การบำบัดสารฟลูออไรด์ในน้ำใต้ดิน โดยการใช้เมนเบรนออสโมซิสย้อนกลับ ชนิดความดันต่ำ และ นาโนเมมเบรน

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GROUNDWATER DEFLUORIDATION BY ULTRA LOW PRESSURE REVERSE OSMOSIS MEMBRANE AND NANO FILTRATION MEMBRANE

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By	Mr. Aunnop Wongrueng
Field of Study	Environmental Management
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อรรณพ วงศ์เรือง: การบำบัดสารฟลูออไรด์ในน้ำใต้ดิน โดยการใช้เมมเบรนออสโมซิสย้อนกลับชนิดความดันต่ำ และ นาโนเมมเบรน. (GROUNDWATER DEFLUORIDATION BY ULTRA LOW PRESSURE REVERSE OSMOSIS MEMBRANE AND NANO FILTRATION MEMBRANE) อ. ที่ปรึกษา: ผศ.ดร. สุรพงษ์ วัฒนะจีระ, 187 หน้า. ISBN: 974-14-1968-6

คุณภาพน้ำใต้ดินของประปาหมู่บ้าน จำนวน 119 แห่ง ในจังหวัดลำพูน ประเทศไทย ได้รับการสำรวจพบว่า น้ำใต้ดินของประปาหมู่บ้าน จำนวน 53 แห่ง (คิดเป็นร้อยละ 44.54) มีค่า ฟลูออไรด์ มากกว่า 0.7 มิลลิกรัมต่อลิตร ซึ่งเป็นค่ามาตรฐานน้ำดื่มบรรจุขวดของกระทรวงอุตสาหกรรม นอกจากนี้ ได้มีการสำรวจระดับความรุนแรงของโรคฟันตกกระในเด็กนักเรียนที่มีอายุระหว่าง 13-18 ปี ในจังหวัดลำพูน พบว่า พื้นที่ที่มีค่าฟลูออไรด์ในน้ำใต้ดินสูง จะสำรวจพบระดับความรุนแรงของโรคฟันตกกระในระดับที่สูง นอกจากการสำรวจคุณภาพน้ำใต้ดินของประปาหมู่บ้านและการสำรวจระดับความรุนแรงของโรคฟันตกกระในเด็กนักเรียนแล้ว ได้มีการดำเนินการศึกษาประสิทธิภาพของเมมเบรนออสโมซิสย้อนกลับ ชนิดความดันต่ำ (UTC-70) และ นาโนเมมเบรน (UTC-60) ในการบำบัดน้ำใต้ดินที่มีการปนเปื้อนของสารฟลูออไรด์ ดังนั้น ตัวอย่างน้ำใต้ดินที่มีการปนเปื้อนของสารฟลูออไรด์ในระดับที่แตกต่างกัน จำนวน 2 แหล่ง ของจังหวัดลำพูน คือ โรงผลิตน้ำบรรจุขวดประตูโขง และ โรงกรองน้ำสันป่าเหียง จึงถูกนำมาทำการวิเคราะห์และทดลอง ระหว่างเดือน กันยายน 2548 ถึงเดือน มกราคม 2549 พบว่า ตัวอย่างน้ำใต้ดินของโรงผลิตน้ำบรรจุขวดประตูโขง มีค่าความเข้มข้นของสารฟลูออไรด์ อยู่ระหว่าง 12.05-16.98 มิลลิกรัมต่อลิตร จัดว่าเป็น น้ำใต้ดินที่มีค่าความเข้มข้นของสารฟลูออไรด์สูงมาก ส่วนตัวอย่างน้ำใต้ดินของโรงกรองน้ำสันป่าเหียง มีค่าความเข้มข้นของสารฟลูออไรด์ อยู่ระหว่าง 2.84-3.12 มิลลิกรัมต่อลิตร จัดว่าเป็น น้ำใต้ดินที่มีค่าความเข้มข้นของสารฟลูออไรด์สูงจากผลการศึกษาประสิทธิภาพของนาโนเมมเบรน (UTC-60) พบว่า น้ำใต้ดินของโรงผลิตน้ำบรรจุขวดประตูโขงมี ประสิทธิภาพสูงสุดในการบำบัดสารฟลูออไรด์ เท่ากับ 80 เปอร์เซ็นต์ ภายใต้ค่าแรงดันน้ำ เท่ากับ 0.5 MPa และค่าพีเอชเริ่มต้นของน้ำใต้ดิน ประมาณ 8 ในส่วนของน้ำใต้ดินของโรงกรองน้ำสันป่าเหียง มีประสิทธิภาพสูงสุดในการบำบัดสารฟลูออไรด์ เท่ากับ 60 เปอร์เซ็นต์ ภายใต้ค่าแรงดันน้ำ เท่ากับ 0.5 MPa และค่าพีเอชเริ่มต้นของน้ำใต้ดิน ประมาณ 7 สำหรับการศึกษาประสิทธิภาพของเมมเบรนออสโมซิสย้อนกลับ ชนิดความดันต่ำ (UTC-70)พบว่า ภายใต้ค่าแรงดันน้ำ เท่ากับ 0.5 MPa และค่าพีเอชเริ่มต้นของน้ำใต้ดิน เท่ากับ 7 ที่สภาวะนี้ ประสิทธิภาพสูงสุดในการบำบัดสารฟลูออไรด์ของน้ำใต้ดินของทั้งสองแหล่งน้ำ มีค่ามากกว่า 90 เปอร์เซ็นต์ ดังนั้น สรุปได้ว่า ประสิทธิภาพของเมมเบรนออสโมซิสย้อนกลับ ชนิดความดันต่ำ (UTC-70) ในการบำบัดน้ำใต้ดินที่มีการปนเปื้อนของสารฟลูออไรด์ มีค่าสูงกว่า ประสิทธิภาพของนาโนเมมเบรน (UTC-60) ในการบำบัดน้ำใต้ดินที่มีการปนเปื้อนของสารฟลูออไรด์ นอกจากนั้นจากผลการทดลอง พบว่า ค่าพีเอชที่จุด isoelectric point ของนาโนเมมเบรน (UTC-60) มีค่าเท่ากับ 5 และ ค่าพีเอชที่จุด isoelectric point ของเมมเบรนออสโมซิสย้อนกลับ ชนิดความดันต่ำ (UTC-70) มีค่าเท่ากับ 6 ตามลำดับ อย่างไรก็ตาม ในกรณีของเมมเบรนออสโมซิสย้อนกลับ ชนิดความดันต่ำ (UTC-70) ควรปรับค่าพีเอชเริ่มต้นของน้ำใต้ดินมากกว่า 4 เพื่อหลีกเลี่ยงการเกิดการบำบัดสารฟลูออไรด์แบบเป็นลบ

สาขาวิชาการจัดการสิ่งแวดล้อม ลายมือชื่อนิสิต......อรรณพ วงศ์เรือง......

ปีการศึกษา 2548 ลายมือชื่ออาจารย์ที่ปรึกษา......

／／4789498420: MAJOR ENVIRONMENTAL MANAGEMENT
KEY WORD: FLUORIDE / ULTRA LOW PRESSURE REVERSE OSMOSIS MEMBRANE / NANO FILTRATION MEMBRANE / DEFLUORIDATION

AUNNOP WONGRUENG: GROUNDWATER DEFLUORIDATION BY ULTRA LOW PRESSURE REVERSE OSMOSIS MEMBRANE AND NANO FILTRATION MEMBRANE. THESIS ADVISOR: ASSIST. PROF. SURAPHONG WATTANACHIRA, D. Eng. 187 pp. ISBN: 974-14-1968-6

Groundwater quality of 119 village waterworks in Lamphun province, Thailand was investigated. It was found that groundwater of 53 village waterworks (44.54%) contain fluoride concentration above 0.7 mg/L which is the bottled drinking water standard by Ministry of Industry of Thailand. Dental fluorosis investigation in children aged between 13 and 18 were also studied. It was found that the severe cases of dental fluorosis were observed significantly in the high fluoride concentration area. Besides the investigation of groundwater quality and severity of dental fluorosis, the experiments of ULPRO membrane (UTC-70) and NF membrane (UTC-60) for defluoridation of fluorotic groundwater were studied so as to remove excessive amount of fluoride in groundwater for serving as drinkable water. Groundwater from 2 selected sites in fluorotic area in Lamphun province, Thailand, namely, Pra Too Khong Bottled Drinking Water Plant (site A) and San Pa Hiang Membrane Plant (site B) were collected between September 2005 and January 2006. Groundwater from site A containing fluoride concentration in the range of 12.05-16.98 mg/L was defined as very high fluoride concentration site (>5 mg/L) whereas groundwater from site B containing fluoride concentration in the range of 2.84-3.12 mg/L was defined as high fluoride concentration site (1-5 mg/L). It was found that the maximum percent fluoride rejection of UTC-60 membrane in groundwater from site A was about 80 % under the operating transmembrane pressure of 0.5 MPa at the feed pH values of natural pH ($\simeq$8) while the maximum percent fluoride rejection in groundwater from site B was about 60 % at the feed pH value of 7. In the case of UTC-70 membrane, more than 90 % of fluoride rejection under OTP of 0.5 MPa at the feed pH value of 7 was achieved in the groundwater from both sites. Thus, it could be stated that the performance of UTC-70 membrane on fluoride removal was higher than that of UTC-60 membrane. In addition, based on the membrane experimental results, it was observed that the approximate pH value at an isoelectric point of UTC-60 membrane was 5 while the pH value at an isoelectric point of UTC-70 membrane was 6. Furthermore, it was found that UTC-70 membrane should not be operated at the feed pH value lower than about 4 so as to avoid negative rejection of fluoride.

