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Development of Reverse Osmosis Membrane Process for Advanced Treatment of Waste Water

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Abstract:

Sewage effluent is being reused increasingly as a new source of water. When sewage effluent is treated by conventional advanced methods such as sand filtration, the low quality of the treated water limits its applications. If the waste water is to be reused in applications such as in water recreation areas, including artificial streams and ponds, its quality must be improved further. Nippon Steel focused attention on the reverse osmosis membrane process as a new method for treating waste water to high-quality levels, and pushed ahead with research and development toward its commercialization. This research and development work clarified the hygiene of waste water treated by the reverse osmosis membrane process, the stability of treatment performance, and the simplicity of maintenance and control in basic experiments and long-term demonstration experiments with full-scale equipment. The operating and equipment costs of the process were studied and its commercial viability was confirmed as an advanced waste water treatment process.

1. Introduction

The quality of a water environment is mainly determined by three factors: water quality, water volume, and water frontage. In recent years, urbanization and industrialization have reduced the quality and quantity of available water, and artificial water fronts have accelerated the deterioration of water environments. The concentration of populations in large cities is predicted to exacerbate the difficulty of meeting future water requirements. In the Basic Environment Plan formulated in December 1994, the "realization of a social system imposing a minimum of environmental load and based on natural cycles"[1] is cited as one long-term goal of environmental policy in Japan.

In Japan, sewage effluent is generated at a rate of about 11 billion cubic meters per year. It is highlighted as a readily available, stable and new source of water, and reused or recycled in increasing amounts. Currently, its quality limits the reuse of waste water to such low-grade applications as toilet flushing water and water for miscellaneous use, and its reuse rate is only about 1%. If waste water is to be reused in applications that require high-quality water such as artificial streams, fountains and other water amenities, its quality must be improved further. The reverse osmosis (RO) membrane process, which can efficiently remove all possible types of water contaminants, is considered as

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a promising process for treating sewage effluent. This filtration process separates substances under pressure using microporous polymer membranes. The RO membrane process features the following:

1) Many components in water can be removed simultaneously.

2) Good-quality water can be constantly obtained.

3) Equipment is compact and highly flexible in layout.

4) Maintenance and control are simple, and fully-automatic operation is easy to set.

The RO membrane process has great potential as an advanced waste water treatment process.

Aiming at the practical application of a highly advanced waste water treatment process by membrane separation, Nippon Steel carried out joint research with the Japan Sewage Works Agency for four and a quarter years between 1990 and 1995.

The selection of membranes, understanding of basic characteristics, and determination of membrane areal load according to the results of basic experiments are already reported in Number 350 of the Shinnittetsu Giho[2]. The present article reports the comparative study results of different types of membranes for the removal of toxic substances such as trihalomethane, the results and equipment used in demonstration experiments, and the comparative study results of operating and equipment costs.

2. Separation Performance of Various Membranes

If the term "water amenity" is defined as a water environment, such as a park with waterways or artificial stream, where people regain their familiarity with water, waste water for such an application must meet the following requirements:

1) Safety (hygiene): Water of such quality that people are not harmed by direct contact with it.

2) Sensory comfort: Water of such quality that it is free from odor, turbidity, unnatural bubbles, and algae.

To select membranes that can treat the sewage effluent to meet the above quality requirements, it is first necessary to grasp the separation performance of various membranes. Using desktop testers, various membranes were compared for their ability to remove dissolved substances and toxic substances, such as trihalomethane and cadmium, in the secondary effluent. Accordingly, membranes suitable for the advanced treatment of sewage were selected.

2.1 Experimental plant

The flow sheet of the experimental plant is shown in **Fig. 1**. The feed water is pressurized by a high-pressure pump. The pressure to be applied to the acrylic plate-and-frame membrane test cell and the flow rate of concentrated water are adjusted with the flow control valve and the pressure control valve. The concentrated water is returned to the feed water tank. The test cell can be fitted with about 60 cm² of plate-and-frame membrane area and can filter the feed water in a crossflow manner.

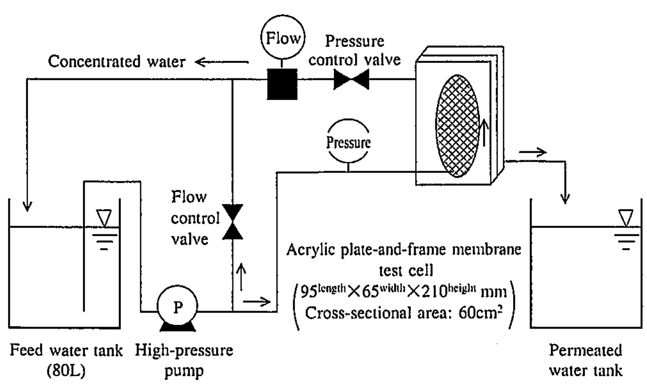

Fig. 1 Flow sheet of plate-and-frame membrane experimental plant

2.2 Specifications and operating conditions of experimental membranes

Separation membranes can be classified by pore size into three main types: microfiltration (MF) membrane, ultrafiltration (UF) membrane, and RO membrane. Two types of MF membranes, one type of UF membrane, and four types of RO membranes with different rejection efficiencies, or seven types of membranes in total, were selected and experimented on. The specifications and experimental conditions of the selected membranes are presented in **Table 1**. The operating pressure was set at a maximum of 10 kg/cm² according to the capacity of the experimental plant.

2.3 Comparison of separation performance

2.3.1 Comparison of separation performance of dissolved substances in secondary effluent

Sand-filtered secondary effluent discharged from a waste water treatment plant was used as feed water. The calculated rejection efficiencies of various components are shown in **Figs. 2** and **3**. The rejection efficiency of a substance is defined as the concentration of the substance in permeated water divided by the mean concentration of the substance in feed water and concentrated water, as calculated by.

$$\text{Rejection efficiency}(\%)=\left[\frac{C_p}{(C_o+C_h)/2}\right]\times 100$$

where C_o = concentration of the substance in feed water; C_h = concentration of the substance in concentrated water; and C_p = concentration of the substance in permeated water.

