A Novel Equipment Centralization Schema Reduces the Cost of Permeate

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Abstract

This will be a three-part study. The first part will look at a software-based integrated hydraulic and financial simulation of RO plants developed by the authors. The hydraulic analysis includes membrane performance simulations calibrated against membrane performance projections from several membrane manufacturers. The hydraulic analysis also includes performance curves (either automatically curve-fitted from user-supplied operating points or generated by the software) for high pressure feed pumps, motors, VFDs, and various types of energy recovery devices including hydraulic pressure boosters and isobaric chambers. The analysis predicts Specific Energy Consumption (SEC) values over a wide range of conditions including variable recovery operation. The software can exhaustively search a range of potential recovery and permeate output rates to find the operating point for minimal SEC or maximum permeate production (or anything in between) for any reasonable value of feed TDS and temperature.

The second part will present a financial analysis derived in part from the hydraulic analysis described above that takes a detailed look at capital and expense items, cost of capital, depreciation and other financial considerations. A simplified income statement that meets Generally Accepted Accounting Practices (GAAP) readily understood by a financial analyst can be generated for the RO facility. This analysis will provide realistic calculations of the Specific Cost of Permeate (SCOP), which the authors firmly believe take precedence over other criteria previously used in selection of RO system equipment and modes of operation.

The final part of the study uses the above analyses to evaluate a modified version of the Hydraulic Pressure Booster (HPB) energy recovery device. This upgraded device, called the Hydraulic Energy Management Integration (HEMI), combines feed flow and pressure control, brine flow and pressure control and brine energy recovery into one module. The HEMI, controlled by two process signals (permeate flow and brine flow), smoothly and quickly adjusts to changes in membrane performance and even upset conditions due to equipment failure. Complex control schemes as well as large VFDs are eliminated in the high-pressure section of the plant.

The HEMI is ideal for a new concept called hybrid centralization that combines the best features of equipment centralization and discrete train designs. Analytical results as well as actual HEMI operating data is presented. The impact of HEMI-based hybrid centralization on reliability, flexibility and SCOP in a hypothetical large scale RO system is likewise explored. Comparisons are made with RO designs utilizing other types of ERDs including isobaric chambers and Pelton turbines.

I. INTRODUCTION

Modern RO plants are complex but they all have one simple purpose: to produce acceptable water in the desired quantity at the cheapest possible price. That plain thought should be the governing idea when taking in consideration all parameters of plant design. For a typical RO plant, these parameters are: total capital investment, depreciation, labor, maintenance cost (including membrane replacement), chemicals, water cost and energy cost. Some of these costs, like chemicals or labor, are fixed mostly due to plant location; therefore, the designer has to accept these as they are. The challenge for the designer is to optimize those areas under his influence and most notably to select equipment that minimizes Life Cycle Cost (LCC). The LCC combines various cost factors that may occur during plant construction (e.g. capital costs), future costs (energy, maintenance, downtime) and decommissioning costs. The power of the LCC is that all of these costs, some occurring on day one and others many years later, can be normalized to a single cost parameter. Thus, the LCC provides perhaps the most powerful figure of merit in equipment selection. Details of LCC calculations will be discussed later in this study.

The LCC can be divided by the amount of permeate produced over the LCC period to determine the Specific Cost of Permeate (SCOP) defined by equation (1). Another parameter, limited in significance but still useful, is the Specific Energy Consumption (SEC) which relates permeate production to energy consumption defined by equation (2):

$$SCOP = LLC / Q_{ptot} \quad (1)$$

$$SEC = C_{energy} / Q_{ptot} \quad (2)$$

Where:

Q_{ptot} = total permeate production over the life cycle period

C_{energy} = total energy cost over the life cycle period

We see that energy consumption is only one component of the LCC, albeit, an important one. Much of the focus of this study will be directed toward calculating realistic energy consumption of RO plants that contend with widely varying feed temperatures and membrane fouling. The authors of this study tackled the problem of calculating energy consumption over variable conditions by developing software that models performance of the major fluid machines in an RO system. This software model performs the vast array of calculations, iterations and extrapolations needed to mimic real plant operation.

However, even the LCC may not be enough to satisfy all of the decision makers. Financial statements such as an income statement pertaining to the equipment in question should also be prepared for review by financial decision makers.

II. EQUIPMENT TO BE ANALYZED

"Generic" high-pressure multistage centrifugal pumps will be assumed with performance estimated from equations developed by the authors.

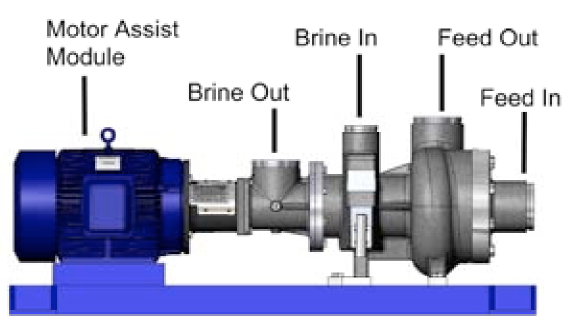

Figure 1 – HEMI major components

This study will focus on two ERDs. One ERD is new technology derived from the existing Hydraulic Pressure Booster (HPB) energy recovery device [1]. This arrangement is called a Hydraulic Energy Management Integration (HEMI). The HPB is converted into the

HEMI by modifying the brine discharge connection and adding a motor that is connected to the HPB rotor. See Figure 1 for a general equipment layout. Figure 2 shows a typical P&ID.

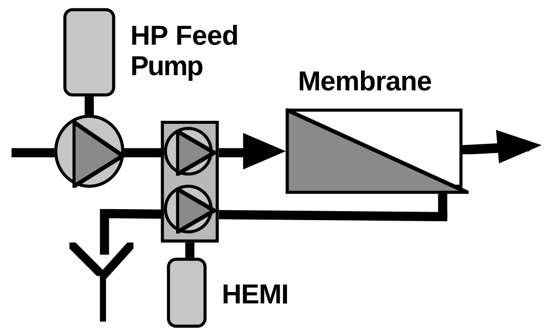

Figure 2 – HEMI P&ID

The other ERD is an isobaric chamber (IC) based on a ceramic rotor incorporating longitudinal passages that spins in a ceramic sleeve [2]. Ceramic end caps incorporating high pressure (HP) and low pressure (LP) feed and brine ports are encased in a fiberglass housing. The IC pumps a side-stream of feed to nearly membrane pressure with the final pressure obtained by a circulating pump. Figure 3 shows a typical P&ID. Note the multiple IC units that reflect limited unit capacity presently available.

