One and a Half Membrane Stages –
An Innovative Application for PX Pressure Exchanger® Devices

Mr. Ian B. Cameron, Energy Recovery, Inc., San Leandro CA USA
icameron@energy-recovery.com, +1-510-483-7370

Abstract

The PX Pressure Exchanger® technology manufactured by Energy Recovery, Inc, has been widely adopted by designers and fabricators as well as owners and operators of single-stage seawater reverse osmosis (SWRO) plants. However, energy recovery devices, including PX devices, have not been widely adopted for brackish water reverse osmosis (BWRO) applications. The author presents an innovative configuration for a two-stage reverse osmosis plant whereby the second stage is fed with both first-stage concentrate and high-pressure feed water from a PX device. Such a design is not a single stage, nor is it a full two stage, hence the name "one-and-one-half stage."

The use and performance of PX energy recovery devices to single-stage SWRO processes has been well-documented. The PX device uses the membrane concentrate to pressurize a portion of the membrane feedwater. The PX device, like any isobaric energy recovery device, imparts a slight salinity increase to the feedwater which results in a slight pressure increase compared to a system operating without energy recovery. The PX device operates in conjunction with a circulation pump which conveys high-pressure water through the membrane array and PX device.

In a conventional two-stage design with a PX device, the PX device feeds the first stage with fresh feedwater pressurized with the second-stage concentrate. A boost pump located between the stages performs two tasks: it raises to the pressure of the second-stage feed and acts as a circulation pump. In a one-and-one-half-stage design, the output from the PX device joins the first-stage concentrate to feed the second stage.

This paper presents an analysis of single-stage, two-stage and one-and-one-half-stage designs conducted using a membrane projection program and PX device performance characteristics at different feed water salinities. The membrane projection program determines the membrane flux and stage recovery rates for the different feed salinity values. The paper presents simplified operating guidelines and control philosophy for these designs. The author anticipates that multiple-stage designs will be shown as a way to bring the energy-saving benefits of PX technology into the mainstream of BWRO designs.

Introduction

The PX Pressure Exchanger® device (PX®), manufactured by Energy Recovery, Inc. (ERI®), is an isobaric energy recovery device for reverse osmosis applications. Since its introduction to the seawater reverse osmosis (SWRO) market in 1997, it has been widely accepted. PX devices are now installed throughout the world in plants ranging in size from 20,000 to over 50 million gallons per day (GPD), on land and onboard ships. By the end of 1997, over 6,000 PX devices had been contracted or installed – enough to save an estimated 624 mega watts of electricity or over $400 million in power costs.

However, energy recovery devices, including PX devices, have not been widely adopted for brackish water reverse osmosis (BWRO) applications. This is because BWRO systems operate at a lower system pressure and a higher membrane recovery rate than SWRO systems, leaving less energy to recover from a smaller membrane reject stream. The payback for installing isobaric energy recovery devices in BWRO systems is 2 to 5 years, depending upon the cost of power, compared to one year or less for most SWRO systems. However, as described in this paper, isobaric energy recovery devices allow the BWRO process designer and operator to achieve better flux balance in multiple-stage designs than is possible in a single-stage design.

PX Energy Recovery Devices in Single-Stage Systems

In single-stage designs, PX devices, along with a circulation or booster pump (CP), work in parallel with a high-pressure pump (HPP) to provide feed water to membranes as shown in Figure 1. PX devices use the high-pressure concentrate reject from the membranes to raise the pressure of the incoming low-pressure feed water nearly to that of the concentrate. At the same time, the pressure of the concentrate is reduced to that of the low-pressure supply. The PX device literally exchanges the pressure of the high-pressure concentrate and the low-pressure feed water, hence the term “pressure exchanger.”

