Desalination and Water Treatment
www.deswater.com

31 (2011) 88–94
July

1944-3994 / 1944-3986
doi: 10.5004/dwt.2011.2405

Integrated pressure and flow control in SWRO with a HEMI turbo booster

Eli Oklejas*, Jason Hunt

Fluid Equipment Development Company, LLC (FEDCO), 800 Ternes Drive, Monroe, MI 48162, USA
Tel. +1 (734) 241-3935; Fax +1 (734) 241-5173; email: eoklejas@fedco-usa.com

Received 15 October 2010; Accepted in revised form 15 December 2010

ABSTRACT

The high pressure hydraulic energy management integration (HP-HEMI) energy recovery device (ERD) centralizes brine hydraulic energy recovery, feed pressure and flow control and brine pressure and flow control into one compact and fully integrated unit. The objective is to dispense with feed pressure control valves (i.e. elimination of throttling losses) as well as a variable frequency drive (VFD) on the high pressure feed pump (HPP) resulting in the twin benefits of a substantial reduction in energy consumption and capital costs. This paper reports on test results of a production HP-HEMI coping with recoveries and pressures that accurately simulate an SWRO system dealing with typical feed temperature and membrane fouling variations. The paper further reports on development of a PLC control scheme that regulates feed flow and brine flow via adjustment of the HP-HEMI control features to meet a wide variety of membrane operating conditions. The paper also outlines future research concerning mitigation of equipment failure and further enhancements of system control.

Keywords: Energy recovery; High pressure hydraulic energy management integration; SWRO

1. Introduction

Modern RO plants are complex engineering systems involving a large array of valves, pipes, pumps and membranes needed for the basic RO process as well as sensors, actuators and PLCs to regulate plant operation. The ever-growing complexity of RO plants, especially mega-scale plants (i.e. permeate flows above 100,000 m^3/d), often seems to be diminishing the promise of cost reductions otherwise expected through economy of scale.

A complicating factor in the RO process is that the feed pressure may need to be varied to accommodate variations in feed salinity and temperature as well as changes in membrane performance brought about by fouling. This seemingly innocuous requirement can greatly complicate plant design and substantially raise capital and operating costs.

Specifically, the centrifugal high pressure pump (HPP) used to pressurize the feed is unable to provide variable pressure discharge when operating at constant flow and constant shaft rotational rate (revolutions per min or rpm). However, centrifugal HPPs are highly refined machines with high reliability, relatively low capital cost and able to deliver high flows at high pressures with efficiencies approaching 90%. There is little choice but to accept this shortcoming.

Four ways may be used to mitigate the pressure control limitation of the centrifugal HPP in RO service:

1. *Feed throttle valve* — the HPP is sized for the highest anticipated pressure requirement with the throttle valve used to dissipate pressure to achieve the desired pressure to the membrane;
2. *Variable frequency drive (VFD)* — A VFD is used to adjust the frequency of the power supply to the HPP motor hence HPP RPM. HPP pressure generation

---

* Corresponding author.

Presented at EuroMed 2010 — Desalination for Clean Water and Energy: Cooperation among Mediterranean Countries of Europe and MENA Region, 3–7 October 2010, David Intercontinental Hotel, Tel Aviv, Israel. Organized by the European Desalination Society.

varies with shaft RPM. Thus, the VFD can be adjusted as required to regulate the HPP discharge pressure;

3. *Trim or jockey pump* — A second pump, called the trim or jockey pump, is placed in series with the HPP. The jockey pump is equipped with a VFD to allow variation of pressure generation. The total pressure generation of the pump pair equals the fixed pressure rise of the HPP (no VFD) plus the variable pressure boost of the jockey pump. The intent is to use a smaller VFD on the jockey pump than otherwise would be required by the HPP;
4. *HEMI* – This device is a modified version of the hydraulic pressure booster (HPB) energy recovery device, which has been widely accepted in SWRO service. The modification (discussed below) permits precise regulation of feed and brine flows and pressures.

The advantages and limitations of each control scheme are amply discussed in a number of earlier research articles [1–4].

2. Objectives

The objective of this research effort is to develop and demonstrate under realistic operating conditions a simple and robust control system that regulates HEMI operation to provide precise control of the feed and brine streams over operating conditions typical of SWRO applications.

In addition to normal system regulation, the research also addresses system startup, shutdown and examination of potential failure modes and the associated consequences.

