentrator including a lower TDS-containing product (particularly lower silica), higher possible desalting recovery, and less pretreatment. But in situations where such advantages are not overriding considerations, coupling of ED with an ion exchange pretreatment as demonstrated at the YDTF and LVS should have significantly lower energy consumption as well as less initial cost as compared to vapor compression [6].

Because RO alone cannot generate as high brine concentrations as ED or vapor compression distillation, RO cannot be considered competitive as a concentrator for brines above about 50 000 mg/L of TDS. In some cases, a combination of processes may be optimum. For example, ED could produce high brine concentrations, thus high recovery, and the ED product could be desalted further to a lower TDS most economically by RO; the RO reject would be recycled to the ED feed [9]. Moreover, the advantages and disadvantages of each desalting, pretreatment, and brine concentration application should be considered individually, and in combination, and the optimum process or combination of processes should be selected according to specific requirements and lowest overall costs. This report describes how ED can be used advantageously for high recovery desalting purposes.

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# APPENDIX A

# ELECTRODIALYSIS OPERATIONAL DATA

Table A-1. – Electrodialysis performance at the YDTF – 1979.

| | March | | | April | | May | | | June | | | | July | | August | | September | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 12 | 19 | 26 | 23 | 30 | 7 | 14 | 29 | 4 | 11 | 18 | 25 | 3 | 6 | 13 | 20 | 4 | 17 | 24 |
| Operating time, hour | 7357.1 | 7444.4 | 7550.3 | 7786.9 | 7825.0 | 7902.8 | 7996.6 | 8169.8 | 8219.3 | 8289.7 | 8376.8 | 8456.1 | 8526.0 | 8842.7 | 8912.0 | 8961.0 | 9141.3 | 9316.5 | 9416.0 |
| Brine concentration, g/m³ | 33 945 | 32 583 | ND | 52 438 | 52 760 | 51 680 | 50 503 | 56 777 | 33 361 | 36 465 | 19 406 | 20 470 | 22 263 | 31 208 | 34 033 | 32 322 | 33 110 | 33 098 | 33 491 |
| Feed temperature, °C | 21.5 | 21.0 | 22.0 | 26.0 | 26.0 | 25.0 | 27.0 | 28.0 | 29.5 | 31.0 | 27.0 | 31.0 | 30.0 | 31.0 | 29.0 | 28.0 | 30.2 | 28.2 | 29.5 |
| Dilute flow rate, L/min | 34 | 34 | 34 | 34 | 34 | 34 | 34 | 34 | 34 | 34 | 34 | 34 | 34 | 34 | 34 | 34 | 34 | 34 | 34 |
| Brine makeup flow rate, L/min | 1.3 | 1.2 | 0 | 0 | 0 | 0 | 0.35 | 0.15 | 1.35 | 1.0 | 4.4 | 4.5 | 3.5 | 1.2 | 1.0 | 0.98 | 1.1 | 1.2 | 1.1 |
| Product flow rate, L/min | 32.4 | 32.19 | 31.83 | 32.4 | 32.6 | 32.7 | 33.0 | 32.9 | 33.0 | 32.7 | 32.0 | 32.8 | 32.6 | 31.7 | 32.5 | 32.2 | 33.0 | 32.6 | 32.4 |
| Brine flow rate, L/min | 2.83 | 2.87 | 1.16 | 1.44 | 1.64 | 1.65 | 1.40 | 1.80 | 3.2 | 2.36 | 5.88 | 7.40 | 5.0 | 2.7 | 2.8 | 2.5 | 2.6 | 2.6 | 2.8 |
| Brine pH, units | 5.77 | 4.3 | 3.8 | 3.88 | 4.27 | 4.54 | 4.36 | 4.01 | 5.24 | 5.95 | 6.45 | 5.85 | 5.85 | 6.11 | 6.17 | 6.80 | 6.88 | 6.72 | 6.67 |
| *Electrical stage 1* | | | | | | | | | | | | | | | | | | | |
| Current, amperes | 22.0 | 20.8 | 23.4 | 24.1 | 24.1 | 23.6 | 24.8 | 26.5 | 24.0 | 24.1 | 21.6 | 21.8 | 22.7 | 24.1 | 21.3 | 20.4 | 21.6 | 21.0 | 20.7 |
| Voltage, volts | 155 | 153 | 153 | 157 | 154 | 153 | 156 | 156 | 154 | 154 | 155 | 153 | 155 | 155 | 152 | 153 | 154 | 154 | 155 |
| Specific cell pair resistance, Ω-cm² | 80.7 | 83.4 | 75.7 | 82.0 | 80.4 | 79.9 | 81.0 | 77.5 | 87.5 | 90.3 | 92.4 | 99.2 | 94.2 | 90.9 | 96.1 | 98.7 | 98.9 | 97.0 | 102.1 |
| *Electrical stage 2* | | | | | | | | | | | | | | | | | | | |
| Current, amperes | 8.6 | 8.2 | 9.7 | 9.6 | 9.6 | 9.6 | 10.6 | 10.5 | 8.6 | 8.6 | 7.4 | 7.3 | 7.7 | 9.7 | 8.2 | 7.8 | 8.4 | 8.2 | 8.2 |
| Voltage, volts | 123 | 122 | 122 | 125 | 122 | 122 | 124 | 124 | 123 | 123 | 124 | 122 | 124 | 124 | 123 | 122 | 124 | 124 | 124 |
| Specific cell pair resistance, Ω-cm² | 163.3 | 168.2 | 145.1 | 163.4 | 159.4 | 156.0 | 150.1 | 155.0 | 194.4 | 201.5 | 215.0 | 235.5 | 221.5 | 180.2 | 201.5 | 205.2 | 204.0 | 199.4 | 205.5 |
| Feed cationic concentration, meq/L | 53.4 | 55.0 | ND | 50.3 | 55.0 | 51.2 | 52.9 | 52.1 | 55.3 | 54.9 | 55.1 | 55.6 | 56.2 | 54.5 | 52.4 | 47.37 | 50.9 | 52.0 | 51.83 |
| Product cationic concentration, meq/L | 6.68 | 7.55 | ND | 7.89 | 7.54 | 7.10 | 6.72 | 8.65 | 6.06 | 6.89 | 6.25 | 6.80 | 5.81 | 5.92 | 8.19 | 6.29 | 7.08 | 7.40 | 7.19 |
| Current efficiency, % | 66.8 | 71.6 | | 54.5 | 72.9 | 61.3 | 57.1 | 51.4 | 66.1 | 64.2 | 73.7 | 73.4 | 72.5 | 62.9 | 65.6 | 63.7 | 63.9 | 66.8 | 67.6 |
| Rectifier energy consumption per volume of product water, kWh/m³ | 2.52 | 2.35 | 2.76 | 3.07 | 2.99 | 2.86 | 3.20 | 3.43 | 3.08 | 3.21 | 2.71 | 2.84 | 2.96 | 3.43 | 2.77 | 2.62 | 2.87 | 2.72 | 2.79 |

Table A-2. – Electrodialysis performance at LaVerkin Springs – 1980.

| Date | units | Jan. 28 | Feb. 11 | Feb. 19[a] | March 3 | March 10 | March 17 | March 26 | March 28 | April 21 |
|---|---|---|---|---|---|---|---|---|---|---|
| Operating time | hour | 9693.0 | 9786.5 | 9907.4 | 96.0 | 210.7 | 351.5 | 546.1 | 587.0 | 1061.8 |
| Brine concentration | $g/m^3$ | 41 100 | 41 600 | 96 800 | 96 500 | 96 500 | 95 940 | 98 300 | 94 900 | 40 700 |
| Recovery using equation (1) | percent | 79.6 | 80.2 | 91.3 | 91.6 | 91.7 | 91.3 | | | |
| Feed temperature | °C | 23.8 | 23.8 | 22.0 | 26 | 25.1 | 23.1 | 24.8 | 24.1 | 30.9 |
| Dilute flow rate | L/s | 0.367 | 0.367 | 0.367 | 0.367 | 0.365 | 0.367 | 0.367 | 0.367 | 0.367 |
| Brine make-up flow rate | L/s | 0.0633 | 0.0617 | 0.0033 | 0.0023 | 0.0033 | 0.0023 | 0.0033 | 0.0017 | 0.0567 |
| Product flow rate | L/s | 0.333 | 0.333 | 0.343 | 0.348 | 0.345 | 0.350 | 0.342 | 0.338 | 0.350 |
| Brine flow rate | L/s | 0.0800 | 0.0717 | 0.0250 | 0.0267 | 0.0267 | 0.0200 | 0.0233 | 0.0250 | 0.0825 |
| Brine pH | units | 6.0 | 6.3 | –[b] | 5.7 | 5.5 | 6.2 | 5.8 | 5.8 | 6.2 |
| Electrical stage 1 | | | | | | | | | | |
| Current | amp | 26.6 | 26.2 | 29.7 | 29.9 | 31.9 | 30.4 | 31.0 | 30.7 | 26.3 |
| Voltage | volts | 109 | 109 | 109 | 97 | 104 | 105 | 105 | 104 | 95 |
| Specific cell pair resistance | $\Omega \cdot m^2$ | 0.00402 | 0.00409 | 0.00348 | 0.00329 | 0.00327 | 0.00333 | 0.00338 | 0.00333 | 0.00403 |
| Electrical stage 2 | | | | | | | | | | |
| Current | amp | 15.5 | 15.6 | 17.7 | 17.9 | 18.1 | 18.3 | 18.0 | 17.5 | 15.4 |
| Voltage | volts | 104 | 104 | 104 | 92 | 98 | 100 | 99 | 98 | 88 |
| Specific cell pair resistance | $\Omega \cdot m^2$ | 0.00656 | 0.00652 | 0.00554 | 0.00518 | 0.00540 | 0.00524 | 0.00546 | 0.00547 | 0.00632 |
| Feed cationic concentration | $eq/m^3$ | 142.6 | 147.2 | 145.2 | 150.8 | 148.9 | 140.5 | 142.4 | 143.2 | 139.7 |
| Product cationic concentration | $eq/m^3$ | 14.7 | 18.2 | 12.4 | 23.1 | 20.5 | 18.5 | 19.6 | 17.6 | 20.7 |
| Current efficiency | percent | 82.6 | 84.0 | 76.3 | 72.7 | 69.5 | 68.1 | 68.2 | 70.9 | 77.6 |
| Rectifier energy consumption per volume of product water | $kWh/m^3$ | 4.31 | 4.28 | 4.55 | 4.34 | 4.82 | 4.50 | 4.78 | 4.65 | 4.03 |

[a] Because of operator error, ED conditions were not recorded at the time samples were collected. Data from conditions taken on February 20, 1980, are presented, as being representative of the conditions which existed when the samples were collected on February 19, 1980.

[b] Brine pH was not recorded when unit conditions were taken.

# APPENDIX B

# ELECTRODIALYSIS STREAM CHEMICAL COMPOSITIONS

Table B-1. – Chemical analysis – Ionics Aquamite V electrodialysis at the YDTF – 1979

| Sample stream | March 12 | | | March 19 | | | March 26 | | |
|---|---|---|---|---|---|---|---|---|---|
| | Feed | Product | Brine | Feed | Product | Brine | Feed | Product | Brine |
| pH units | 7.0 | 6.4 | 5.8 | 6.9 | 6.0 | 5.8 | 7.3 | 5.2 | 3.8 |
| TDS, g/m$^3$ | 3418 | 502 | 33 945 | 3483 | 517 | 32 583 | | | |
| Conductivity at 25 °C, $\mu$S/cm | 5802 | 810 | 45 644 | 5824 | 866 | 43 505 | 5938 | 921 | 63 583 |
| E. F. | 0.59 | 0.62 | 0.74 | 0.60 | 0.60 | 0.75 | | | |
| Silica, g/m$^3$ | 12.2 | 5.8 | 5.5 | 10.7 | 10.4 | 10.0 | 7.0 | 7.1 | 8.0 |
| Calcium, g/m$^3$ | 12.7 | 1.3 | 154 | 6.1 | 1.6 | 86 | 3.2 | 1.7 | 75 |
| Magnesium, g/m$^3$ | 30.6 | 2.8 | 350 | 20.5 | 2.3 | 203 | 7.0 | 1.6 | 257 |
| Sodium, g/m$^3$ | 1148 | 146 | 11 430 | 1215 | 167 | 11 580 | | | |
| Potassium, g/m$^3$ | 12.1 | 1.2 | 135 | 6.8 | 0.8 | 59 | | | |
| Total iron, g/m$^3$ | <0.10 | <0.10 | <0.10 | <0.10 | <0.10 | <0.10 | | | |
| Total manganese, g/m$^3$ | <0.30 | <0.30 | <0.30 | <0.30 | <0.30 | <0.30 | | | |
| Strontium, g/m$^3$ | 0.3 | 0.2 | 2.1 | 0.8 | 0.7 | 1.9 | | | |
| Bicarbonate, g/m$^3$ | 24.4 | 7.3 | 43.9 | 25.4 | 8.3 | 32.7 | 17.1 | 6.3 | N/D |
| Carbonate, g/m$^3$ | N/D | N/D | N/D | N/D | N/D | N/D | N/D | N/D | N/D |
| Sulfate, g/m$^3$ | 994 | 214 | 9420 | 1004 | 227 | 8370 | | | |
| Chloride, g/m$^3$ | 1196 | 129 | 12 410 | 1204 | 109 | 12 250 | | | |
| T-alkalinity as CaCO$_3$, g/m$^3$ | 20.0 | 6.0 | 36.0 | 20.8 | 6.8 | 26.8 | 14.0 | 5.2 | N/D |
| T-acidity as CaCO$_3$, g/m$^3$ | — | — | — | — | — | — | — | — | — |
| T-phosphorus as PO$_4$, g/m$^3$ | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | | | |
| Hydroxide, g/m$^3$ | N/D | N/D | N/D | N/D | N/D | N/D | N/D | N/D | N/D |
| $\Sigma$ anions, meq/L | 54.8 | 8.22 | 547.0 | 55.3 | 7.94 | 520.5 | — | — | — |
| $\Sigma$ cations, meq/L | 53.4 | 6.68 | 537.2 | 55.0 | 7.57 | 526.3 | — | — | — |
| Control value, meq/L | +1.50 | +6.56 | +1.14 | +0.27 | +1.61 | -0.71 | — | — | — |