Field of study Environmental Management　　Student's signature... Aunnop Wongrueng
Academic year 2005　　Advisor's signature... Suraphong

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ABBREVATIONS AND SYMBOLS

Ca	Calcium
CaF_2	Calcium fluoride
Cl^-	Chloride
$m^3/m^2 \cdot day$	Cubic meter per square meter per day
$Na_3Al \cdot F_6$	Cryorite (sodium aluminium fluoride)
ºC	Degree Celsius
DOC	Dissolved Organic Carbon
DWL	Drinking Water Limit
EC	Electrical Conductivity
FI	Flow Indicator
F^-	Fluoride
$Ca_5(PO_4) \cdot F$	Flurapatite
HMWC	High molecular weight component
HCl	Hydrochloric acid
HF	Hydrogen fluoride
I^-	Iodide
kg/kmol	kilogram per kilo Molar
PbF_2	Lead fluoride
L/m^2	Liter per square meter
LMWC	Low molecular weight component
MPa	Mega Pascal
MF membrane	Microfiltration membrane
µg/g	Microgram per gram
µm	Micrometer
µS/cm	Micro siemens per centimeter
mg/kg	Milligram per kilogram
mg/L	Milligram per Liter

mg/L as $CaCO_3$	Milligram per Liter as calcium carbonate
MW	Molecular Weight
MWCO	Molecular Weight Cut Off
NF membrane	Nano Filtration membrane
nm	Nano meter
NO_3^-	Nitrate
NO_2^-	Nitrite
OTP	Operating Transmembrane Pressure
PO_4^{3-}	Phosphate
K	Potassium
PSCF	Preferential Sorption-Capillary Flow Model
PI	Pressure Indicator
RO membrane	Reverse osmosis membrane
SiF_4	Silicon tetrafluoride
Na	Sodium
NaF	Sodium fluoride
cm^2	Square centimeter
SO_4^{2-}	Sulfate
T-Alk	Total Alkalinity
T-Fe	Total Iron
TOC	Total Organic Carbon
Tp	Transmembrane pressure
THMFP	Trihalomethane Formation Potential
ULPRO membrane	Ultra low pressure reverse osmosis membrane
UF membrane	Ultrafiltration membrane
UTC	Ultra Thin Composite
WHO	World Health Organization

CHAPTER I

INTRODUCTION

1.1 Motivation

Fluoride is a hazardous inorganic specie that seriously endangers the aquatic environment (Ndiaye et al., 2005). Fluoride is found in the earth's crust, especially in a form of fluorspar (CaF_2), a common mineral containing fluoride (Connett and Connett, 2003). Cryorite (Na_3AlF_6), flurapatite ($Ca_5 (PO_4).F$), granitic rocks, and other phosphate rocks are also mineral source of fluoride.

Fluoride is naturally released into groundwater through two main processes: the weathering process and leaching process. Most high fluoride concentrations are normally found at the foot of high mountains and in the bedrock aquifers of granites (Banks et al., 1998; Dowgiallo, 2000; Botha and Van Rooy, 2001; Shanker et al., 2003). It is also released from the effluent of some industries to surface water; for instance, in the effluents from the electronics industry and steel manufacturers.

The northern part of Thailand, especially Lamphun province, has an excessive amount of fluoride in their groundwater, which is used as drinking water. The high fluoride level in the groundwater in Lamphun province is in part of geological origin because the bedrock aquifers of the granites in this region have a fluoride ledge, which lies across the aquifers (Intercountry Centre for Oral Health, 1997). Therefore, many villagers in Lamphun province have been affected by dental and skeletal fluorosis for many years. Groundwater in some districts of Lamphun province is found to have fluoride levels of between 10 and 15 mg/L, which is higher than the drinking water limit set by the World Health Organization (1.5 mg/L) and high enough to be a risk to the health of villagers in districts such as Muang district and Ban Thi districts.

In the past, ion exchange by bone charcoal was applied to remove fluoride in the groundwater in Lamphun province. Although this method could remove fluoride efficiently, it was not appreciated the villagers because grease from the bones was released and made the effluent water undesired.

Membrane filtration by reverse osmosis membrane was a technology which was applied for defluoridation in Lamphun province (Matsui, 2004). This technology provides the highest quality of produced water when compared with other technologies. However, the disadvantage of the reverse osmosis membrane process is its high operating cost, since this membrane is operated at high pressures, 1.5-15 MPa. Therefore, many villages have difficulty in gaining this technology.

To deal with above problems, groundwater samples from the fluorotic area in Lamphun province were used as the water samples. New kinds of membranes, namely, ultra low pressure reverse osmosis membrane (ULPRO membrane) and nano filtration membrane (NF membrane) were studied. Therefore, this study focused on the performance of ULPRO membrane for treatment of fluorotic groundwater and compared it to the NF membrane results. Additionally, site investigation for the survey of fluoride concentration in groundwater in Lamphun province, urine test, and severity of dental fluorosis examination were also done to evaluate the effect of fluoride on humans' health.

1.2 Objectives

- To investigate the fluoride concentration in groundwater and the severity of dental fluorosis in a fluorotic area in Lamphun province.

- To study the performance of the ultra low pressure reverse osmosis membrane (ULPRO membrane) process for the defluoridation of fluorotic groundwater.
- To determine the optimal condition for fluoride removal using the ULPRO membrane.
- To compare the nano filtration membrane (NF membrane) process for groundwater defluoridation with the results of the ULPRO membrane process.

1.3 Hypothesis

- The ULPRO membrane is a new membrane especially developed for operation under low pressure conditions (0.100-0.500 MPa) whereas a typical RO membrane requires very high operating pressure (1.5-15 MPa).
- The ULPRO membrane may be an alternative way to remove fluoride from fluorotic groundwater.
- The principal operating factors for defluoridation by a membrane process are operating transmembrane pressure, feed pH and fluoride concentration.

1.4 Scope of the Study

- Fluoride concentration and characteristics of groundwater in the fluorotic area in Lamphun province were investigated.
- The severity of dental fluorosis in students from high fluorotic area and low fluorotic area was also investigated.
- Groundwater samples from 2 sites in the fluorotic area in Lamphun province categorized in terms of very high (>5 mg/L) and high (1-5 mg/L) fluoride concentrations in Lamphun province were used in the membrane experiment.

- The ULPRO membrane (UTC-70 membrane) and the NF membrane (UTC-60 membrane) of Toray Company, Japan was employed in the membrane experiment.
- Effects of various experimental conditions of operating transmembrane pressures and pH were studied.

1.5 Benefits of this Study

- Knowing the performance of the ULPRO membrane (UTC-70 membrane) and the NF membrane (UTC-60 membrane) for the defluoridation of fluorotic groundwater that has higher fluoride concentration than the drinking water standard.
- Results from this study would be useful for minimizing the risk of dental fluorosis and skeletal fluorosis in fluorotic areas by using the ULPRO membrane (UTC-70 membrane) and the NF membrane (UTC-60 membrane) for the defluoridation of fluorotic groundwater.
- Results from this study would be useful for reducing the operating cost by using the ULPRO membrane (UTC-70 membrane) and the NF membrane (UTC-60 membrane) instead of the typical reverse osmosis membrane (RO membrane).
- Knowing the severity of dental fluorosis in students in both high fluorotic area and low fluorotic area in Lamphun province.
- Results from this study would be useful for developing a new membrane to remove fluoride efficiently for Thailand in the future.

CHAPTER II

BACKGROUND AND LITERATURE REVIEWS

2.1 Fluoride

2.1.1 Background and History

Fluoride (F^-) is the ionic form of fluorine which commonly occurs in aqueous solutions. As a halogen, fluorine forms a monovalent ion (-1 charge). Gerenally, fluoride forms a binary compound with another element or radical (Wikipedia, 2005). Examples of common fluoride compounds include hydrogen fluoride (HF), calcium fluoride (CaF_2), sodium fluoride (NaF), etc.

Fluoride exists fairly abundantly in the earth's crust and can enter the groundwater by natural processes; the soil at the foot of mountains is particularly likely to be high in fluoride from the weathering and leaching of bedrock with high fluoride content (UNICEF, 2005). The concentration of fluoride in water resources depends on the solubility of the mineral containing fluoride. High fluoride concentrations are found in water resources with low calcium concentrations and in groundwater in which there is some interaction between water and minerals containing fluoride.

UNICEF (2005) proposed that high levels of fluoride concentration in water are very harmful to aquatic organisms and humans who used the water for drinking. Both dental fluorosis and skeletal fluorosis are among the threatening epidemics to human’s health. Many countries suffer from dental and skeletal fluorosis for example India, South

Africa, China, Mexico, Sri Lanka, Argentina, Egypt, Bangladesh, Uganda, Australia, New Zealand, and Thailand.

Fluorides also pollute the environment via coal combustion and process waters and waste from various industrial processes; including steel manufacture, primary aluminum, copper, and nickel production, phosphate ore processing, phosphate fertilizer production, glass, brick and ceramic manufacturing, and glue and adhesive production (Environmental Health Criteria 227 (EHC 227), 2002).

Since the days of World War II, when the world's first atomic bomb was built, U.S. public health leaders had claimed that a low concentration of fluoride was safe for people, and good for children's teeth (Griffiths and Bryson, 2004). For this reason, fluoride was added to public drinking water (fluoridation) in the United States from the 1945's after World War II to prevent tooth decay. Many countries in Asia and Europe added fluoride to public drinking water for years too.

Since that in the 1950's, fluoride has been put into commercial products such as toothpaste, other dental products, and dietary supplements (American Dental Hygienists' Association, 2005). Nowadays fluoride is involved in many products that are associated with household consumption. Few people have awareness of the effects of fluoride to their health. The reason is only the advantages of fluoride are advertised while the disadvantages of fluoride are buried.

However, Griffiths and Bryson (2004) showed the secret World War II documents including declassified papers of the Manhattan Project, the U.S. military group that built the atomic bomb. That document indicated that fluoride was the key chemical in atomic bomb production. A large quantity of fluoride approximately millions of tons was essential for the manufacture of bomb-grade uranium and plutonium for nuclear weapons throughout the Cold War. As one of the most toxic chemicals known, fluoride rapidly arose as the leading chemical health hazard of the U.S. atomic bomb program, both for workers and the surrounding communities.

Barry (2002) reported that fluoride was a poison, more poisonous than lead, and slightly less poisonous than arsenic. Fluoride is also compiled in bones and tissues, not only the teeth. Many studies were done on animals and indicated the obvious dangers.

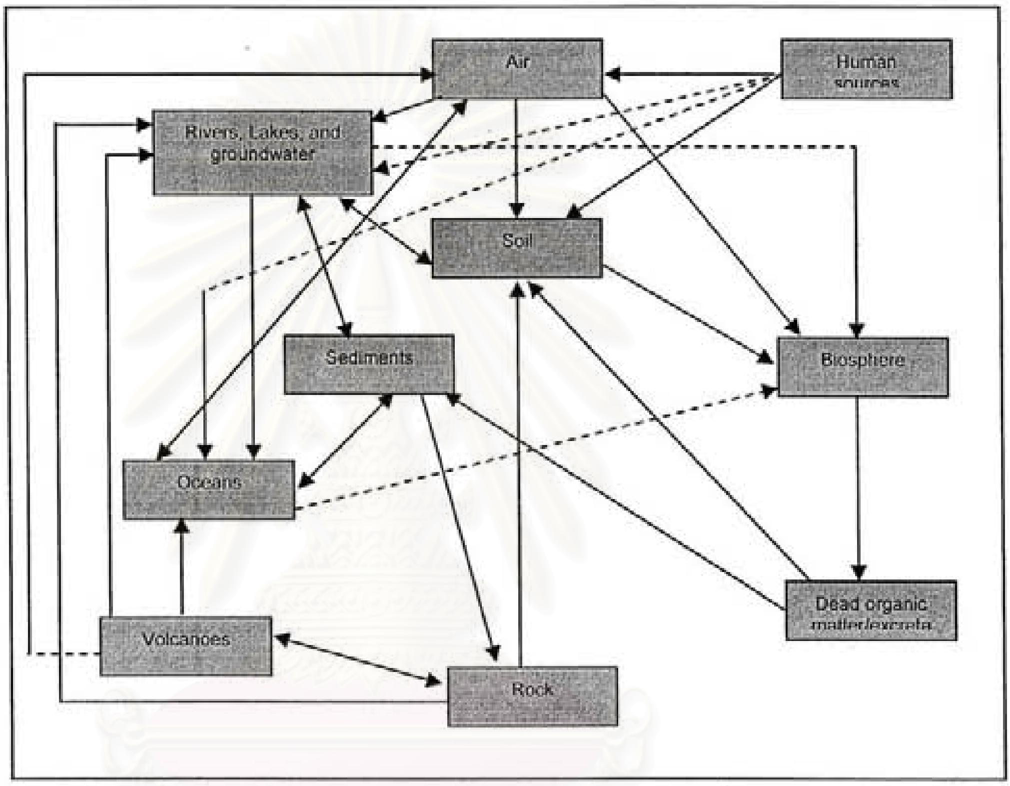
Leverett, (1986) and the National Research Council, (1993) indicated that dental fluorosis was the first observable symptom of fluoride poisoning. It affects from 8% to 51% of children who drinking fluoridated water and has substantially increased over the last 40 years. It was also symptomatic of neurological impairment.