2.1. HEMI function

The HEMI (hydraulic energy management integration) is the combination of a standard HPB with a motor and VFD. The HPB's integrated pump impeller and turbine impeller are coupled to an external motor and all rotate together as a unit. The HEMI pump section operates in series with the HPP and the turbine section recovers brine hydraulic energy (Fig. 1).

The HEMI boosts feed pressure to the desired membrane pressure regardless of the pressure supplied by the HPP (within the rating of the unit). The brine turbine powers the HEMI pump section. If the turbine cannot meet the power requirement, the attached HEMI motor provides the balance. Typically, the HEMI motor is about 10–15% of the motor rating of the HPP. Fig. 2 illustrates the HEMI device.

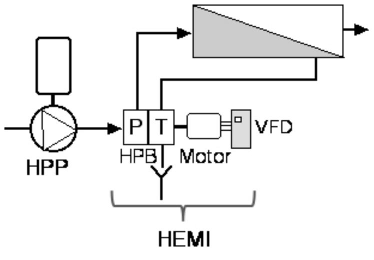


Fig. 1. HEMI system.

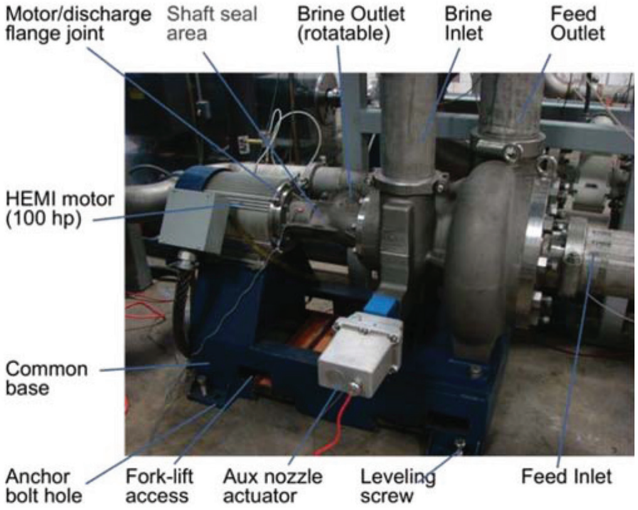


Fig. 2. HEMI features.

2.2. HEMI control

A control objective in RO systems is to maintain constant permeate and brine flows regardless of variations in feed salinity, feed temperature or membrane fouling. This is obtainable by control of feed pressure and brine pressure.

The HEMI provides hydraulic control in two ways. The first is that the pressure boost generated by the HEMI is a function of HEMI RPM, which is controlled by the HEMI motor. HEMI motor RPM is controlled by a VFD (typically 380 or 460 V and 150–300 kW). The VFD is controlled by the HEMI PLC. Hence, the PLC controls feed pressure boost of the HEMI.

The second control feature is that the HEMI can maintain a constant brine flow over a wide variation of brine pressure using an integral variable area turbine nozzle. This nozzle is adjusted by an actuator under control of the PLC. Thus, the HEMI PLC controls brine flow and pressure. Fig. 3 illustrates the basic control scheme. Table 1 illustrates the general control response.

A secondary hydraulic interaction arises from the fact that a change in rotor speed (N) also changes the turbine pressure vs. flow characteristic as illustrated in Fig. 4. Specifically, for a given brine flow, an increase in rotor speed increases turbine flow resistance. This response is actually desirable as such a speed increase also generally corresponds to a higher brine pressure, which requires increased turbine flow resistance. Thus, the effects of

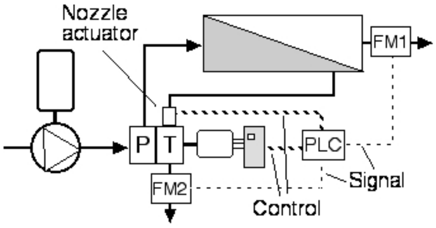


Fig. 3. HEMI control scheme.

Table 1
Caption ???