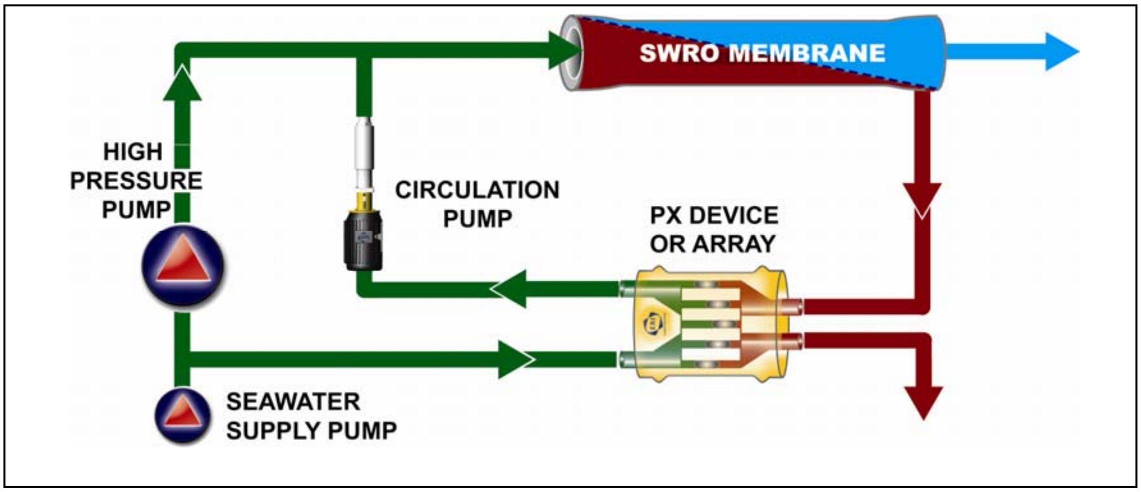

Figure 1: Schematic of a Single-Stage Design

The PX device is driven by flow and does not function like an impeller; therefore, a circulation pump is required to move water through the membranes and PX devices. The circulation pump supplies just the differential pressure lost to friction through the membranes and PX device along the high-pressure flow path, so it consumes relatively little power. It is the high-pressure pump, not the PX devices or the circulation pump, that builds pressure in the system. The flow rate of water supplied by the circulation pump is approximately equal the concentrate flow rate. Therefore, the high-pressure pump is sized to the flow rate of the permeate stream.

Two-Stage Systems with Interstage Boost

Many BWRO applications use two membrane stages with a booster pump between the stages. Separating the stages allows the system to operate at a relatively high recovery rate overall while the individual stages operate at lower recovery rates. The booster pump compensates for the increase in osmotic pressure through the first stage and also serves as a circulation pump, moving water through the second stage membranes and the PX device. A control valve at the high-pressure outlet of the PX device is typically required to control pressure and flow in the second membrane stage. A schematic of the design is shown in Figure 2.