Lewis, (1937), Hodge, (1979), the National Research Council, (1993) and the WHO, (1999) proposed that fluoride can cause severe skeletal fluorosis at high levels of fluoride concentration. Long-term exposure to fluoride was found in water and foods. The beginning stages of skeletal fluorosis includes pains in bones and joints, sensations of burning, pricking, and tingling in the limbs, muscle weakness, chronic fatigue, gastrointestinal disorders, reduced appetite, backache, osteoarthritis, etc. In severe cases, the bone structure may change and ligaments may be calcified, resulting in the impairment of muscles and pain.

Mullenix et al. (1995) showed that fluoride accumulated in the brains of animals when they were exposed to moderate levels. Rupture to the brain occurred and the behavior patterns of the animals was adversely effected. The young pregnant animals that received a relatively low concentration of fluoride showed permanent effects to the brain which were seen as hyperactivity. Both young animals and adult animals that were given fluoride experienced opposite effects either hypoactivity or sluggishness.

2.1.2 Cycle of fluoride in environment

Figure 2.1 shows the cycle of fluoride in environment and it could be summarized that all components in this cycle have a relationship with each of the other components.



(Source: EHC 227, 2002)

Figure 2.1 Cycle of fluoride in environment

The fate of fluoride in the atmosphere is initially influenced by vaporization, aerosol formation, wet and dry deposition, and hydrolysis (Environment Canada, 1994). Gaseous forms include hydrogen fluoride, silicon tetrafluoride (SiF_4), fluorosilicic acid and sulfur hexafluoride. Particulate forms include sodium aluminium fluoride (cryolite), aluminium fluoride, calcium fluoride, sodium hexafluorosilicate, lead fluoride (PbF_2) and calcium phosphate fluoride (fluorapatite) (EHC 227, 2002).

In water resources, the fate of fluoride is influenced by pH, water hardness and the presence of ion-exchange materials such as clays (Environment Canada, 1994).

In the areas of high acidity and alkalinity, fluoride may leach from fluoride-containing minerals into water resource (Cuker and Shilts, 1979).

Fluoride in soil is mainly bound in complex forms (EHC 227, 2002). Factors that influence the mobility of inorganic fluorides in soils are pH and the formation of aluminium and calcium complexes (Pickering, 1985; Environment Canada, 1994). The fate of fluoride released to soils also depends on its chemical form, its rate of deposition, soil chemistry, and climate (Davison, 1983).

2.1.3 Human Exposure to Fluoride

It has been observed that human exposure to fluoride has increased since World War II, not only through fluoridation but also through fluoridated commercial products. And fluoride which polluted to environment by some industries should be considered as sources of human exposure to fluoride (Bryson and Griffiths, 2004).

2.1.3.1 Drinking Water

Fluoride is commonly found in the environment and thus, sources of drinking-water are likely to contain some small amount of fluoride (EHC 227, 2002). The amount of fluoride present naturally in non-controlled fluoridated drinking-water is widely variable and dependence upon the geological condition from which the water is obtained (EHC 227, 2002).

In areas that endemic of dental and skeletal fluorosis have been reported, fluoride concentration in groundwater have been recognized in the range of 3 mg/L to more than 20 mg/L (WHO, 1984; Krishnamachari, 1987; Kaminsky et al., 1990; US DHHS, 1991). Fluoride in drinking water from three countries is summarized in Table 2.1.

Table 2.1 Fluoride in drinking water in some countries

Location	F^- (mg/L)	Reference
Canada [a]	0.05-0.21	Health Canada (1993)
Germany [b]	0.02-0.17	Bergmann (1995)
USA [c]	< 0.1-1.0	US EPA (1985) and US DHHS (1991)

(Source: EHC 227, 2002)

[a] Non-fluoridated samples collected between 1984 and 1989 from 67 communities in 5 provinces
[b] Drinking-water collected from various facilities in Germany between 1975 and 1986
[c] 62% of the US population served by public supplies range from <0.1 to 1.2 mg/liter
14% of the US population served by public supplies range from 1 to 2 mg/liter

2.1.3.2 Food Products

Fluoride concentrations in foods are affected by the fluoride in water that is used in preparation or processing. It is mostly found in beverages and dry foodstuffs to which water is added before consumption (Kumpulainen & Koivistoinen, 1977; Schamschula et al., 1988).

Kabasakalis and Tsolaki (1994) proposed that fluoride concentrations in vegetables irrigated with water containing fluoride 10 mg/L increased compared with fluoride concentrations in vegetables grown with irrigation water containing low fluoride concentrations (0.15 mg/L). Results of various studies in which fluoride concentration in foods have been evaluated are presented in Table 2.2.

Table 2.2 Fluoride in foodstuffs

Food	F^- (mg/kg)	Remark	Reference
Milk and milk products	0.019-0.16 [a]	Sampled between 1981 and 1989 in Germany	Bergmann (1995)
Meat and poultry	0.04-1.2	17 varieties of (cooked and raw) meat and poultry in Canada	Dabeka and McKenzie (1995)
Fish	0.06-1.7	6 varieties of fish available in USA	Whitford (1996)
Baked goods and cereals	0.06-0.49	13 varieties of baked goods and cereals available in Hungary	Schamschula et al. (1988a)
Vegetables	0.28–1.34	Three staple vegetables consumed in three villages in China	Chen et al. (1996)
Fruits and fruit juices	0.02–2.8 [a]	532 varieties of fruit juice and juice-flavored beverages in USA	Kiritsy et al. (1996)

(Source: EHC 227, 2002)
[a] For liquid products, concentration in mg/L

2.1.3.3 Dental Products

Dental products generally contain fluoride at concentrations between 1000 and 1500 μg/g (Whitford, 1987; Sloof et al., 1989; Newbrun, 1992). Some dental products produced for children contain lower levels of fluoride between 250 and 500 μg/g (Newbrun, 1992). Dental products which include toothpaste, mouthwash and fluoride supplements have been suggested as major sources of fluoride (Ekstrand, 1987; Drummond et al., 1990). Additionally, mouth rinses products might contain fluoride about 250-500 mg/L whereas mouthwash products provided for weekly or biweekly use might contain about 900-1000 mg/L of fluoride (Sloof et al., 1989; Grad, 1990; Whitford, 1996).

2.1.4 Health Effects

Major effects of fluoride exposure on human health which accepted worldwide include dental fluorosis and skeletal fluorosis. The effects of fluoride on human health are summarized in Table 2.3.

Table 2.3 Effects of fluoride on human's health

Fluoride concentration	Effects
Low	Protection against dental caries
0.9 - 1.2 mg/L	An adverse effect on tooth enamel and give rise to mild dental fluorosis (prevalence: 12~33%)
3 - 6 mg/L	Skeletal fluorosis with adverse changes in bone structure
Over 10 mg/L	Crippling skeletal fluorosis

(Source: International Program on Chemical Safety, 2002)

2.1.4.1 Dental Fluorosis

Dental fluorosis is a condition that results from ingestion of the excessive amount of fluoride concentrations during the formation of the tooth. It is termed as hypoplasia or hypomineralization of dental enamel which is associated with the excessive incorporation of fluoride into these structures.

The severity of dental fluorosis, usually characterized as ranging from mild to severe or ranging from level 0 to level 5, it is related to the degree of fluoride exposure during the formation of tooth. Mild dental fluorosis is commonly characterized by the appearance of small white areas in the enamel whereas severe dental fluorosis is a condition that the enamel is stained and pitted (mottled) in appearance (EHC 227, 2002).

In human fluorotic teeth, the most important feature is a hypomineralization of the dental enamel. The staining and pitting of fluorosis dental enamel are both post eruption phenomena (i.e., acquired after tooth eruption and occur as a consequence of the enamel hypomineralization). The incorporation of excessive amounts of fluoride into enamel is believed to interfere with its normal maturation, as a result of alterations in the rheologic structure of the enamel matrix and effects on cellular metabolic processes associated with normal enamel development (WHO, 1994; Aoba, 1997; Whitford, 1997). Experimental animal studies suggest that this hypomineralization results from fluoride disturbance of the process of enamel maturation (Richards et al., 1986).

Figure 2.2, 2.3, and 2.4 illustrate the severity of dental fluorosis; mild fluorosis, moderate fluorosis, and severe fluorosis, respectively.

Figure 2.2 Dental fluorosis-mild fluorosis

Figure 2.3 Dental fluorosis-moderate fluorosis

Figure 2.4 Dental fluorosis-severe fluorosis

2.1.4.2 Skeletal Fluorosis

Skeletal fluorosis is a clinical condition that may arise following long-term exposure (both inhalation and ingestion) to a high fluoride concentration. Although the incorporation of fluoride into bone may increase the stability of the crystal lattice and render the bone less soluble, bone mineralization is delayed or inhibited (Grynpas, 1990), and accordingly the bones may become brittle and their tensile strength may be reduced.

The severity of the effects associated with skeletal fluorosis is related to the amount of fluoride incorporated into bone. In a preclinical phase, the fluorotic patient may be relatively asymptomatic, with only a slight increase in bone mass, detected radiographically.

Sporadic pain and stiffness of the joints, chronic joint pain, osteosclerosis of cancellous bone and the calcification of ligaments are associated with the first and second clinical stages of skeletal fluorosis. Crippling skeletal fluorosis (the third clinical stages) may be associated with the limited movement of the joints, skeletal deformities, intense calcification of ligaments, muscle wasting and neurological deficits (Krishnamachari, 1987; Kaminsky et al., 1990; US DHHS, 1991). A consistent finding in cases of chronically elevated fluoride uptake is an increase in mineralization lag time of bone, which can be demonstrated by dynamic histomorphometry (Boivin et al., 1989).