Condition	HEMI Response
Permeate flow too low	Rotor speed increases
Permeate flow too high	Rotor speed decreases
Brine flow too high	Close turbine nozzle
Brine flow too low	Open turbine nozzle

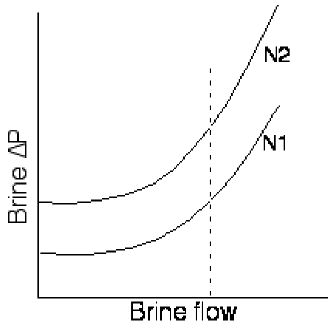


Fig. 4. Turbine characteristic.

rotor speed on turbine flow resistance contributes to a semi-passive control of the HEMI. This effect reduces the required variation in the turbine nozzle to achieve a given increment in turbine flow resistance.

2.3. Operational flexibility

Note that each train in an RO system may have its own HEMI and PLC control unit. Thus, each train can operate at different feed and brine pressures as necessary to obtain optimal operation. For example:

1. Recently cleaned trains may operate optimally at a lower pressure than other trains;
2. A train may have received new membranes thus run better at a lower pressure;
3. New "low energy/low pressure" membranes can be evaluated on a train before committing the entire facility to the new membrane;
4. Trains can operate at different recoveries by set point adjustments of the PLC on each train. This allows fine-tuning of plant operation to maximize permeate production or minimize specific energy consumption (SEC) or improve permeate quality.

2.4. Train startup

The startup scenario is to:

1. Start the HPP;
2. HEMI (without input power from the HEMI motor) comes up to a stable operating condition (i.e. HEMI is in passive mode);
3. PLC adjusts HEMI speed and turbine variable nozzle to obtain the set point values of permeate and brine flows.

Several membrane suppliers prefer a gradual increase in feed pressure until the duty pressure has been required. For example, one supplier has specified a 1–2 bar/min rise that results in a 40+ min startup. HPP discharge pressure at startup rises in proportion to the motor speed increase. Direct online starting (DOL), however, provides a brisk startup thus the HPP pressure would increase faster than desired for the membrane.

A low cost solution to control the rate of membrane pressurization is to use a plug valve on the feed pump discharge line (upstream of the HEMI) with an actuator controlled by the HEMI PLC.

Another potential method is to have a closely coordinated startup of the HEMI and the HPP. Such a technique would require detailed analysis of HPP characteristics but it would have attractive cost advantages. HEMI systems equipped with regenerative VFDs are capable of absorbing excess pump power directly, which may reduce the need for a control valve during startup. In addition, a regenerative VFD provides greater overall efficiency because excess brine energy can be reintroduced to the electrical grid.

2.5. Train shutdown

Train shutdown may be planned or may be unscheduled due to an emergency trip for any number of reasons. There appears to be no requirements from membrane suppliers for a rate of pressure reduction thus no provisions are needed for membrane depressurization control.

In the case of a scheduled shutdown, a stop signal is sent simultaneously to the HPP and the HEMI PLC. The PLC would shut the power to the HEMI motor putting the HEMI into the passive mode and it will coast to a stop like a typical HPB at shutdown.

In the case of an unscheduled shutdown, a signal to the PLC puts the HEMI into the passive mode and the unit coasts to a stop. The HEMI PLC will also command a shutdown when the feed inlet pressure drops below a calibrated threshold. This allows automatic shutdown in case of sudden HPP pressure loss or insufficient HEMI inlet pressure.

3. Demonstration system

A production HPB-1000 was modified to include a motor, motor adapter, drive shaft and brine outlet module (Fig. 2). HPB transfer efficiency was about 78%. HPBs exceed 80% in the 1600 m^3/h feed flow range.

The HEMI test motor was rated at 75 kW at 7,200 rpm. The motor was connected to a VFD that accepts a 4–20 mA signal to control frequency output. The motor was undersized as typically a 150+ kW motor would be appropriate. However, with adjustments in the test conditions, the small motor would allow the HEMI to be operated over a sufficient flow range to test the PLC control logic.

The HPB was also equipped with an actuator that accepts a 4–20 mA signal to control nozzle position.

A PLC was programmed to accept signals from the permeate and brine flow meters. Both flow meters were magnetic type. The PLC generated two 4–20 mA output signals, which controlled the HEMI VFD and the HEMI turbine nozzle actuator. Figs. 5 and 6 show the PLC and the HEMI on the test system respectively. The HEMI PLC would control start, operation and shutdown of the high pressure train without interaction with other control systems.

The HEMI was installed in a test loop using a FEDCO SSD-500 HPP. Although the HPP motor was driven by a VFD, motor speed was held constant during all testing.