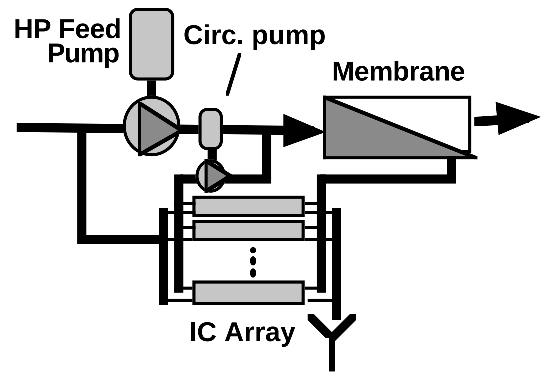

Figure 3 – Simplified IC P&ID

A major challenge of RO system design is having the feed pump live in harmony with the membranes. However, the nature of the feed pump is to deliver a constant pressure while the nature of the membrane is to have a variable pressure requirement. In certain regions of the world with highly variable feed conditions, this mismatch can be a serious detriment to efficient operation. Various strategies have been adopted to mitigate this mismatch such as use of variable frequency drives (VFDs) to adjust HP pump speed. This paper will exclude use of large VFDs (1,000 kW+) due to high cost, inherent energy losses and a reluctance by many end-users to use such equipment. As will be shown later, the benefits of large VFDs can be obtained with other equipment configurations.

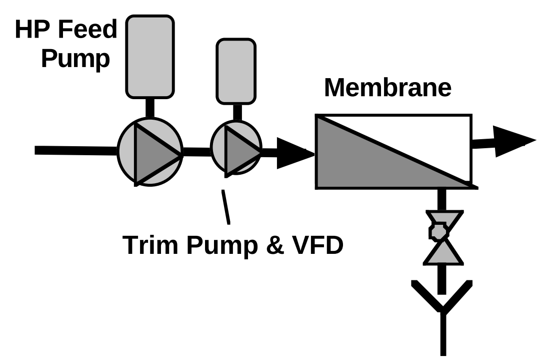

Figure 4 – Pressure trim pump

One method to provide variable feed pressure without resorting to feed throttling or large VFDs is to add a pressure "trim" pump in series with the HP pump that uses a VFD to provide pressure modulation (see Figure 4). However, analysis of pump curves at varying RPM shows that such a strategy can only efficiently accommodate pressure variations of about 35% of the trim pump's design point differential pressure, ΔP. For example, a 10 bar pressure range may take a trim pump with 30 bar ΔP at the duty point, otherwise unfavorable efficiency will occur over a part of the operating regime (refer to Figure 5). The need for a high ΔP trim pump defeats the effort to minimize VFD size.

However, the above analysis led to the concept of the HEMI, in which the trim pump develops a large portion of the required membrane pressure. Yet, to eliminate the large motor and VFD, this pump should primarily be driven by another source of energy; the obvious choice being a brine recovery turbine. Now, the VFD size is reduced to just make up an energy shortage for those operating conditions where turbine power is insufficient to drive the pump at the speed required for the desired ΔP.

It should be noted that ICs cannot modulate the feed pressur
a way to modulate feed pressure is not available to this class

III. HYDRAULIC MODEL

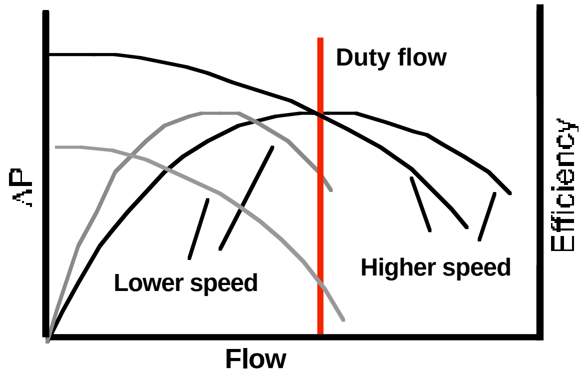

Figure 5 – Effects of large speed changes on pump ΔP and efficiency

The first step in analyzing RO plant performance is to define
envelope represents the extremes of flows and pressures t
train. For a train with constant production and recovery (i.e.
defined by the maximum and minimum feed and brine pres
occur with the lowest feed temperature, maximum feed
minimum pressure would occur with warmest temperature,
minimum TDS and clean/new membranes. See Figure 6.

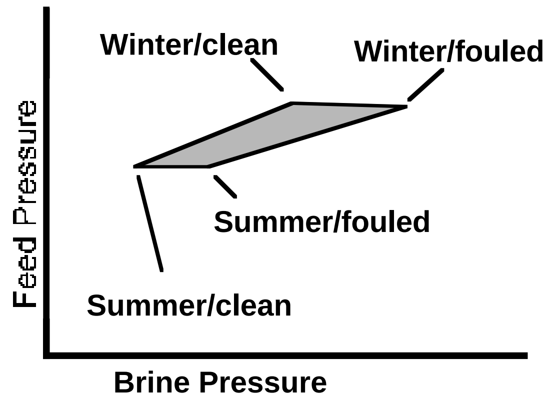

Figure 6 – Hydraulic envelope, constant flows

The important concept here is to seek out the extremes of operation in order to specify a feed pump and ERD able to accommodate the worst combination of factors without jeopardizing permeate quantity and quality required by the customer.

A hydraulic model of an RO system provides a way to estimate plant performance throughout the hydraulic envelope. A realistic model would include effects of off-duty operation on feed pump pressure and efficiency. Such a hydraulic model was developed and implemented in software by one of the authors (Oklejas) and used to prepare pump and ERD performance data for various turbine-based ERDs[4].