Osteomalacia may be observed in fluorotic individuals with a reduced or suboptimal intake of calcium; secondary hyperparathyroidism may also be observed in a subset of patients (Krishnamachari, 1987; US DHHS, 1991). Apparently in combination with nutritional deficiencies, high intakes of fluoride and the subsequent osteomalacia may also lead to bone deformities in children such as genu valgum, originally described as Kenhardt bone disease (Jackson, 1962; Krishnamachari & Krishnaswamy, 1973; Krishnamachari, 1976; Chakma et al., 2000). The pictures of skeletal fluorosis are shown in Figure 2.5.

(a) Crippling skeletal fluorosis

(b) Skeletal fluorosis

Figure 2.5 Skeletal fluorosis

A number of factors, such as age, nutritional status, renal function and calcium intake, in addition to the extent and duration of exposure, can influence the amount of fluoride deposited in bone and, consequently, the development of skeletal fluorosis (US DHHS, 1991). Individuals with impaired renal function, such as those with diabetes, may be more prone to developing fluoride-related toxicological effects due to their diminished excretion of fluoride (Kaminsky et al., 1990; US DHHS, 1991). Skeletal fluorosis may be reversible to some degree in a manner that is dependent upon the extent of bone remodeling (Grandjean & Thomsen, 1983).

2.2 Membrane Filtration

2.2.1 Background

Membrane filtration is technology which is applied to purify water that is contaminated with undesirable components by passing water through a membrane as a filter material (Fujita et al., 1994). Certain components can pass through the membrane, while other components are rejected (Lenntech, 2005).

The membrane can be categorized into four types, microfiltration membrane (MF membrane), ultrafiltration membrane (UF membrane), nanofiltration membrane (NF membrane), and reverse osmosis membrane (RO membrane), by using differential pressure on both sides of each membrane and the pore size of each membrane (Metcalf and Eddy, 2003). The characteristics of membranes are shown in Table 2.4.

Table 2.4 Characteristics of RO membrane, NF membrane, UF membrane, MF membrane

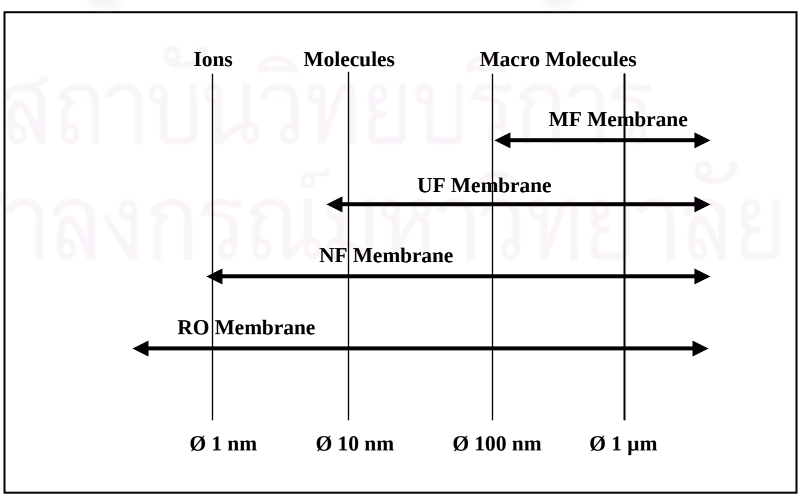
	RO membrane	NF membrane	UF membrane	MF membrane
Structure	Asymmetrical	Asymmetrical	Asymmetrical	Asymmetrical Symmetrical
Pore size	< 0.002 μm	< 0.002 μm	0.2 - 0.02μm	4 – 0.02 μm
Rejection	HMWC, LMWC glucose, amino acids	HMWC, polyvalent neg. ions	Macro molecules, polysaccharides	Particles, clay
Membrane material	Cellulose acetate, Thin film composite	Cellulose acetate, Thin film composite	Polysulfone, Thin film composite	Ceramic, Polysulfone
Operating pressure	1.5-15 MPa	0.5-3.5 MPa	0.1-1 MPa	< 0.2 MPa
Method	Dead-end filtration Cross-flow filtration	Dead-end filtration Cross-flow filtration	Dead-end filtration Cross-flow filtration	Dead-end filtration Cross-flow filtration

Source: Jørgen Wagner, 2001)
HMWC = High Molecular Weight Component, LMWC = Low Molecular Weight Component

The required pressure to operate the NF membrane (approximately 0.5-3.5 MPa) and the RO membrane (approximately 1.5-15 MPa) is higher than the required pressure for the MF membrane (approximately < 0.2 MPa) and the UF membrane (approximately 0.1-1.0 MPa) (Wagner, 2001). Generally, the MF membrane, the UF membrane, and the NF membrane are followed the principle of pores while the RO membrane is operated under the molecular interaction and diffusion. However, NF membrane is also operated under electrical repulsion since the charged layer on its surface.

The MF membrane and the UF membrane are considered when undesirable components are larger particles. Because the permeate flux of these two membranes are high while the differential pressures are low. When ions are considered to be removed from water, NF membrane and RO membrane are employed. In contrast, while the permeate water flux of these two membranes are low, the differential pressures are high.

Figure 2.6 illustrates the operating range of each membrane to remove undesirable components. It can be concluded that the RO membrane has the widest operating range to remove almost all undesirable components in water while the MF membrane has the narrowest operating range to remove undesirable components and the MF membrane should be strongly recommended as a pretreatment unit.



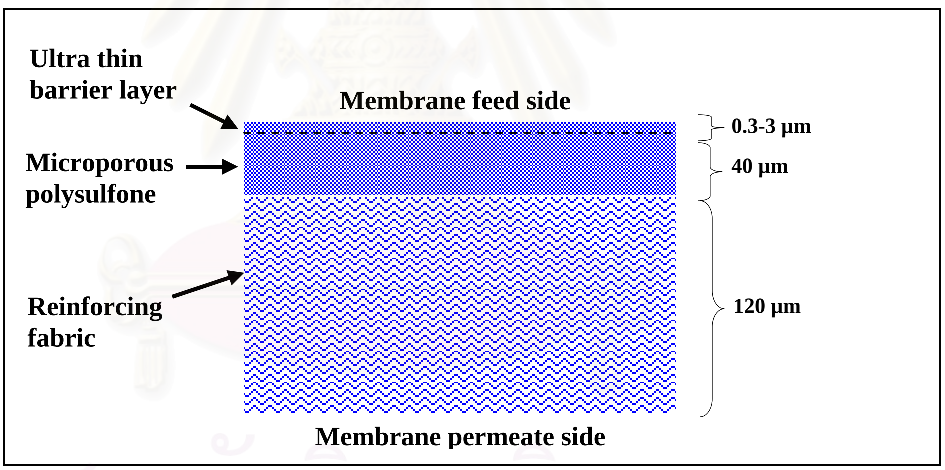
(Source: Lenntech, 2005)

Figure 2.6 Operating ranges of membranes on undesirable components removal

2.2.2 Nano Filtration Membrane (NF membrane)

Nanofiltration is a new pressure driven membrane between ultrafiltration membrane and reverse osmosis membrane with some interesting features (Rautenbach et al., 1990; Madaeni, 1999). They are as follows:

- The NF membrane can be operated typically under a transmembrane pressure between 0.5 and 2.0 MPa.
- A fraction capacity for various organic components in aqueous solutions, the molecular weight cut off is in the range of 300 kg/kmol molecular weight.
- The potential of realizing the Donnan effect with respect to anions of different valency.



(Source: Adapted from Robert, 1993)

Figure 2.7 Cross-section of thin film composite membrane

Most NF membranes are thin film composite membranes as shown in Figure 2.7. The ultra thin layer generally consists of negatively charged chemical groups. Salt rejection by the NF membrane is mainly due to the electrostatic interaction between ions and membranes. For an ion selective membrane, solutions which contain different free ions, an unequal distribution of ions result across the membrane. This is recognized as the Donnan effect (Raman et al., 1994). Because almost all NF membranes contain negatively charged hydrophilic groups attached to a hydrophobic ultrafiltration support membrane (polysulfone), they have higher fluxes than the typical RO membrane. This is due to the favorable orientation of water dipoles. Due to the negatively charged chemical groups on its surface, the NF membrane also has improved fouling resistance against hydrophobic colloids, oils, proteins, and other organics (Raman et al., 1994). However, components with a charge opposite to the charge of the membrane interact with it, cause membrane fouling.

The NF membranes have been employed for many purposes especially in drinking water treatment processes. These membranes provide high flux at low operating pressure and low operating costs as opposed to the RO membranes. Rautenbach et al. (1995) recommended the preferable areas of application as follows

- A high rejection for single valent salts is not required or even unwanted.
- A separation of anions of a different valency must be achieved.
- Separation of high and low molecular weight organics is required.
- Removal of color is required while TOC reduction is necessary.

Rautenbach and Groschl (1990) reported the application of the NF membrane on the separation of nitrate from well water. The NF-40 membrane from Film Tec was used in this studied. It was found that nitrate rejection of well water was low for feed containing sulfate. Sulfate added to well water containing nitrate would result in nitrate passing through the membrane while sulfate and other highly charged ions would be rejected. The permeate water then could be treated with ion exchange to remove the nitrate.

Simons (1993) studied the removal of sulfate, boron, fluoride, and selenium from ash dam water by using various types of NF membranes such as Nitto Denko NTR-7410, Film Tec NF-40, and Toray UTC-60. It was found that NTR-7410 with a flux of about 17 L/m^2 at 1 MPa could reject sulfate at about 97% and selenium >80% for all range of pH;

however, it had zero rejection for fluoride if the pH was less than 4.5; and zero rejection for boron for all ranges of pH. For NF-40, it was observed that at a pH of 3, the rejection of selenium was very large, exceeding that of sulfate. However, the rejection of fluoride and boron were close to zero. In the case of UTC-60 at a pH of 3, the rejection of selenium was less than those of NTR-7410 and NF-40. However, fluoride rejection was high in UTC-60. The reason was that Toray membranes consist of both weakly basic and weakly acidic functional groups.

Ratanatamskul et al. (1996) investigated the application of new low pressure nanofiltration membranes on the treatment of anionic pollutants such as nitrate, nitrite, phosphate, sulfate, and chloride ions. These anionic pollutants were examined as a function of transmembrane pressure, cross-flow velocity, and temperature under an operating transmembrane pressure in the range of 0.49-0.03 MPa. Negative rejection was also studied under referred operating transmembrane pressure in the case of membrane type NTR-7250.