The rejection efficiency of the total dissolved solids (TDS) improves with increasing separation performance of the membranes. All membranes can reduce biological oxygen demand (BOD) and chemical oxygen demand (COD) to certain levels, but the RO membranes had the highest COD rejection efficiencies. The rejection efficiencies for inorganic substances were the same as those observed for TDS. As far as nutrient salts are concerned, the RO membranes can efficiently reject phosphorus, but cannot reject nitrogen as easily as phosphorus.

2.3.2 Comparison of toxic substance separation performance

Pure water was used as the feed water. Substances 1 to 3, 4, and 5 to 8 listed in **Table 2** were added to the feed water in three different portions. Experimental runs were performed to remove them from the feed water. The concentrations of these additions were basically set at 100 times in accordance with their effluent standards, except that the concentration of 1,1,1-trichloroethane was set at 10 times because of its higher effluent standard. **Fig. 4** shows the calculated rejection efficiencies of the experimental membranes.

Lead and cadmium were only slightly removed by the membranes up to the No. 4 RO membrane with a rejection efficiency of 10%. The arsenic was reduced to a low 20%, even with the No. 5 RO membrane having a rejection efficiency of 50%. The cyanides were removed in small amounts even with the membranes of high rejection efficiency and are considered to require RO membranes with still higher rejection efficiency. The organic substances were removed with an efficiency of about 50% or

Table 1 Specifications of membranes[3)]

Membrane type				MF membrane		UF membrane	RO membrane*2			
Membrane No.				1	2	3	4	5	6	7
Membrane model No.				N5201	Metal membrane	N3150	N7410	N7450	N729HF	N769SR
Performance	Rejection efficiency		%	—	—	—	10	50	93	97
Performance	Evaluation conditions	Liquid	—	0.5%*1	—	Pure water	0.5%NaCl		0.2%NaCl	0.05%NaCl
Performance	Evaluation conditions	Pressure	kg/cm²	0.5	—	2	5	10	10	15
Performance	Evaluation conditions	Temperature	°C	25	—	25	25			
Performance	Evaluation conditions	pH	—	—	—	—	6.5			
Performance	Evaluation conditions	Recovery	%	—	—	—	50		15-25	10-20
Performance	Fractional molecular weight		—	—	—	50,000	—			
Pore size			μm	0.2	0.4	—	—			
Membrane material				Fluoric resin	SUS316	Polysulfone	Polymer composite membrane			
Experimental pressure			kg/cm²	2	2	2	5	10	10	10
Concentrated water flow rate			L/min	0.513						

*1. Water solution of polyethylene glycol.
*2. In recent classifications, RO membranes used in this study are called nanofiltration membranes or loose RO membranes because they fall between UF membranes and high-rejection RO membranes used for sea water desalination in terms of performance and are employed at relatively low pressures.

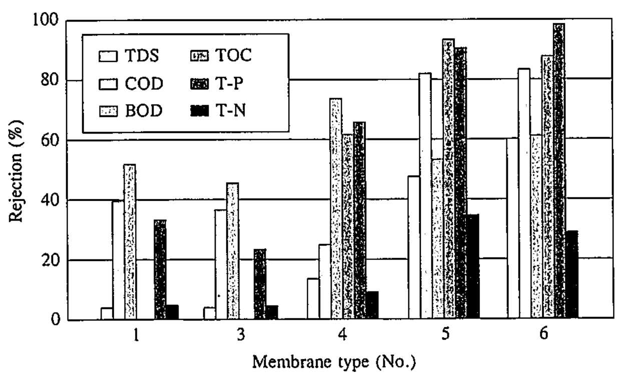

Fig. 2 Separation performance comparison of membranes — Part 1
TDS : Total dissolved solids　COD : Chemical oxygen demand
BOD : Biochemical oxygen demand　TOC : Total organic carbon
T-P : Total phosphorus　T-N : Total nitrogen

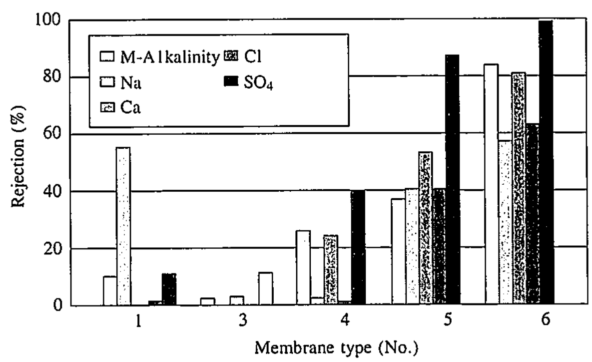

Fig. 3 Separation performance comparison of membranes — Part 2

Table 2 Names and concentrations of toxic substances

No.	Name	Concentration (mg/L)
1	Cadmium	1
2	Lead	10
3	Arsenic	5
4	Cyanide	10
5	Tetrachloroethylene	1
6	Trichloroethylene	3
7	Total trihalomethane	10
8	1,1,1-trichloroethane	3

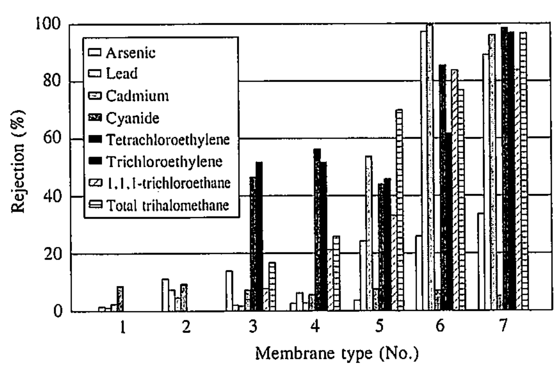

Fig. 4 Separation performance comparison of membranes — Part 3

more by the UF membranes. The overall trend was that the removal efficiency of the toxic substances and the quality of the permeated water improved with increasing rejection efficiency of the membranes.

These experimental results suggest that RO membranes capable of separating various components are ideal for treating sewage effluent into high-quality waste water suitable for recreational use while meeting the above-mentioned conditions.

