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The Interaction of Technical and Economic Demands in the Design of Large-Scale Electrodialysis Demineralizers

Donald A. Cowan
University of Dallas

THE INTERACTION OF TECHNICAL AND ECONOMIC DEMANDS IN THE DESIGN OF LARGE-SCALE ELECTRODIALYSIS DEMINERALIZERS

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by

Donald A. Cowan

Chairman, Physics Department, University of Dallas
Consultant to Texas Electric Service Company, Fort Worth, Texas

Work Performed at Fort Worth Laboratories of

Texas Electric Service Company

The two aspects of design -- economic and technical -- are rather powerful determinants of an electrodialysis plant design. In essence, economics control the quantity of membranes required, technical demands control the arrangement. I should like to dispose of the economic aspect first.

The cost equation is shown in Table I. Here the elements of cost are divided into three groups which are affected differently by current density. Because salt is carried by current, less membrane area per volume is required as current density increases, so that all costs associated with area vary inversely with current density. The electric sosts -- the I^2R costs -- increase with current density; and a third group is unaffected by current density. The electrode and concentration potentials V can be handled as a perturbation of resistance and so will not appear specifically in the subsequent expressions.

If we set the derivative with respect to current density equal to zero and solve for current density, we get the current density which will produce the water at the least cost. Table II shows this least cost, the required "optimum" current, and the resulting membrane area. There are no limitations placed on the arrangement by this least cost requirement. Many short parallel stacks or a few long stacks satisfy the requirement; only the total area is specified.

Table I

COST EQUATION

$$MF \int_{N}^{N_o} dN/j \; + \; EF \int_{N}^{N_o} (jr + V)\,dN \; + \; C$$

$$12.4¢/\text{kgal} \;\; M \int_{N}^{N_o} dN/j \; + \; 0.101¢/\text{kgal} \;\; E \int_{N}^{N_o} (jr + V)\,dN \; + \; C$$