The model has been updated for this study to include the IC and the HEMI. In addition, the model now includes a membrane performance extrapolation function. Here, the user inputs the feed pressure, axial pressure drop, feed TDS, permeate TDS and feed temperature for a single element (obtained from membrane supplier software or from field experience). The software iteratively calculate various membrane performance coefficients. Subsequently, the user defines the membrane array configuration and input feed TDS, feed temperature, desired recovery and permeate production to explore various operating scenarios. The hydraulic model extrapolates membrane performance to the new conditions as well as predicts feed pump and ERD performance. Membrane extrapolations generally agree with membrane projection software to within +/- 5% over typical variations encountered in RO systems. This should not be viewed as a substitute for comprehensive analysis, but rather as a way to quickly evaluate a variety of operating strategies with the most promising ones selected for detailed analysis.

3.1 Data Inputs and Methodology

Feed pressure	Recovery
Feed flow	Brine pressure
Feed TDS	

Table 1 – inputs to the hydraulic model

The model requires two sets of data. One set describes membrane performance as indicated in Table 1. The other data set defines hydraulic performance of the HP pump and ERD. The model uses this data to generate a set of quadratic equations that define hydraulic performance of the feed pump and ERD. Experience has suggested 2nd or 3rd degree equations provide accurate fits with typical performance curves.

The equations may be defined by two methods. One method is to input performance data points obtained, for example, from pump performance curves. The software generates curve-fitting coefficients using an algorithm able to accommodate an arbitrary number of points and calculate curve coefficients to an arbitrary degree. The software reports on deviations between input data points and curve projections. The user may then adjust the degree of the equation to minimize deviations. For example, a 3^{rd} degree equation for feed pump efficiency as a function of pump flow is:

$$Eff_{fp} = AQ_{fp}^3 + BQ_{fp}^2 + CQ_{fp} + D \quad (3)$$

Where:

Q_{fp} = pump flow
A, B, C, D = values generated by the model.

The other method calculates pump characteristics (head and efficiency) based on generic curve coefficients embedded in the model. The pump curves may be "normalized" by the user to specify best efficiency point capacity and peak efficiency. The model itself determines the necessary ΔP based on analysis of the hydraulic envelope. This method is preferred when comparing various ERDs as the feed pump performance is consistently calculated thus eliminating peculiarities in specific pump performance data.

The authors decided that hydraulic conditions used in a previous paper [4] would serve as the input to the present analysis. Please refer to Tables 2 and 3. The previous analysis thoroughly explored the response of Pelton turbines and turbochargers (with feed throttling or VFDs on the HP pump) thus permitting comparison of the results presented in this study with the previous analysis.

3.2 Component performance

Feed flow rate	950 m3/hr
Permeate recovery	40%
Minimum array/pipe loss	2 bar
Maximum array/pipe loss	6 bar

Table 3 – Membrane data

Month	**Salinity (mg/l)**	**Min temp(C)**	**Max temp (C)**	**P_m (bar)**	**P_b (bar)**
January	45.10	18	22	81.5	77.0
February	45.80	18	22	81.2	78.3
March	45.70	20	24	80.5	76.0
April	45.94	24	30	76.6	71.9
May	45.84	28	33	73.1	69.9
June	46.47	32	34	71.6	70.4
July	46.37	34	36	70.2	69.3
August	44.86	34	36	67.5	66.5
September	44.78	32	35	68.3	66.8
October	45.18	26	30	73.2	70.4
November	45.24	20	26	79.5	73.4
December	45.20	18	22	82.1	77.1

Table 2 – Hydraulic model input data

The model calculates pump and motor efficiencies based on pump flow per the following equations developed by the authors:

$$Eff_p = 0.043\ln(Q_{fp}) + 0.4768 - 0.06(40/Q_{fp})^2 \quad (4)$$

$$Eff_m = 0.016\ln(Pow_m) + 0.85 \quad (5)$$

Note that "ln" is natural log

Where:

Q_{fp} = pump flow (gpm)
Pow_m = pump inlet power (horsepower)

The above formulae are applied to all pumps, regardless of the type of ERD. However, if the pump must handle a high inlet pressure as is the case of the IC circulating pump, an additional factor is applied that slightly reduces efficiency to reflect extra mechanical drag from the shaft seal and thrust bearing (high inlet pressure generates high axial thrust). At the flow rates in the example system, this effect is negligible.

In this study, the HEMI displays an average transfer efficiency, N_{te}, of 78% with about a +/- 2% variation over the hydraulic envelope. This efficiency range estimate is based on extrapolation of current turbocharger performance using accepted industry procedures and computational fluid dynamic (CFD) analysis available to the authors [5]. Transfer efficiency is defined by equation (6) below. The efficiency of the HEMI motor and VFD are taken at a constant 94% and 96% respectively.

$$N_{te} = P_b / (R \Delta P_r) \quad (6)$$

Where:

P_b = Pressure boost generated by the device

R = Q_r / Q_f

ΔP_r = brine pressure differential across the device

The IC performance parameters used in the study were based on the manufactures published data sheets [6] and are summarized below:

HP pressure loss = 1.75 bar (includes IC and manifold losses)
Leakage = 3.5 % of feed flow passing through the IC
Brine/feed mixing = 7%

The IC circulating pump is driven by a VFD in order to improve the energy efficiency of the IC system. Brine/feed mixing increases feed TDS to the membranes thereby raising osmotic pressure, which is accounted for in this study.

Component	**HEMI**	**IC**
HP pump eff	84%	80%
# of ERDs/train	1	13
HP motor eff	97%	97%
Circ. pump / motor eff.	n.a.	81% / 93%
HEMI motor eff.	94%	n.a.

Table 4 – Pump efficiencies

Based on maximum unit capacities offered by the manufacturers, 13 ICs or one HEMI would be required. An obvious concern is the impact of 13 units on system reliability. To better understand the effects of multiple IC units, consider that a failed unit (i.e. its rotor stops spinning) creates a flow path from the brine channel to the feed inlet. The rate of brine flow into the feed side appears to be equal or slightly more than the nominal feed capacity of the unit. With this information, the effects of a failed IC unit on feed TDS and, hence, on membrane performance can be closely calculated.

Based on the forgoing, the subject system can operate with up to 3 failed units without replacement or repair albeit with degraded system operation due to high feed TDS. A 4^{th} failure would likely necessitate a shutdown based on the author's analysis. To generalize this statement, approximately, 25% of the ICs can fail before a system shutdown is needed (assuming increased feed and permeate TDS are tolerable).