In the case of the NF membranes, namely, UTC-60 membrane of Toray company which employed in this study, it could be applied in many drinking water applications. UTC-60 membrane is similar to UTC-70 membrane in terms of the material and structure, but has pores sizes that are ten times larger. Thus, UTC-60 membrane specific information can be found in description of material and structure of UTC-70 membrane in section 2.2.3.

2.2.3 Ultra Low Pressure Reverse Osmosis Membrane (ULPRO membrane)

Most of ultra low pressure reverse osmosis membranes (ULPRO membrane) are also thin film composite membranes as same as the NF membrane. The ultra thin layer also consists of negatively charged sulphone or carboxyl group as illustrated in Figure 2.7.

ULPRO membranes can be described as the NF membranes but are better than the commercial NF membranes in ions rejection and flux production (Ozaki et al., 2000).

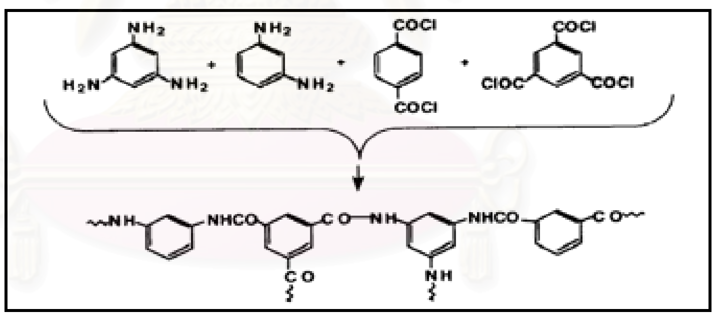
ULPRO membrane is utilized under the operating transmembrane pressure in the range of 0.2-0.9 MPa. In this referred range, ULPRO membrane can provide a specific flux of more than 60 L/m^2-h·MPa. This specific flux is about 2 times of the specific flux of current generations of composite reverse osmosis membranes (Ozaki et al., 2000). ULPRO membranes have been identified as energy saving membranes with effectively rejecting salts, trihalomethane formation potential (THMFP), heavy metals, color, and all micro organisms (Masahiko and Hiroki, 1996; Gerard et al., 1998).

For more details of a thin film composite membrane, a thin film composite membrane may be defined as a bi-layer film formed by a two-step process. Such a membrane typically consists of a thick, porous, nonselective layer formed in the first process step, which is subsequently overcoated with an ultra thin barrier layer on its top surface in a second process step. The two layers are always different from one another in chemical composition (Petersen, 1993).

A typical thin film composite membrane as generally produced today is shown schematically in Figure 2.7. A base layer of a woven or a non-woven fabric (for handling strength) is overcoated with a layer of an anisotropic micro porous polymer (usually polysulfone). The surface of the micro porous support is coated with an ultra thin polymeric composition, which provides the controlling properties as semi-permeability (Petersen, 1993).

Petersen (1993) concluded that each individual layer can be optimized for its particular function, i.e. the ultra thin barrier layer can be optimized for the desired combination of solvent flux and solute rejection, while the porous support layer can be optimized for maximum strength and compression resistance combined with minimum resistance to permeate flow. Moreover, various chemical compositions can be formed into ultra thin barrier layers, including both linear and cross-linked polymers. The ability to generate an ultra thin layer in situ on a micro porous substrate also allows one to generate and use several of the cross-linked polymeric compositions, which can exhibit superior hydrophilic (viz. higher water permeability) and superior chemical resistance compared to linear polymeric compositions.

With regard to UTC-70 membrane, Petersen (1993) reviewed that it was developed by Toray Corporation, Japan and was the basis of their SU-700 series of spiral element products. This membrane contains an aromatic polyamide barrier layer consisting of a blend of diamine and triamine interfacial reacted with a blend of diacyl and triacyl halides. The diamine is 1, 3-benzenediamine and the triamine appears to be 1, 3, 5-benzenetriamine. The triacyl halide is apparently trimesoyl chloride, and the diacyl halide, terephthaloyl chloride. The probable chemistry of UTC-70 membrane is given in Figure 2.8.

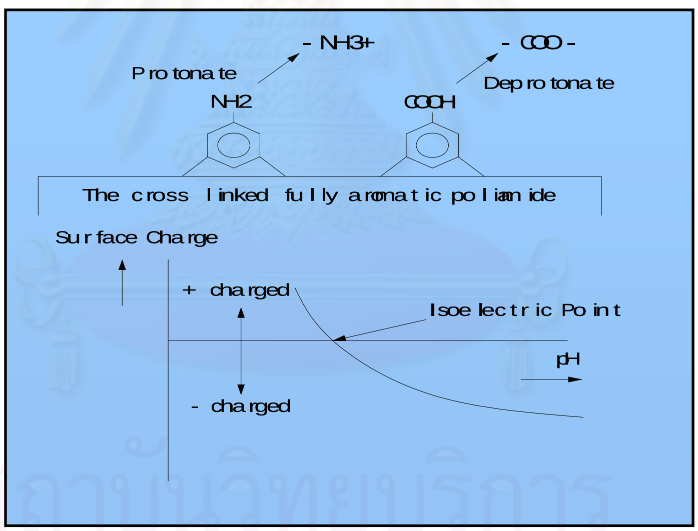


(Source: Toray Industries)

Figure 2.8 Probable chemistry of UTC-70 membrane

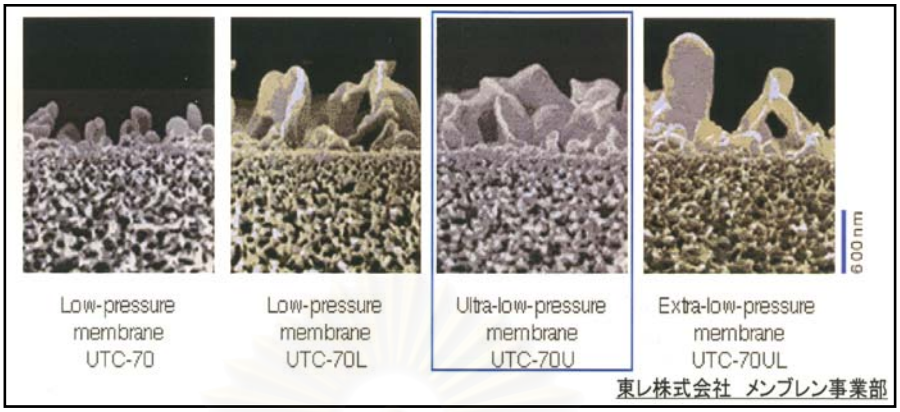
The 1, 3, 5-benzenetriamine monomer, if reacted solely with trimesoyl chloride, would have given such a rigid, a cross-linked structure, that the resulting barrier layer likely would have been too brittle. This is apparently mitigated by using di-functional intermediates in the reactant blends. The partition coefficients of the triamine and the diamine are likely different, the triamine being potentially more water-bound. Thus, as mentioned earlier for the case of a 1, 3-benzenediamine/piperaxine blend, the final membrane composition would not necessarily duplicate the starting ratio of the aromatic amines in the aqueous solution. Nor, for that matter, has isophthaloyl or terephthaloyl chloride been proven to be equal in reactivity with trimesoyl chloride toward aromatic amines.

Figure 2.9 is a drawing of UTC-70 membrane surface. It was found that there are 2 functional groups on its surface consist of amine group and carboxylate group. It could be indicated that UTC-70 membrane consists of negative charges on its surface at a pH above isoelectric point whereas at a pH lower than isoelectric point, positive charges on its surface are observed. The pH value at the isoelectric point of UTC-70 membrane which studied by Yasuhiro Matsui with titration method was observed at pH value about 6. The pictures of the surface of UTC-70 membrane series are depicted in Figure 2.10.



(Source: Toray Industries)

Figure 2.9 Drawing of UTC-70 membrane surface



(Source: Toray Industries)

Figure 2.10 Surfaces of UTC-70 membrane series

In the case of NF membrane (UTC-60), Szoke et al. (2002) proposed that an isoelectric point of the NF membrane could be roughly estimated at a feed pH value at which a turning point of an ion rejection was observed. At this point, membrane surface charge is nearly zero and named as "isoelectric point".

Theoretically, when the feed pH values of this membrane were higher than the isoelectric point, the ionization of the polar head groups would occur to form hydrogen ions in the subphase and carboxylate ions on membrane surface as

Negative surface charge

$$C_n\, H_{2n+1}\, COOH \;\; <\!\text{- - - -}\!> \;\; \boxed{\mathbf{C_n\, H_{2n+1}\, CO_2^-}} + H^+$$

This phenomenon gave membrane having negative charged surface. However, when the feed pH values were less than the isoelectric point of membrane, amine group on surface of the membrane would take part and the membrane surface became a positive charged surface as the following equation.

Positive surface charge

$$C_n\, H_{2n+1}\, NH_2 + H_3O^+ \;\; <\!\text{- - - -}\!> \;\; \boxed{\mathbf{C_n\, H_{2n+1}\, COONH_3^+}} + H_2O$$

2.2.4 Specification of UTC-60 membrane and UTC-70 membrane

The NF membrane, namely, UTC-60 membrane and the ULPRO membrane, namely, UTC-70 membrane were developed by Toray Company, Japan. Both of them which employed in this study were necessary to operate the membrane process at low pressure in ranges of 0.100-0.500 MPa. Some specifications of UTC-60 membrane and UTC-70 membrane which reviewed by Kurihara in 2003 were reported in Table 2.5.

Table 2.5 Specifications of UTC-60 membrane and UTC-70 membrane

	UTC-70 membrane	UTC-60 membrane
Material	Crosslinked Aromatic Polyamide	Crosslinked Aromatic Polyamide
Structure	Thin film composite membrane	Thin film composite membrane
Rejection	Low MW Organic materials, Monovalent ions	Middle and high MW materials, Multivalent ions
MWCO	MW $\simeq$ 60 [a]	MW > 60 [b]
Mechanism	Electric repulsion Solution diffusion Molecular interaction	Size exclusion Electric repulsion
Pore size	< 1 nm	$\simeq$ 1-10 nm

(Source: Kurihara, Toray Company, 2003)
[a] Yashinari, 1999
[b] Kurihara, 1987

2.2.5 Theory

Some mechanistic and mathematical models have been proposed to describe nanofiltration membranes and charged reverse osmosis membranes. For water transport through nanofiltration membranes and charged membranes, the Preferential Sorption-

Capillary Flow Model (PSCF) could be used while ions separations could be explained by the Charged Membrane Model.

2.2.5.1 Preferential Sorption-Capillary Flow Model (PSCF)

The preferential sorption-capillary flow (PSCF) model was presented by Sourirajan in 1970. This model assumes that the mechanism of separation is determined by both surface phenomena and fluid transport through pores in these membranes. The model mentions that the membrane barrier layer has chemical properties such that it has a preferential sorption for the solvent or preferential repulsion for the solutes of the feed solution. As a result, a layer of almost pure solvent is preferentially absorbed on the surface and in the pores of the membrane. Solvent transport occurs as solvent from this layer is forced through the membrane capillary pores under pressure.