M in ¢/sq ft yr

E in ¢/kwhr

j in milliamp/cm^2

N in equiv/liter

r in ohm cm^2 per cell pair

C in ¢/kgal

Table II

MINIMUM COST

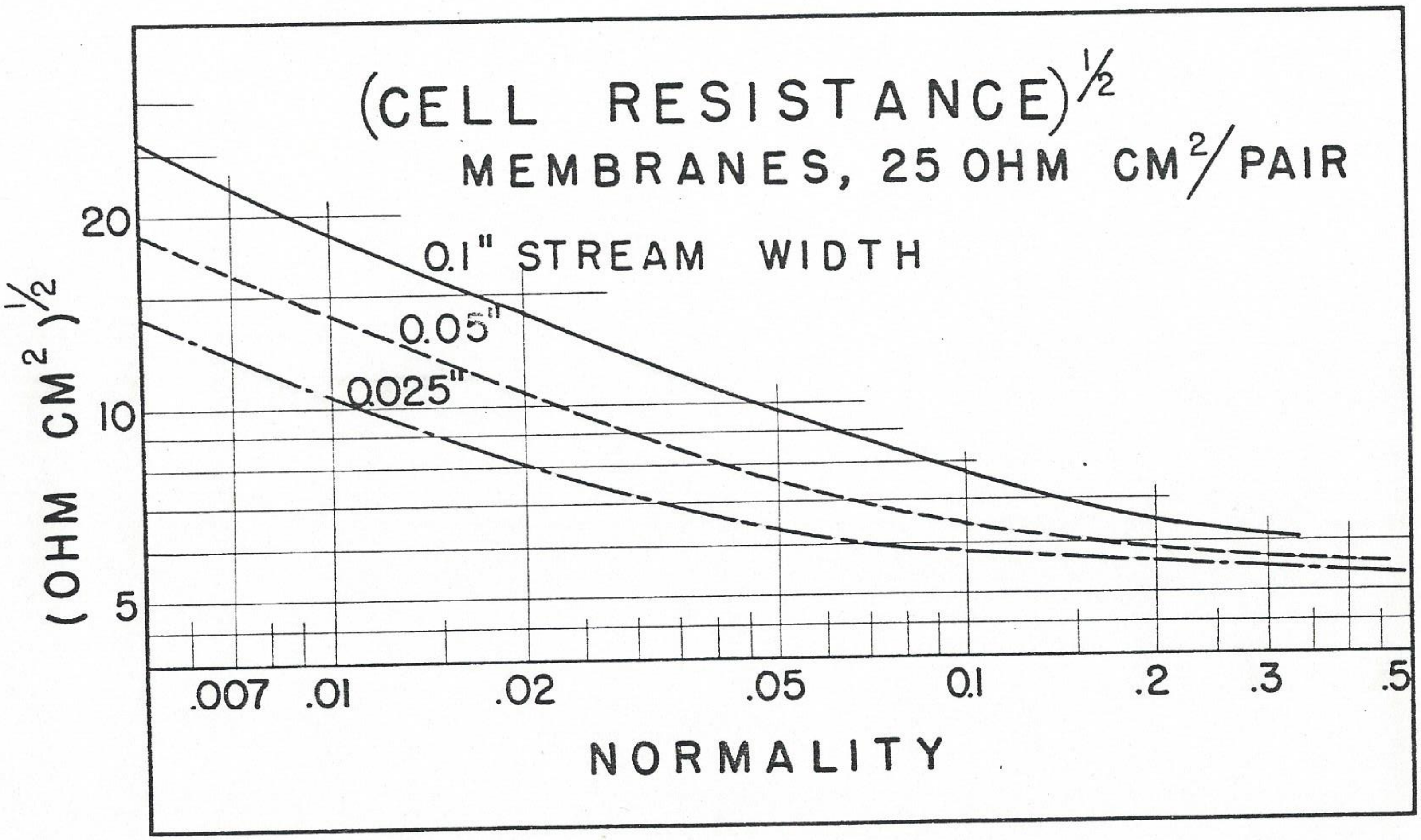
$$2.24¢/\text{kgal} \sqrt{ME} \int_{N}^{N_o} \sqrt{r} \; dN + C$$

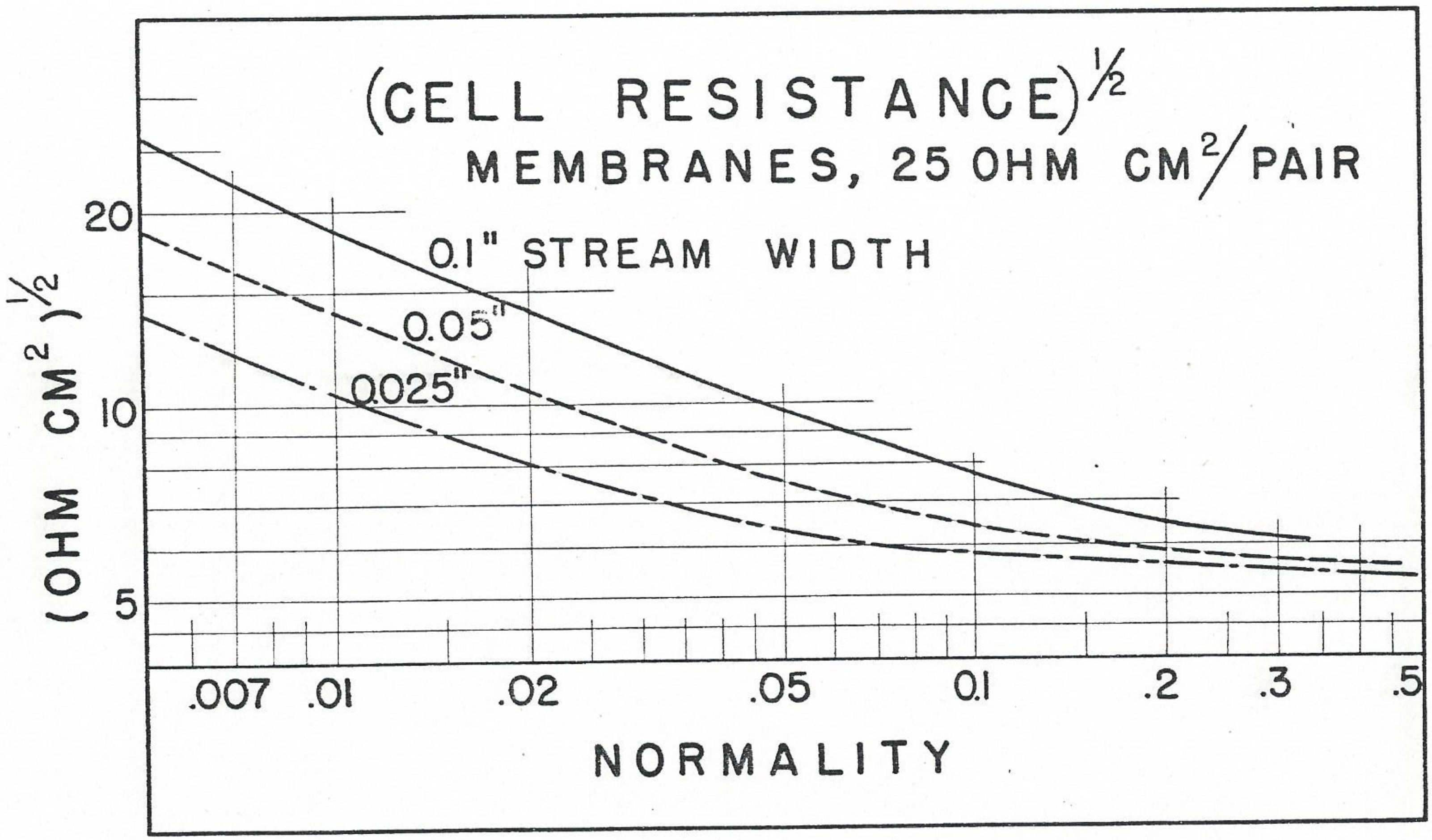
current condition $\quad j = 11.1 \sqrt{M/Er} \quad ma/cm^2$