Table B-1. – Chemical analysis – Ionics Aquamite V electrodialysis at the YDTF – 1979 – Continued.

| Sample stream | April 23 | | | April 30 | | | May 7 | | |
|---|---|---|---|---|---|---|---|---|---|
| | Feed | Product | Brine | Feed | Product | Brine | Feed | Product | Brine |
| pH, units | 6.6 | 5.1 | 3.8 | 7.0 | 5.4 | 4.8 | 6.8 | 5.6 | 4.4 |
| TDS, g/m$^3$ | 3162 | 509 | 52 438 | 3498 | 520 | 52 760 | 3251 | 494 | 51 680 |
| Conductivity at 25 °C, $\mu$S/cm | 5122 | 746 | 62 670 | 5829 | 876 | 63 622 | 5413 | 814 | 62 830 |
| E. F. | 0.62 | 0.68 | 0.84 | 0.60 | 0.59 | 0.83 | 0.60 | 0.61 | 0.82 |
| Silica, g/m$^3$ | 4.6 | 4.6 | 4.0 | 4.5 | 4.5 | 3.0 | 3.5 | 3.6 | 3.5 |
| Calcium, g/m$^3$ | 5.8 | 0.6 | 107 | 6.5 | 0.9 | 128 | 7.1 | 1.2 | 117 |
| Magnesium, g/m$^3$ | 21.2 | 2.3 | 395 | 16.9 | 1.4 | 354 | 19.7 | 1.6 | 35.4 |
| Sodium, g/m$^3$ | 1103 | 175 | 18 090 | 1218 | 169 | 18 760 | 1126 | 158 | 18 140 |
| Potassium, g/m$^3$ | 11.0 | 2.2 | 184 | 10.6 | 1.2 | 148 | 11.2 | 1.6 | 188 |
| Total iron, g/m$^3$ | <0.10 | <0.10 | 0.28 | <0.10 | <0.10 | <0.10 | <0.10 | <0.10 | <0.10 |
| Total manganese, g/m$^3$ | <0.30 | <0.30 | <0.30 | N/D | N/D | N/D | <0.30 | <0.30 | <0.30 |
| Strontium, g/m$^3$ | 0.5 | 0.5 | 1.9 | 0.7 | 0.6 | 3.2 | 0.7 | 0.6 | 2.3 |
| Bicarbonate, g/m$^3$ | 10.2 | 4.9 | N/D | 17.1 | 7.3 | 26.8 | 14.6 | 2.4 | 17.1 |
| Carbonate, g/m$^3$ | N/D | N/D | N/D | N/D | N/D | N/D | N/D | N/D | N/D |
| Sulfate, g/m$^3$ | 910 | 195 | 15 360 | 1010 | 218 | 15 140 | 970 | 215 | 15 100 |
| Chloride, g/m$^3$ | 1100 | 128 | 18 300 | 1218 | 122 | 18 200 | 1114 | 114 | 18 080 |
| T-alkalinity as CaCO$_3$, g/m$^3$ | 8.4 | 4.0 | N/D | 14.0 | 6.0 | 22.0 | 12.0 | 2.0 | 14.0 |
| T-acidity as CaCO$_3$, g/m$^3$ | — | — | — | — | — | — | — | — | — |
| T-phosphorus as PO$_4$, g/m$^3$ | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| Hydroxide, g/m$^3$ | N/D | N/D | N/D | N/D | N/D | N/D | N/D | N/D | N/D |
| $\Sigma$ anions, meq/L | 50.15 | 7.75 | 836.19 | 55.68 | 8.10 | 829.23 | 51.53 | 7.21 | 824.85 |
| $\Sigma$ cations, meq/L | 50.31 | 7.90 | 829.50 | 54.98 | 7.55 | 855.42 | 51.26 | 7.73 | 802.70 |
| Control value, meq/L | -0.18 | -0.66 | 0.51 | +0.72 | +2.37 | -2.02 | +0.30 | -0.74 | -1.72 |

Table B-1. – Chemical analysis – Ionics Aquamite V electrodialysis at the YDTF – 1979 – Continued.

| | May 14 | | | May 29 | | | June 4 | | |
|---|---|---|---|---|---|---|---|---|---|
| Sample stream | Feed | Product | Brine | Feed | Product | Brine | Feed | Product | Brine |
| pH, units | 7.0 | 5.4 | 4.5 | 6.5 | 5.1 | 3.5 | 6.9 | 5.0 | 4.8 |
| TDS, g/m$^3$ | 3353 | 476 | 50 503 | 3368 | 708 | 56 777 | 3443 | 435 | 33 361 |
| Conductivity at 25 °C, $\mu$S/cm | 5443 | 767 | 60 782 | 5423 | 985 | 65 645 | 5797 | 736 | 43 176 |
| E. F. | 0.62 | 0.62 | 0.83 | 0.62 | 0.72 | 0.86 | 0.60 | 0.59 | 0.77 |
| Silica, g/m$^3$ | 4.9 | 5.0 | 5.0 | 3.7 | 1.6 | 18.5 | 4.0 | 4.2 | 6.5 |
| Calcium, g/m$^3$ | 5.3 | 0.5 | 79 | 8.3 | 0.7 | 174 | 9.6 | 0.7 | 109 |
| Magnesium, g/m$^3$ | 22.4 | 1.7 | 360 | 14.0 | 1.6 | 289 | 15.6 | 1.1 | 190 |
| Sodium, g/m$^3$ | 1164 | 150.0 | 17 620 | 1157 | 194 | 19 800 | 1224 | 136 | 11 500 |
| Potassium, g/m$^3$ | 7.4 | 1.0 | 110 | 9.8 | 1.8 | 171 | 10.0 | 0.7 | 101 |
| Total iron, g/m$^3$ | <0.10 | <0.10 | 0.12 | <0.10 | <0.10 | <0.32 | <0.10 | <0.10 | <0.10 |
| Total manganese, g/m$^3$ | <0.30 | <0.30 | <0.30 | <0.30 | <0.30 | <0.30 | <0.30 | <0.30 | <0.30 |
| Strontium, g/m$^3$ | 0.1 | <0.10 | 0.6 | 0.9 | 0.8 | 3.1 | 0.7 | 0.6 | 1.8 |
| Bicarbonate, g/m$^3$ | 19.5 | 4.9 | 13.7 | 9.8 | 2.4 | N/D | 19.5 | 5.9 | 12.2 |
| Carbonate, g/m$^3$ | N/D | N/D | N/D | N/D | N/D | N/D | N/D | N/D | N/D |
| Sulfate, g/m$^3$ | 984 | 220 | 14 620 | 1038 | 359 | 17 740 | 960 | 205 | 9340 |
| Chloride, g/m$^3$ | 1150 | 98 | 17 700 | 1130 | 146 | 18 600 | 1200 | 81.2 | 12 100 |
| T-alkalinity as CaCO$_3$, g/m$^3$ | 16.0 | 4.0 | 11.2 | 8.0 | 2.0 | N/D | 16.0 | 4.8 | 10.0 |
| T-acidity as CaCO$_3$, g/m$^3$ | — | — | — | — | — | 70.0 | — | — | — |
| T-phosphorus as PO$_4$, g/m$^3$ | 0.49 | 0.10 | 1.25 | <0.01 | <0.01 | <0.01 | 0.01 | 0.02 | 0.01 |
| Hydroxide, g/m$^3$ | N/D | N/D | N/D | N/D | N/D | N/D | N/D | N/D | N/D |
| $\Sigma$ anions, meq/L | 53.26 | 7.42 | 804.1 | 53.66 | 8.96 | 894.23 | 54.17 | 6.66 | 536.1 |
| $\Sigma$ cations, meq/L | 52.93 | 6.71 | 802.9 | 52.17 | 8.67 | 898.20 | 55.28 | 6.07 | 523.9 |
| Control value, meq/L | +0.35 | +3.21 | +0.10 | +1.49 | +1.13 | -0.28 | -1.17 | +2.79 | +1.44 |

Table B-1. – Chemical analysis – Ionics Aquamite V electrodialysis at the YDTF – 1979 – Continued.

| | June 11 | | | June 18 | | | June 25 | | |
|---|---|---|---|---|---|---|---|---|---|
| Sample stream | Feed | Product | Brine | Feed | Product | Brine | Feed | Product | Brine |
| pH, units | 7.1 | 5.4 | 6.2 | 7.2 | 4.8 | 6.4 | 6.9 | 5.0 | 6.0 |
| TDS, g/m$^3$ | 3436 | 481 | 36 465 | 3487 | 431 | 19 406 | 3510 | 461 | 20 470 |
| Conductivity at 25 °C, $\mu$S/cm | 5482 | 756 | 44 625 | 5718 | 696 | 27 008 | 5624 | 687 | 27 853 |
| E. F. | 0.63 | 0.64 | 0.82 | 0.61 | 0.62 | 0.72 | 0.62 | 0.67 | 0.73 |
| Silica, g/m$^3$ | 5.3 | 4.4 | 5.5 | 4.6 | 1.8 | 6.5 | 4.0 | 4.0 | 3.5 |
| Calcium, g/m$^3$ | 10.0 | 0.9 | 137 | 18.5 | 1.7 | 128 | 22.4 | 2.3 | 159 |
| Magnesium, g/m$^3$ | 22.0 | 1.90 | 280 | 30.5 | 2.7 | 210 | 31.1 | 2.2 | 206 |
| Sodium, g/m$^3$ | 1203 | 153 | 12 560 | 1180 | 136 | 6570 | 1203 | 148 | 6900 |
| Potassium, g/m$^3$ | 11.3 | 1.4 | 129 | 12.4 | 1.2 | 68 | 11.6 | 0.6 | 73 |
| Total iron, g/m$^3$ | 0.18 | <0.10 | <0.10 | <0.10 | <0.10 | <0.10 | <0.10 | <0.10 | <0.10 |
| Total manganese, g/m$^3$ | <0.30 | <0.30 | <0.30 | <0.30 | <0.30 | <0.30 | 0.03 | <0.01 | 0.04 |
| Strontium, g/m$^3$ | 0.8 | 0.7 | 2.6 | 0.3 | 0.1 | 1.5 | 0.4 | 0.1 | 1.6 |
| Bicarbonate, g/m$^3$ | 23.4 | 4.9 | 51.2 | 20.5 | 3.9 | 41.5 | 17.1 | 2.9 | 26.8 |
| Carbonate, g/m$^3$ | N/D | N/D | N/D | N/D | N/D | N/D | N/D | N/D | N/D |
| Sulfate, g/m$^3$ | 1000 | 230 | 10 100 | 1020 | 213 | 5050 | 990 | 235 | 5750 |
| Chloride, g/m$^3$ | 1160 | 84 | 13 200 | 1200 | 71 | 7330 | 1230 | 66 | 7350 |
| T-alkalinity as CaCO$_3$, g/m$^3$ | 19.2 | 4.0 | 42.0 | 16.8 | 3.2 | 34.0 | 14.0 | 2.4 | 22.0 |
| T-acidity as CaCO$_3$, g/m$^3$ | — | — | — | — | — | — | — | — | — |
| T-phosphorus as PO$_4$, g/m$^3$ | 0.02 | 0.01 | 0.30 | 0.02 | 0.02 | 0.03 | 0.01 | <0.01 | <0.01 |
| Hydroxide, g/m$^3$ | N/D | N/D | N/D | N/D | N/D | N/D | N/D | N/D | N/D |
| $\Sigma$ anions, meq/L | 53.94 | 7.24 | 583.6 | 55.43 | 6.50 | 312.6 | 55.60 | 6.80 | 327.6 |
| $\Sigma$ cations, meq/L | 54.95 | 6.91 | 579.6 | 55.09 | 6.26 | 311.2 | 56.31 | 6.75 | 326.9 |
| Control value, meq/L | -1.07 | +1.52 | +0.44 | +0.36 | +1.19 | +0.29 | -0.74 | +0.25 | +0.13 |

Table B-1. – Chemical analysis – Ionics Aquamite V electrodialysis at the YDTF – 1979 – Continued.