3. Summary of Results of Basic Experiments

The basic experiments were conducted at the Japan Sewage Works Agency's General Laboratory in the Research and Technology Development Division in Toda City, Saitama Prefecture. The secondary effluent from the Arakawa Left Bank Waste Water Treatment Plant was used as the feed water. The results of the basic experiments, such as the pretreatment conditions required to meet a fouling index (FI) of less than 4 established as design criterion for the demonstration plant and the basic properties of RO membranes, are summarized in **Table 3**. For details, refer to the Number 350 of the Shinnittetsu Giho[2].

Additional basic experiments were undertaken to apply UF membranes as a new pretreatment process and to simplify pretreatment. Good results were obtained.

4. Demonstration Experiments

Demonstration experiments were carried out to verify the results of the basic experiments on a full-scale basis and to investigate the following factors that would assume importance during the commercialization of the RO process:

1) Confirmation of long-term viability of pretreatment equipment
2) Confirmation of long-term performance of RO membrane
3) Confirmation of quality of treated water
4) Calculation of operating cost

4.1 Description of demonstration plant

The flow sheet of the demonstration plant is shown in **Fig. 5**. Nonchlorinated secondary effluent is used as the feed water. The feed water is sent from the final sedimentation tank at the waste water treatment plant to the automatic strainer (mesh of 250 μm), where suspended solids (SS) and other components are removed. The turbidity components are coagulated and separated in a Krofta dissolved-air flotation unit, which has treatment performance comparable to that of a coagulation and settling unit but requires 90% less space. Sand filtration completes the pretreatment of the feed water. The pretreated water is passed through the RO membrane unit by the high-pressure pump. The RO membrane unit separates the pretreated water into permeated water free of dissolved components and concentrated water containing dissolved components. The permeated water obtained is pumped to the treated water evaluation equipment to investigate the growth of algae and to a fountain in the waste water treatment plant. The concentrated water is returned to the primary sedimentation tank. The demonstration plant recovers 80% of the feed water and treats the feed water at a rate of 210 m³/d. The equipment operating data can be accessed via a telephone line, and the equipment operating conditions can be monitored remotely. Main equipment item specifications are listed in **Table 4**. The high-pressure pump is inverter controlled to save electricity. The RO

Table 3 Summary of results of basic experiments

Basic experiment flow			Pretreatment (flocculent settling and two-layer sand filtration) → RO
Pretreatment	Flocculent settling	Selected coagulant	Polyaluminum chloride (PAC) was selected in jar test.
		Optimum addition of coagulant	Optimum addition of coagulant was set at 20 mg/L as Al_2O_3 in plant test.
		Stirring time	Stirring time was set at 5 min in jar test.
		Surface loading rate	Surface loading rate was set at 13 m³/m²·d in plant test.
	Sand filtration	Filter medium composition	Time during which filtered water can maintain FI<4 and bed thickness/harmonic mean size of filter medium, or L/D value, were obtained. If linear velocity is 150 m/d, therefore, L/D value of about 1,550 is required for filtered water to maintain FI<4 for 24 h.
		Filtered water discard time	To maintain FI<4, it is necessary that filtered water of poor quality after backwashing should be discarded to some degree. This time was set at 30 min according to experimental results.
RO	Selection of RO membrane		Spiral RO membrane NTR-729HF of Company N was selected after studying RO membrane catalogs of manufacturers regarding performance and considering water quality, permeated water flow rate and contamination-resistant membrane structure.
	Understanding basic characteristics of RO membrane		Relationships between pressure and permeated water flow rate, between water temperature and permeation coefficient, and between pressure and rejection efficiency when RO process was applied to waste water treatment were clarified and expressed by mathematical equations.
	Determination of permeated water loading		Permeated water load at which membrane performance drops by 20% after one month of continuous treatment was taken as optimum, and this optimum permeated water load was experimentally set at 0.6 m³/m²·d.
	Chemical washing method		Chemical washing interval was set at one month, and chemical and chemical washing methods effective in membrane performance recovery were selected.
	Development of RO membrane arrangement calculation program		Based on experimental results, RO arrangement calculation program was developed for predicting RO membrane operating pressure, permeated water flow rate, permeated water quality, etc.