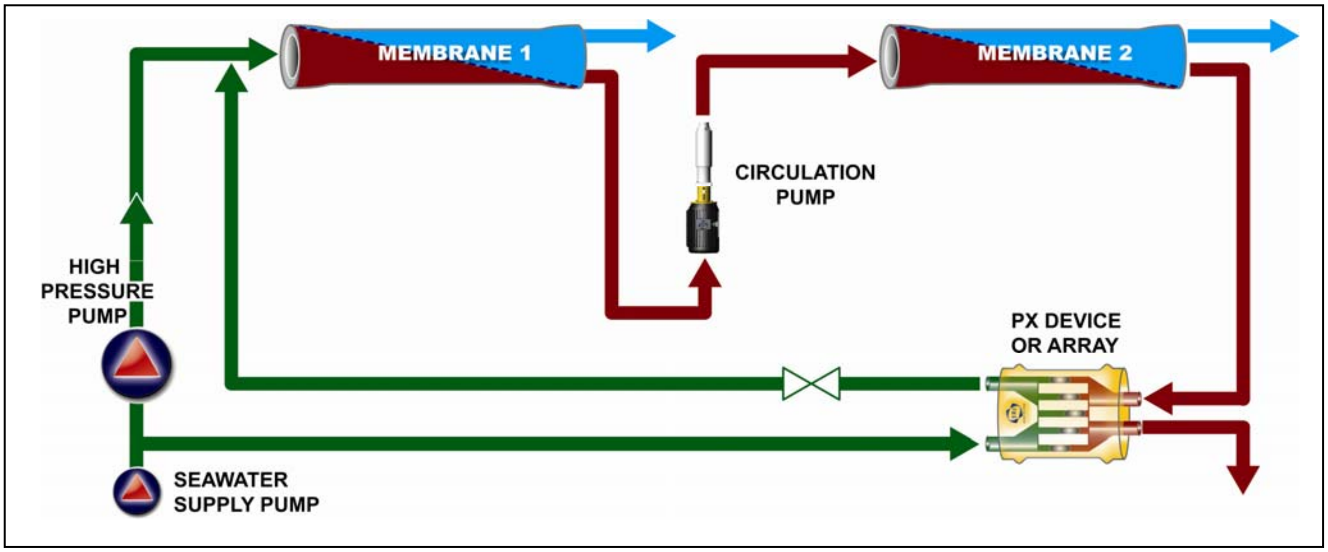

Figure 2: Schematic of a Two-Stage Design

Just as in a single-stage design, the high-pressure pump is sized to the flow rate of the combined permeate streams and the rest of the membrane feed flow is provided by the booster pump and PX device. The system is typically designed to maintain a constant flow rate through the booster pump. If the control valve is throttled closed, the booster pump speed is increased with a variable-frequency drive to maintain the flow rate, resulting in higher pressure and more permeate flow from the second stage. Because the high-pressure pump sets the total amount of permeate produced, therefore, the control valve controls the ratio of permeate produced by the two stages.

One-and-One-Half-Stage Arrangement

An innovative two-stage design, first conceived by Mr. G.G. Pique of ERI, differs from the two-stage system described above in that the high-pressure output from the PX device feeds the second stage rather than the first stage. Therefore, the feed to the second membrane stage consists of first-stage concentrate and additional feed water pressurized by the PX device with the second stage concentrate and a circulation pump. The flow rate of permeate from the second stage is approximately equal to the concentrate flow rate from the first stage. Another way of describing this stage arrangement is that it is a conventional single stage PX design, described above, with an additional membrane stage inserted immediately after the high-pressure pump. The name “one and a half stage” is applied because it is neither a single-stage design, nor a two-stage design where the second stage-feed consists only of first-stage concentrate. Figure 3 shows a schematic of the one-and-one-half-stage design.

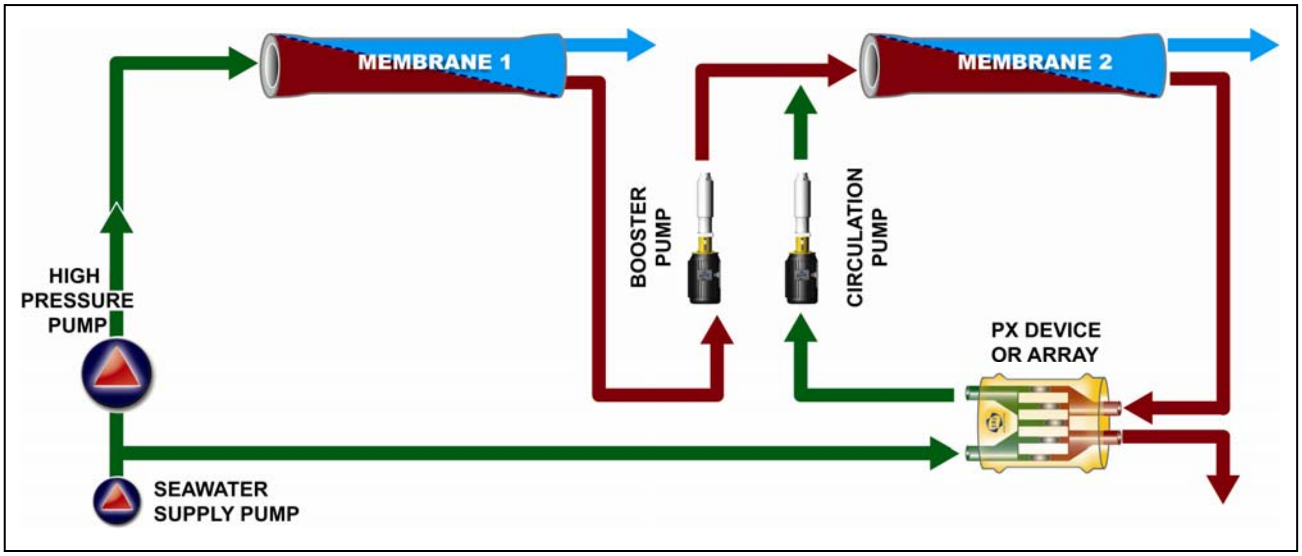

Figure 3: Schematic of a One-and-One-Half-Stage Design

The primary benefit of the one-and-one-half-stage design is that the membrane fluxes of the stages are typically more equal than in a two-stage design. Also, because the recovery rate in each stage in a one-and-one-half-stage design is lower than in a single-stage system operating at the same overall recovery rate, the fluxes through the membrane elements in each vessel are more equal in the former. It is generally understood that equal, low flux through a membrane array improves membrane life.