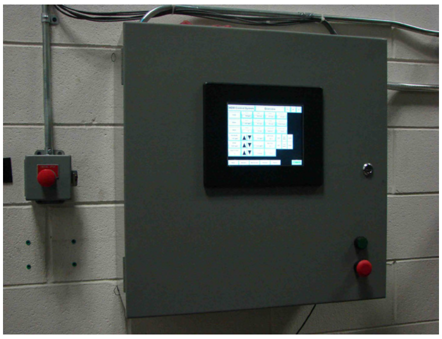


Fig. 5. HEMI PLC.

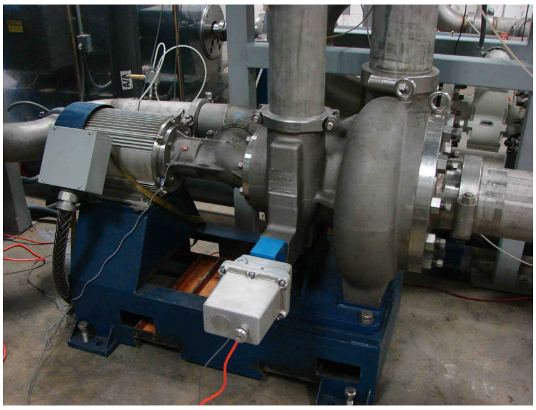


Fig. 6. HEMI on test stand.

4. Test setup

The test configuration is illustrated in Fig. 7. Note that simulated permeate flow is returned to the feed inlet of the HEMI. This arrangement reduces the feed flow required by the test pump thus saving energy and reducing the heat load on the test loop. It has absolutely no effect on the accuracy of the instrumentation, performance of the HEMI or reduction in fidelity of the RO simulation.

4.1. Test protocol

The test protocol was as follows:

1. Brine flow and permeate flow set points are programmed in the PLC;
2. HPP is started and brought up to speed (speed is held constant throughout the test);
3. Recirculation valve is adjusted to obtain duty point recovery;
4. HEMI PLC is engaged;
5. PLC adjusts the HEMI VFD and turbine nozzle actuator to obtain set point values of permeate flow and brine flow;
6. Recirculation valve is adjusted to simulate changes in feed conditions or membrane fouling:
   a. To simulate a reduction in feed temperature or increase in salinity or membrane fouling Recirculation valve is partially closed resulting in a reduction in permeate flow and increase in brine flow;
   b. To simulate an increase in feed temperature or decrease in salinity or fouling (i.e. membrane cleaning), recirculation valve is opened resulting in an increase in permeate flow and reduction in brine flow;
7. After each recirculation valve adjustment, the PLC response is monitored.

5. Test results

Testing was hampered by an undocumented design flaw in the VFD, which prevented "fly catching" above 120 Hz. Fly catching refers to the ability of a VFD to sense the speed of a free-running motor, adjust its frequency to synchronize with the motor and then gradually adjust the motor speed to the desired value.

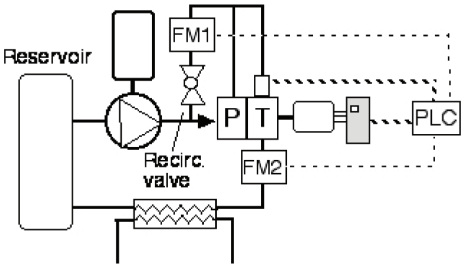


Fig. 7. Test loop configuration.

Table 2
Flow in m^3/h, pressure in bar, time in min

P_t	P_m	P_r	Time	Comments
1	46.0	43.9	Start	Aux fully open, no HEMI motor power
2	48.1	46.0	<1.0 min	Aux partially closed, VFD ramp up
3	50.1	48.1	<1.0 min	Recirculation valve partially open
4	53.0	51.0	<1.0 min	"
5	56.2	54.2	<1.0 min	"
6	59.2	57.2	<1.0 min	"
7	63.4	61.4	<1.0 min	Aux closed, HEMI motor at maximum

Table 2 illustrates a typical set of test results (normalized to design flow). Feed and permeate flows were held constant by the HEMI control system at all duty points.

Recirculation valve adjustment took typically 3–6 s. The "Time" entry in Table 2 refers to the time it took the PLC to restore the set point flows after changes in the recirculation valve.