2.2.5.2 Charged Membrane Models

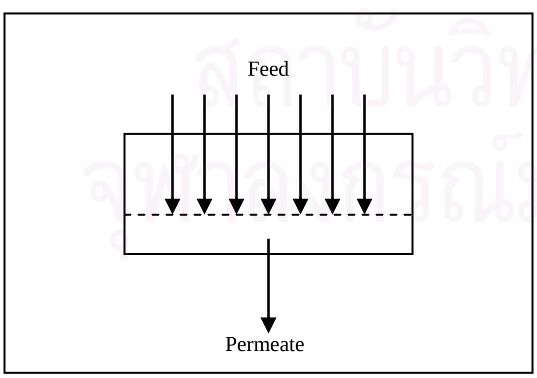
Although water transport through nanofiltration membranes and charged reverse osmosis membranes is adequately described by the previous model, the Charged Membrane Model must be used to predict ionic solute separations. This model accounts for electrostatic effects in order to describe the solute separation.

Donnan Equilibrium Models

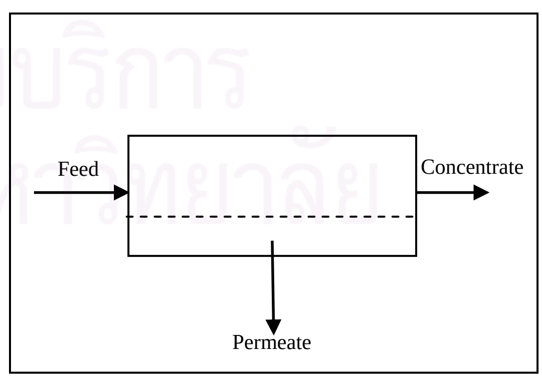
Donnan equilibrium models assumed that a dynamic equilibrium is established when a charged membrane is placed in a salt solution (Bhattacharyya and Cheng, 1986; Bhattacharyya and Williams, 1992c). The counter-ion of the solution, opposite in charge to the fixed membrane charge (typically carboxylic or sulfonic groups), is present in the membrane at a higher concentration than that of the co-ion (same charge as the fixed membrane charge) because of electrostatic attraction and repulsion effects. This creates the Donnan potential which prevents the diffusive exchange of the counter-ion and co-ion between the solution and membrane phase. When a pressure driving force is applied to force water through the charged membrane, the effect of the Donnan potential is to repel the co-ion from the membrane; since electro-neutrality must be maintained in the solution phase, the counter-ion is also rejected, resulting in ionic solute separation. A Donnan equilibrium model utilized by Bhattacharyya and Cheng (1986) described the distribution coefficient between a negatively-charged membrane and the solution phase of a salt.

2.2.6 System design

The system design for membrane filtration could be categorized into 2 types: dead-end operation and cross-flow operation, as shown is Figure 2.11. All the feed is driven through the membrane, which implies that the concentration of rejected components in the feed increases and consequently the quality of the permeate decreases with time (Thanuttamavong, 2002). In many cases, a cross-flow operation is preferred because of the lower fouling tendency relative to the dead-end operation. In the cross-flow operation, the feed flows parallel to the membrane surface with the inlet feed stream entering the membrane module at a certain composition. The feed stream inside the module is separated into 2 parts: a permeate stream and a concentrate stream (Thanuttamavong, 2002).



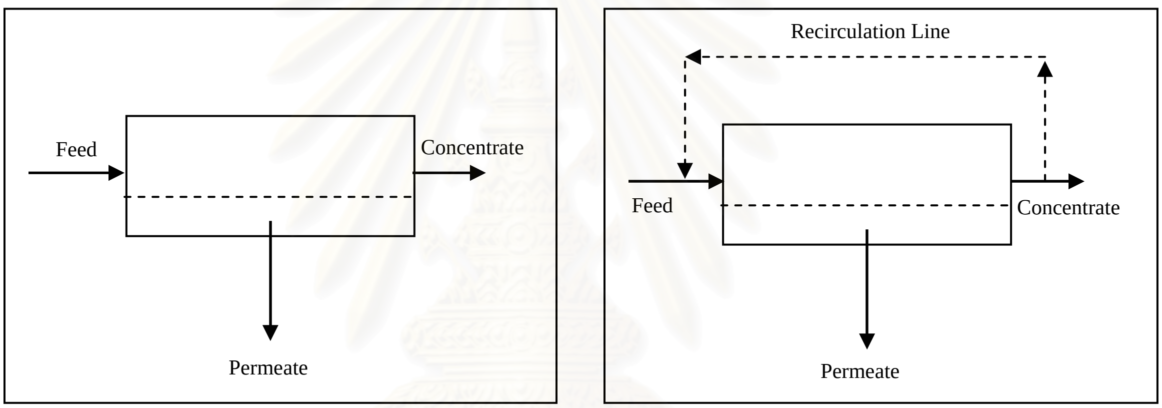
(a) Dead-end



(b) Cross-flow

(Source: Adapted from Thanuttamavong, 2002)
Figure 2.11 System design for membrane filtration

A cross-flow operation is also separated into 2 methods: the single-pass method and the recirculation method. The schematic diagram of both methods is given as Figure 2.12. In the single-pass method, the feed solution passes only once through the module. Hence, the volume of the feed solution decreases with path length, while in the recirculation method, the feed solution is sent back and allowed to pass the module several times (Thanuttamavong, 2002). In the recirculation method, flow velocity and pressure can be adjusted to reduce the pressure drop and to minimize fouling and concentration polarization.



(a) Single pass method (b) Recirculation method

Figure 2.12 Method of the cross-flow operation

As mentioned previously, the important problems in membrane processes in water treatment are fouling and concentration polarization. Fouling is a contamination of the membrane, either decreasing flux or increasing operating transmembrane pressure. The fouling may necessary to maintenance a permeate water flux processes or clean a membrane. Concentration polarization is the accumulation of retained solute on the surface of the membrane. This phenomenon is caused by a combination of factors including operating transmembrane pressure, viscosity, solute concentration and cross flow velocity (Pollution engineering, 2005). Therefore, fouling and concentration polarization should be considered when membrane processes were utilized in water treatment plants.

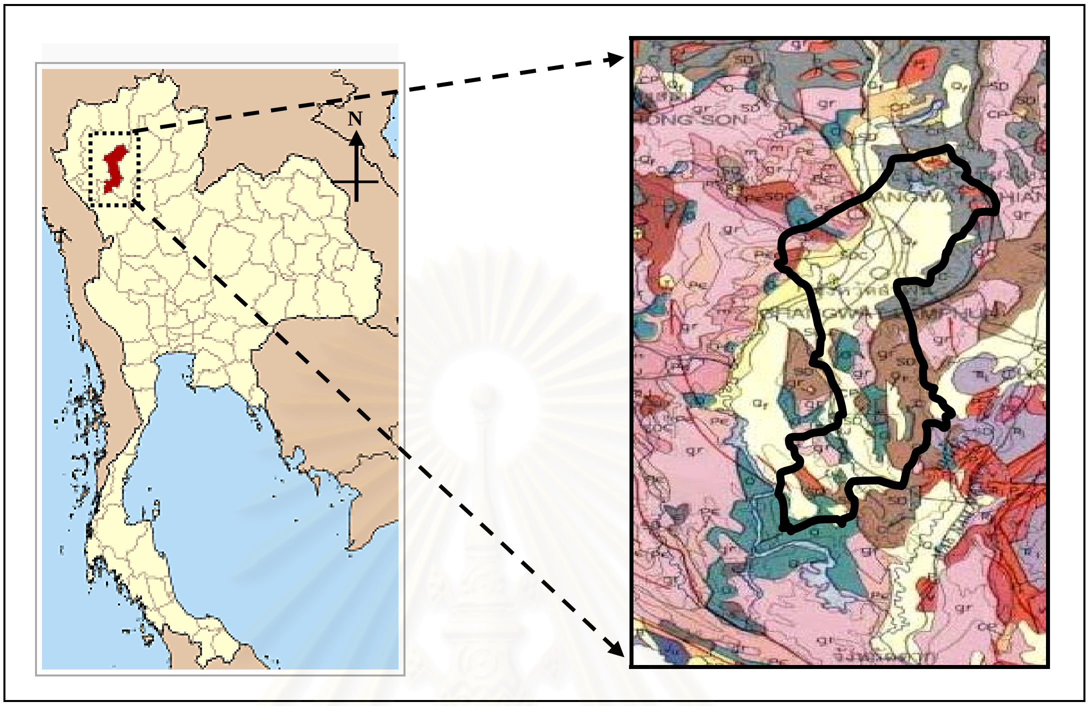
CHAPTER III

METHODOLOGY

3.1 The study area

The study area is in Lamphun province which is located in the northern part of Thailand. It situated between 17°-19° north latitude and 98°-99° east longitude. Lamphun province's area is 4,506 km^3 with a population in 2005 of 404,727 (Department of Provincial Administration, 2006). The mountainous area is about 60% of the province, and the remaining 40% is the plain terrain (Matsui, 2005).

Figure 3.1 is a geological map of Lamphun province; it could be described that Lamphun province consists of various kinds of rocks. The northern part of the province is mainly composed of sedimentary and meta-sedimentary rocks of Permian and Carboniferous; for instance shale, quartzite, and quartzitic-feldspathic sandstone. The middle part and southern part of the province are mainly composed of metamorphic rocks of Cambrian, Silurian and Devonian; such as phyllite, quartzite, and sedimentary rocks of Ordovician (Department of Mineral Resource, 2000). The eastern part of the province is a granitic mountainous area which mostly consists of biotite granite and muscovite granite, both of them are characterized by phenocrystic potassium feldspar (Department of Mineral Resource, 2000 and Kawada et al, 1987). These various geological conditions lead to a difference of hydrological conditions (Department of Mineral Resource, 2000).



(Source: Wikipedia, 2005 and Department of Mineral Resource, 2005)

Figure 3.1 Geological map of Lamphun province

As mentioned in Chapter I, Lamphun province has a fluoride ledge which lies across the aquifers and also has the bedrock aquifers of granites in this region. The weathering process and leaching process of the fluoride ledge by groundwater are the two main processes during which fluoride can be released into groundwater (Intercountry Centre for Oral Health, 1997). Therefore, groundwater which is used for drinking water has high fluoride concentrations and has a negative influence on human health, in particular dental fluorosis and skeletal fluorosis.

3.2 Groundwater quality investigation for village waterworks

Groundwater quality investigation for village waterworks in Lamphun province was done in August 2005 and November 2005. The main objective of this activity was to investigate fluoride concentration and groundwater quality for the village waterworks in the study area in Lamphun province.