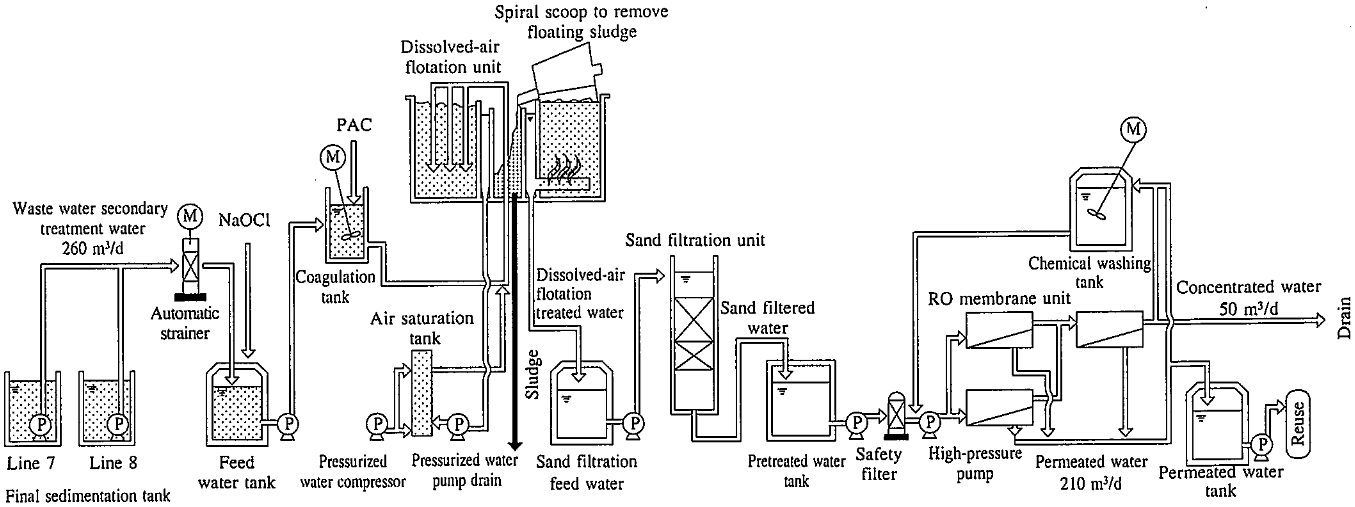

Fig. 5 Flow sheet of demonstration plant

Table 4 Specifications of main equipment at demonstration plant

Type of feed water			Secondary effluent (before chlorination)	
Design flow rate			Pretreated water: 260 m³/d RO membrane permeated water: 210 m³/d (recovery of 80%)	
Water temperature			10-30°C (design water temperature of 15°C)	
Plant location area			6m×13m	
Experimental site			Hanamigawa terminal waste water treatment plant for Inbanuma basin, Chiba Prefecture	
Experimental period			May 1993-May 1995	
	Equipment name	Quantity	Design flow rate	
Equipment specification	Dissolved-air flotation unit (Krofta)	1 set	260m³/d	Type and shape: Vertical and cylindrical Tank size: 1,800mm ϕ ×400mm height Material: Stainless steel
	Sand filtration unit	1 set	260m³/d	Type: Gravity type Shape: Cylindrical Filter media Sand: 0.6 mm ϕ ×1,200 mm height Anthracite: 0.4 mm ϕ ×1,200 mm height
	High-pressure pump	1	260m³/d	Type: Multistage centrifugal Material: Stainless steel Electric power: 200V×11kW×3 ϕ ×50Hz
	RO membrane element (NTR-729HF-S8)	15	210m³/d Pressure vessel containing 5 elements×3	Membrane material: Polyvinyl alcohol composite Element size: 200mm ϕ ×1,016mm length ×15elements Salt rejection*1: 92% Permeated water production*2: 36 m³/d·element

Test conditions for *1 and *2: Water temperature of 25°C, pressure of 10 kg/cm², NaCl concentration of 1,500 ppm in feed water, and pH of 7

membrane unit has 15 eight-inch membrane elements of the same material as used in the basic experiments.

4.2 Results of pretreatment experiments

The membranes are packed tightly into the RO membrane elements to increase the membrane area and to reduce size. When SS are contained in the feed water, they plug the membranes, build up on the membrane surfaces, and sharply lower the permeation performance of the membranes. For this reason, the RO membrane unit requires a pretreatment step to remove the SS from the feed water.

Pretreatment experiments were carried out to formulate the operating conditions under which an FI of less than 4 would be stably obtained as an indicator of low turbidity and to confirm the long-term performance of the RO membranes. When an ordinary secondary effluent was used as the feed water, the operating conditions shown in **Table 5** were established as the conditions under which permeated water with an FI less than 4 could be stably produced. To guard against any unexpected deterioration of feed water quality, the pretreatment performance was verified when the feed water deteriorated in quality.

Fig. 6 shows the experimental results of the dissolved-air flotation unit. The SS levels and turbidity of feed water were

Table 5 Operating conditions of pretreatment equipment

	Item	Condition
Coagulation tank	Chlorine addition rate	5 mg/L as 12%Cl
	Coagulant	PAC=20 mg/L as Al_2O_3
	Stirring time	5 min
	Stirrer rotational speed	80 rpm
Dissolved-air flotation unit	Detention time	5 min
	Surface loading rate	140 $m^3/m^2 \cdot d$
	Air supply rate	24%(1air/1wt)
	Dissolved-air water ratio	30 %
	Dissolved-air water pressure	590kPa (6kg/cm²)
Sand filtration unit	Filtration rate	150 $m^3/m^2 \cdot d$
	Backwashing frequency	1 time/d
	Filtered water discard time after backwashing	30 min

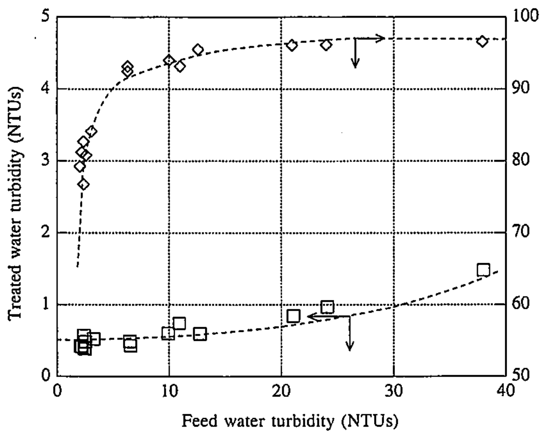

Fig. 6 Turbidity removal by dissolved-air flotation unit

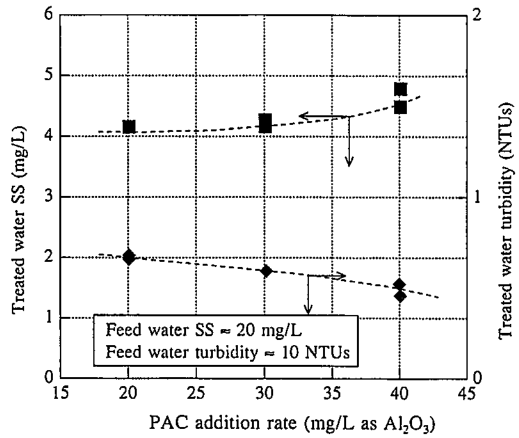

Fig. 7 Relationship between PAC addition rate and treatment performance in dissolved-air flotation unit

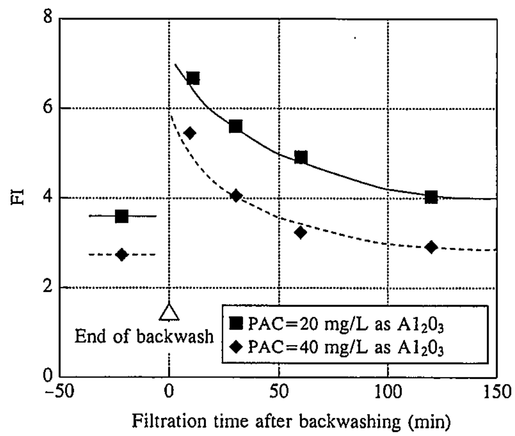

Fig. 8 Change in FI after backwashing of sand filtration unit

adjusted by adding sludge. The turbidity of the treated water is practically constant when the nephelometric turbidity units (NTUs) are 10 or less, but worsens with increasing turbidity of the feed water when the NTUs are greater. This situation was attributed to the insufficient addition of polyaluminum chloride (PAC) as coagulant. Multivalent cations such as Al^{3+} neutralize the charge of colloidal particles. At the same time, hydroxides such as $Al_2(OH)_3$ adsorb and flocculate the colloidal particles. When the addition rate of PAC is too low, therefore, some non flocculated colloidal particles remain in the treated water.