If we assume a Mean Time Between Failure (MTBF) of the IC that is exactly the same as a single unit device such as the HEMI, we would expect approximately a 300% greater occurrence of system downtime with the IC. However, due to a lack of verifiable data on IC MTBFs, the impact of this potential higher failure rate on system reliability cannot be estimated. The only unambiguous conclusion is that a single unit provides higher system reliability than multiple units with a similar unit MTBF.

As indicated in Table 4, feed pump efficiency is lower with the IC due to a lower HP pump flow (equal to permeate flow) compared to the HEMI in which the HP pump handles the entire flow (at a lower ΔP).

It must be understood that this is due simply to inherent characteristics of centrifugal pumps [7] in which lower pump flow is associated with lower efficiency. Also note that pump efficiencies are not spectacular as this study focuses on lifetime efficiency, which must include detrimental factors such as wear ring enlargement and internal corrosion.

For each set of data, the model calculates the electrical input to the HP feed pump and HEMI motor, and the electrical input to the HP feed pump and HP circulating pump required by the IC. For each month, four data sets are analyzed (see Table 5). Thus, the model will generate 48 sets of results for each ERD.

Cool feed / clean membrane
Cool feed / fouled membrane
Warm feed / clean membrane
Warm feed / fouled membrane

Table 5 – Data points for model

3.3 HEMI Design Considerations

The hydraulic model examines the operating conditions to determine the pressure boosts provided by the HEMI without motor assist. It then selects the lowest boost amount, which is used to calculate the feed pump ΔP requirement, P_{hpp}, per equation (7).

$$\Delta P_{hpp} = P_m - P_b - P_{inlet} \tag{7}$$

Where:

P_m = membrane pressure

P_b = pressure boost

P_{inlet} = feed pressure at HPP inlet

The model determines the power requirement of the HEMI motor for all other operating conditions, taking into account off-duty performance, and identifies the highest requirement which is used to size the HEMI motor.

3.4 Results of the Analysis

Figure 7 shows the average SEC on a monthly basis. Figure 7 also displays the SEC if no ERD were used.

Both ERDs are a distinct improvement over no ERD. The HEMI generally has a lower SEC than the IC. Note that the HEMI SEC closely tracks membrane pressure variations showing the HEMI's adaptability to changing hydraulic conditions.

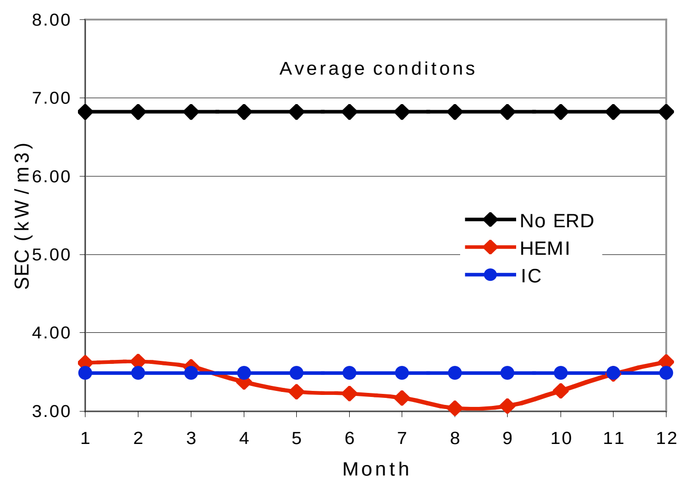

Figure 7 – SEC of HEMI, IC and no ERD

An analysis was also run based on a standard HPB and a VFD on the HP pump. Perhaps surprisingly, the HEMI displayed about a 2% lower SEC. The primary reason is that VFD losses of 4% apply to the entire 1,200 kW when used on the HP pump but only to an average of about 125 kW on the HEMI (48 kW versus 5 kW of losses).

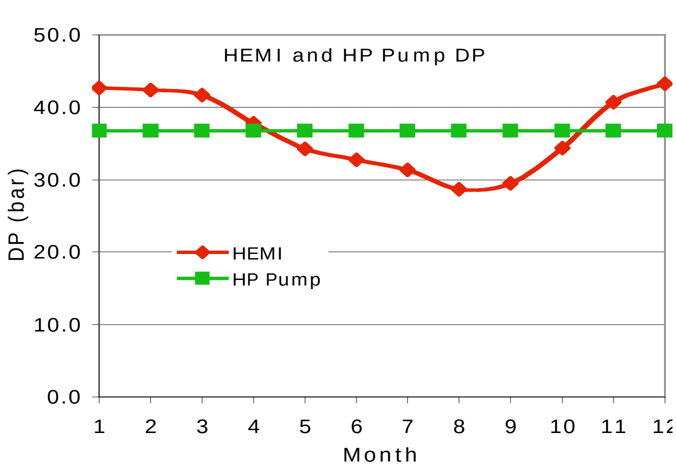

Figure 8 – HP pump and HEMI feed ΔP

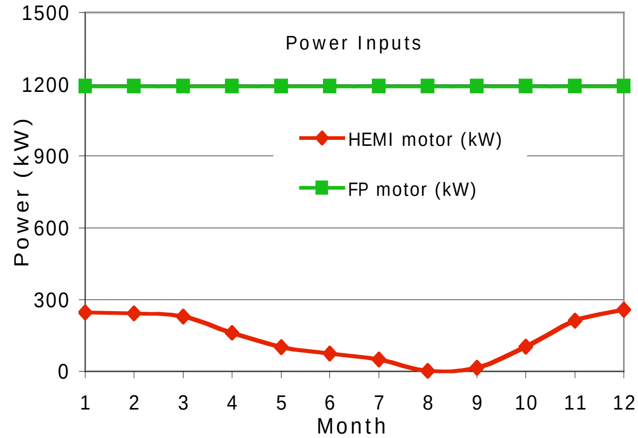

Figure 9 – HP pump and HEMI power consumption

Figure 8 shows the ΔP developed by the HEMI and the HP pump. The average HEMI feed ΔP closely matches the HP pump ΔP although this is more of a coincidence than an indication of a fundamental relationship. Figure 9 again shows the HEMI's ability to handle variable feed pressure operation as the input energy closely matches the variations in feed pressure. The HEMI motor and VFD would be sized for a maximum load of about 250 kW. Note that the feed pump load is a constant 1,200 kW.