The first stage in a one-and-one-half-stage is smaller and the second stage is larger than their counterparts in a two-stage design. In some cases, the second stage of a one-and-one-half-stage design is larger that the first stage; i.e. it has more pressure vessels, more membranes, and produces more permeate. Also, the salinity of the feed to the second stage is lower in the one-and-one-half-stage design illustrated above than in a comparable two-stage design.

The ratio of permeate flow from the stages in a one-and-one-half-stage design is controlled by the speed of the booster pump, by the second-stage pressure as adjusted by the circulation pump, or by throttling the permeate flow from the first stage. However, it is possible to operate a one-and-one-half-stage design without a booster pump. In this case, feedwater delivered by the PX device and circulation pump reduces the pressure of the second-stage feed by lowering the osmotic pressure.

Analytical Procedure

Single-stage, two-stage and one-and-one-half-stage designs were analyzed using membrane projection software and an ERI PX Power Model. Published membrane design software was found to support only single- and two-stage arrangements. Therefore, the one-and-one-half-stage design was modeled as two single stages using a beta-test version (1.1.28) of a new membrane design software called Toray Design System (TDS)[1]. This software was chosen because of its ease of use and the high level of support and assistance provided by the manufacturer. Feedwater salinity to the second stage was computed with the Power Model in accordance with equations presented in the literature.[2]

For each design, the following parameters were held constant: overall permeate flow (10,000 cubic meters per day (m3/d) or 2,642,000 GPD), number of membrane elements per vessel (7), model of membrane element (Toray TM820-400) and overall recovery rate (50%). A relatively high overall permeate flow was chosen in an attempt to minimize the effect of adding or subtracting one pressure vessel from a stage so the system could be fine tuned within the constraints. In the case of the one-and-one-half-stage system, the first-stage recovery rate was fixed which, when combined with the overall recovery rate, fixed the recovery rate for the second stage. The interstage boost pressure for the two-stage system was set to five (5) bar because significantly more would result in excessive energy loss through the control valve.

The variables were the following: feed salinity, stage recovery rate and the number of pressure vessels per stage. Feed salinities of 20,000, 30,000 and 40,000 parts per million were analyzed. In each case, the number of pressure vessels was lowered just up to the point where the membrane software gave an alarm, for example, for high average flux. The membrane software calculated permeate salinity, permeate flow from each stage, inlet pressure, membrane differential pressure, and additional system performance characteristics.

Analytical Results

Table 1 – Single Stage, 40,000 ppm Feed Salinity

S1 Feed Pressure (bar)	74.9		S2 Feed Pressure (bar)	n/a
S1 Feed Salinity (ppm)	41248		S2 Feed Salinity (ppm)	n/a
S1 Recovery Rate (%)	50		S2 Recovery Rate (%)	n/a
S1 Permeate Flow (m3/d)	10000		S2 Permeate Flow (m3/d)	n/a
S1 Permeate Salinity (ppm)	503		S2 Permeate Salinity (ppm)	n/a
S1 Pressure Vessels (qty)	108		S2 Pressure Vessels (qty)	n/a
S1 Brine Salinity (ppm)	81998		S2 Brine Salinity (ppm)	n/a
S1 Lead Element Flux (GFD)	14.39		S2 Lead Element Flux (GFD)	n/a
S1 Avg Ele Flux (GFD)	8.72		S2 Avg Ele Flux (GFD)	n/a
Estimated Specific Energy (kWh/m3)	2.59		Overall Permeate (ppm)	503