membrane area $\quad 2 \times 0.408 \sqrt{E/M} \int_{N}^{N_o} \sqrt{r} \; dN \quad$ sq ft/gal/day

electric energy $\quad 1.12 \sqrt{M/E} \int_{N}^{N_o} \sqrt{r} \; dN \quad$ kwhr/kgal

The evolution of the parameters can be made with only a cursory consideration of design. The area resistance r is composed of the membrane resistance and the stream resistance. It is the square root of this resistance which appears in the least cost expression. For a membrane resistance per pair of 25 ohm cm^2 , the function for three different stream thicknesses is plotted against normality in Fig. 1. The effect of stream-thickness is clearly evident on this graph. There is, of course, a saving at thinner spacing, but it is a minor saving -- about 2¢ difference per kilogal for brackish water between 100 and 50 mils. Furthermore, it is not available unless we are operating near optimum current. Until we are speaking of 12¢ water instead of 30¢, this 2¢ worth does not enter the picture. Anyone who has worked with the design, the construction, or the operation of electrodialysis cells will, I am sure, readily agree that the problem of getting water in and out, and of keeping it flowing, is much more easily solved in the wider passages than in the thinner ones. Admittedly, a cell must be twice as long if it is twice as thick, in order to accomplish the same dilution; but twice as much water comes out when its size is doubled. The only penalty is that shown here. For sea water, the penalty for 100 mil over 50 mil is worth about 7¢; but of far more importance is the membrane resistance, where greater saving could be effected. Until we are speaking of 50¢ water instead of that costing $1.00 or more, again the thinner passages are an unnecessary complication. The integral expression used


(CELL RESISTANCE)^½
MEMBRANES, 25 OHM CM²/PAIR
0.1" STREAM WIDTH
0.05"
0.025"
(OHM CM²)^½
20
10
5
.007
.01
.02
.05
0.1
.2
.3
.5
NORMALITY