Device	SEC
HEMI	3.36
IC	3.49
No ERD	6.82

Table 6 -Average SEC

Table 6 summarizes the average annual SEC values. The HEMI holds about a 4% SEC advantage relative to the IC.

IV. HYBRID CENTRALIZATION

The HEMI permits a novel equipment arrangement called Hybrid Centralization, which combines features of HP pump centralization and discrete train designs (see Figure 10). A six train configuration, based on the preceding data, would produce 55,000 m3/d of permeate. Two or three HP pumps feed all six trains through a common manifold. Each discrete train includes a HEMI that permits independent train control to achieve optimal feed and brine pressures regardless of the central pump performance. The central pumps do not use a VFD or throttle valves. This equipment arrangement is subject to US and international patent applications.

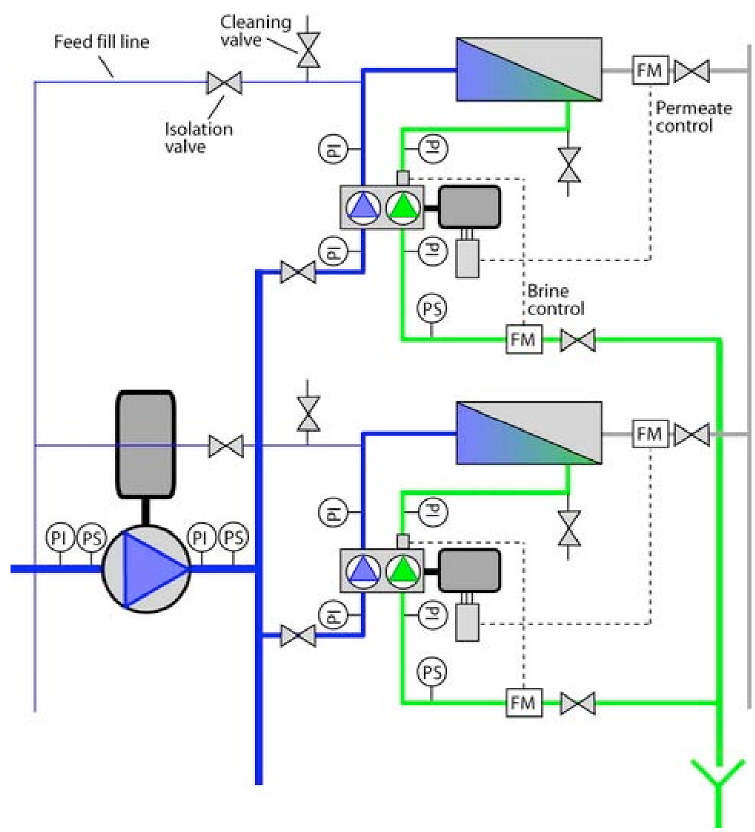

Figure 10 – Hybrid centralization P&ID showing 2 trains

4.1 Control of a Hybrid Plant

Large SWRO plants have complex control schemes especially when using ERDs. However, the hybrid plant control scheme is quite simple. Each train is equipped with permeate and brine flow meters. A signal from the permeate meter controls the HEMI motor VFD to adjust pressure as needed to maintain constant permeate flow. A signal from the brine flow meter regulates the HEMI's variable brine nozzle to maintain constant brine flow. There is no need for the trains to "talk" to each other or to the central HP pumps. Distributive control such as this arrangement is generally more robust in face of unexpected operating conditions and easily accommodate plant expansions or equipment modifications

Hybrid centralization provides the ability to remove a train from service without disrupting production. When a train is to be taken out of service, the operator has two choices. One choice is to accept the lost production. However, the central pumps would then handle less feed thus run further back on the curves resulting in a higher discharge pressure. In order to keep each remaining train at the original conditions, the HEMI VFD would be commanded to slow down thereby producing a smaller boost in the feed stream. In the case where the operator wishes to maintain production with one fewer train, each HEMI motor would be commanded to speed up thus raising membrane pressure and recovery (of course while observing membrane pressure and flux rate limits).

Placing a train in production involves opening the feed fill line to flush entrapped air from the train. Then, the isolation valves are opened. The HEMI would then come up to speed under control of the permeate and brine flow meters. Removing a train from production would simply reverse this sequence.

V. THREE-CENTER DESIGN

The Ashkelon SWRO plant in Israel adopted a "Three-Center" design arrangement, which separates membranes, HP feed pumps and ERDs into three individual centers [8]. In the Three-Center design scheme, a set of large HP pumps supply a feed manifold. A relatively large number of membrane arrays, each equipped with isolation valves, are connected to the manifold. The third center provides brine energy recovery with ICs (a different version from the type considered in this analysis), which pressurize a portion of the membrane feed flow. The key concept is that each center can be optimized without regard to individual component capacity thereby permitting unlimited scaling of the design. However, the control scheme can