Table 2 – One-and-One-Half Stage, 40,000 ppm Feed Salinity

S1 Feed Pressure (bar)	64.4		S2 Feed Pressure (bar)	82.7
S1 Feed Salinity (ppm)	40000		S2 Feed Salinity (ppm)	51594
S1 Recovery Rate (%)	40		S2 Recovery Rate (%)	37.35
S1 Permeate Flow (m3/d)	4039		S2 Permeate Flow (m3/d)	5961
S1 Permeate Salinity (ppm)	364		S2 Permeate Salinity (ppm)	599
S1 Pressure Vessels (qty)	44		S2 Pressure Vessels (qty)	68
S1 Brine Salinity (ppm)	66424		S2 Brine Salinity (ppm)	82061
S1 Lead Element Flux (GFD)	12.90		S2 Lead Element Flux (GFD)	12.64
S1 Avg Ele Flux (GFD)	8.65		S2 Avg Ele Flux (GFD)	8.26
Estimated Specific Energy (kWh/m3)	2.74		Overall Permeate (ppm)	504

Table 3 – Two Stage, 40,000 ppm Feed Salinity

S1 Feed Pressure (bar)	72.8		S2 Feed Pressure (bar)	76.7
S1 Feed Salinity (ppm)	41247		S2 Feed Salinity (ppm)	69354
S1 Recovery Rate (%)	41		S2 Recovery Rate (%)	16
S1 Permeate Flow (m3/d)	8146		S2 Permeate Flow (m3/d)	1854
S1 Permeate Salinity (ppm)	347		S2 Permeate Salinity (ppm)	1189

S1 Pressure Vessels (qty)	76		S2 Pressure Vessels (qty)	38
S1 Brine Salinity (ppm)	69354		S2 Brine Salinity (ppm)	81991
S1 Lead Element Flux (GFD)	14.20		S2 Lead Element Flux (GFD)	6.37
S1 Avg Ele Flux (GFD)	10.10		S2 Avg Ele Flux (GFD)	4.59
Estimated Specific Energy (kWh/m3)	2.71		Overall Permeate (ppm)	503

Table 4 – Single Stage, 30,000 ppm Feed Salinity

S1 Feed Pressure (bar)	56.4		S2 Feed Pressure (bar)	n/a
S1 Feed Salinity (ppm)	30938		S2 Feed Salinity (ppm)	n/a
S1 Recovery Rate (%)	50		S2 Recovery Rate (%)	n/a
S1 Permeate Flow (m3/d)	10000		S2 Permeate Flow (m3/d)	n/a
S1 Permeate Salinity (ppm)	295		S2 Permeate Salinity (ppm)	n/a
S1 Pressure Vessels (qty)	108		S2 Pressure Vessels (qty)	n/a
S1 Brine Salinity (ppm)	61582		S2 Brine Salinity (ppm)	n/a
S1 Lead Element Flux (GFD)	14.31		S2 Lead Element Flux (GFD)	n/a
S1 Avg Ele Flux (GFD)	8.72		S2 Avg Ele Flux (GFD)	n/a
Estimated Specific Energy (kWh/m3)	1.93		Overall Permeate (ppm)	295

Table 5 – One-and-One-Half Stage, 30,000 ppm Feed Salinity

S1 Feed Pressure (bar)	49.8		S2 Feed Pressure (bar)	60.6
S1 Feed Salinity (ppm)	30000		S2 Feed Salinity (ppm)	38709
S1 Recovery Rate (%)	40		S2 Recovery Rate (%)	37.4
S1 Permeate Flow (m3/d)	4037		S2 Permeate Flow (m3/d)	5963
S1 Permeate Salinity (ppm)	233		S2 Permeate Salinity (ppm)	323
S1 Pressure Vessels (qty)	44		S2 Pressure Vessels (qty)	64
S1 Brine Salinity (ppm)	49845		S2 Brine Salinity (ppm)	61643
S1 Lead Element Flux (GFD)	12.47		S2 Lead Element Flux (GFD)	12.67
S1 Avg Ele Flux (GFD)	8.65		S2 Avg Ele Flux (GFD)	8.77
Estimated Specific Energy (kWh/m3)	2.04		Overall Permeate (ppm)	287