(CELL RESISTANCE)½
MEMBRANES, 25 OHM CM²/PAIR
0.1" STREAM WIDTH
0.05"
0.025"
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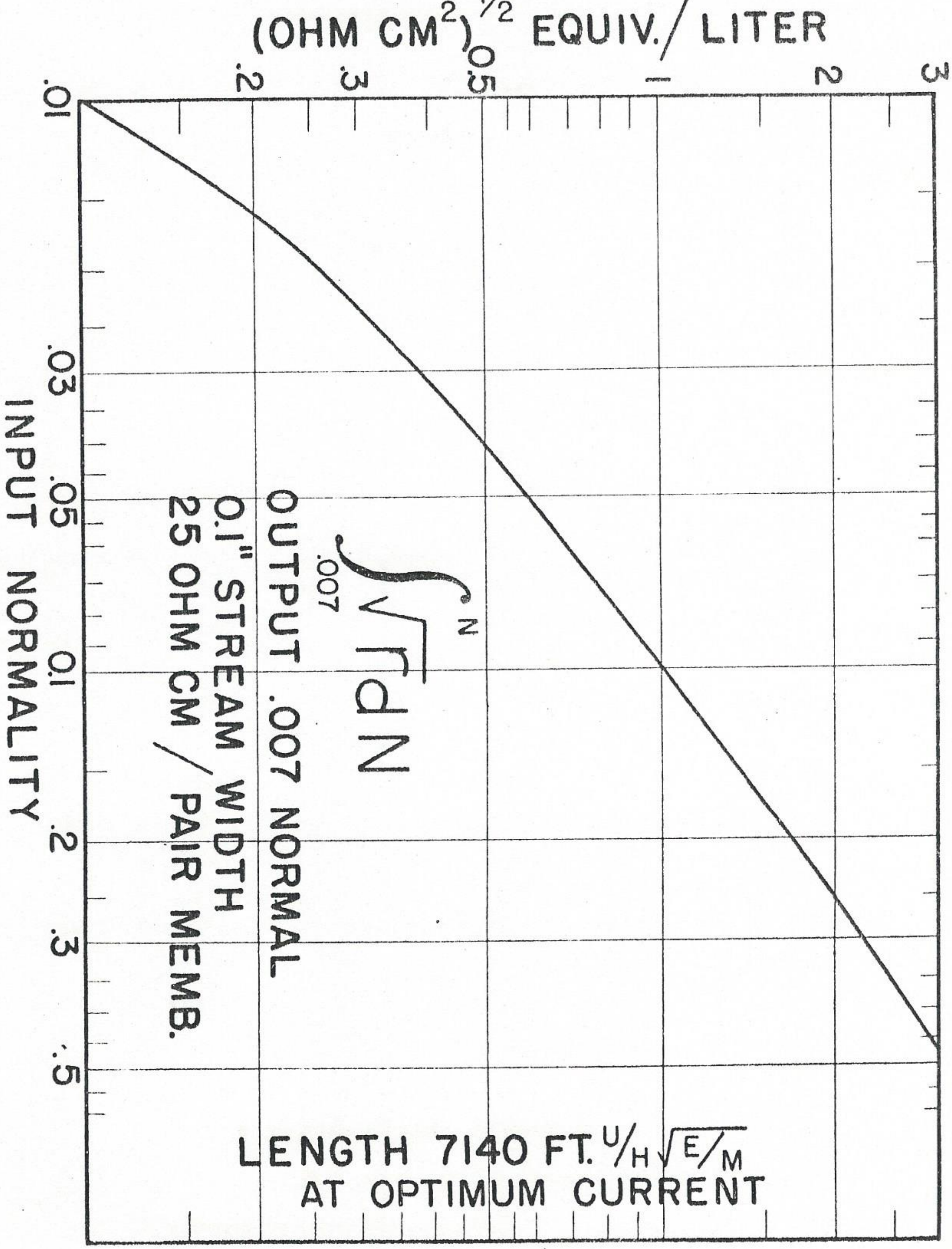
20
10
5
.007
.01
.02
.05
0.1
.2
.3
.5
NORMALITY



(OHM CM²)^½ EQUIV./LITER
.2
.3
0.5
1
2
3
.01
.03
.05
0.1
.2
.3
.5
INPUT NORMALITY
∫ from .007 to N √r dN
OUTPUT .007 NORMAL
0.1" STREAM WIDTH
25 OHM CM / PAIR MEMB.
LENGTH 7140 FT. U/H √E/M
AT OPTIMUM CURRENT

in the cost equation is shown in Fig. 2.