| Sample stream | July 3 | | | August 6 | | | August 13 | | |
|---|---|---|---|---|---|---|---|---|---|
| | Feed | Product | Brine | Feed | Product | Brine | Feed | Product | Brine |
| pH, units | 6.8 | 4.9 | 5.9 | 7.1 | 4.8 | 6.3 | 7.1 | 5.1 | 6.3 |
| TDS, $g/m^3$ | 3575 | 410 | 22 263 | 3434 | 407 | 31 208 | 3279 | 516 | 34 033 |
| Conductivity at 25 °C, μS/cm | 5674 | 660 | 35 137 | 5569 | 692 | 41 958 | 5253 | 754 | 43 139 |
| E. F. | 0.63 | 0.62 | 0.63 | 0.62 | 0.59 | 0.74 | 0.62 | 0.68 | 0.79 |
| Silica, $g/m^3$ | 3.9 | 3.4 | 4.0 | 3.0 | 2.2 | 27.5 | 2.7 | 2.5 | 3.0 |
| Calcium, $g/m^3$ | 20.1 | 1.9 | 176 | 9.3 | 1.0 | 28.0 | 10.8 | 0.9 | 29.2 |
| Magnesium, $g/m^3$ | 28.3 | 1.8 | 228 | 11.0 | 0.79 | 147 | 19.3 | 1.5 | 216 |
| Sodium, $g/m^3$ | 1208 | 128 | 7470 | 1216 | 133 | 10 900 | 1149 | 184 | 12 000 |
| Potassium, $g/m^3$ | 13.2 | 1.0 | 93 | 9.0 | 0.7 | 102 | 11.0 | 0.7 | 122 |
| Total iron, $g/m^3$ | <0.10 | <0.10 | <0.10 | <0.10 | <0.10 | <0.10 | <0.10 | <0.10 | <0.10 |
| Total manganese, $g/m^3$ | <0.30 | <0.30 | <0.30 | <0.30 | <0.30 | <0.30 | <0.30 | <0.30 | <0.30 |
| Strontium, $g/m^3$ | 0.1 | <0.01 | 1.7 | 0.4 | 0.3 | 1.6 | 0.17 | 0.05 | 2.0 |
| Bicarbonate, $g/m^3$ | 17.1 | 3.4 | 20.5 | 17.1 | 2.4 | 41.5 | 18.0 | 4.9 | 41.0 |
| Carbonate, $g/m^3$ | N/D | N/D | N/D | N/D | N/D | N/D | N/D | N/D | N/D |
| Sulfate, $g/m^3$ | 1068 | 207 | 6050 | 1030 | 205 | 8600 | 990 | 244 | 9580 |
| Chloride, $g/m^3$ | 1216 | 63 | 8220 | 1138 | 62 | 11 360 | 1078 | 78.0 | 12 040 |
| T-alkalinity as $CaCO_3$, $g/m^3$ | 14.0 | 2.8 | 16.8 | 14.0 | 2.0 | 34.0 | 14.8 | 4.0 | 33.6 |
| T-acidity as $CaCO_3$, $g/m^3$ | — | — | — | — | — | — | — | — | — |
| T-phosphorus as $PO_4$, $g/m^3$ | <0.01 | <0.01 | <0.01 | 0.05 | 0.03 | 0.07 | 0.04 | 0.02 | 0.06 |
| Hydroxide, $g/m^3$ | N/D | N/D | N/D | N/D | N/D | N/D | N/D | N/D | N/D |
| $\Sigma$ anions, meq/L | 56.83 | 6.15 | 358.2 | 53.84 | 6.05 | 500.28 | 51.33 | 7.36 | 539.87 |
| $\Sigma$ cations, meq/L | 56.21 | 5.81 | 354.9 | 54.50 | 5.92 | 490.28 | 52.39 | 8.19 | 544.39 |
| Control value, meq/L | +0.63 | +1.52 | +0.60 | -0.71 | +0.61 | +1.27 | -1.18 | -3.76 | -0.53 |

Table B-1. – Chemical analysis – Ionics Aquamite V electrodialysis at the YDTF – 1979 – Continued.

| Sample stream | August 20 | | | September 4 | | | September 17 | | |
|---|---|---|---|---|---|---|---|---|---|
| | Feed | Product | Brine | Feed | Product | Brine | Feed | Product | Brine |
| pH, units | 7.0 | 5.0 | 6.6 | 7.1 | 5.2 | 6.6 | 7.2 | 5.7 | 6.7 |
| TDS, $g/m^3$ | 3072 | 446 | 32 322 | 3223 | 489 | 33 110 | 3290 | 556 | 33 098 |
| Conductivity at 25 °C, μS/cm | 5038 | 718 | 42 247 | 5171 | 787 | 43 272 | 5236 | 955 | 41819 |
| E. F. | 0.61 | 0.62 | 0.76 | 0.62 | 0.62 | 0.76 | 0.63 | 0.58 | 0.79 |
| Silica, $g/m^3$ | 6.3 | 6.0 | 6.5 | 3.9 | 3.7 | 4.5 | 3.2 | 3.1 | 3.5 |
| Calcium, $g/m^3$ | 8.1 | 0.2 | 19.6 | 23.6 | 2.3 | 281 | 8.7 | 1.1 | 137 |
| Magnesium, $g/m^3$ | 31.1 | 2.4 | 358 | 14.5 | 1.3 | 190 | 13.7 | 1.6 | 200 |
| Sodium, $g/m^3$ | 1015 | 139 | 10 710 | 1111 | 157 | 11 290 | 1155 | 165 | 11 600 |
| Potassium, $g/m^3$ | 9.6 | 0.9 | 119 | 10.0 | 1.1 | 112 | 9.6 | 1.3 | 106 |
| Total iron, $g/m^3$ | <0.10 | <0.10 | <0.10 | <0.10 | <0.10 | <0.10 | <0.10 | <0.10 | <0.10 |
| Total manganese, $g/m^3$ | <0.30 | <0.30 | <0.30 | <0.30 | <0.30 | <0.30 | <0.30 | <0.30 | <0.30 |
| Strontium, $g/m^3$ | 0.4 | 0.4 | 1.1 | 0.4 | 0.1 | 3.6 | 0.1 | <0.1 | 3.2 |
| Bicarbonate, $g/m^3$ | 19.5 | 2.4 | 68.3 | 23.4 | 4.9 | 88.8 | 22.0 | 4.9 | 87.8 |
| Carbonate, $g/m^3$ | N/D | N/D | N/D | N/D | N/D | N/D | N/D | N/D | N/D |
| Sulfate, $g/m^3$ | 914 | 222 | 9040 | 944 | 242 | 8940 | 966 | 273 | 8860 |
| Chloride, $g/m^3$ | 1068 | 73.2 | 12 000 | 1092 | 76.8 | 12 200 | 1112 | 106 | 12 100 |
| T-alkalinity as $CaCO_3$, $g/m^3$ | 16.0 | 2.0 | 56.0 | 19.2 | 4.0 | 72.8 | 18.0 | 4.0 | 72.0 |
| T-acidity as $CaCO_3$, $g/m^3$ | — | — | — | — | — | — | — | — | — |
| T-phosphorus as $PO_4$, $g/m^3$ | 0.04 | 0.06 | 0.08 | 0.09 | 0.05 | 0.24 | 0.02 | 0.01 | 0.02 |
| Hydroxide, $g/m^3$ | N/D | N/D | N/D | N/D | N/D | N/D | N/D | N/D | N/D |
| $\Sigma$ anions, meq/L | 49.49 | 6.73 | 527.94 | 50.85 | 7.29 | 531.84 | 51.85 | 8.76 | 527.33 |
| $\Sigma$ cations, meq/L | 47.37 | 6.29 | 499.38 | 50.96 | 7.08 | 523.71 | 52.05 | 7.40 | 530.67 |
| Control value, meq/L | +2.42 | +2.10 | +3.44 | -0.12 | +0.94 | +0.97 | -0.22 | +5.61 | -0.40 |

Table B-1. – Chemical analysis – Ionics Aquamite V electrodialysis at the YDTF – 1979 – Continued.

| Sample stream | September 24 | | |
|---|---|---|---|
| | Feed | Product | Brine |
| pH, units | 7.1 | 5.1 | 6.6 |
| TDS, g/m$^3$ | 3262 | 513 | 33 491 |
| Conductivity at 25 °C, µS/cm | 5205 | 907 | 43860 |
| E. F. | 0.63 | 0.56 | 0.76 |
| Silica, g/m$^3$ | 2.2 | 2.0 | 3.5 |
| Calcium, g/m$^3$ | 13.1 | 0.6 | 179 |
| Magnesium, g/m$^3$ | 15.1 | 1.5 | 216 |
| Sodium, g/m$^3$ | 1142 | 161 | 11 690 |
| Potassium, g/m$^3$ | 9.8 | 1.3 | 104 |
| Total iron, g/m$^3$ | <0.10 | <0.10 | <0.10 |
| Total manganese, g/m$^3$ | <0.30 | <0.30 | <0.30 |
| Strontium, g/m$^3$ | 0.3 | 0.1 | 3.2 |
| Bicarbonate, g/m$^3$ | 19.5 | 2.4 | 75.6 |
| Carbonate, g/m$^3$ | N/D | N/D | N/D |
| Sulfate, g/m$^3$ | 960 | 248 | 8900 |
| Chloride, g/m$^3$ | 1100 | 96 | 12 320 |
| T-alkalinity as $CaCO_3$, g/m$^3$ | 16.0 | 2.0 | 62.0 |
| T-acidity as $CaCO_3$, g/m$^3$ | N/D | N/D | N/D |
| T-phosphorus as $PO_4$, g/m$^3$ | 0.46 | 0.32 | 1.80 |
| Hydroxide, g/m$^3$ | N/D | N/D | N/D |
| $\Sigma$ anions, meq/L | 51.35 | 7.91 | 534.17 |
| $\Sigma$ cations, meq/L | 51.83 | 7.19 | 537.95 |
| Control value, meq/L | -0.54 | +3.15 | -0.45 |

Table B-2. – Chemical analyses of ED water samples collected at LaVerkin Springs – 1980.

| Quantity | Units | Jan. 28<br>Feed | <br>Product | <br>Brine | Feb. 11<br>Feed | <br>Product | <br>Brine | Feb. 19<br>Feed | <br>Product | <br>Brine |
|---|---|---|---|---|---|---|---|---|---|---|
| pH | | 7.8 | 7.4 | 7.3 | 7.9 | 7.5 | 7.4 | 7.8 | 7.5 | 6.6 |
| TDS (calculated) | $g/m^3$ | 9110 | 909 | 41 100 | 9140 | 1150 | 41 600 | 9170 | 775 | 96 800 |
| TDS (evaporated @ 180 °C) | $g/m^3$ | 9180 | 905 | 41 300 | 8880 | 1130 | 41 300 | 8950 | 752 | 98 000 |
| Conductivity @ 25 °C | mS/m | 1350 | 165 | 5050 | 1360 | 205 | 5090 | 1360 | 144 | 9850 |
| Silica | $g/m^3$ | 13 | 12 | 15 | 12 | 12 | 17 | 14 | 13 | 22 |
| Calcium | $g/m^3$ | 95 | 5.6 | 420 | 60 | 2.4 | 310 | 50.0 | 0 | 430 |
| Magnesium | $g/m^3$ | 64.1 | 4.4 | 287 | 54.9 | 3.9 | 275 | 36.6 | 2.0 | 348 |
| Sodium | $g/m^3$ | 2880 | 315 | 13 500 | 3110 | 402 | 13 900 | 3110 | 274 | 33 400 |
| Potassium | $g/m^3$ | 284 | 13.3 | 684 | 176 | 12.5 | 860 | 176 | 10.9 | 1740 |
| Iron, total | $g/m^3$ | 0.04 | 0 | 0.29 | 0.06 | 0 | 0.42 | 0.07 | 0 | 1.0 |
| Manganese, total | $g/m^3$ | <0.05 | <0.05 | 0.11 | <0.05 | <0.05 | 0.13 | <0.05 | <0.05 | 0.32 |
| Strontium | $g/m^3$ | 0 | 0.1 | 6.0 | 1.5 | 0 | 5.5 | 1.0 | 0.1 | 9.0 |
| Bicarbonate | $g/m^3$ | 45.1 | 20.1 | 70.2 | 46.4 | 22.0 | 82.4 | 43.9 | 12.2 | 107 |
| Carbonate | $g/m^3$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Sulfate | $g/m^3$ | 2120 | 133 | 9580 | 2040 | 196 | 9620 | 2100 | 90.2 | 22 800 |
| Chloride | $g/m^3$ | 3 630 | 415 | 16 600 | 3660 | 513 | 16 600 | 3660 | 378 | 38 000 |
| T-alkalinity as $CaCO_3$ | $g/m^3$ | 37 | 17 | 58 | 38 | 18 | 68 | 36 | 10 | 88 |
| P-alkalinity as $CaCO_3$ | $g/m^3$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| E. F. [TDS (calculated)/ cond.] | | 6.7 | 5.5 | 8.1 | 6.7 | 5.6 | 8.2 | 6.7 | 5.4 | 9.8 |
| E. F. [TDS (evaporated)/ cond.] | | 6.8 | 5.5 | 8.2 | 6.5 | 5.5 | 8.1 | 6.6 | 5.2 | 9.9 |
| $\sum$ Anions | $eq/m^3$ | 147.3 | 14.79 | 667.4 | 146.4 | 18.88 | 668.6 | 147.6 | 12.74 | 1549.0 |
| $\sum$ Cations | $eq/m^3$ | 142.3 | 14.66 | 648.0 | 147.0 | 18.24 | 666.0 | 145.0 | 12.36 | 1544.0 |
| Control value | $eq/m^3$ | +2.09 | +0.39 | +1.86 | −0.25 | +1.60 | +0.25 | +1.09 | +1.25 | +0.21 |

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[a] Samples collected prior to March 17, 1980, were analyzed in the Regional Chemical laboratory in Boulder City, Nevada. Samples collected on March 17, 1980 and later were analyzed at the E&R Center chemical laboratory.