Groundwater samples from 119 wells of the village waterworks were collected and analyzed for physical, chemical, and natural organic matter as reported in Table 3.1. Almost all groundwater samples were collected before mentioned groundwater samples were pumped into the elevation tanks. The reason was to obtain the groundwater samples that can be represented the groundwater samples from the underground.

Table 3.1 Groundwater quality investigation for village waterworks in Lamphun province

Date	Number of wells of village waterworks	Analytical parameters of groundwater quality investigation for village waterworks
16-18 August 2005	40	pH Electrical Conductivity (EC) Alkalinity Temperature DOC Cationic ions: Na, K, Ca, Mg, and T-Fe Anionic ions: F^-, Cl^-, SO_4^{2-}, NO_3^-, NO_2^-, and PO_4^{2-}
21-25 November 2005	79	pH Electrical Conductivity (EC) Alkalinity Temperature DOC Cationic ions: Na, K, Ca, Mg, and T-Fe Anionic ions: F^-, Cl^-, SO_4^{2-}, NO_3^-, NO_2^-, and PO_4^{2-}

The groundwater sample collecting point for groundwater quality investigation at the studied village waterwork is shown in Figure 3.2.

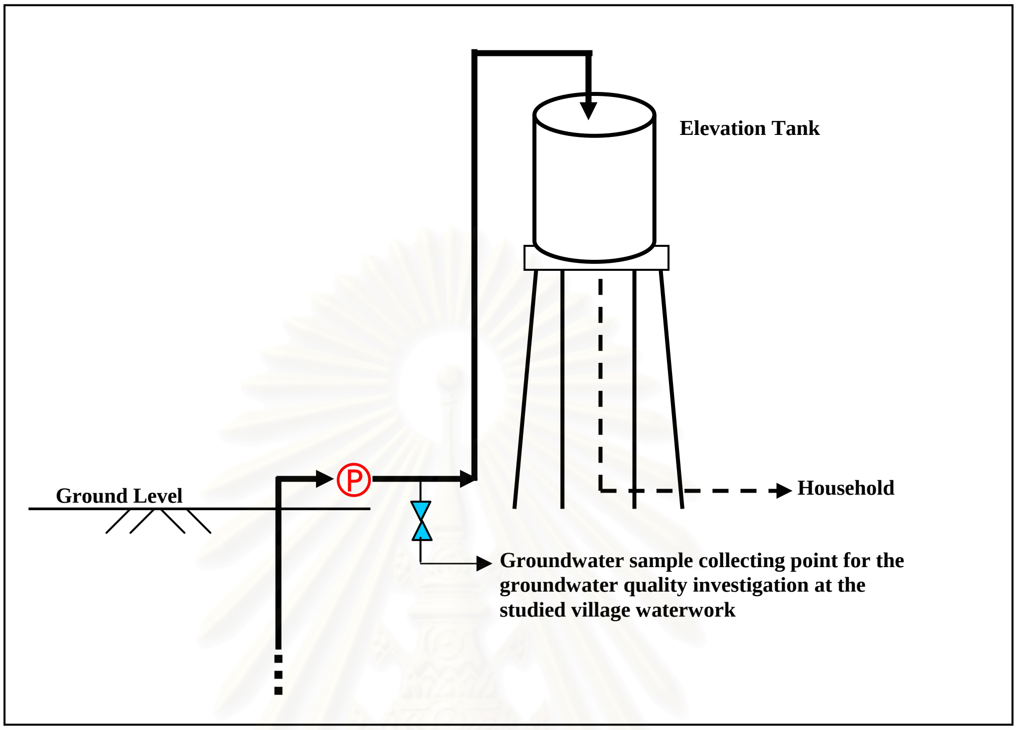
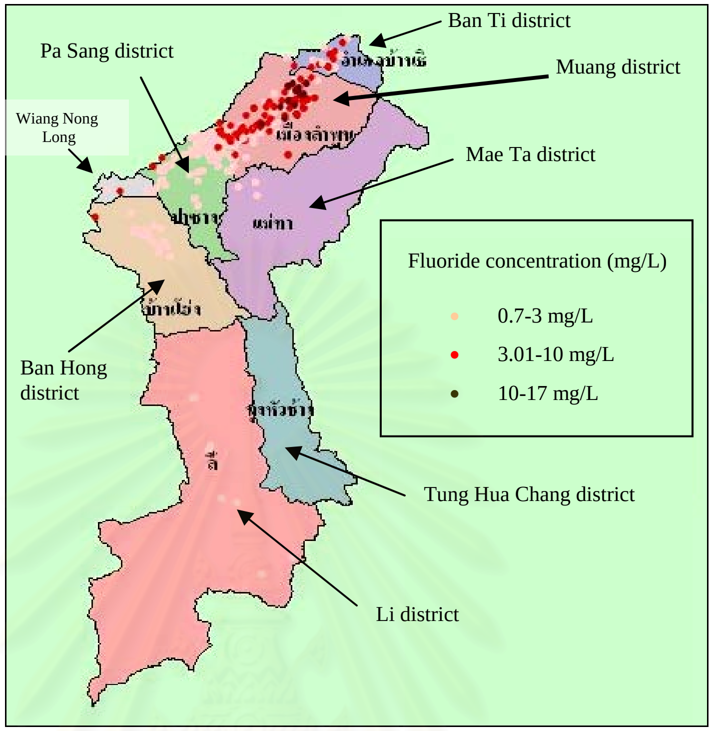


Figure 3.2 Groundwater sample collecting point for the groundwater quality investigation at the studied village waterwork.

3.3 Severity of dental fluorosis investigation

The severity of dental fluorosis investigation was done in November 2005 with a great help of Intercountry Centre for Oral Health (ICOH), Department of Health, Ministry of Public Health.

According to the study of fluoride concentration in groundwater in Lamphun province by Department of Groundwater Resource in 2003, it was observed that high fluoride concentration in groundwater was found in Muang district whereas low fluoride concentration in groundwater was found in Pa Sang district. A distribution of fluoride concentration of this referred study is shown in Figure 3.3.



(Source: Department of Groundwater Resource, 2003)

Figure 3.3 Distribution of fluoride concentration in Lamphun province based on the study of Department of Groundwater Resource

Based on the obtained data from the study of fluoride concentration in groundwater in Lamphun province by Department of Groundwater Resource in 2003, the severity of dental fluorosis investigation was done in November 2005 to investigate the severity of dental fluorosis in children from both high fluoride concentration area and low fluoride concentration area. Thus, 65 Students with age in the range of 13-17 year old and lived in tambon Ma Kua Chae (located in high fluoride concentration area), Muang district from Wat San Ka Yom School were investigated the severity of dental fluorosis. Moreover, 66 students with age in the range of 13-18 year old and lived in tambon Nakornchaedee (located in low fluoride concentration area), Pa Sang district from Dhammasathitsueksa School and Wachirawit Pa Sang School were investigated the severity of dental fluorosis too.

The severity of dental fluorosis investigation in the selected students was diagnosed by dentists of ICOH between 16 and 18 November 2005. The details of the severity of dental fluorosis investigation are briefly reported in Table 3.2.

Table 3.2 Details of the severity of dental fluorosis investigation

Place	Area Categorization	Number of selected students	Age of selected students	Address of selected students
Wat San Ka Yom School	High fluoride concentration area	65	13-17	Tambon Ma Kua Chae, Muang district, Lamphun province
Dhammasathitsueksa School and Wachirawit Pa Sang School	Low fluoride concentration area	66	13-18	Tambon Nakornchaedee, Pa Sang district, Lamphun province

3.4 Membrane experiment

3.4.1 Water sampling sites of membrane experiment

Based on groundwater quality investigation for village waterworks and the data of Department of Groundwater Resource, groundwater from 2 sites in the fluorotic area of Lamphun province (where membrane plants were established), categorized in terms of very high (>5 mg/L) and high (1-5 mg/L) fluoride concentration were selected for this study.

The first site was at the Pra Too Khong Bottled Drinking Water Plant (site A), Tambon Ban Klang, Muang district, Lamphun province, which was defined as a very high fluoride concentrations site (>5 mg/L). This site was established by a private company to produce the bottled drinking water for people in Tambon Ban Klang because the groundwater in Tambon Ban Klang was strongly recommended that could not be used directly as drinking water.

The second site was at the San Pa Hiang Membrane Plant (site B), Tambon Ma Kua Chae, Muang district, Lamphun province, which was defined as a high fluoride concentration site (1-5 mg/L). This membrane plant was one of thirty membrane plants which the Thai government noticed to have a negative influence on public health arising from the fluorotic groundwater.

Figure 3.4 indicates location of both selected sites in Muang district, Lamphun province while Figure 3.5 shows the pictures of the selected sites in this study.

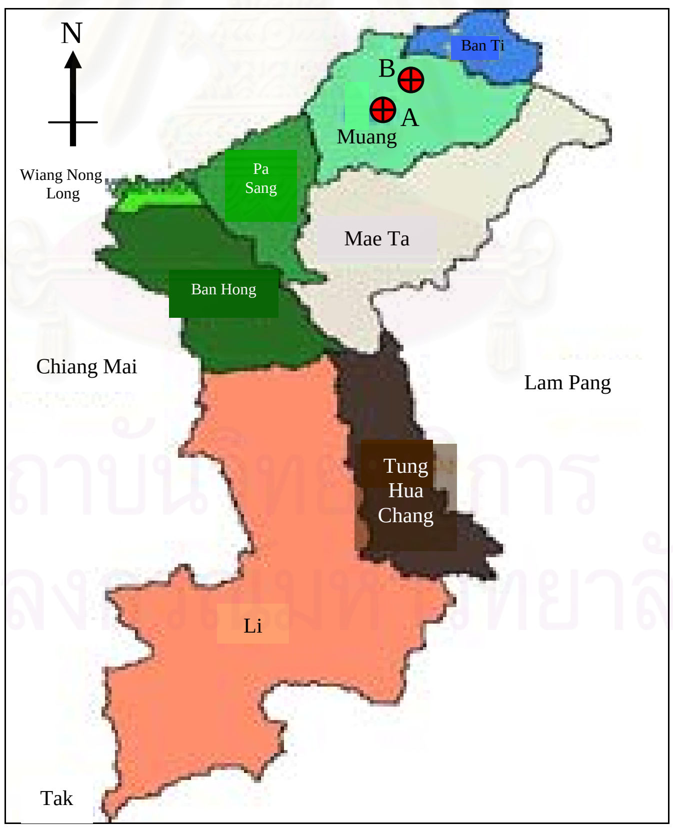


Figure 3.4 Location of the selected sites

(a) Pra Too Khong Bottled drinking Water Plant (b) San Pa Hiang Membrane Plant

Figure 3.5 Selected sites in this study

The reasons why groundwater samples from Pra Too Khong Bottled Drinking Water Plant (site A) and San Pa Hiang Membrane plant (site B) were selected for the membrane experiment include

1. Fluoride concentrations in groundwater from both sites were related to the target fluoride concentration in the scope of this study.
2. It was convenient to collect the water samples from both sites because the distance between Chiang Mai University and both sites was not so far.