Fig. 7 shows the changes in the addition rate of PAC and the quality of treated water when the SS and turbidity of the feed water were about 20 mg/L and 10 NTUs, respectively. As the adition of PAC increases, the treated water decreases in turbidity and increases in SS. These results may be explained as follows. The increased addition of PAC accelerates the flocculation of colloidal particles and clarifies the treated water. All of the floc cannot float to the surface, however, and some are detected as SS.

Fig. 8 shows the changes in the FI of dissolved-air flotation treated water after sand filtration. PAC was added at two levels of 20 and 40 mg/L as Al_2O_3. It was confirmed that the FI dropped faster after backwashing the sand filtration unit at the PAC addition of 40 mg/L as Al_2O_3 and fell to less than 4 within the treated water discard time of 30 min after backwashing. As a result, it was clear that when the feed water declined in quality, the desired pretreatment performance could be maintained by adding PAC at such a rate as to flocculate the turbid substances contained.

The above results confirmed the ability of the pretreatment equipment to accommodate any sudden deterioration in feed water quality and to treat the feed water stably at a FI less than 4.

4.3 Results of RO membrane treatment experiments

The changes in the operating pressure, permeated water flow rate, and concentrated water circulation rate of the RO membrane unit for about 8,000 hours of continuous operation are shown in **Fig. 9**. The operating conditions of the RO membrane unit for the same period are given in **Table 6**. The changes in the water temperature and recovery efficiency are shown in **Fig. 10**, and the changes in the rejection efficiency of the RO membranes are shown in **Fig. 11**.

4.3.1 Confirmation of appropriateness of control method

In Run 1, the RO membrane unit was continuously operated under the conditions established as calculated by the Nippon Steel-developed RO membrane arrangement calculation program derived from the basic experiment results. The flow rate of permeated water was controlled at 210 m³/d by adjusting the inverter

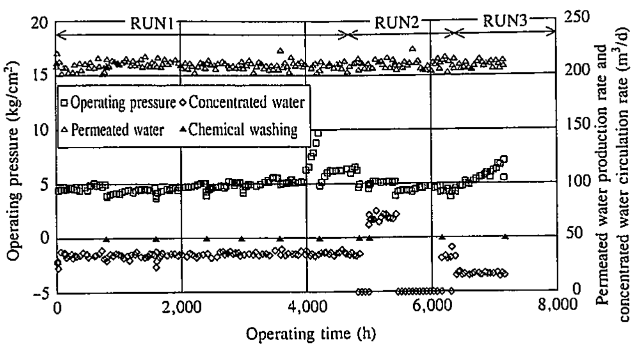

Fig. 9 Changes in operating pressure, permeated water production rate, and concentrated water circulation rate

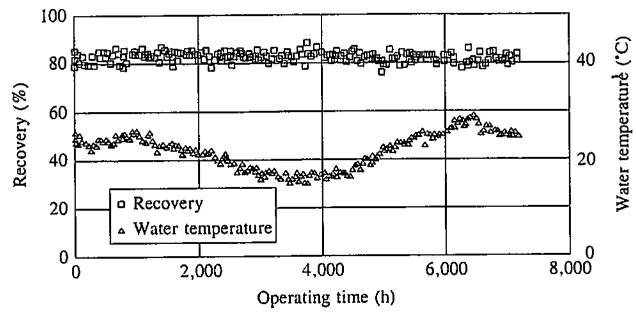

Fig. 10 Changes in recovery and water temperature

Table 6 Operating conditions of demonstration experiments

Condition	Pretreated water flow (m³/d)	Permeated water flow (m³/d)	Concentrated water flow (m³/d)	Recovery (%)
Run 1 Continuous load experiment	260	210	40	80
Run 2 Concentrated water circulation effect confirmation experiment	260	210	0,36,70	80
Run 3 Membrane area load change experiment	260	210 or 170	20	80

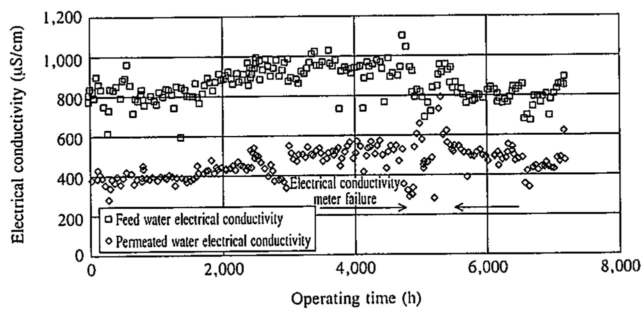

Fig. 11 Change in electrical conductivity

of the high-pressure pump and the pressure control valve on the concentrated water side of the RO membrane module. The contamination of the membranes raised the operating pressure, and the water temperature change altered the required pressure. Despite these conditions, the permeated water production rate and the feed water recovery efficiency were held constant at 210 m³/d and 80%, respectively. When the quality of permeated water was degraded by a sand filtration timer setting error during the experimental period, the operating pressure rose, but the permeated water production rate and the feed water recovery efficiency were kept practically constant. These results verified the appropriateness of the control method.

4.3.2 Change in operating pressure

The membrane areal load adopted was about 0.6 m³/m²·d as the load at which the performance of the membranes would drop by 20% in one month of operation as determined from the results of the basic experiments. The operating pressure remained stable at 4 to 6 kg/cm² during the period of Run 1. The design performance drop of about 20% during one month of continuous operation was approximately satisfied.