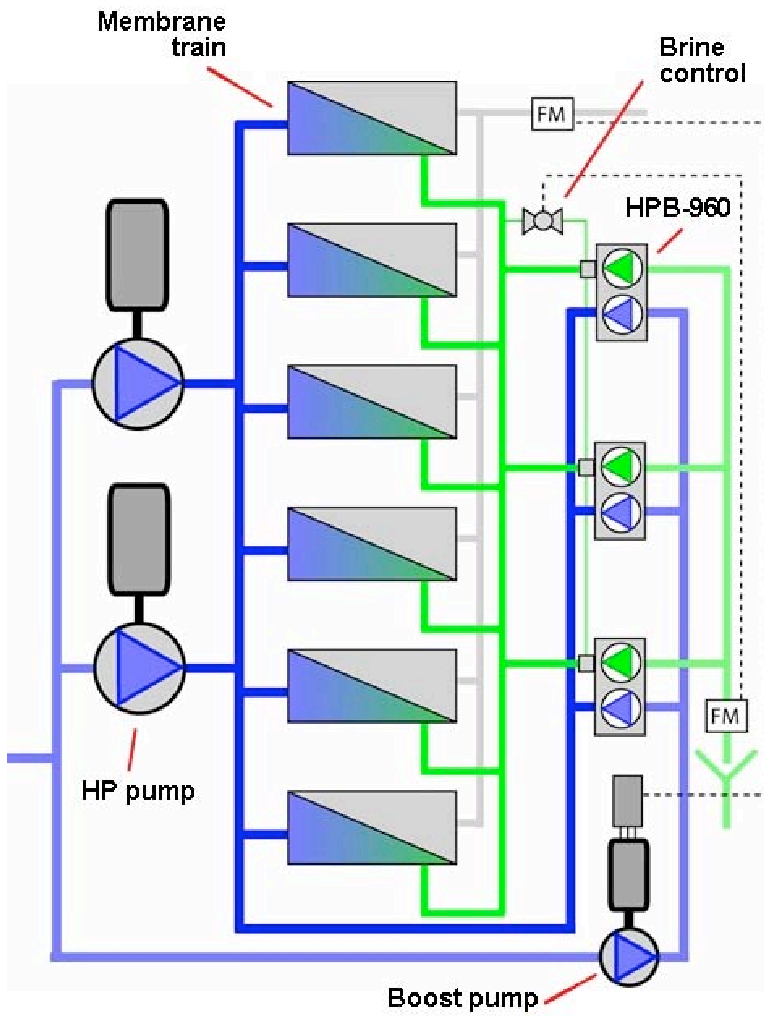

Figure 12 – P&ID for new arrangement of three-center layout

apparently become quite complex.

The new configuration uses standard HPBs to replace the IC units. The HPB array accepts brine from the HP brine manifold and feed flow from a manifold pressurized by a booster pump that is equipped with a VFD. The HPB raises the feed pressure to the membrane level. The combined flow from the HP pump center and HPB center flows to the membrane center. Please refer to Figure 12.

The HPB can handle a feed flow range that may be less than, equal to or greater than the brine flow as may be desired for optimal operation. The amount of HP feed flow from the ERD section is controlled by the ΔP generated by the boost pump. By raising boost pump speed, the resulting pressure increase permits the HPB to pump more feed flow. Reducing the booster pump speed reduces the feed flow delivered by the ERD center. The boost pump ΔP would typically be 15% to 25% of the membrane pressure. Therefore, the ERD center delivers variable feed flow controlled by a signal to the boost pump VFD and can accommodate independently a variable brine flow. In contrast, ICs are locked into providing a feed flow equal to the brine flow thus removing this degree of operating freedom.

One other unique aspect of this arrangement is brine flow control. Each HPB is equipped with two brine nozzles. The main nozzle handles about 85% of the maximum rated brine flow. An auxiliary nozzle in the turbine section accommodates a flow may be varied from 0 to about 15% of the total brine flow. In the Three-Center configuration, each HPB auxiliary nozzle is connected to a manifold. A valve regulates brine flow in the manifold. To increase brine flow, the valve is opened and to reduce brine flow the valve is closed simultaneously adjusting all HPBs. Thus, all HPBs are controlled by two signals; one signal to the VFD on the booster pump and one signal to the auxiliary brine manifold valve. The HPBs respond in unison with no individual controls needed. In essence the control scheme is no more complicated than a small single train SWRO plant. Figure 13 illustrates the ERD section for a large Three-Center plant. The simplicity and compact size should be evident. This equipment arrangement and control scheme is subject to US and international patent applications.

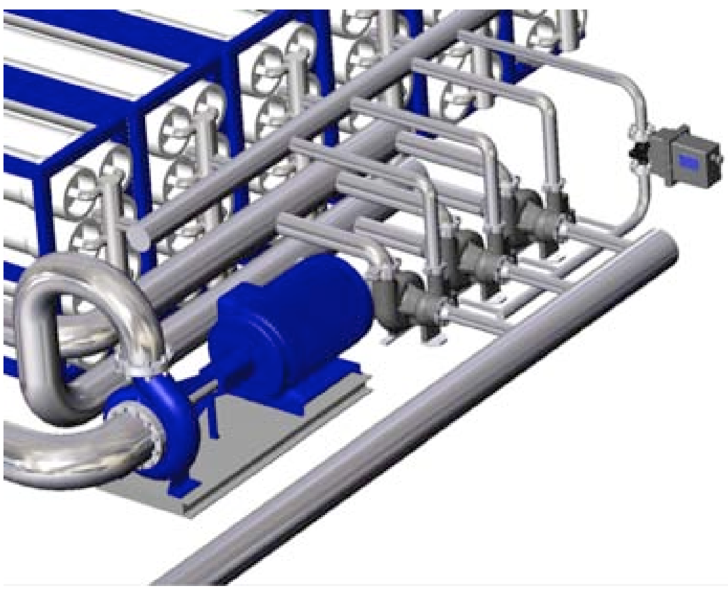

Figure 13 – ERD center of a 40-50,000 m3/day Three-Center plant using three HPB-960 units

VI. LIFE CYCLE COST ANALYSIS

The life cycle cost analysis (LCCA) is an economic analysis tool used to evaluate total cost associated with a piece of equipment over its life span. LCCA can be used to evaluate new products and designs, along with evaluating costs attributable to design changes and equipment overhaul. The LCCA is a valuable tool in estimating the overall costs of equipment alternatives and allows for a better selection process as it quantifies the lowest cost of ownership. LCCA helps justify equipment and selections based on total costs and not just initial purchase price or operating cost, thereby, presenting more effective financial alternatives. The authors preferred method of calculating LCC is based on the model developed by the Hydraulic Institute and Europump [9]. The basic LCC equation is:

$$LCC = (C_{ic} + C_{in} + C_e + C_o + C_m + C_s + C_{env} + C_d) \quad (8)$$

C_{ic}: Initial cost = Purchase price and capital expenses of the components and equipment being evaluated under the LCC. These costs may include engineering and design fees, purchase order administration, and inspection. Initial costs are the up front investment cost paid in the initial year of the project.

C_{in}: Installation and start-up cost = Installation and start-up costs that are not included in the purchase price. These costs include foundations, connection of piping, wiring, and instrumentation, commissioning of the equipment, performance testing and evaluation at start-up, and staff training.

C_e: Energy costs = Cost of electrical energy consumption of the equipment over the LCC period.