Table B-2. – Chemical analyses of ED water samples collected at LaVerkin Springs – 1980 – Continued.

| Quantity | Units | Feb. 25<br>Feed | <br>Product | <br>Brine | March 3<br>Feed | <br>Product | <br>Brine | March 10<br>Feed | <br>Product | <br>Brine |
|---|---|---|---|---|---|---|---|---|---|---|
| pH | | 7.7 | 6.9 | 7.7 | 6.9 | 6.7 | 6.3 | 7.3 | 7.4 | 6.8 |
| TDS (calculated) | $g/m^3$ | 9310 | 1360 | 99 200 | 9380 | 1420 | 96 500 | 9180 | 1280 | 96 500 |
| TDS (evaporated @ 180 °C) | $g/m^3$ | 9280 | 1370 | 99 700 | 9160 | 1490 | 94 900 | 9080 | 1250 | 96 100 |
| Conductivity @ 25 °C | mS/m | 1390 | 245 | 9830 | 1390 | 272 | 9610 | 1370 | 225 | 9670 |
| Silica | $g/m^3$ | 18 | 16 | 25 | 11 | 10 | 20 | 16 | 19 | 26 |
| Calcium | $g/m^3$ | 50.0 | 0 | 490 | 45 | 1.8 | 390 | 35 | 5.0 | 310 |
| Magnesium | $g/m^3$ | 36.6 | 4.3 | 415 | 39.7 | 1.6 | 451 | 51.9 | 3.1 | 506 |
| Sodium | $g/m^3$ | 3110 | 475 | 32 800 | 3220 | 511 | 32 800 | 3170 | 449 | 33 000 |
| Potassium | $g/m^3$ | 235 | 21.5 | 2420 | 205 | 23.5 | 1990 | 196 | 19.6 | 1960 |
| Iron, total | $g/m^3$ | 0.06 | 0 | 0.72 | 0.05 | 0 | 0.77 | 0.04 | 0 | 0.72 |
| Manganese, total | $g/m^3$ | <0.05 | <0.05 | 0.22 | <0.05 | <0.05 | 0.24 | <0.05 | <0.05 | 0.30 |
| Strontium | $g/m^3$ | 0.5 | 0 | 5.3 | 0.3 | 0 | 2.8 | 0.3 | 0 | 2.3 |
| Bicarbonate | $g/m^3$ | 45.1 | 23.2 | 54.9 | 44.5 | 20.1 | 85.4 | 40.3 | 26.2 | 68.9 |
| Carbonate | $g/m^3$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Sulfate | $g/m^3$ | 2210 | 197 | 25 500 | 2150 | 181 | 23 900 | 2040 | 190 | 22 900 |
| Chloride | $g/m^3$ | 3630 | 636 | 37 500 | 3690 | 676 | 36 900 | 3650 | 580 | 37 800 |
| T-alkalinity as $CaCO_3$ | $g/m^3$ | 37 | 19 | 45 | 37 | 17 | 70 | 33 | 22 | 57 |
| P-alkalinity as $CaCO_3$ | $g/m^3$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| E. F. [TDS (calculated)/cond.] | | 6.7 | 5.6 | 10.1 | 6.7 | 5.2 | 10.0 | 6.7 | 5.7 | 10.0 |
| E. F. [TDS (evaporated)/ cond.] | | 6.7 | 5.6 | 10.1 | 6.6 | 5.5 | 9.9 | 6.6 | 5.6 | 9.9 |
| $\sum$ Anions | $eq/m^3$ | 149.0 | 22.40 | 1589.0 | 149.5 | 23.14 | 1539.0 | 145.9 | 20.72 | 1545.0 |
| $\sum$ Cations | $eq/m^3$ | 146.5 | 21.55 | 1549.0 | 150.8 | 23.02 | 1533.0 | 149.0 | 20.50 | 1542.0 |
| Control value | $eq/m^3$ | +1.03 | +1.87 | +1.62 | −0.54 | +0.26 | +0.25 | −1.30 | +0.51 | +0.12 |

Table B-2. – Chemical analyses of ED water samples collected at LaVerkin Springs – 1980 – Continued.

| | | March 17 | | | March 26 | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Quantity | Units | Feed | Product | Brine | Positive dilute | Positive mid-stage dilute | Positive concentrate | Feed | Negative dilute | Negative mid-stage concentrate | Negative concen-trate |
| pH | | 7.5 | 7.1 | 7.0 | 7.4 | 7.4 | 7.5 | 7.7 | 7.4 | 7.2 | 7.0 |
| TDS (calculated) | g/m³ | 9330 | 1110 | 95 940 | 1220 | 3800 | 98 660 | 8740 | 1150 | 90 070 | 90 410 |
| TDS (evaporated @ 180 °C) | g/m³ | 9060 | 1150 | 95 600 | 1160 | 3740 | 98 300 | 8840 | 1080 | 95 200 | 95 100 |
| Conductivity @ 25 °C | mS/m | 1350 | 282 | 8450 | 220 | 660 | 9600 | 1 320 | 189 | 9600 | 8120 |
| Silica | g/m³ | 8.0 | 8.0 | 7.5 | 10.1 | 9.8 | 12.1 | 10.4 | 9.1 | 15.1 | 14.7 |
| Calcium | g/m³ | 32.0 | 3.20 | 192 | 1.60 | 5.40 | 416 | 32.0 | 1.20 | 240 | 320 |
| Magnesium | g/m³ | 48.8 | 1.95 | 78.1 | 2.20 | 12.3 | 869 | 68.3 | 2.32 | 744 | 683 |
| Sodium | g/m³ | 2940 | 406 | 34 000 | 430 | 1270 | 33 200 | 2940 | 406 | 29 400 | 29 400 |
| Potassium | g/m³ | 275 | 21.9 | 2970 | 23.5 | 94.2 | 3170 | 286 | 21.5 | 3150 | 3110 |
| Iron, total | g/m³ | 0.04 | 0.02 | 0.35 | 0.05 | 0.09 | 2.00 | 0.18 | 0.60 | 1.90 | 1.90 |
| Manganese, total | g/m³ | 0.02 | 0.01 | 0.09 | ND | ND | 0.28 | 0.01 | 0.03 | 0.26 | 0.27 |
| Strontium | g/m³ | 0.07 | ND | 1.75 | ND | ND | 1.70 | 0.30 | ND | 1.70 | 1.60 |
| Bicarbonate | g/m³ | 44.5 | 15.9 | 93.9 | 17.7 | 29.3 | 93.9 | 42.7 | 17.7 | 18.9 | 87.2 |
| Carbonate | g/m³ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Sulfate | g/m³ | 2100 | 76.8 | 23 000 | 197 | 850 | 23 600 | 2090 | 176 | 22 300 | 22 600 |
| Chloride | g/m³ | 3590 | 575 | 35 600 | 540 | 1530 | 37 300 | 3270 | 518 | 34 200 | 34 200 |
| T-alkalinity as $CaCO_3$ | g/m³ | 42 | 20 | 90 | 14.5 | 24.0 | 77.0 | 35.0 | 14.5 | 15.5 | 71.5 |
| P-alkalinity as $CaCO_3$ | g/m³ | 0 | 0 | 0 | ND | ND | ND | ND | ND | ND | ND |
| E. F. [TDS (calculated)/cond.] | | 6.9 | 3.9 | 11.4 | 5.5 | 5.8 | 10.3 | 6.6 | 6.1 | 9.4 | 11.1 |
| E. F. [TDS (evaporated)/cond.] | | 6.7 | 4.1 | 11.3 | 5.3 | 5.7 | 10.2 | 6.7 | 5.7 | 9.9 | 11.7 |
| $\sum$ Anions | eq/m³ | 146.73 | 18.06 | 1480.5 | 19.60 | 61.38 | 1543.54 | 136.20 | 18.55 | 1429.31 | 1434.43 |
| $\sum$ Cations | eq/m³ | 140.63 | 18.58 | 1571.9 | 19.56 | 58.79 | 1613.00 | 142.51 | 18.50 | 1433.50 | 1431.60 |
| Control value | eq/m³ | +2.56 | −1.35 | −3.96 | +0.10 | +2.45 | −2.89 | −2.85 | +0.13 | −0.19 | +0.13 |

Table B-2. – Chemical analyses of ED water samples collected at LaVerkin Springs – 1980 – Continued.

| | | March 28 | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Quantity | Units | Feed | Negative dilute | Negative mid-stage concentrate | Negative concen-trate | Positive dilute | Positive mid-stage dilute | Positive concen-trate |
| pH | | 7.7 | 7.1 | 7.8 | 6.9 | 7.5 | 7.6 | 7.2 |
| TDS (calculated) | g/m³ | 9350 | 1140 | 86 100 | 92 850 | 1100 | 3860 | 91 540 |
| TDS (evaporated @ 180 °C) | g/m³ | 8660 | 1060 | 93 900 | 93 800 | 1100 | 4000 | 94 900 |
| Conductivity @ 25 °C | mS/m | 1340 | 206 | 8800 | 7540 | 200 | 580 | 8800 |
| Silica | g/m³ | 10.1 | 8.9 | 14.6 | 14.0 | 9.5 | 8.9 | 9.5 |
| Calcium | g/m³ | 32.0 | 1.60 | 320 | 320 | 1.60 | 4.80 | 240 |
| Magnesium | g/m³ | 78.1 | 1.95 | 615 | 439 | 1.46 | 9.52 | 493 |
| Sodium | g/m³ | 2940 | 406 | 27 600 | 32 400 | 389 | 1330 | 32 100 |
| Potassium | g/m³ | 286 | 16.4 | 2350 | 2480 | 17.2 | 70.4 | 2500 |
| Iron, total | g/m³ | 0.16 | 0.04 | 2.0 | 2.10 | 0.41 | 0.07 | 2.5 |
| Manganese, total | g/m³ | 0.01 | ND | 0.28 | 0.27 | ND | ND | 0.28 |
| Strontium | g/m³ | 0.2 | ND | 1.0 | 1.1 | ND | ND | 1.0 |
| Bicarbonate | g/m³ | 43.3 | 14.0 | 105 | 96.4 | 18.9 | 31.1 | 88.5 |
| Carbonate | g/m³ | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Sulfate | g/m³ | 1520 | 197 | 22 400 | 21 900 | 123 | 872 | 2110 |
| Chloride | g/m³ | 4440 | 490 | 32 700 | 35 200 | 540 | 1530 | 54 000 |
| T-alkalinity as $CaCO_3$ | g/m³ | 35.5 | 11.5 | 86.1 | 79.1 | 15.5 | 25.5 | 72.6 |
| P-alkalinity as $CaCO_3$ | g/m³ | ND | ND | ND | ND | ND | ND | ND |
| E. F. [TDS (calculated)/cond.] | | 7.0 | 5.5 | 9.8 | 12.3 | 5.5 | 6.7 | 10.4 |
| E. F. [TDS (evaporated)/cond.] | | 6.5 | 5.1 | 10.7 | 12.4 | 5.5 | 6.9 | 10.8 |
| $\sum$ Anions | eq/m³ | 157.41 | 18.14 | 1389.72 | 1449.58 | 18.08 | 61.91 | 1565.40 |
| $\sum$ Cations | eq/m³ | 143.31 | 18.36 | 1326.60 | 1525.40 | 17.54 | 60.52 | 1516.30 |
| Control value | eq/m³ | +5.54 | −0.57 | +2.92 | −3.36 | +1.40 | +1.30 | +2.01 |

Table B-2. – Chemical analyses of ED water samples collected at LaVerkin Springs – 1980 – Continued.

| | | April 21 | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Quantity | Units | Feed | Positive dilute | Positive mid-stage dilute | Positive concentrate | Negative concentrate | Negative mid-stage concentrate | Negative dilute |
| pH | | 7.9 | 7.4 | 7.7 | 7.8 | 7.5 | 7.8 | 7.4 |
| TDS (calculated) | $g/m^3$ | 8610 | 1240 | 3990 | 38 380 | 38 440 | 36 940 | 1130 |
| TDS (evaporated @ 180 °C) | $g/m^3$ | 8820 | 1130 | 3940 | 40 700 | 39 900 | 38 200 | 1080 |
| Conductivity @ 25 °C | mS/m | 1350 | 195 | 614 | 3170 | 4830 | 4610 | 253 |
| Silica | $g/m^3$ | 9.5 | 9.6 | 9.4 | 6.9 | 9.6 | 6.8 | 9.6 |
| Calcium | $g/m^3$ | 48.0 | 1.20 | 16.0 | 240 | 224 | 224 | 16.0 |
| Magnesium | $g/m^3$ | 58.6 | 18.8 | 39.0 | 224 | 283 | 254 | 24.4 |
| Sodium | $g/m^3$ | 2940 | 433 | 1340 | 13 000 | 12 900 | 12 600 | 369 |
| Potassium | $g/m^3$ | 181 | 10.2 | 54.3 | 843 | 796 | 796 | 10.2 |
| Iron, total | $g/m^3$ | ND | ND | ND | ND | ND | ND | ND |
| Manganese, total | $g/m^3$ | ND | ND | ND | ND | ND | ND | ND |
| Strontium | $g/m^3$ | 0.3 | ND | ND | 1.2 | 1.3 | 1.2 | ND |
| Bicarbonate | $g/m^3$ | 36.0 | 15.3 | 26.8 | 37.8 | 32.9 | 45.8 | 15.3 |
| Carbonate | $g/m^3$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Sulfate | $g/m^3$ | 1 960 | 211 | 847 | 9630 | 9600 | 9110 | 214 |
| Chloride | $g/m^3$ | 3380 | 540 | 1660 | 14 400 | 14 600 | 13 900 | 469 |
| T-alkalinity as $CaCO_3$ | $g/m^3$ | 29.5 | 12.6 | 22.0 | 31.0 | 27.0 | 37.6 | 12.6 |
| P-alkalinity as $CaCO_3$ | $g/m^3$ | ND | ND | ND | ND | ND | ND | ND |
| E. F. [TDS (calculated)/cond.] | | 6.4 | 6.4 | 6.5 | 12.1 | 8.0 | 8.0 | 4.5 |
| E. F. [TDS (evaporated)/cond.] | | 6.5 | 5.8 | 6.4 | 12.8 | 8.3 | 8.3 | 4.3 |
| $\sum$ Anions | $eq/m^3$ | 136.59 | 19.85 | 64.94 | 607.62 | 612.54 | 582.75 | 17.91 |
| $\sum$ Cations | $eq/m^3$ | 139.83 | 20.66 | 63.79 | 619.00 | 614.80 | 602.40 | 19.06 |
| Control value | $eq/m^3$ | −1.46 | −1.96 | +1.03 | −1.19 | −0.24 | −2.15 | −2.99 |