The parameter M -- that is, the cost per square foot of membrane area per year -- Table III covers most of the cost items listed in the standard cost procedure pamphlet PB 161375 issued by the Office of Saline Waters. These costs are not based on a detailed design, but are estimates for use in fixing the specifications on which an actual design can be based. Consequently, some of the items are based on projected future costs. For example, a membrane cost of 50¢ per square foot is used. Membrane costs have been about $2.00 per square foot, but I believe the present cost would be about half this figure for a large order, and manufacturers assure us that the 50¢ figure is in sight. The total cost per square foot year is 92¢, of which 77¢ is for three year life items -- membranes, spacers, inlets and outlets, and assembly cost. Should the stack prove to have a 10-year life, then the total cost would drop to 41¢ per square foot year, and I think we might accept this figure as the optimistic limit.

The electric cost (Table IV) is the cost at the suggested 7 mil/kwhr of the energy previously calculated increased by 10% to account for pumps, lighting, and rectifier efficiency and another 10% for current efficiency.

The cost group unaffected by current density - Table V, includes the operating costs and certain portion of the amortization. Wages have been distributed among the three categories.

With these figures, we can specify the cost of 500 ppm water produced by a plant of optimum design now -- that is,

Table III

M
Costs proportional to Area

20 year life	\$/sq ft		Amortization Inter. & Ins.
Press	0.50		
Side strips	0.40		
Instrumentation	0.03		
Contingencies	0.19		
Engineering	0.21		
		1.33	0.122
3 year life			
Membranes	1.10		
Spacers	0.50		
Inlets & outlets	0.01		
Assembly	.42		
		2.03	0.769
1 year life			
Electrodes			0.030
Labor, Adm. & Overhead			0.007
Interest on Working Capital			0.001
		M =	0.924

M = 92.4¢/sq ft yr

Table IV

E
Costs proportional to Current

	$/kwhr
Demineralizing current	0.007
Add 10%, efficiency and 10%, pumping	0.0014
Instrumentation	0.0002
Rectifiers	0.0001
Labor, Adm. & Ovhd	0.0007
E	$ 0.0094/kwhr

E = 0.94¢/kwhr

Table V

C

Costs proportional to volume only

	$/kgpd capacity		$/kgal
20 year life			
Building & site	$ 8.00		
Raw water supply			
20% blowdown	6.00		
Product water stg.	10.00		
Pumps & pipes	2.00		
Construction	7.14		
Contingencies	3.14		
Engineering	3.40		
		$39.63	$ 0.010
Taxes and insurance			0.003
Fuel, chemicals, supplies			0.003
Labor, Adm. & ovhd.			0.008
			$ 0.014/kgl