4.3.3 Change in rejection efficiency

Fig. 11 shows the change in the electrical conductivity of the feed water and the permeated water. The rejection efficiency slightly varied with the operating conditions but was kept at about 50% during the operating period. As a result, it was confirmed that after the RO membranes treated the feed water for a long period of time, their basic separation performance was kept close to the initial value. A malfunctioning of the electrical conductivity meter caused sections of data indicating low rejection efficiency.

4.3.4 Effect of chemical washing

The RO membrane unit was chemically washed every month with an oxalic acid water solution of pH 2 and an ethylenediamine-tetraacetic acid (EDTA) water solution of pH 10, two chemical solutions selected according to the results of the basic experiments. In **Fig. 9**, the solid triangles (▲) indicate the times when the reverse osmosis membrane unit was chemically washed. Under the operating conditions of Run 1, the chemical washing cycle established according to the results of the basic experiments, or 20 minutes circulation, followed by 20 minutes immersion, 20 minutes circulation and flushing, restored the membrane operating pressure to the initial level and returned the membranes to their initial performance levels. It was also confirmed that when the membranes were covered with more contaminants than originally expected due to feed water quality deterioration or because of other causes, their performance could be restored by extending chemical washing time or chemically washing them twice.

4.3.5 Effect of circulating concentrated water

The RO membrane elements adopted in the demonstration plant are of the spiral type and designed for cross-flow filtration. The cross-flow filtration method does not filter all of the feed water, but passes some of the feed water normal to the membrane surface and prevents the buildup of contaminants by the turbulence effect on the feed water-side membrane surface. To maintain the desired performance of the membrane, therefore, it is necessary to circulate a given amount of water on the membrane surface to ensure a certain concentrated water circulation rate.

The membrane manufacturer set the minimum concentrated water circulation rate at 45 L/min for the 8-inch elements. In Run 2, the feed water was experimentally treated by the RO membrane unit by changing the concentrated water recirculation rate, and the effect of the concentrated water recirculation rate (membrane surface turbulence) on the membrane performance was confirmed. During the experiment, three levels of concentrated water recirculation rate were tried. The experimental conditions are shown in **Table 7**. Case 2 is equivalent to Run 1 here. Case 2 is taken as the base case. When the concentrated water recirculation rate was increased, the operating pressure slightly rose due to the resultant pressure loss, and the rate of drop in the membrane performance decreased. When the concentrated water recirculation rate was lowered, on the other hand, the operating pressure fell slightly, and the rate of drop in the membrane performance increased. These results suggest that when operating costs are considered the conditions of Case 2 are appropriate for keeping the membrane performance at the design value with a minimum concentrated water recirculation rate.

4.3.6 High-load operation

In Run 3, the number of the 8-inch membrane elements used per unit was changed from 15 to 12, and the membrane areal load was increased to treat the same amount of the feed water. The membrane performance deteriorated by about 30% after one month of operation, but was confirmed to be still good enough to adequately treat the feed water. If the RO membrane unit is operated in this mode, the contamination of the membranes will increase to a greater extent than under the design operating conditions. It was necessary to prolong their chemical washing time to restore the membranes to their initial performance levels.

4.3.7 Confirmation of suitability of RO membrane arrangement calculation program

Fig. 12 shows the operating conditions of the demonstration experiments analyzed by the RO membrane arrangement calculation program developed based on the results of the basic experiments. The computational results of the operating pressure, rejection efficiency, and other conditions agreed with the experimental results and verified the validity of the program for calculating the arrangement of membranes for waste water treatment.

4.4 Study of permeated water quality

The average values of water quality analysis during the experimental period appear in **Table 8**. The RO membrane process eliminated the SS to practically zero and efficiently removed the organic matter indices, COD and BOD. Phosphorus, an index of eutrophication, was removed to less than 0.01 mg/L, the minimum rate at which algae grow. The rejection efficiency of the nitrogen was low. This is because to reduce the treatment costs the loose RO membranes (nanofiltration membranes) that can produce a large volume of permeated water at low pressure were

Table 7 Concentrated water circulation rate

Case	Concentrated water return rate (m^3/d)	Minimum concentrated water circulation rate (m^3/d) [L/min]
1	70	86.4[60]
2	36	68.6[47]
3	0	49.9[34]

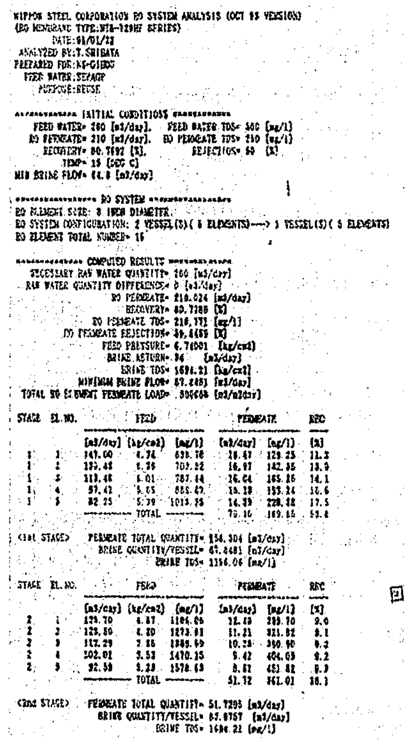

Fig. 12 Result of computation by membrane arrangement calculation program

used in this experimental work.

If the permeated water is to be used in water for recreational use, such as in artificial ponds and streams, algal growth is an important factor to be studied. **Fig. 13** shows the test results of algal growth potential (AGP). Chlorella was used as test alga. It was cultivated at 20°C and 4,000 lux for 14 days, after which the dry-weight concentration of SS was determined. The AGP value was greater than 100 for the secondary effluent but dropped to nearly zero for the permeated water. **Photo 1** shows the growth of algae in permeated water evaluation units at the demonstration plant. The measured results of algal deposits are shown in **Fig. 14**. These results confirmed the virtual absence of algal growth in the water treated by the RO membrane process.

The above results show that the water treated by the RO membrane process can be reused in applications requiring high-quality water and was pure enough to be reused even as drinking water.

4.5 Operating cost

The operating cost of the RO membrane process calculated for one month during the experimental period is given in **Table 9**. The operating cost, including the cost of changing membranes (change frequency estimated), was 64.5 ¥/m^3. The electricity cost included lighting and air conditioning for the experimental house. The labor cost was excluded from the operating cost calculation, although 52.4 working days/year were estimated as the labor required for inspections and maintenance, such as daily inspections, chemical washing, and equipment maintenance.