# APPENDIX C

# COMPUTER OUTPUT OF STATISTICAL ANALYSES

```
********************************************************************************
*                    BASIC STATISTICS AND DATA MANIPULATION                    *
********************************************************************************


********************************************************************************
*                    BASIC STATISTICS AND DATA MANIPULATION                    *
********************************************************************************
                              E D UNIT PERFORMANCE

Data file name: DATA
Number of observations: 28
Number of variables: 7

Variables names:
   1. TIME
   2. BRINE CONC
   3. FEED TEMP
   4. SP CELL R1
   5. SP CELL R2
   6. CURRENT EF
   7. ENERGY

Subfile name     beginning observation--number of observations
 1. E D YUMA                         1                       19
 2. E D LV SPR                      20                        9

Observation # 24 Variable # 1 -- correct value =  10210.7
Observation # 25 Variable # 1 -- correct value =  10351.5
Observation # 27 Variable # 1 -- correct value =  10546.1
Observation # 28 Variable # 1 -- correct value =  10587






Observation # 26 has been deleted, 27 observations remain.

Observation # 28 Variable # 1  =  1061
Observation # 28 Variable # 2  =  40700
Observation # 28 Variable # 3  =  30.9
Observation # 28 Variable # 4  =  .00403
Observation # 28 Variable # 5  =  .00632
Observation # 28 Variable # 6  =  .776
Observation # 28 Variable # 7  =  4.07

  Total number of observations now =  28
```

```
                              E D UNIT PERFORMANCE

     Variable # 1   Variable # 2   Variable # 3   Variable # 4   Variable # 5
        Variable # 6   Variable # 7
OBS#
   1
       7357.10000    33945.00000       21.50000         .00708         .01411
              .66800        2.53000
   2
       7444.40000    32583.00000       21.00000         .00731         .01452
              .71600        2.36000
   3
       7550.30000    34300.00000       22.00000         .00663         .01252
      -9999999.99999        2.78000
   4
       7786.90000    52438.00000       26.00000         .00717         .01408
              .55000        3.09000
   5
       7825.00000    52760.00000       26.00000         .00702         .01371
              .61600        3.01000
   6
       7902.80000    51680.00000       25.00000         .00698         .01344
              .58100        2.88000
   7
       7996.60000    50503.00000       27.00000         .00706         .01290
              .57100        3.22000
   8
       8169.80000    56777.00000       28.00000         .00674         .01328
              .51400        3.46000
   9
       8219.30000    33361.00000       29.50000         .00757         .01657
              .66100        3.11000
  10
       8289.70000    36465.00000       31.00000         .00776         .01708
              .64200        3.24000
  11
       8376.80000    19406.00000       27.00000         .00805         .01847
              .73700        2.73000
  12
       8456.10000    20470.00000       31.00000         .00852         .01994
              .73400        2.86000
  13
       8526.00000    22263.00000       30.00000         .00814         .01886
              .72500        2.99000
  14
       8842.70000    31208.00000       31.00000         .00782         .01527
              .62900        3.46000
  15
       8912.00000    34033.00000       29.00000         .00832         .01720
              .65600        2.79000
  16
```

```
      8961.00000    32322.00000       28.00000           .00858           .01757
            .63700         2.65000
  17
      9141.30000    33110.00000       30.20000           .00853           .01736
            .63900         2.89000
  18
      9316.50000    33098.00000       28.20000           .00842           .01708
            .66800         2.74000
  19
      9416.00000    33491.00000       29.50000           .00883           .01753
            .67600         2.81000
  20
      9693.00000    41100.00000       23.80000           .00402           .00656
            .82600         4.34000
  21
      9786.50000    41600.00000       23.80000           .00409           .00652
            .84000         4.31000
  22
      9907.40000    96800.00000       22.00000           .00348           .00554
            .76300         4.57000
  23
      9988.80000    99200.00000       23.80000           .00326           .00493
            .71000         4.30000
  24
     10210.70000    96500.00000       25.10000           .00327           .00540
            .69500         4.86000
  25
     10351.50000    95940.00000       23.10000           .00333           .00524
            .68100         4.53000
  26
     10546.10000    98300.00000       24.80000           .00338           .00546
            .68200         4.82000
  27
     10587.00000    94900.00000       24.10000           .00333           .00547
            .70900         4.68000
  28
      1061.00000    40700.00000       30.90000           .00403           .00632
            .77600         4.07000

*******************************************************************************
*                   BASIC STATISTICS AND DATA MANIPULATION                    *
*******************************************************************************
                            E D UNIT PERFORMANCE

Data file name: DATA
Number of observations: 28
Number of variables: 7

Variables names:
   1. TIME
   2. BRINE CONC
   3. FEED TEMP
   4. SP CELL R1
   5. SP CELL R2
   6. CURRENT EF
   7. ENERGY

Subfile name      beginning observation--number of observations
 1. E D YUMA                        1                        19
 2. E D LV SPR                     20                         9
```

```
********************************************************************************
                                    MANUAL REGRESSION ON

                                 Subfile:E D YUMA
********************************************************************************


Dependent variable:SP CELL R1
Independent variable(s) =    TIME
                             BRINE CONC
                             FEED TEMP
Tolerance = .001

                                    CORRELATION MATRIX

                        TIME BRINE CONC  FEED TEMP SP CELL R1
TIME               1.0000000  -.3583561   .7594253   .8660755
BRINE CONC                    1.0000000  -.2543240  -.6582651
FEED TEMP                                1.0000000   .6499989
SP CELL R1                                           1.0000000

********************************************************************************

               F TO  PART         F TO        REGRESSION COEFFICIENTS        STD
#--VARIABLE    ENTER  CORR   TOL DELETE  STD.FORMAT            E-FORMAT    ERROR
 1.TIME        51.02  .866 1.000
 2.BRINE CONC  13.00  .658 1.000
 3.FEED TEMP   12.44  .650 1.000
********************************************************************************
STEP NUMBER 1
VARIABLE'TIME' ADDED
R-SQUARED =  .75008673118

                                            AOV

SOURCE                DF      SUM OF SQUARES        MEAN SQUARE        F-VALUE
TOTAL                 18              .00001
REGRESSION             1              .00001             .00001          51.02
RESIDUAL              17              .00000             .00000

STANDARD ERROR =  3.62483569732E-04

               F TO  PART         F TO        REGRESSION COEFFICIENTS        STD
#--VARIABLE    ENTER  CORR   TOL DELETE  STD.FORMAT            E-FORMAT    ERROR
 1.TIME                          51.02       .00000  .972658599977E-06     .0000
 2.BRINE CONC  20.01  .745  .872
 3.FEED TEMP     .01  .024  .423

Constant = -4.01418595150E-04
********************************************************************************
STEP NUMBER 2
VARIABLE'BRINE CONC' ADDED
R-SQUARED =  .88895571927

                                            AOV

SOURCE                DF      SUM OF SQUARES        MEAN SQUARE        F-VALUE
TOTAL                 18              .00001
```

```
REGRESSION          2             .00001            .00000          64.04
RESIDUAL           16             .00000            .00000

STANDARD ERROR =  2.49061291420E-04

                F TO  PART         F TO        REGRESSION COEFFICIENTS        STD
#--VARIABLE     ENTER  CORR    TOL DELETE  STD.FORMAT            E-FORMAT    ERROR
 1.TIME                            65.65       .00000  .812013216440E-06    .0000
 2.BRINE CONC                      20.01      -.00000 -.252810600053E-07    .0000
 3.FEED TEMP      .00  .003  .423

Constant =  1.86232748590E-03


********************************************************************************
                              MANUAL REGRESSION ON

                           Subfile:E D YUMA
********************************************************************************

Dependent variable:CURRENT EF
Independent variable(s) =   TIME
                            BRINE CONC
                            FEED TEMP
Tolerance = .001


                                CORRELATION MATRIX


                     TIME BRINE CONC  FEED TEMP CURRENT EF
TIME            1.0000000  -.3924205   .7302642   .1942500
BRINE CONC                 1.0000000  -.3017807  -.9195279
FEED TEMP                             1.0000000   .0696492
CURRENT EF                                       1.0000000


********************************************************************************

                F TO  PART         F TO        REGRESSION COEFFICIENTS        STD
#--VARIABLE     ENTER  CORR    TOL DELETE  STD.FORMAT            E-FORMAT    ERROR
 1.TIME           .63  .194 1.000
 2.BRINE CONC   87.58  .920 1.000
 3.FEED TEMP      .08  .070 1.000
********************************************************************************
STEP NUMBER 1
VARIABLE'BRINE CONC' ADDED
R-SQUARED =  .84553161984

                                       AOV

SOURCE              DF     SUM OF SQUARES        MEAN SQUARE        F-VALUE
TOTAL               17             .06718
REGRESSION           1             .05680             .05680          87.58
RESIDUAL            16             .01038             .00065

STANDARD ERROR =  2.54672024757E-02

                F TO  PART         F TO        REGRESSION COEFFICIENTS        STD
#--VARIABLE     ENTER  CORR    TOL DELETE  STD.FORMAT            E-FORMAT    ERROR
 1.TIME          4.04  .461  .846
 2.BRINE CONC                      87.58      -.00001 -.504910885986E-05    .0000
```

```
 3.FEED TEMP    6.67  .555  .909

Constant =  .830037503394
********************************************************************************
STEP NUMBER 2
VARIABLE'TIME' ADDED
R-SQUARED =  .87833605653

                                      AOV

SOURCE             DF     SUM OF SQUARES        MEAN SQUARE        F-VALUE
TOTAL              17             .06718
REGRESSION          2             .05901             .02950          54.15
RESIDUAL           15             .00817             .00054

STANDARD ERROR =  2.33430043691E-02

                F TO  PART        F TO        REGRESSION COEFFICIENTS       STD
#--VARIABLE    ENTER  CORR   TOL DELETE  STD.FORMAT            E-FORMAT    ERROR
 1.TIME                            4.04      -.00002 -.191728878121E-04    .0000
 2.BRINE CONC                    103.64      -.00001 -.547341668680E-05    .0000
 3.FEED TEMP    2.18  .367  .466

Constant =  1.00547312185
```

```
                            Subfile:E D YUMA
********************************************************************************
Dependent variable:ENERGY
Independent variable(s) =   TIME
                            BRINE CONC
                            FEED TEMP
Tolerance = .001


                               CORRELATION MATRIX


                     TIME BRINE CONC  FEED TEMP     ENERGY
TIME            1.0000000  -.3583561   .7594253   .1064374
BRINE CONC                 1.0000000  -.2543240   .4208949
FEED TEMP                             1.0000000   .5604344
ENERGY                                           1.0000000


********************************************************************************

                F TO  PART        F TO        REGRESSION COEFFICIENTS       STD
#--VARIABLE    ENTER  CORR   TOL DELETE  STD.FORMAT            E-FORMAT    ERROR
 1.TIME          .19  .106 1.000
 2.BRINE CONC   3.66  .421 1.000
 3.FEED TEMP    7.78  .560 1.000
********************************************************************************
STEP NUMBER 1
VARIABLE'BRINE CONC' ADDED
R-SQUARED =  .17715251248

                                      AOV

SOURCE             DF     SUM OF SQUARES        MEAN SQUARE        F-VALUE
TOTAL              18            1.51464
REGRESSION          1             .26832             .26832           3.66
RESIDUAL           17            1.24632             .07331

STANDARD ERROR =  .270763566341

                F TO  PART        F TO        REGRESSION COEFFICIENTS       STD
#--VARIABLE    ENTER  CORR   TOL DELETE  STD.FORMAT            E-FORMAT    ERROR
 1.TIME         1.63  .304  .872
 2.BRINE CONC                      3.66       .00001  .109738000330E-04    .0000
 3.FEED TEMP   21.99  .761  .935

Constant =  2.52536028198
********************************************************************************
STEP NUMBER 2
VARIABLE'FEED TEMP' ADDED
R-SQUARED =  .65348924656

                                      AOV

SOURCE             DF     SUM OF SQUARES        MEAN SQUARE        F-VALUE
TOTAL              18            1.51464
REGRESSION          2             .98980             .49490          15.09
RESIDUAL           16             .52484             .03280

STANDARD ERROR =  .181114566123

                F TO  PART        F TO        REGRESSION COEFFICIENTS       STD
```

```
#--VARIABLE    ENTER  CORR    TOL DELETE  STD.FORMAT              E-FORMAT    ERROR
 1.TIME         8.19  .594   .394
 2.BRINE CONC                      15.67       .00002  .157058333078E-04    .0000
 3.FEED TEMP                       21.99       .06526  .652557234084E-01    .0139

Constant =  .56342631675


********************************************************************************
                                      MANUAL REGRESSION ON

                                 Subfile:E D LV SPR
********************************************************************************


Dependent variable:SP CELL R1
Independent variable(s) =    TIME
                             BRINE CONC
                             FEED TEMP
Tolerance = .001


                                      CORRELATION MATRIX


                        TIME BRINE CONC  FEED TEMP SP CELL R1
TIME              1.0000000   .5656888  -.9143767  -.5372481
BRINE CONC                   1.0000000  -.4676151  -.9822855
FEED TEMP                               1.0000000   .3990240
SP CELL R1                                         1.0000000



********************************************************************************

                F TO   PART         F TO        REGRESSION COEFFICIENTS        STD
#--VARIABLE    ENTER   CORR    TOL DELETE  STD.FORMAT              E-FORMAT    ERROR
 1.TIME         2.84   .537 1.000
 2.BRINE CONC 192.34   .982 1.000
 3.FEED TEMP    1.33   .399 1.000
********************************************************************************
STEP NUMBER 1
VARIABLE'BRINE CONC' ADDED
R-SQUARED =  .96488486608

                                              AOV

SOURCE                 DF      SUM OF SQUARES          MEAN SQUARE          F-VALUE
TOTAL                   8              .00000
REGRESSION              1              .00000               .00000           192.34
RESIDUAL                7              .00000               .00000

STANDARD ERROR =  7.18674791185E-05

                F TO   PART         F TO        REGRESSION COEFFICIENTS        STD
#--VARIABLE    ENTER   CORR    TOL DELETE  STD.FORMAT              E-FORMAT    ERROR
 1.TIME          .09   .119   .680
 2.BRINE CONC                     192.34      -.00000 -.126161630119E-07    .0000
 3.FEED TEMP     .92   .364   .781

Constant =  4.56498884111E-03
```

```
********************************************************************************
                                   MANUAL REGRESSION ON

                              Subfile:E D LV SPR
********************************************************************************


Dependent variable:CURRENT EF
Independent variable(s) =    TIME
                             BRINE CONC
                             FEED TEMP
Tolerance = .001


                                  CORRELATION MATRIX


                    TIME BRINE CONC  FEED TEMP CURRENT EF
TIME           1.0000000   .5656888  -.9143767  -.2905984
BRINE CONC                1.0000000  -.4676151  -.8754781
FEED TEMP                            1.0000000   .0906395
CURRENT EF                                      1.0000000

********************************************************************************

               F TO  PART         F TO        REGRESSION COEFFICIENTS        STD
#--VARIABLE    ENTER  CORR   TOL DELETE  STD.FORMAT                E-FORMAT    ERROR
 1.TIME          .65  .291 1.000
 2.BRINE CONC  22.97  .875 1.000
 3.FEED TEMP     .06  .091 1.000
********************************************************************************
STEP NUMBER 1
VARIABLE'BRINE CONC' ADDED
R-SQUARED =  .76646193339

                                        AOV

SOURCE              DF      SUM OF SQUARES         MEAN SQUARE        F-VALUE
TOTAL                8              .02990
REGRESSION           1              .02292              .02292          22.97
RESIDUAL             7              .00698              .00100

STANDARD ERROR =  3.15829361982E-02

               F TO  PART         F TO        REGRESSION COEFFICIENTS        STD
#--VARIABLE    ENTER  CORR   TOL DELETE  STD.FORMAT                E-FORMAT    ERROR
 1.TIME         2.15  .514  .680
 2.BRINE CONC                     22.97      -.00000 -.191612243319E-05    .0000
 3.FEED TEMP    7.54  .746  .781

Constant =  .89254921781
********************************************************************************
STEP NUMBER 2
VARIABLE'FEED TEMP' ADDED
R-SQUARED =  .89649539946

                                        AOV

SOURCE              DF      SUM OF SQUARES         MEAN SQUARE        F-VALUE
TOTAL                8              .02990
REGRESSION           2              .02680              .01340          25.98
RESIDUAL             6              .00309              .00052

STANDARD ERROR =  2.27105098568E-02
```

```
                F TO  PART         F TO        REGRESSION COEFFICIENTS      STD
#--VARIABLE    ENTER  CORR    TOL DELETE  STD.FORMAT             E-FORMAT    ERROR
 1.TIME         1.69  .503  .140
 2.BRINE CONC                     51.49   -.00000 -.233364039327E-05    .0000
 3.FEED TEMP                       7.54   -.00986 -.986202379825E-02    .0036

Constant =  1.16786243242

********************************************************************************
                               MANUAL REGRESSION ON

                          Subfile:E D LV SPR
********************************************************************************


Dependent variable:ENERGY
Independent variable(s) =   TIME
                            BRINE CONC
                            FEED TEMP
Tolerance = .001


                               CORRELATION MATRIX


                     TIME BRINE CONC  FEED TEMP     ENERGY
TIME            1.0000000   .5656888  -.9143767   .6666325
BRINE CONC                 1.0000000  -.4676151   .7239801
FEED TEMP                             1.0000000  -.4388230
ENERGY                                           1.0000000



********************************************************************************

                F TO  PART         F TO        REGRESSION COEFFICIENTS      STD
#--VARIABLE    ENTER  CORR    TOL DELETE  STD.FORMAT             E-FORMAT    ERROR
 1.TIME         5.60  .667 1.000
 2.BRINE CONC   7.71  .724 1.000
 3.FEED TEMP    1.67  .439 1.000
********************************************************************************
STEP NUMBER 1
VARIABLE'TIME' ADDED
R-SQUARED =  .44439891624

                                      AOV

SOURCE             DF      SUM OF SQUARES          MEAN SQUARE        F-VALUE
TOTAL               8             .55676
REGRESSION          1             .24742                .24742           5.60
RESIDUAL            7             .30933                .04419

STANDARD ERROR =  .210215532356

                F TO  PART         F TO        REGRESSION COEFFICIENTS      STD
#--VARIABLE    ENTER  CORR    TOL DELETE  STD.FORMAT             E-FORMAT    ERROR
 1.TIME                            5.60        .00006  .578285366103E-04    .0000
 2.BRINE CONC   2.80  .564  .680
 3.FEED TEMP    2.82  .566  .164

Constant =  3.97004740346
********************************************************************************
```

```
STEP NUMBER 2
VARIABLE'BRINE CONC' ADDED
R-SQUARED =  .62134290361

                                      AOV

SOURCE             DF     SUM OF SQUARES        MEAN SQUARE        F-VALUE
TOTAL               8             .55676
REGRESSION          2             .34594             .17297           4.92
RESIDUAL            6             .21082             .03514

STANDARD ERROR =  .187447522538

                F TO  PART        F TO        REGRESSION COEFFICIENTS       STD
#--VARIABLE    ENTER  CORR   TOL DELETE  STD.FORMAT            E-FORMAT    ERROR
 1.TIME                             1.54       .00003  .327963990691E-04    .0000
 2.BRINE CONC                       2.80       .00000  .481783829487E-05    .0000
 3.FEED TEMP    2.67  .590  .160

Constant =  3.82106638225
********************************************************************************
STEP NUMBER 3
VARIABLE'FEED TEMP' ADDED
R-SQUARED =  .75325208512

                                      AOV

SOURCE             DF     SUM OF SQUARES        MEAN SQUARE        F-VALUE
TOTAL               8             .55676
REGRESSION          3             .41938             .13979           5.09
RESIDUAL            5             .13738             .02748

STANDARD ERROR =  .165757818844

                F TO  PART        F TO        REGRESSION COEFFICIENTS       STD
#--VARIABLE    ENTER  CORR   TOL DELETE  STD.FORMAT            E-FORMAT    ERROR
 1.TIME                             4.38       .00011  .108001189558E-03    .0001
 2.BRINE CONC                       2.66       .00000  .419241685408E-05    .0000
 3.FEED TEMP                        2.67       .09463  .946343477104E-01    .0579

Constant =  .85575334859
```