Table 6 – Two Stage, 30,000 ppm Feed Salinity

S1 Feed Pressure (bar)	52.5		S2 Feed Pressure (bar)	56.1
S1 Feed Salinity (ppm)	30938		S2 Feed Salinity (ppm)	48280
S1 Recovery Rate (%)	36		S2 Recovery Rate (%)	22
S1 Permeate Flow (m3/d)	7214		S2 Permeate Flow (m3/d)	2786
S1 Permeate Salinity (ppm)	199		S2 Permeate Salinity (ppm)	538
S1 Pressure Vessels (qty)	67		S2 Pressure Vessels (qty)	47
S1 Brine Salinity (ppm)	48280		S2 Brine Salinity (ppm)	61583
S1 Lead Element Flux (GFD)	13.57		S2 Lead Element Flux (GFD)	8.12
S1 Avg Ele Flux (GFD)	13.15		S2 Avg Ele Flux (GFD)	5.58
Estimated Specific Energy (kWh/m3)	1.99		Overall Permeate (ppm)	294

Table 7 – Single Stage, 20,000 ppm Feed Salinity

S1 Feed Pressure (bar)	42.0		S2 Feed Pressure (bar)	n/a
S1 Feed Salinity (ppm)	20626		S2 Feed Salinity (ppm)	n/a
S1 Recovery Rate (%)	50		S2 Recovery Rate (%)	n/a

S1 Permeate Flow (m3/d)	10000		S2 Permeate Flow (m3/d)	n/a
S1 Permeate Salinity (ppm)	167		S2 Permeate Salinity (ppm)	n/a
S1 Pressure Vessels (qty)	107		S2 Pressure Vessels (qty)	n/a
S1 Brine Salinity (ppm)	41085		S2 Brine Salinity (ppm)	n/a
S1 Lead Element Flux (GFD)	12.84		S2 Lead Element Flux (GFD)	n/a
S1 Avg Ele Flux (GFD)	8.81		S2 Avg Ele Flux (GFD)	n/a
Estimated Specific Energy (kWh/m3)	1.42		Overall Permeate (ppm)	167

Table 8 – One-and-One-Half Stage, 20,000 ppm Feed Salinity

S1 Feed Pressure (bar)	37.9		S2 Feed Pressure (bar)	44.2
S1 Feed Salinity (ppm)	20000		S2 Feed Salinity (ppm)	25811
S1 Recovery Rate (%)	40		S2 Recovery Rate (%)	37.4
S1 Permeate Flow (m3/d)	4039		S2 Permeate Flow (m3/d)	5961
S1 Permeate Salinity (ppm)	141		S2 Permeate Salinity (ppm)	183
S1 Pressure Vessels (qty)	44		S2 Pressure Vessels (qty)	64
S1 Brine Salinity (ppm)	33240		S2 Brine Salinity (ppm)	41087
S1 Lead Element Flux (GFD)	11.40		S2 Lead Element Flux (GFD)	11.87
S1 Avg Ele Flux (GFD)	8.65		S2 Avg Ele Flux (GFD)	8.78
Estimated Specific Energy (kWh/m3)	1.52		Overall Permeate (ppm)	166

Table 9 – Two Stage, 20,000 ppm Feed Salinity

S1 Feed Pressure (bar)	39.6		S2 Feed Pressure (bar)	43.1
S1 Feed Salinity (ppm)	20626		S2 Feed Salinity (ppm)	31115
S1 Recovery Rate (%)	34		S2 Recovery Rate (%)	24
S1 Permeate Flow (m3/d)	6768		S2 Permeate Flow (m3/d)	3232
S1 Permeate Salinity (ppm)	121		S2 Permeate Salinity (ppm)	284
S1 Pressure Vessels (qty)	65		S2 Pressure Vessels (qty)	43
S1 Brine Salinity (ppm)	31115		S2 Brine Salinity (ppm)	41094
S1 Lead Element Flux (GFD)	12.15		S2 Lead Element Flux (GFD)	9.28
S1 Avg Ele Flux (GFD)	9.81		S2 Avg Ele Flux (GFD)	7.09
Estimated Specific Energy (kWh/m3)	1.48		Overall Permeate (ppm)	159

Analysis of Data

The data support the following observations and conclusions:

- One-and-one-half-stage and two-stage designs effectively lower the recovery rate in each stage while maintaining a relatively high overall recovery rate compared to single-stage designs
- A one-and-one-half-stage design allows the system designer or operator to set the fluxes of the two stages to be more equal than can be easily achieved with a two-stage design
- Permeate quality is essentially independent of the stage design
- Approximately three to five percent more energy is required to operate a two-stage design than is required for a comparable single-stage design.
- Approximately five to seven percent more energy is required to operate a one-and-one-half-stage design than is required for a comparable single-stage design.

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