C_o: Operating costs = Cost of operating the equipment, excluding the energy costs, over the LCC period. These costs include labor required to operate and monitor the equipment.

C_m: Maintenance and repair costs = Cost of planned maintenance and repairs, over the LCC period. These costs are calculated per event and include replacement parts, routine maintenance labor, reinstallation, and transportation costs.

C_s: Downtime cost = Cost of lost production and lost revenues during periods of downtime, over the LCC period.

C_{env}: Environmental cost = Costs associated with environmental compliance of the equipment, over the LCC period. These costs include environmental permits, inspection and containment disposal.

C_d: Decommissioning cost = Costs to decommission equipment at the end of its lifetime, over the LCC period. These costs include disposal of the equipment and restoration of local environment, if required. Decommissioning costs can be negated in cases of equipment having a salvage/scrap value at the end of its useful life.

6.1 Calculating Life Cycle Costs

When calculating the LCC of equipment, there are financial considerations that must be factored into the equation. The considerations include; expected useful life of the equipment, interest expense, inflation, discounting, interest rates, and energy rates.

Inflation is an increase in prices, resulting in a decline in the purchasing power of money. Since the LCC evaluates future expenses, inflation must be factored into the equation.

In order to be able to add and compare cash flows that are incurred at different times during the life cycle analysis, they have to be made time-equivalent. To do so, the LCC method converts them to present values by discounting. The interest rate used for discounting is a rate that reflects opportunity cost of money over time. The discount rate used in calculating the LCC, Table 7, is set to the cost of capital, which is 9% in this case.

Present value (PV) is the amount that a future sum of money is worth today. Thus, to perform an effective LCCA, the PV of future costs must be determined. The formula to calculate present cost of a single cost element is:

$$C_p = C_n / [1 + (i - p)]^n \qquad (9)$$

Where:

n = number of years
p = anticipated annual inflation rate
i = interest rate
$i - p$ = discount rate
C_n = cost paid after "n" years

6.2 LCCA Model Applied

Now that the LCCA cost components and formulas have been identified, the information can be applied to develop a comparative LCCA of the HEMI and isobaric chamber (IC) considered early in this study. Table 7 presents the LCC results based on the following assumptions:

- Initial Investment Costs – Table 7 outlines the large difference in capital costs between the two systems. Due to the IC's limited flow capacity relative to the HP-HEMI-960, 13 IC's would be required to process the same flow as a single HP-HEMI-960. THE HP-HEMI-960 cost includes its associated motor, VFD, and piping. The IC units, however, must be manifolded together and should have isolation valves at each connection (four total per IC) in order to allow the user to make online change-outs of failed units. This capability would bring the IC reliability close to that of the HP-HEMI. Thus, a total of 52 duplex stainless steel 3" ball valves are required. The user also needs to fabricate a stand-alone steel support structure for the IC array as well as an acoustical enclosure to reduce operating noise. High pressure flow meters are required per the IC installation and operation manual for proper flow balancing as well. The cost of this instrumentation and the associated PLC programming are reflected. Finally, due to the operational nature of the IC device, a booster pump rated for high inlet and working pressures are required along with an associated motor and VFD.
- Energy price of .0596 USD/kWh, which is based on the most current published prices in the US from the Energy Information Administration. [10]
- Life cycle analysis period of 3 years. The rationale for this period is based on the conflicting priorities of the manufacture and end-user. The manufacturer desire a long LCC period to maximize justification of the ERD. The end-user desired to mitigate unknown risks by minimizing extrapolations of reliability and costs. The ERD warranty duration is an indication of the manufacturer's confidence in equipment reliability and represents a period of minimum risk to the user. Therefore, the LCC period will be set to 3 years which is the longest ERD warranty offered.
- Interest rate of 9%
- Inflation rate of 4%
- Equipment operating continuously, 8,760 hours per year.
- Installation & start-up costs – Due to the IC's complexity and large number of units in the IC array, it is assumed three days each for installation and training. One day is assumed for the HEMI.
- Maintenance costs – To maximize fairness in this comparison, it will be assumed that each unit will require an overhaul at six year intervals. Since there is only 1 HEMI for the system, its rotor would be replaced on average once each 6 years. For the IC, 13 rotors would be replaced during the same

six year period. This would give a rotor replacement rate of 2.167 rotors per year (round down to 2). The HEMI overhaul cost is about $35,000 per 6 years or about $5,800/year average. The IC overhaul cost is about $20,000 per unit based on discussions with end users or about $40,000/year average.

- Downtime Costs – Per the maintenance cost discussion above, the IC may be expected to trigger two downtime periods/year versus one per six years with the HEMI. However, by equipping the IC array with individual isolation valves to permit online removal of failed units and installation of new/repaired units, downtime with the IC array may be eliminated (added capital costs of the valve array has been included). Downtime of the HEMI is attributed to annual replacement of the thrust bearing. However, the downtime can be scheduled for a planned outage thus contributing no additional downtime. Therefore, neither ERD is charged with downtime costs.
- For purposes of this LCCA, the cost of chemicals and membranes are not included.
- There are no decommissioning or environmental costs factored into the LCCA during the period of evaluation.
- Discount factor of 2.72, which can be extrapolated from Table 8 below.
- High pressure pumps are not consider in the LCCA, as they are judged to be equal in cost.
- All other data is based on field experience.

The LCCA formulas being applied in Table 7 are widely accepted in the pump industry, as it has been extensively researched and documented by the Hydraulic Institute and Europump [9].

Based on the LCCA in Table 7, the HEMI is favored by a lower LCC than the IC by $753,549. The lower LCC represents an approximate savings of 23.5% over the 3-year evaluation period.