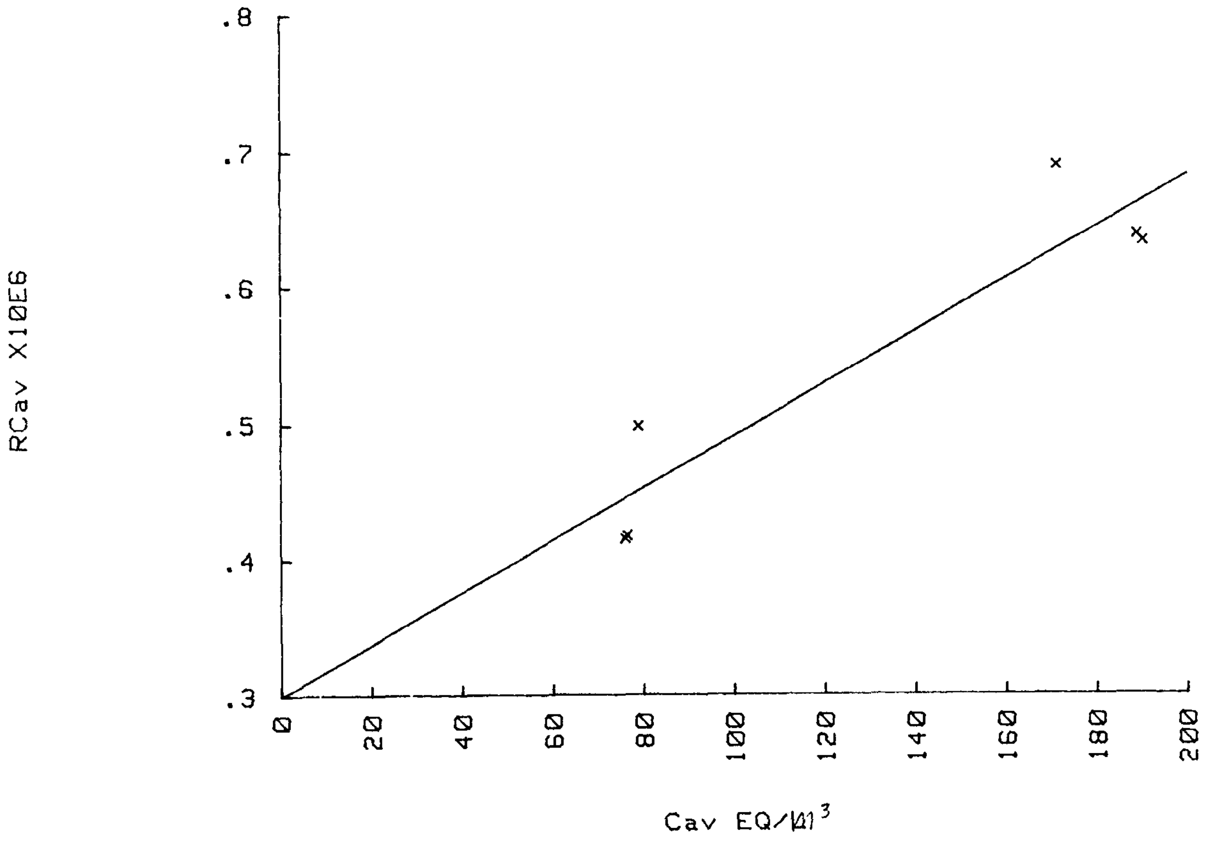
```
********************************************************************************
                                MANUAL REGRESSION ON

                           Subfile:E D LV SPR
********************************************************************************


Dependent variable:ENERGY
Independent variable(s) =   TIME
                            BRINE CONC
                            FEED TEMP
Tolerance = .001


                               CORRELATION MATRIX


                     TIME BRINE CONC  FEED TEMP     ENERGY
TIME            1.0000000   .5656888  -.9143767   .6666325
BRINE CONC                 1.0000000  -.4676151   .7239801
FEED TEMP                             1.0000000  -.4388230
ENERGY                                            1.0000000


********************************************************************************

                F TO  PART        F TO        REGRESSION COEFFICIENTS       STD
#--VARIABLE    ENTER  CORR   TOL DELETE  STD.FORMAT            E-FORMAT    ERROR
 1.TIME         5.60  .667 1.000
 2.BRINE CONC   7.71  .724 1.000
 3.FEED TEMP    1.67  .439 1.000
********************************************************************************
STEP NUMBER 1
VARIABLE'BRINE CONC' ADDED
R-SQUARED =  .52414712639

                                      AOV

SOURCE             DF      SUM OF SQUARES        MEAN SQUARE        F-VALUE
TOTAL               8              .55676
REGRESSION          1              .29182             .29182           7.71
RESIDUAL            7              .26493             .03785

STANDARD ERROR =  .194544791469

                F TO  PART        F TO        REGRESSION COEFFICIENTS       STD
#--VARIABLE    ENTER  CORR   TOL DELETE  STD.FORMAT            E-FORMAT    ERROR
 1.TIME         1.54  .452  .680
 2.BRINE CONC                     7.71       .00001  .683776485890E-05    .0000
 3.FEED TEMP     .17  .164  .781

Constant =  3.96212247377


 OBS#      OBSERVED Y     PREDICTED Y         RESIDUAL       STAND.RES.    SIGNIF.
   20         4.34000         4.24315           .09685           .49781
   21         4.31000         4.24657           .06343           .32603
   22         4.57000         4.62402          -.05402          -.27766
   23         4.30000         4.64043          -.34043         -1.74987
   24         4.86000         4.62197           .23803          1.22354
   25         4.53000         4.61814          -.08814          -.45305
```

```
   26          4.82000          4.63427          .18573          .95467
   27          4.68000          4.61103          .06897          .35454
   28          4.07000          4.24042         -.17042         -.87599


********************************************************************************

MULTIPLE LINEAR REGRESSION on Subfile'E D LV SPR' of
                              E D UNIT PERFORMANCE
********************************************************************************

--where:  Dependent variable = ENERGY
          Independent variable(s) = TIME
                                    BRINE CONC
                                    FEED TEMP

                                                           STANDARD     COEFFICIENT
VARIABLE        N            MEAN        VARIANCE         DEVIATION    OF VARIATION
TIME            9      9125.77778   9248326.61937        3041.10615        33.32435
BRINE CONC      9     78337.77778
780188344.45 M7D.5D
     27931.85179       35.65566
FEED TEMP       9        24.60000         6.39500           2.52883        10.27981
ENERGY          9         4.49778          .06959            .26381         5.86529


                                 CORRELATION MATRIX


               BRINE CONC  FEED TEMP     ENERGY
TIME             .5656888  -.9143767   .6666325
BRINE CONC                 -.4676151   .7239801
FEED TEMP                             -.4388230

R-SQUARED = .753252086294
STANDARD ERROR OF ESTIMATE = .165757818452


                                         AOV

SOURCE                DF      SUM OF SQUARES        MEAN SQUARE        F-VALUE


TOTAL                 8              .55676
REGRESSION            3              .41938              .13979              5.09
 TIME                  1              .24742              .24742              9.01
 BRINE CONC            1              .09851              .09851              3.59
 FEED TEMP             1              .07344              .07344              2.67
RESIDUAL              5              .13738              .02748


                        REGRESSION COEFFICIENTS            STANDARD ERROR
VARIABLE             STD. FORMAT            E-FORMAT     REG. COEFFICIENT       T-VALUE
'CONSTANT'                .85575   .855753338440E+00              1.82478           .47
TIME                      .00011   .108001189817E-03               .00005          2.09
BRINE CONC                .00000   .419241685291E-05               .00000          1.63
FEED TEMP                 .09463   .946343480303E-01               .05788          1.63


                                          99 % CONFIDENCE INTERVAL
                     COEFFICIENT           LOWER LIMIT          UPPER LIMIT
```

```
****************************************************************************
*                  BASIC STATISTICS AND DATA MANIPULATION                  *
****************************************************************************
      HIGH RECOVERY ELECTRODIALYSIS AT LA VERKIN SPRINGS--RCav VERSUS Cav

Data file name:
Number of observations: 6
Number of variables: 2

Variables names:
   1. Cav EQ/m3
   2. RCav X10E6



      HIGH RECOVERY ELECTRODIALYSIS AT LA VERKIN SPRINGS--RCav VERSUS Cav


    Variable # 1   Variable # 2
OBS#
   1
       188.90000         .63850
   2
        76.50000         .41780
   3
       190.20000         .63360
   4
        76.00000         .41580
   5
       171.20000         .68990
   6
        78.90000         .49880

****************************************************************************
POLYNOMIAL REGRESSION ON DATA SET:
      HIGH RECOVERY ELECTRODIALYSIS AT LA VERKIN SPRINGS--RCav VERSUS Cav
****************************************************************************

--where:  Dependent variable = RCav X10E6
          Independent variable = Cav EQ/m3


                                                     STANDARD     COEFFICIENT
VARIABLE       N          MEAN         VARIANCE      DEVIATION    OF VARIATION
Cav EQ/L       6     130.28333       3435.93367       58.61684        44.99182
RCav X10E6     6        .54907           .01450         .12041        21.93041

CORRELATION =  .933570671669


Selected degree of regression =  1
R-SQUARED = .871554198932
STANDARD ERROR OF ESTIMATE = 4.82488229437E-02


                                      AOV

SOURCE                 DF      SUM OF SQUARES       MEAN SQUARE       F-VALUE


TOTAL                  5            .07250
```

```
REGRESSION          1           .06318           .06318          27.14
 X^1                 1           .06318           .06318          27.14
RESIDUAL            4           .00931           .00233


                      REGRESSION COEFFICIENTS          STANDARD ERROR
VARIABLE         STD. FORMAT            E-FORMAT     REG. COEFFICIENT     T-VALUE
'CONSTANT'            .29921  .299213167231E+00                .05185        5.77
X^1                   .00192  .191777024002E-02                .00037        5.21


                                      95 % CONFIDENCE INTERVAL
                   COEFFICIENT         LOWER LIMIT        UPPER LIMIT
'CONSTANT'              .29921              .15526             .44317
X^1                     .00192              .00090             .00294
```