5. Study of Economy by Trial Design

Commercial RO membrane plants were trial designed under

Table 8 Average quality values of water treated at demonstration plant

Index	Item	Unit	Secondary effluent	Pretreatment effluent	RO membrane permeate	RO membrane rejection (%)	Tap water quality standard*11	Industrial water quality standard	Amenity water quality target*4)
Solids	SS*1	mg/L	5.2	3.6	<0.4	—	—	—	—
	TDS*2	mg/L	350	390	230	41	<500*12	<250	—
Organic matter	COD*3-Mn	mg/L	12	9	2.9	68	<10*13	—	—
	ATU-BOD*4	mg/L	3.3	1.6	0.73	53	—	—	<3
	TOC*5	mg/L	12	7.3	0.36	95	—	—	—
Eutrophi-cation	T-P*6	mg/L	0.7	0.03	<0.01	—	—	—	—
	T-N*7	mg/L	22	25	17	34	—	—	—
	NH_3-N*8	mg/L	20	20	13	36	—	—	—
	NO_2-N*9	mg/L	0.7	2	2	—	<10	—	—
	NO_3-N*10	mg/L	1.1	1.3	1.4	—	<10	—	—
Inorganic matter	pH	—	7.3	7	6.8	—	5.8-8.6	6.5-8.0	5.8-8.6
	M-alkalinity	mg/L	150	120	66	44	—	<75	—
	Electrical conductivity	μS/cm	722	809	490	39	—	—	—
	Na	mg/L	67	75	50	33	<200	—	—
	Ca	mg/L	26	28	11	61	<300*14	<120	—
	Cl	mg/L	85	120	93	22	<200	<80	—
	SO_4	mg/L	46	59	4.5	92	—	—	—
	Si	mg/L	12	10	8.9	13	—	—	—
	Fe	mg/L	<0.1	<0.1	<0.1	—	<0.3	<0.3	—
	Mn	mg/L	<0.1	<0.1	<0.1	—	<0.05	—	—
	Al	mg/L	<0.1	<0.1	<0.1	—	—	—	—
Bacterial count			—	100	0	100	<100 mL	—	—
Coliform count			—	0	0	100	Not detectable	—	<50 colonies/100 mL

*1Suspended solid; *2Total dissolved solids; *3Chemical oxygen demand; *4Allylthiourea-biochemical oxygen demand; *5Total organic carbon; *6Total phosphorus; *7Total nitrogen; *8Ammonia nitrogen; *9Nitrite nitrogen; *10Nitrate nitrogen; *11Ordinance No. 5 of Ministry of Health and Welfare on August 31, 1983; *12Evaporation residue; *13Potassium permanganate consumption; *14Total hardness;

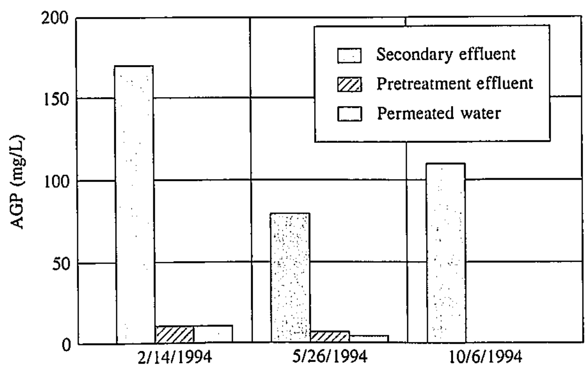

Fig. 13 AGP of various waters

the following conditions to comparatively study their economic viability, including the equipment and operating costs:

(1) Feed water: Standard secondary effluent

(2) Capacity

(i) 100 m^3/d

(ii) 200 m^3/d

(iii) 500 m^3/d

(iv) 1,000 m^3/d

(3) Pretreatment method

(i) Chemical precipitation (CP) and sand filtration (SF)

(ii) Dissolved-air flotation with coagulation (DC) and sand filtration (SF)

(iii) Filtration with coagulation (FC) and sand filtration

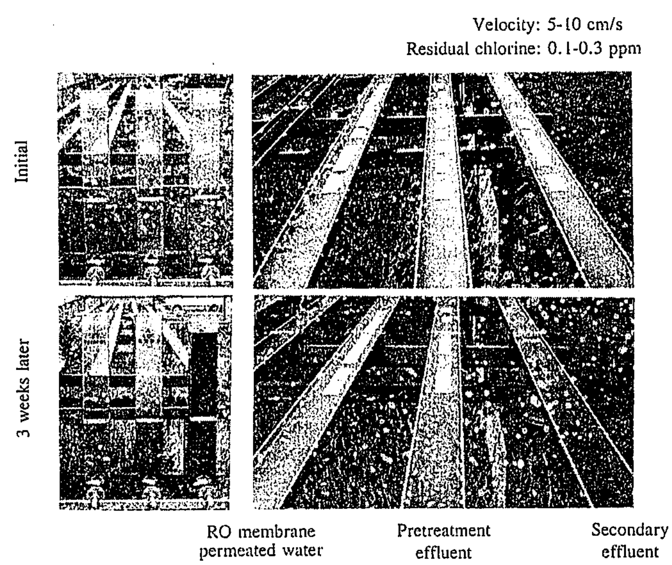

Photo 1 Algal growth in permeated water evaluation units

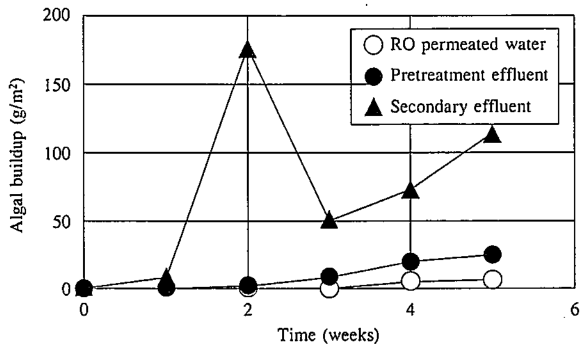

Fig. 14 Changes in algal buildup

Table 9 Operating cost of demonstration plant

Item		Operating cost (¥/m³) (Availability of 93.5%)	Remarks
Electricity		26.9	Including control panel, light, and heat expenses
Chemicals	PAC	11.1	
	NaOCl 10%	5.0	
	Acid	0.4	Chemical washing: Once/month
	EDTA	0.2	
Consumables		4.1	Safety filter, drive lubricating oil, etc.
RO membrane exchange cost		16.7	Estimated for life of 5 years
Total		64.5	

(SF)

(iv) MF membrane filtration (MF)

(4)Recovery in RO membrane section: 80%

The RO membrane section was designed to the same specifications for the different capacities, and the pretreatment section was designed in accordance with the specific methods. The combination of chemical precipitation, rapid filtration and activated charcoal absorption was studied as a conventional process, although it produces water of inferior quality this process is adopted in waste water treatment and many other applications.