C = 1.4¢/kgal

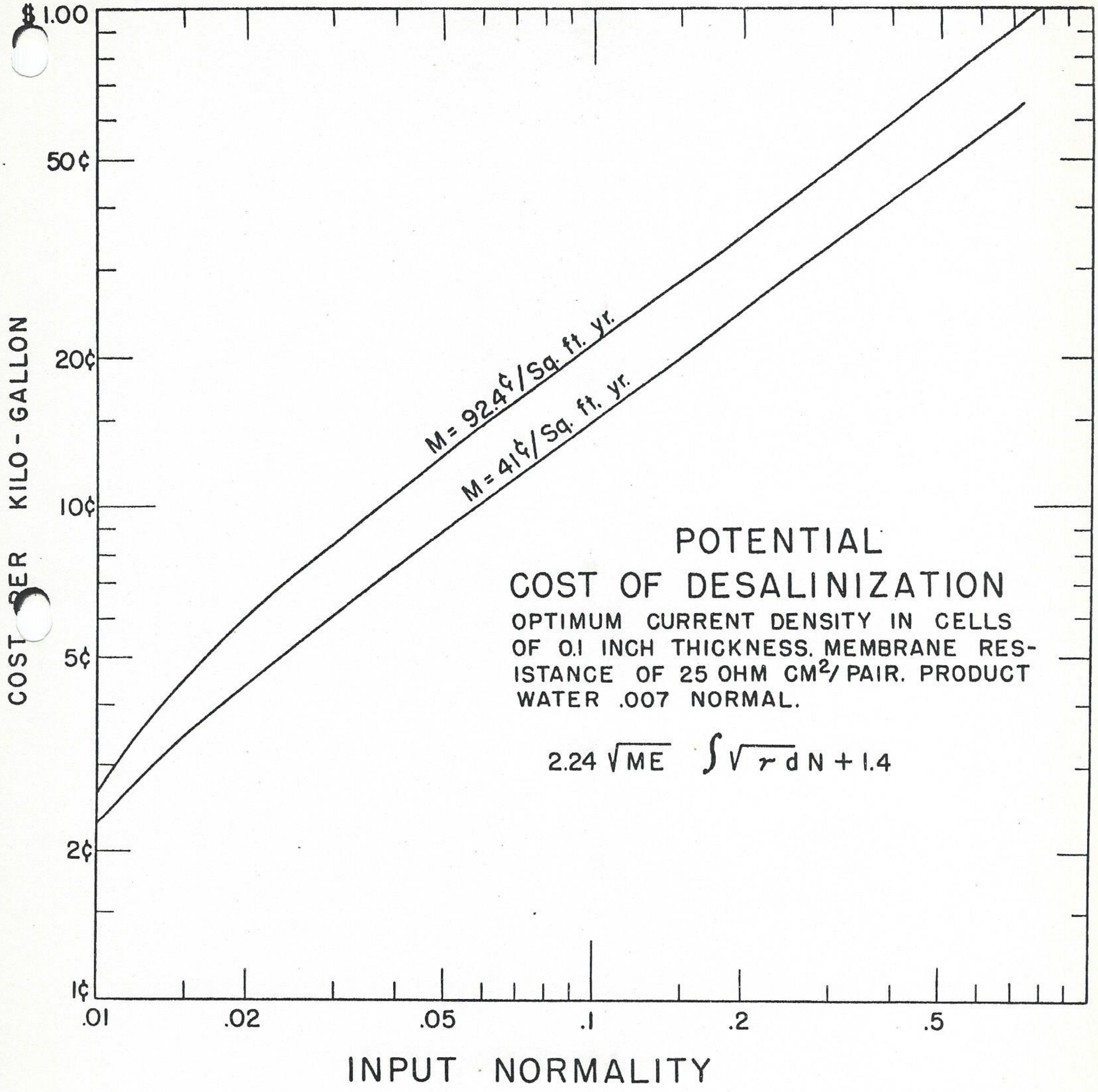
the 92¢ per square foot year cost -- and the cost at the optimistic limit (Figure 3).

There are two additional elements of cost which apply primarily to inland waters; the cost of clear, raw water and the cost of waste disposal. Surface water must, quite likely, be treated and also must, quite likely, be purchased. This cost may be about 4¢ per thousand gallons. Waste disposal problems have not yet been solved. It seems probable that this requirement will add 20% - 50¢ to the cost of water.

In summary of the economics, what we have is the opportunity to make brackish water of 2100 ppm into good water of 500 ppm at a cost of about 18¢ per thousand gallons, including waste disposal, with a possibility of producing it at about 14¢. Similarly, sea water can be made usable at 72¢/kilogal, with an optimistic limit of 48¢. The problem with which we are faced, then, is how nearly can we approach these optimum conditions which allow minimum costs?

In a design we are free to arrange the membranes in any way we choose -- long cells or short cells. The economic requirement that we place on design is that it insure the optimum current density at all places. Nature, however, has placed a technical requirement -- that the current density be in the neighborhood of the "diffusion limiting current."