HIGH RECOVERY ELECTRODIALYSIS AT LA VERKIN SPRINGS--RCav VERSUS Cav



# APPENDIX D

# MEMBRANE SPECIFICATIONS

IONICS
IONICS, INCORPORATED
65 Grove Street, Watertown, Massachusetts 02172 U.S.A.
Telephone: (617) 926-2500 Telex: 922473

Bulletin No. CR 61.0-D

# CATION–TRANSFER MEMBRANES

## TYPE CR 61

## GENERAL INFORMATION

Ionics' CR 61 membranes are cation-selective membranes comprising cross-linked sulfonated copolymers of vinyl compounds. The membranes are homogeneous films, cast in sheet form on synthetic reinforcing fabrics.

Ionics' cation-transfer membranes have a combination of properties and characteristics which is unique. This includes:

- Low electrical resistance
- High permselectivity (ability to exclude anions)
- High burst strength
- Rugged reinforced construction
- Very high dimensional stability in solutions of different compositions
- Excellent long-term stability at temperatures up to 65°C. May be used for brief periods at temperatures up to 85° C.
- Long-term resistance to aqueous acid, alkaline and mild oxidizing solutions
- Extensive use in more than 1000 electrodialysis installations
- Ability to withstand harsh chemical and physical treatments to remove surface and interior deposits. Ionics' membranes may be sandpapered, steel-wooled, wire-brushed or contacted with 5-10% acids, bases, salts or stabilized chlorine dioxide when the cleaning requirements warrant same. Ionics' membranes have been produced for more than 25 years. Ionics can custom-make membranes of various electrochemical and mechanical properties having reinforcing fabrics which are resistant to oxidative and other corrosive media. These are briefly described in Bulletin CR 61.4-D.
- All membranes produced at Ionics are required to pass rigorous quality control examinations.

## REINFORCING FABRICS

Modacrylic Polymer (copolymer of vinyl chloride and acrylonitrile) is the fabric most commonly used. Other fabrics are used for applications where modacrylic exhibits insufficient chemical stability. These can be furnished on special order.

Some fabrics can be furnished in various thicknesses or weights. The lower the weight of the fabric, the lower in general will be the electrical resistance of the membrane. On the other hand, membranes with heavy-weight fabrics may exhibit a longer life than membranes with lighter fabrics, especially in applications where erosion may become a factor.

## POROSITY

The formulation of CR61 membranes can be varied to impart various total pore volumes and average pore sizes to the membrane. The lower the average pore size of a membrane, the lower will be the transfer of non-electrolytes accompanying ion transfer, but the higher will be the electrical resistance of the membrane.

Ionics offers two different standard total pore volumes in production membranes. A variety of total pore volumes can be made to custom order.

## CHEMICAL STABILITY

The ion exchange resin of CR 61 membranes is not attacked by non-oxidizing solutions below pH 11 and has fair stability up to pH 14. It has fair resistance to mild oxidants and is not attacked by reducing agents. It may be used at temperatures up to 65$^{o}$C and sometimes up to 85$^{o}$C, depending on conditions and the nature of the media with which it is contacted.

## PHYSICAL STABILITY

If kept wet, physical stability is excellent. Membranes shrink upon extensive drying and, therefore, cracking may occur.

## HANDLING/MOUNTING

Membranes can be mounted between gum rubber, neoprene, SBR, polyethylene, silicone, plasticized PVC, or other soft, insulating gaskets. Moderate gasket pressure will seal a membrane satisfactorily for most uses. Membranes (except the 389 series) may be bent around curves of large radius, but caution should be observed. Membranes may be cemented together or to other applicable substrates by the use of fast curing epoxy cements.

## PATENTS

Ionics, Incorporated, owns many U.S. and foreign patents covering the manufacture and/or certain uses of ion-transfer membranes, and the sale of these membranes shall not be construed as a license for their use in conflict with existing patents or patent applications owned by Ionics or others.

## STORAGE

If long-term (many months) storage of any CR 61 membrane is contemplated, the water of storage should be made up by first dissolving 1 gram of benzoic acid in 10 ml of ethyl alcohol and pouring this into each liter of storage water. This 0.1% solution will inhibit the growth of microorganisms during storage.

***

IONICS

IONICS, INCORPORATED

65 Grove Street, Watertown, Massachusetts 02172 U.S.A.
Telephone: (617) 926-2500 Telex: 922473

Bulletin No. CR 61.1-E

# CATION–TRANSFER MEMBRANES

## TYPE 61 AZL 386

## PROPERTIES AND CHARACTERISTICS

Many standard Ionics electrodialysis reversal ("EDR") plants are furnished with 61-AZL-386 Modacrylic fiber-backed cation-transfer membranes for the transport of cations while retarding anions. The property data are typical values only and no warranty as to such properties is given.

| | | | |
|---|---|---|---|
| Reinforcing Fabric: | Modacrylic (copolymer of vinyl chloride and acrylonitrile) | | |
| Weight: | 4 oz/yd$^2$ | Specific Weight: | 13.7 mg/cm$^2$ |
| Membrane Thickness: | 20 mils (0.5 mm) | | |
| Burst Strength (Mullen): | 75 psi (5.25 kg/cm$^2$) | | |
| Water Content: | 46% of wet resin only | | |
| Capacity: | 2.44 meq/dry gram resin (minimum) | | |

## VARIOUS ELECTROCHEMICAL PROPERTIES

| Concentration | 0.01 N NaCl | 0.1 N NaCl | 1.0 N NaCl | 3.0 N NaCl |
|---|---|---|---|---|
| Area Specific Resist. (ohm-cm$^2$) | 16.7 | 11 | 4 | 2 |
| Spec. Conductance mho/cm | $3 \times 10^{-3}$ | $4.5 \times 10^{-3}$ | $12.5 \times 10^{-3}$ | $25 \times 10^{-3}$ |
| Current Efficiency $\tau_+$ (Fraction of current carried by cation only) | 0.98 | 0.92 | 0.86 | — |

## OTHER PROPERTIES

| | |
|---|---|
| Water Transport: | 0.200 liters per Faraday in 0.6N NaCl @ 16 ma/cm$^2$ |
| Sucrose Transport: | 30 grams per Faraday from 30% sucrose in 0.2N KCl into 0.2N KCl @ 16 ma/cm$^2$ |

NOTICE: For patent and license notice, see Bulletin CR 61.0-D.

BULLETIN No. CR61.4-C 61CZL183

## PROPERTIES AND CHARACTERISTICS

Ionics' Dynel-backed cation-transfer membrane 61CZL183 has a tighter matrix than membrane 61AZL183. Therefore, it is suggested for use in electrodialysis as a means for transporting cations while excluding anions in applications where loss of solvent and of non-ionized product must be reduced below that obtainable with membrane 61AZL183.

| | | | | |
|---|---|---|---|---|
| Backing - | Type: | Dynel | Specific Weight: | 14 mg/cm$^2$ |
| | Weight: | 4 oz/yd$^2$ | Content: | 34 wt% (dry) |

| | |
|---|---|
| Membrane Thickness: | 24 mils (0.6 mm) |
| Burst Strength (Mullen): | 115 psi (8 kg/cm$^2$) |
| Water Content: | 40% of wet resin only |
| Capacity: | 2.7 meq/dry gram resin |

| | 0.01 N NaCl | 0.1 N NaCl | 1.0 N NaCl | 3.0 N NaCl |
|---|---|---|---|---|
| Area Specific Resist. (ohm-cm$^2$) | 13 | 11 | 8 | 5 |
| Spec. Conductance (mho/cm) | 5 x $10^{-3}$ | 6 x $10^{-3}$ | 8 x $10^{-3}$ | 12 x $10^{-3}$ |

Sucrose Transport @ 16 ma/cm$^2$, 30% sucrose in 0.2 N KCl/0.02 N KCl (g/Faraday) -- 6

NOTICE:

1. The property data are typical values only and no warranty as to such properties is given.
2. Ionics, Incorporated, will be pleased to advise on procedures for measurement of membrane characteristics, including resistance, ion-exchange capacity, burst strength, moisture content, density, water transport, transport number, and/or leakage (pinholes). Alternatively, Ionics will be pleased to measure pertinent properties on membranes after use by the customer to check for possible degradation.
3. For patent and license clause, see Bulletin CR61.

IONICS, INCORPORATED
65 Grove Street, Watertown, Massachusetts 02172 U.S.A.
Telephone: (617) 926-2500 Telex: 922473

Bulletin No. AR 103.0-E

Printed in USA

# ANION–TRANSFER MEMBRANES

## TYPE AR 103

## GENERAL INFORMATION

Ionics' AR 103 membranes are anion-selective membranes comprising cross-linked copolymers of vinyl monomers and containing quaternary ammonium anion exchange groups. The membranes are homogeneous films, cast in sheet form on reinforcing synthetic fabrics.