5.1. Observations

The HEMI and its PLC performed as predicted. The HEMI PLC responded smoothly with a minimum of overshooting or hunting for the set point values. An actual RO system would have a different response from the simulated system employing a throttling process to represent membrane performance. However, there appears to be no membrane response characteristics that would frustrate the feedback control scheme demonstrated in this experiment.

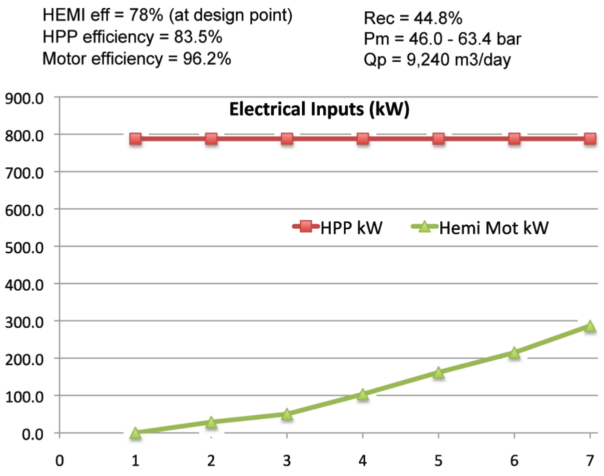
The achieved pressure range was 28% (from point 1 to point 7), which would be sufficient to meet the largest feed pressure variations likely to be encountered in SWRO applications. In actual operation, changes in feed or membrane conditions of the magnitude in Table 2 would take from hours to days to occur. In such cases, the HEMI PLC would adjust the system in essentially real time resulting in negligible departure from duty point conditions.

Testing encountered a condition in which the turbine power exceeded the power required by the pump end resulting in more pressure boost than desired. In such cases, the HEMI PLC commanded the VFD to slow the rotor resulting in a net electrical output from the HEMI motor. A standard VFD has limited capacity to absorb this back flow or "regeneration" of power. There are three solutions:

1. Installation of resistor banks in the VFD to allow greater regeneration power dissipation;
2. Use of a regenerative VFD, which has the capability to return regeneration power to the plant electrical system (hence reducing net plant energy consumption);
3. Avoid any potential for regeneration by sufficiently reducing HPP discharge pressure and increasing the power rating of the HEMI motor.

Since a regenerative VFD was used in the test system, solution (2) was adopted. The ability to absorb excess turbine power extended the pressure boost range to about 45% (vs. 28% without turbine power absorption). Use of such a VFD to absorb turbine power expands the potential for energy recovery and has been the subject of much research by the authors. It is an intriguing new variable in the design of ERDs for RO applications.

Figs. 8 and 9 show the expected distribution of electrical energy and pressure boosts respectively. Per HEMI operating mode, zero electrical energy is consumed at the lowest membrane pressure condition (point 1) with increasing input power to the HEMI as the membrane pressure requirement increases (Fig. 8). The pressure boost contribution by the HEMI increases steadily as membrane pressure and the corresponding brine pressure increases until the HEMI is producing more boost than the HPP (35 bar vs. 26 bar). At the highest pressure condition, the brine turbine shaft output is about 710 kW with the HEMI motor providing about 268 kW shaft output to the rotor.


HEMI eff = 78% (at design point)
HPP efficiency = 83.5%
Motor efficiency = 96.2%

Rec = 44.8%
Pm = 46.0 - 63.4 bar
Qp = 9,240 m3/day

Fig. 8. Electrical power to HEMI.

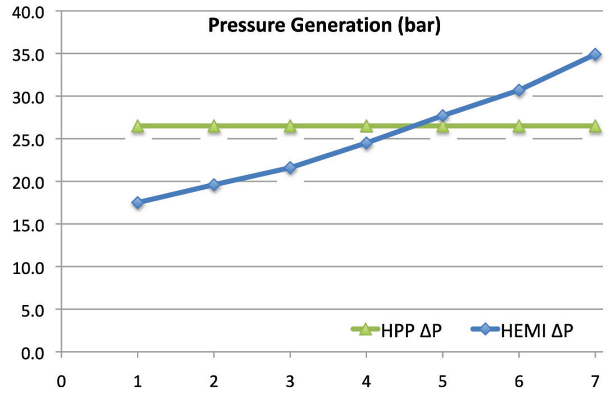


Fig. 9. Pressure boost in HEMI system.