The phenomenon of "limiting current" is marked by a non-ohmic increase of voltage as current is increased. A rather simple study of the ratio of current to voltage will



POTENTIAL COST OF DESALINIZATION

OPTIMUM CURRENT DENSITY IN CELLS OF 0.1 INCH THICKNESS. MEMBRANE RESISTANCE OF 25 OHM CM^2/ PAIR. PRODUCT WATER .007 NORMAL.

$$2.24\sqrt{ME} \int \sqrt{r}\, dN + 1.4$$

reveal this increase. The voltage is the sum of the electrode voltage, V_e, whatever polarization voltages are present, V_p, and the IR drop:

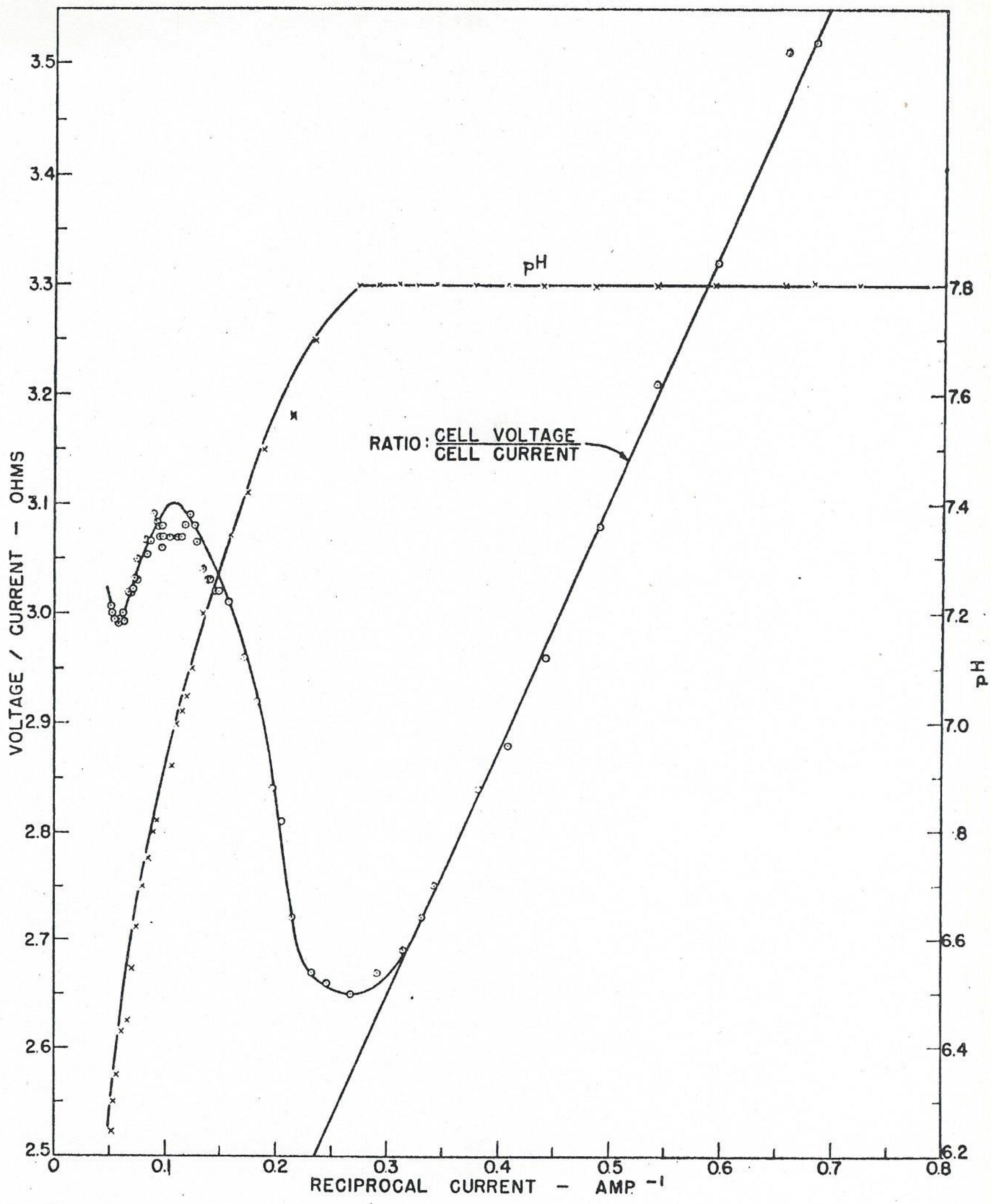
$$V = V_e + V_p + IR$$

The data can be sharpened by changing the variables:

$$V/I = R + (V_e + V_p) /I.$$

Now the plot of V/I against I^{-1} has R for the intercept and V_e for the slope until polarization sets in as a sharp change of slope. A plot of experimental data showing this slope change at a critical current density is shown in Figure 4. At this same value of current, the pH begins to change. This "diffusion limiting current" point moves to higher values of current density as the stream velocity increases, and, of course, as concentration increases.

In experimental work at the Texas Electric laboratory we have established the relationship and reported it in the literature. (Industrial and Engineering Chemistry, 51, 1445, December, 1959). The work reported was confined to fluids in turbulent flow and so to relatively high velocities. Since that time we have extended the studies to lower velocities. A pierced, corrugated material placed in the streams with the corrugations in the direction of flow so as to cause least pressure drop, was inserted in the cell in order to support thin membranes; it was found to induce strong mixing and simulate turbulence at quite low Reynolds Numbers. On the basis of these studies we have constructed an empirical expression



VOLTAGE / CURRENT - OHMS
3.5
3.4
3.3
3.2
3.1
3.0
2.9
2.8
2.7
2.6
2.5
pH
7.8
7.6
7.4
7.2
7.0
.8
6.6
6.4
6.2
RATIO: CELL VOLTAGE / CELL CURRENT
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
RECIPROCAL CURRENT - AMP. $^{-1}$

for the limiting current density over the entire range of velocities.

$$j = 0.04\ N/w \quad U^{1/2}(U + 1.9)^{1/3}$$

where U is the flow rate of the diluting stream in gallons per minute per inch of width, w is stream thickness in inches, and N is normality in equivalents per liter. The expression is based on studies with sodium sulfate; other salts will have only slightly different limiting current densities.

A number of effects set in at current densities above this limiting value. The voltage increases above ohmic values; the pH changes, dropping in the dilute stream and increasing in the concentrate; the membranes themselves become polarized, forming electrets which persist for hours. We believe scaling is associated with one of these effects, so that scaling problems can be avoided if the cell is operated below limiting current. Our experiments thus far indicate that trouble is associated with current densities in excess of the limit, and we have accepted it as a dictate of nature that we not polarize the membranes or change the pH of the water -- that is, that we stay below limiting current. On the other hand there is a reason to operate as near to limiting current as possible. In recent studies we have noted that current efficiency of demineralization is quite low when we are operating at current densities well below limiting current.

Here, then, is the technical demand in electrodialysis plant design -- that we fix the conditions so that we operate always near limiting current. This demand was revealed in experimental studies; it is not a theoretical nicety but a practical requirement. Fortunately there is some leeway on each side of the critical conditions which allow practical designs at small penalties, but it is necessary to change the flow rate from stage to stage downstream in order to maintain limiting current.

The design problem resolves itself to the satisfying of two conditions, "optimum current" and "limiting current." We can set the current density at the optimum value by adjusting the voltage from stage to stage. We can make this optimum current the limiting current by adjusting the flow rate through paralleling of stream from stage to stage. Thus the two conditions can be satisfied. The resulting design will inevitably call for a large plant -- the single unit will approach two million gallons a day as we now envision it, but this size is quite acceptable for community supplies. A stage length of 40 feet appears to be practical for cells with stream thicknesses of a tenth inch; Texas Electric is now operating a 40-foot stage as part of a developmental study. A brackish water plant might use three of these stages. A sea water plant would require only nine of such stages in series but many parallel stacks at the input so that the entering water would flow quite slowly. If we are bold enought to take advantage of the freedom in design which large scale, community-sized plants allow, the electrodialysis demineralizer can furnish the water needed to keep our cities healthy.