Ionics' anion-transfer membranes have a combination of properties and characteristics which is unique. This includes:

- Low electrical resistance
- High permselectivity (ability to exclude cations)
- High burst strength
- Rugged reinforced construction
- Except in hydroxide ion form, excellent long-term stability at temperatures up to 65°C and in solutions having pH's < 9. May be used for brief periods at temperatures up to 95°C
- Long-term resistance to aqueous acid solutions
- Very high dimensional stability in solutions of different compositions
- Ability to withstand harsh chemical and physical treatments to remove surface and interior deposits. (Ionics membranes may be sandpapered, steel wooled or wire-brushed, contacted with 5-10% acids or salts and stabilized chlorine dioxide when the cleaning requirements warrant same.)
- Extensive use in more than 1000 electrodialysis installations. Ionics membranes have been produced for more than 25 years.
- All membranes produced at Ionics are required to pass rigorous quality control examinations.

Ionics can custom make membranes for special applications, varying mechanical and electrochemical properties or using reinforcing fabrics which are resistant to oxidation, caustic or other corrosive media.

## REINFORCING FABRICS

Modacrylic Polymer is the fabric most commonly used in Type AR 103. Other fabrics can be furnished for applications where a modacrylic would exhibit insufficient chemical stability. Fabrics can be furnished in various thicknesses or weights. The lower the weight of the fabric, the lower in general will be the electrical resistance of the membrane. On the other hand, membranes with heavy weight fabrics may exhibit a longer life than membranes with lighter fabrics, especially in applications where erosion may become a factor.

## POROSITY

The formulation of AR 103 membranes can be varied to impart various average pore sizes or total pore volumes to the membrane. The smaller the average pore size of a membrane, the lower will be the transfer of non-electrolytes which accompany ion transfer, but the higher will be the electrical resistance of the membrane. The larger the total pore volume, the less efficient a membrane will be.

Ionics offers two different standard total pore volumes in production membranes. A variety of total pore volumes and average pore sizes can be made to custom order.

## CHEMICAL STABILITY

At room temperature, the AR 103 anion membranes are stable to non-oxidizing solutions between pH 0 and 9 and exhibit fair stability to solutions outside of this range, e.g. 4-5 N HCl and $H_2SO_4$. They may be used at temperatures up to 65°C (except in the hydroxide ion form) on a continuous operation in this pH range and for brief periods up to 95°C. At operating temperatures in the 65-95°C region slow losses in ion exchange capacity can be expected.

Contact with oxidizing agents (chlorine, hypochlorites) and strong bases, e.g. 0.5 N sodium hydroxide should be avoided as should contact with low molecular weight organic polyelectrolytes such as salts of humic acid, lignates, branched chain alkyl or aryl sulfonates, tannins, etc., the anions of which tend to be irreversibly absorbed on the surface of anion selective membranes if present at appreciable concentrations.

## PHYSICAL STABILITY

If kept wet, physical stability is excellent. Membranes shrink upon drying and crack upon excessive drying.

Swelling of membranes in water as the temperature is increased is minimal for all types of Ionics membranes and rarely exceeds 5% in any dimension when heated from room temperature to 100°C.

## HANDLING/MOUNTING

Membranes can be mounted between gum rubber, neoprene, SBR, polyethylene, plasticized PVC, silicone and other soft, insulating elastomeric or thermoplastic materials.

Moderate pressure will seal a membrane against such materials satisfactorily for most uses. Membrane sheets may be bent around curves of large radius but caution should be observed.

## NOTE

Anion membranes intended to be stored for long periods may sometimes contain small amounts of hydrochloric acid added during manufacture. Before use, such membranes should be flushed in water, preferably containing ions present in the solution to be processed.

## STORAGE

If long term (many months) storage of any AR 103 membrane is contemplated, the water of storage should be made up by first dissolving 1 gram of benzoic acid in 10 ml of ethyl alcohol and pouring this into each liter of storage water. This 0.1% solution will inhibit the growth of various micro-organisms during storage.

## PATENTS

Ionics, Incorporated, owns many U.S. and foreign patents pertaining to the manufacture and/or use of ion transfer membranes and the sale of these membranes shall not be construed as a license for their use in conflict with existing patents or patent applications owned by Ionics or others.

**IONICS**

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Bulletin No. AR 103.1-E

Printed in USA

# ANION–TRANSFER MEMBRANES

TYPE 103-PZL-386

## PROPERTIES AND CHARACTERISTICS

Many standard Ionics electrodialysis reversal ("EDR") plants are furnished with 103-PZL-386 Modacrylic fiber-backed anion transfer membranes for the transport of anions while retarding cations. The property data are typical values only and no warranty as to such properties is given.

| | | | |
|---|---|---|---|
| Reinforcing Fabric: | Modacrylic (copolymer of vinyl chloride and acrylonitrile) | | |
| Weight: | 4 oz/yd$^2$ | Specific Weight: | 13.7 mg/cm$^2$ |
| Membrane Thickness: | 20 mils (0.5 mm) | | |
| Burst Strength (Mullen): | 100 psi (7.0 kg/cm$^2$) | | |
| Water Content: | 46% of wet resin only | | |
| Capacity: | 1.72 meq/dry gram resin (minimum) | | |

## VARIOUS ELECTROCHEMICAL PROPERTIES

| Concentration | 0.01 N NaCl | 0.1 N NaCl | 1.0 N NaCl | 3.0 N NaCl |
|---|---|---|---|---|
| Area Specific Resist. (ohm-cm$^2$) | 18.5 | 12 | 5 | 2 |
| Specific Conductance mho/cm | $2.7 \times 10^{-3}$ | $4.2 \times 10^{-3}$ | $10 \times 10^{-3}$ | $25 \times 10^{-3}$ |
| Current Efficiency $\tau_-$ (Fraction of current carried by anions only) | 0.99 | 0.95 | 0.81 | — |

## OTHER PROPERTIES

| | |
|---|---|
| Water Transport: | 0.152 liters per Faraday in 0.6 NaCl @ 16 ma/cm$^2$ |
| Sucrose Transport: | 13.5 grams per Faraday from 30% sucrose in 0.2 N KCl into 0.02 N KCL @ 16 ma/cm$^2$ |

<u>NOTICE</u>:
1) The property data are typical values only and no warranty as to such properties is given.
2) For patent and license notice, see Bulletin AR 103.0-E

IONICS, INCORPORATED
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Bulletin No. AR 204.0-A

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# ANION-TRANSFER MEMBRANES

TYPE AR 204

## GENERAL INFORMATION

Ionics' AR 204 membranes are anion-selective membranes comprising cross-linked copolymers of vinyl monomers and containing quaternary ammonium anion exchange groups. The membranes are homogeneous films, cast in sheet form on reinforcing synthetic fabrics.

Ionics' anion-transfer membranes have a combination of properties and characteristics which is unique. This includes:

- Low electrical resistance
- High permselectivity (ability to exclude cations)
- High burst strength
- Rugged reinforced construction
- Except in hydroxide ion form, excellent long-term stability at temperatures up to 65°C and in solutions having pH's < 9. May be used for brief periods at temperatures up to 95°C.
- Long-term resistance to aqueous acid solutions
- Very high dimensional stability in solutions of different compositions
- Ability to withstand harsh chemical and physical treatments to remove surface and interior deposits. (Ionics membranes may be sandpapered, steel wooled or wire-brushed, contacted with 5-10% acids, or salts and stabilized chlorine dioxide when the cleaning requirements warrant same.)
- Extensive use in electrodialysis installations.
- All membranes produced at Ionics are required to pass rigorous quality control examinations. Ionics membranes have been produced for more than 25 years.

Ionics can custom make membranes for special applications, varying mechanical and electrochemical properties or using reinforcing fabrics which are resistant to oxidation, caustic or other corrosive media.

## REINFORCING FABRICS

Modacrylic Polymer is the fabric most commonly used in Type AR 204. Other fabrics can be furnished for applications where a modacrylic would exhibit insufficient chemical stability. Fabrics can be furnished in various thicknesses or weights. The lower the weight of the fabric, the lower in general will be the electrical resistance of the membrane. On the other hand, membranes with heavy weight fabrics may exhibit a longer life than membranes with lighter fabrics, especially in applications where erosion may become a factor.

## POROSITY

The formulation of AR 204 membranes can be varied to impart various average pore sizes or total pore volumes to the membrane. The smaller the average pore size of a membrane, the lower will be the transfer of non-electrolytes which accompany ion transfer, but the higher will be the electrical resistance of the membrane. The larger the total pore volume, the less efficient a membrane will be.

Ionics offers two different standard total pore volumes in production membranes. A variety of total pore volumes and average pore sizes can be made to custom order.

## CHEMICAL STABILITY

At room temperature, the AR 204 anion membranes are stable to non-oxidizing solutions between pH 0 and 9 and exhibit fair stability to solutions outside of this range, e.g. 4-5 N HCl and $H_2SO_4$. They may be used at temperatures up to 65°C (except in the hydroxide ion form) on a continuous operation in this pH range and for brief periods up to 95°C. At operating temperatures in the 65-95°C region slow losses in ion exchange capacity can be expected.

Contact with oxidizing agents (chlorine, hypochlorites) and strong bases, e.g. 0.5 N sodium hydroxide should be avoided as should contact with low molecular weight organic polyelectrolytes such as salts of humic acid, lignates, branched chain alkyl or aryl sulfonates, tannins, etc., the anions of which tend to be irreversibly absorbed on the surface of anion selective membranes if present at appreciable concentrations.

## PHYSICAL STABILITY

If kept wet, physical stability is excellent. Membranes shrink upon drying and crack upon excessive drying.

Swelling of membranes in water as the temperature is increased is minimal for all types of Ionics membranes and rarely exceeds 5% in any dimension when heated from room temperature to 100°C.

## HANDLING/MOUNTING

Membranes can be mounted between gum rubber, neoprene, SBR, polyethylene, plasticized PVC, silicone and other soft, insulating elastomeric or thermoplastic materials.

Moderate pressure will seal a membrane against such materials satisfactorily for most uses. Membrane sheets may be bent around curves of large radius but caution should be observed.

## NOTE

Anion membranes intended to be stored for long periods may sometimes contain small amounts of hydrochloric acid added during manufacture. Before use, such membranes should be flushed in water, preferably containing ions present in the solution to be processed.

## STORAGE

If long term (many months) storage of any AR 204 membrane is contemplated, the water of storage should be made up by first dissolving 1 gram of benzoic acid in 10 ml of ethyl alcohol and pouring this into each liter of storage water. This 0.1% solution will inhibit the growth of various micro-organisms during storage.

## PATENTS

Ionics, Incorporated, owns many U.S. and foreign patents pertaining to the manufacture and/or use of ion transfer membranes and the sale of these membranes shall not be construed as a license for their use in conflict with existing patents or patent applications owned by Ionics or others.

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# ANION–TRANSFER MEMBRANES

## TYPE 204-SXZL-386

## PROPERTIES AND CHARACTERISTICS

Many standard Ionics electrodialysis reversal ("EDR") plants are furnished with 204-SXZL-386 Modacrylic fiber-backed anion transfer membranes for the transport of anions while retarding cations. The property data are typical values only and no warranty as to such properties is given.

Reinforcing Fabric: Modacrylic (copolymer of vinyl chloride and acrylonitrile)

Weight: 4 oz/yd$^2$ Specific Weight: 13.7 mg/cm$^2$

Membrane Thickness: 20 mils (0.5 mm)

Burst Strength (Mullen): 100 psi (7.0 kg/cm$^2$)

Water Content: 46% of wet resin only

Capacity: 2.20 meq/dry gram resin (minimum)

## VARIOUS ELECTROCHEMICAL PROPERTIES

| Concentration | 0.01 N NaCl | 0.1 N NaCl | 1.0 N NaCl | 3.0 N NaCl |
|---|---|---|---|---|
| Area Specific Resist. (ohm-cm$^2$) | 14.0 | 11 | 5 | 2 |
| Specific Conductance mho/cm | 3.6 x $10^{-3}$ | 4.5 x $10^{-3}$ | 10 x $10^{-3}$ | 25 x $10^{-3}$ |
| Current Efficiency $\tau_-$ (Fraction of current carried by anions only) | 0.99 | 0.96 | 0.88 | — |

## OTHER PROPERTIES

Water Transport: 0.120 liters per Faraday in 0.6 NaCl @ 16 ma/cm$^2$

Sucrose Transport: 11.5 grams per Faraday from 30% sucrose in 0.2 N KCl into 0.02 N KCL @ 16 ma/cm$^2$

NOTICE:
1) The property data are typical values only and no warranty as to such properties is given.
2) For patent and license notice, see Bulletin AR 204.0-A.

## Mission of the Bureau of Reclamation

*The Bureau of Reclamation of the U.S. Department of the Interior is responsible for the development and conservation of the Nation's water resources in the Western United States.*

*The Bureau's original purpose "to provide for the reclamation of arid and semiarid lands in the West" today covers a wide range of interrelated functions. These include providing municipal and industrial water supplies; hydroelectric power generation; irrigation water for agriculture; water quality improvement; flood control; river navigation; river regulation and control; fish and wildlife enhancement; outdoor recreation; and research on water-related design, construction, materials, atmospheric management, and wind and solar power.*

*Bureau programs most frequently are the result of close cooperation with the U.S. Congress, other Federal agencies, States, local governments, academic institutions, water-user organizations, and other concerned groups.*

A free pamphlet is available from the Bureau entitled "Publications for Sale." It describes some of the technical publications currently available, their cost, and how to order them. The pamphlet can be obtained upon request from the Bureau of Reclamation, Attn D-922, P O Box 25007, Denver Federal Center, Denver CO 80225-0007.