5.2. Failure modes

Identified potential failure modes and possible mitigations include:

1. Due to extremes of operation, the HEMI cannot produce enough pressure boost even with the HEMI motor at full power. In such a case, the HEMI motor would continue to operate at maximum rated power until the pressure requirement diminishes. Such a problem faces any pump in an RO system. Avoiding the problem comes down to judicious decisions on equipment ratings. Since the HEMI motor and VFD are low voltage (hence relatively low cost), adding a "reserve capacity" to cover contingencies is often warranted;
2. Low feed pressure to the HEMI caused by HPP failure — a pressure sensor at the feed inlet would indicate to the HEMI PLC that the HEMI VFD should be disengaged and the unit enter a passive operating mode;
3. Loss of flow meter signals or spurious signals — if flow meter signals go to zero or are unreasonably large or small, the PLC will take the HEMI VFD off-line and the HEMI will operate in a passive mode;
4. Fault detected with the HEMI motor or VFD — HEMI is place in passive operating mode;
5. HEMI motor load increases in a non-expected way (e.g. RPM versus load is unexpected) — fault signal is sent to the main control system, HEMI VFD is placed off-line. High load needs to be investigated at earliest convenient time;
6. VFD fails — HEMI PLC can continue to operate unit in a semi-passive mode as turbine nozzle control can continue to function to obtain set point brine flow;
7. Turbine nozzle actuator fails — HEMI PLC can continue to operate unit in a semi-passive mode as the HEMI VFD can continue to function to obtain set point feed flow. The actuator, if equipped with a hand-wheel can be manually adjusted.

The main theme of the above is that failure associated with the HEMI components (motor, VFD, sensors, flow meters) is a soft failure — the HEMI "defaults" back to a standard HPB and the train can continue to operate in an acceptable mode until a convenient time for maintenance.

6. Potential impact of HEMI on SWRO economics

This research has shown that the HEMI eliminates the need for feed throttle valves and large and expensive VFDs on the high pressure feed pump as means to regulate feed pressure to the membranes. This, in itself, yields significant cost advantages in an SWRO system.

A larger question is the HEMI's impact on the cost of permeate. Earlier research yielded a theoretical life cycle cost analysis (LCCA) analysis along with a pro forma income statement on an SWRO equipped with a HEMI [4]. These findings indicated that the HEMI will have a favorable impact on the cost of permeate.

With accurate performance data as well as manufacturing costs now established, a future topic of research will be to quantify to a high level of confidence the impact of the HEMI on permeate costs relative to other types of commercially available ERDs.

7. Future research

Future development work will finalize the control philosophy for general field applications of the HEMI. This will involve verification that the PLC programming can handle equipment failures or operator errors by simulating the following events:

1. Emergency trip of the HPP;
2. Major pipe breaks;
3. Loss of signals from one or both flow meters;
4. Flow meter signals that are grossly in error;
5. High vibration reading or high bearing temperature;
6. Unreasonable permeate and brine set points (operator error);
7. Momentary power loss to the PLC;
8. Other conditions to be determined by a failure mode effects analysis.

Other development work will include testing the HEMI in regenerative operation.

8. Conclusions

Findings of this research include:

1. RO feed, brine and permeate flows can be regulated by the HEMI using a simple PLC system;
2. The HEMI PLC system handles startup and shutdown of the high pressure RO train;
3. A HEMI failure is benign as it defaults back to a standard feed pressure boosting HPB which may continue to operate the RO train in an acceptable manner;
4. The HEMI PLC can possibly reduce the complexity of the RO plant control system.

References

[1] T. Manth, E. Oklejas, Jr. and R. Oklejas, "RO energy consumption under variable parameters of operation, Proc. 2002 AMTA Tiburon, CA, USA, October 2002.

[2] E. Oklejas, Jr., Energy efficiency consideration for an RO plant: a method for evaluation, Proc. 2001 Canagua Conference, Las Palmas, Spain, November 2001.

[3] E. Oklejas, Jr. and T. Manth, Energy efficiency considerations for RO plants: A comparative study, Proc. 2002 IDA Conference, Manama, Bahrain, March 2002.

[4] E. Oklejas, Jr., L.M. Leachman, R.T. Kitzmiller, A. Seisan and E. Kadaj, A novel equipment centralization schema reduces the cost of permeate, Proc. 2007 International Desalination World Congress, Maspalomas, Gran Canaria, Spain, October 2007.