LCCA INPUT DATA:			HP-HEMI			IC	
n - No. of years			3			3	
I - Interst rate			9%			9%	
p - Inflation rate			4%			4%	
Intial Investment Costs:		1	165,000		1	606,000	
HP-HEMI-960 w/motor, VFD & piping			165,000				
PX-220 (13 units @ $25,000 each)						325,000	
3" Duplex Valve (Per PX, total 52 valves @ $1,750)						91,000	
AL6XN piping manifolds (40 ft. @ $1,000 per. Ft.)						40,000	
Duplex pipe fittings						20,000	
Fabrication costs						30,000	
Stainless Steel couplings						10,000	
Booster pump for PX system, includes pump, motor, VFD						90,000	
Installation & Start-up Cost		2	14,500		2	38,500	
Foundation			2,500			7,500	
Wiring			10,000			10,000	
Instrumentation (Flow meters, sample valves)			-			15,000	
ERD Installation ($1,000 per day)			1,000			3,000	
ERD Training ($1,000 per day)			1,000			3,000	
Energy Price per kWh			0.0596			0.0596	
Energy Consumption in kWh			1,277			1,360	
Average operating hours per year			8,760			8,760	
Energy cost/year		3		666,717	3		710,051
Operating cost/year		4	150,000		4	150,000	
Average maintenance cost/per year		5	2,250		5	41,000	
HP-HEMI (1 bearing kit @ $1,750 + $500 for 1/2 day labor)			2,250				
IC (2 rotors @ $20,000 + $1,000 for 1 day labor-1/2 day per rotor)						41,000	
Downtime cost/year		6	0		6	0	
Other yearly costs		7	0		7	0	
Sum of yearly costs:	(3+4+5+6+7)	8		818,967	8		901,051
Present value of yearly costs, using discount factor		df x 8 = 9	2,227,589		9	2,450,858	0
(See table 1.1)		2.72	= df				
Decommissioning and disposal cost (final year)		10			10		
Present value of final year costs	(Cp/Cn x 10)	= 11			11		
RESULT							
Present LCC-value	(1+2 +9 +11)			2,407,089			3,095,358
of which present energy cost is		(3 x df)	1,813,469	HP-HEMI		1,931,338	IC
and routine maintenance cost is		(5 x df)	6,120			111,520	

Table 7 – LCCA of HEMI and IC

VII. FINANCIAL ANALYSIS

The focus of the financial analysis is on cost of capital, depreciation, cost of installation, energy, operations, maintenance, and downtime. The financial analysis includes a realistic calculation of the Specific Cost of Permeate (SCOP).

No. of years (n)	Discount Rate						
	0	1	2	3	4	5	6
1	1.00	0.99	0.98	0.97	0.96	0.95	0.94
2	2.00	1.97	1.94	1.91	1.89	1.86	1.83
3	3.00	2.94	2.88	2.83	2.78	**2.72**	2.67
4	4.00	3.90	3.81	3.72	3.63	3.55	3.47
5	5.00	4.85	4.71	4.58	4.45	4.33	4.21

Table 8 - Real discount rate table (interest rate - inflation rate, in percent)

7.1 Cost of Capital

For any capital project that is financed, there will be a cost of capital. The cost in this model applies specifically to interest over the duration of the finance period.

Costs of capital from the LCCA have been amortized for both the HEMI and the IC, over an assumed loan period of 7 years, which is typical for capital equipment (see Table 9).

	HEMI	IC
Loan Amount	$165000	$606,000
Annual Interest Rate	9.00%	9.00%
Length of loan (years)	7	7
Payments/year	12	12
Total Number of Periods	84	84
Payment/period	$2,655	$9,750
Total Interest Paid	$57,995	$212,998
Total Payments	$222,995	$818,998

Table 9 – Amortization Table

7.2 Depreciation

Straight-line depreciation is used in this financial analysis. The straight-line method is based on the premise that the asset's life equals the depreciation period and that the benefits from the asset are constant over its life. The formula to calculate straight-line depreciation is:

S/L Depreciation Table	HEMI	IC
Cost of Asset	$165,000	$606,000
Residual Value	0	0
Years	10	10
Yearly Depreciation	$16,500	$60,600

Table 10 – Depreciation Table

$$D_{pn} = (C-R)/N \qquad (10)$$

Where:

D_{pn}= annual straight-line depreciation charge
C = cost of the asset
R = residual value of the asset
N = useful economic life of the asset (years)

As shown in Table 10, there were no residual values factored for either equipment. However, the HEMI has a significant salvage value due to the high content of stainless steel that can be recycled at the end of its life span.

7.3 Comparative Income Statement

The comparative income statement, Table 11, is not all-inclusive for an entire plant operation. The statement is intended to compare the profitability between similar devices during a one-year period. The total revenue is based on generating 380 m3/hr at an average price of $0.53/m3. The water prices were estimated based on

	HEMI	IC	Savings	%
REVENUES	$1,764,264	$1,764,264	-	-
EXPENSES				
Installation & Start-up Cost	$14,500	$38,500	$24,000	62.3
Electric cost ($0.0596/kWh)	$666,717	$710,051	$43,334	6.1
Amortization	$8,285	$30,428	$22,143	72.8
Depreciation	$16,500	$60,600	$44,100	72.8
Operating cost	$150,000	$150,000	-	-
Maintenance cost	$2,250	$41,000	$38,750	94.5
Downtime cost	0	0		
Total Expenses	$858,252	$1,030,579	$172,327	
NET PROFIT	**$906,012**	**$733,685**	**$172,327**	**23.5%**

Table 11 – Comparative Income Statement

similar large RO plants in the Middle East. The income statement results favor the HEMI over the IC, based on increased profitability of 23.5%.

7.4 SCOP

The Specific Cost of Permeate (SCOP) is based on the amount of permeate produced over the LCC period. Based on LCCA results in Table 7 and the annual production, we can calculate the SCOP per equation (1).

	HEMI	IC	Savings
LCC	$2,407,089	$3,095,358	
Q_{ptot} (m3)	9,986,400	9,986,400	
SCOP	$0.241	$0.31	$0.069

Table 12 – SCOP values

The SCOP in Table 12 shows the HEMI has a reduced cost of permeate in the amount of $0.075/m3 over the life cycle of the equipment.

VIII. CONCLUSIONS

We must never lose sight of the purpose of an RO plant, which is to supply permeate in the quality and quantity needed by the end-user at the lowest possible total cost. We have seen in this study that equipment efficiency is only one factor among many affecting the cost of permeate. This study has described how to properly evaluate energy costs of two major ERDS in today's market. Finally, this study has demonstrated that based on the best available knowledge to the authors that a new technology ERD device called the HEMI can deliver significantly lower cost permeate in a realistic operating scenarios than other ERDs.

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