5.1 Equipment costs

The equipment cost of the conventional process is calculated as follows:

$(599.1 \times Q^{0.649} - 299.2 \times Q^{0.622}) \times (114.8/100.9)$[5,6]

= ((Activated sludge process + Conventional process) − Activated sludge process) × Deflator

where Q is the daily maximum flow rate at 1,000 m³/d, and the cost units are in millions of yen per year.

Fig. 15 compares the equipment cost of the RO membrane process and the conventional process as calculated on the basis of trial design. The equipment cost of the RO membrane process is about twice that of the conventional process. This is because the RO membrane process requires pretreatment equipment comparable to that of the conventional process. As the unit price of RO membranes falls due to the development of new membrane technology by membrane manufactures and by the greater demand for RO membrane modules, the equipment costs for the RO membrane process will diminish.

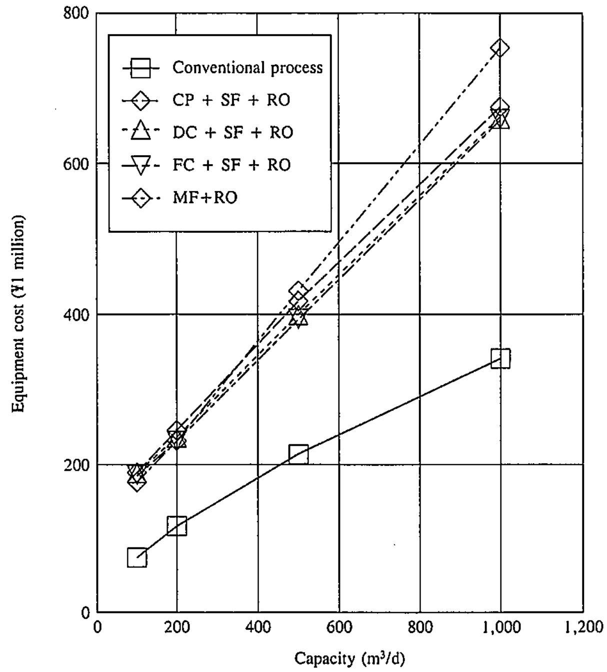

Fig. 15 Equipment cost study results

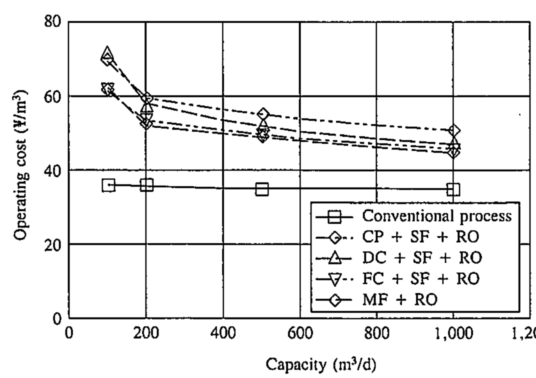

Fig. 16 Operating cost study results

5.2 Operating cost

The operating cost of the conventional process is calculated as follows:

$(15.35 \times Q^{0.942} - 4.23 \times Q^{0.848}) \times (114.8/100.9)$[5,6]

= ((Activated sludge process + Conventional process) − Activated sludge process) × Deflator

where Q is the daily maximum flow rate at 1,000 m³/d, and the cost units, excluding the labor cost, are in millions of yen per year.

Fig. 16 shows the results. For a capacity of 1,000 m³/d, the operating cost of the RO membrane process decreases with increasing capacity and is about 1.4 times higher than that of the conventional process. If the water treated by the RO membrane process is to be used as a substitute for tap water other than for drinking water, its cost is considered relatively low when operating costs, including depreciation expenses, are taken into account.

6. Conclusions

The development results of a RO membrane treatment plant for reuse of sewage effluent have been described. The RO membrane process can produce water of quality comparable to that of tap water. Permeated water from the RO membrane process can be reused for recreational use. Operations and control stability, and consistency of permeated water quality were verified by experimentation with a full-scale demonstration plant. The operating cost of a commercial RO membrane plant was confirmed to be similar to that of an equivalent-capacity plant to produce tap water.

The authors will work toward the commercialization of the RO membrane process, an advanced waste water treatment process. Greater use of the RO membrane process is expected to lead to the protection of water environments at waste water treatment plants and in surrounding communities, and encourage the construction of innovative, and appealing water environments.

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References

1) Water Quality Control Division, Water Quality Bureau, Environmental Agency: Journal of Japan Sewage Works Association. 32 (392), December 1995
2) Toma, H. et al.: Shinnittetsu Giho. (350), 94 (1993)
3) Company N: Catalog of RO membranes
4) Advanced Treatment Conference, Ministry of Construction: Manual for Use of Sewage Effluent for Landscape and Amenity Purposes (Draft)
5) Sewage Tertiary Treatment Research Laboratory, Public Works Research Institute, Ministry of Construction: Report on Advanced Waste Water Treatment Plan and Advanced Treatment Introduction Program — Evaluation of Secondary Effluent Quality, Cost of Advanced Treatment, and Concept of Advanced Treatment Introduction. 1988
6) Japan Sewage Works Association: Guidelines and Commentary on the Survey of Overall Sewerage Improvement Plan by Watershed. 1993