The descriptions of both membrane plants included the position, elevation, depth of groundwater wells, and utilization of the mentioned groundwater, as shown in Table 3.3.

Table 3.3 Description of the selected sites

The selected site	Name	Position	Elevation [a] (m)	Depth of groundwater well (m)	Groundwater utilization	Remark
Site A	Pra Too Khong Bottled Drinking Water Plant	18° 34.016’ N 99° 02.833’ E	302	280	Household use Agricultural use Miscellaneous purposes Bottled drinking water (produced by RO membrane)	very high fluoride concentration site (> 5 mg/L)
Site B	San Pa Hiang Membrane Plant	18° 37.369’ N 99° 06.076’ E	309	130	Household use Agricultural use Miscellaneous purposes Drinking water (produced by RO membrane)	high fluoride concentration site (1-5 mg/L)

a = elevation on the ground level above mean sea level (ASL)

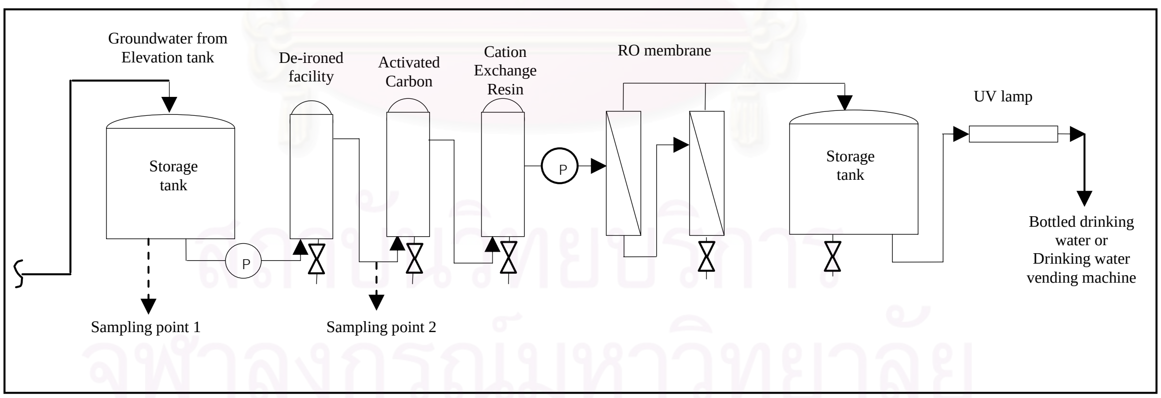
b = depth from the ground level to the bottom of borehole

3.4.2 Membrane experimental procedure

3.4.2.1 Water sampling

The groundwater which passed through a de-ironed facility was analyzed and collected as water samples for membrane experiment. The reason was to remove ferrous ions which can be oxidized and clog the membrane. This phenomenon reduced a permeate water flux and finally, the membrane could not work properly anymore. However, groundwater before passed through the de-ironed facility was also collected and analyzed to compare its characteristics with the groundwater which passed through the de-ironed facility.

Figure 3.6 illustrates a schematic diagram of the typical water production processes of reverse osmosis membrane plants. It was observed that the water production processes of Pra Too Khong Bottled Drinking Water Plant (site A) and San Pa Hiang Membrane Plant (site B) were quite the same.



(Source: Adapted from Tomoko, 2005)
Figure 3.6 Schematic diagram of typical production processes of membrane plants

From Figure 3.6, it is also showed sampling point 1 and sampling point 2 of the groundwater before passed through the de-ironed facility and groundwater which passed through the de-ironed facility of both selected sites, respectively.

3.4.2.2 Membrane experimental conditions

The following steps were the brief membrane experimental procedures and membrane experimental conditions of groundwater samples at sampling point 1 and groundwater samples at sampling point 2 from the selected sites which were analyzed and experimented in the laboratory of the Department of Environmental Engineering, Faculty of Engineering, Chiang Mai University.

1. 1 L of groundwater samples at sampling point 1 and 1 L of groundwater samples at sampling point 2 were collected from each selected site for determination of pH, electrical conductivity (EC), alkalinity, temperature, cationic ions (Na, K, Ca, Mg, and T-Fe), anionic ions (F^-, Cl^-, SO_4^{2-}, NO_3^-, NO_2^-, and PO_4^{2-}), and DOC.
2. 600 L of groundwater samples at sampling point 2 from each selected site was collected for the membrane experiment and carried to the laboratory.
3. The membrane experiment was done with the NF membrane (UTC-60 membrane) first and followed by the ULPRO membrane (UTC-70 membrane).
4. Effects of various experimental conditions of operating transmembrane pressures and the feed pH were studied. The operating transmembrane pressure of 0.1-0.5 MPa was set up and the feed pH values of 4-8 were used for this study. Table 3.4 demonstrates the experimental conditions utilized in this study.

Table 3.4 Experimental conditions in this study

Experimental Conditions	Sampling Site	
	High fluoride concentration site (1-5 mg/L)	Very high fluoride concentration site (>5 mg/L)
Type of membrane	ULPRO membrane (UTC-70) NF membrane (UTC-60)	ULPRO membrane (UTC-70) NF membrane (UTC-60)
Operating trans-membrane pressure	0.1-0.5 MPa (approx. 0.1, 0.2, 0.3, 0.4, and 0.5 MPa)	0.1-0.5 MPa (approx. 0.1, 0.2, 0.3, 0.4, and 0.5 MPa)
pH	4±0.1, 5±0.1, 6±0.1, 7±0.1 and natural pH	4±0.1, 5±0.1, 6±0.1, 7±0.1 and natural pH

3.4.2.3 Preparation of the membrane experiment

The NF membrane (UTC-60 membrane) and the ULPRO membrane (UTC-70 membrane) are polyamide composite membranes which were preserved in 0.1% solution of a sodium bisulfate acid solution. In this experiment, UTC-60 membrane was employed first and followed by UTC-70 membrane. The membranes were prepared using the following procedure.

1. The membrane was cut and washed in milli-Q water. Then it was set up properly in the cell unit.
2. It was put through the module for 3 hours under pressure 0.10 MPa with 1-2 L of milli-Q water for washing the membrane.
3. Bypassed water, concentrated water, and permeate water were recycled to the feed tank.

Figure 3.7 shows a diagram of the membrane experiment. This experiment was set for a bench scale cross-flow operation. The equipment in this experiment included a feed tank with 20 L capacity, 2 controlled valves (V), 2 pressure indicators (P), a flow indicator (F), a bypass valve, a concentrated water valve, a cell unit of the Nitto Denko Corporation, Japan which provides 60 cm^2 surface area for filtration, a permeate water bottle, and a pump of the Iwaki company, Japan which could be operated at maximum operating pressure of 0.55 MPa and a maximum capacity of 2.0-2.4 liter per minute.

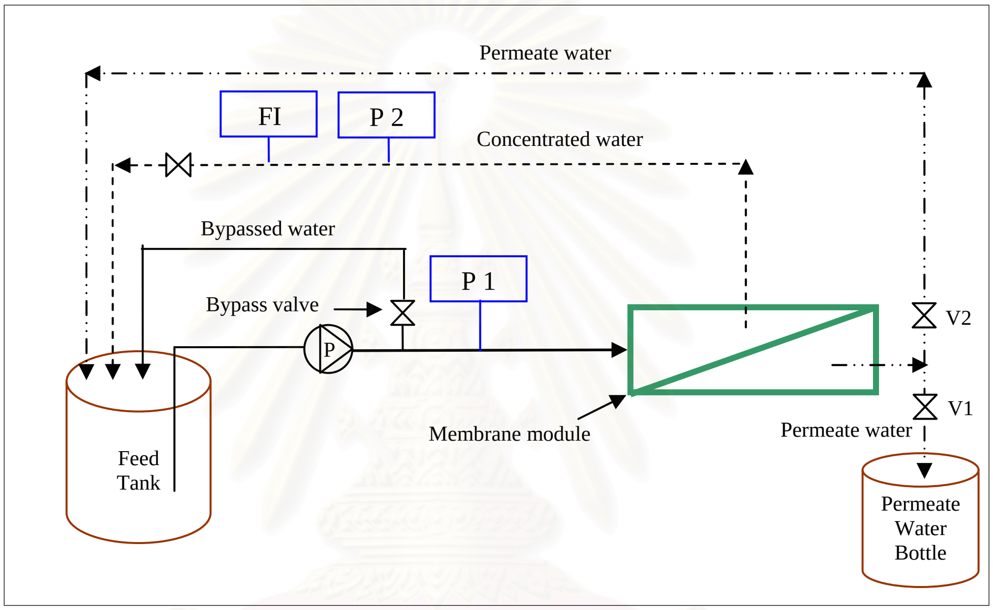


Figure 3.7 Diagram of the membrane experiment

3.4.2.4 Determination of the sampling time at steady state

Determination of the sampling time for each desired operating transmembrane pressure was determined as follows.

1. The module was run under the desired operating transmembrane pressure by using 20 L of groundwater samples at sampling point 2 without any pH adjustment (natural pH). The concentrated water, permeate water (V1 was closed while V2 was opened), and bypassed

water were recycled to a feed tank. The feed tank was sealed to prevent evaporation from occurring during the running time.

2. The water flux of the permeate water was checked and the sampling time at steady state was determined as follows:

   - The permeate water flux of the initial 1st hour is expected to have much fluctuation, so that the permeate water flux was observed every 20 minutes (20, 40, and 60 minutes, respectively).
   - From 2nd to 6th hour, the permeate water flux was observed every 60 minutes (60, 120, 180, and 360 minutes, respectively) to reach the permeate water flux termination.
   - 7th to 24th hour, the permeate water flux was observed every 180 minutes (540, 720, 900… and 1440 minutes, respectively) to confirm the water flux termination.
   - Finally, the permeate water flux was plotted as a function of time. (In this step the sampling time under the desired operating transmembrane pressure at steady state was obtained)

3.4.2.5 Membrane experiment

When the sampling time at steady state under the desired operating transmembrane pressure was obtained, the following procedure was followed:

1. Groundwater samples at sampling point 2 were adjusted to pH values of 4, 5, 6, and 7 with HCl.
2. The feed water in the feed tank was changed to groundwater samples at sampling point 2 without any pH adjustment again. Then, the membrane module was run while the concentrated water, the permeate

water (V1 was closed while V2 was opened), and the bypassed water were recycled to a feed tank until the sampling time at steady state was reached. When it reached the steady state, a V1 was opened while a V2 was closed.

3. The permeate water was collected in the permeate water bottles for determinations of pH, electrical conductivity (EC), alkalinity, temperature, cationic ions (Na, K, Ca, Mg, and T-Fe), anionic ions (F^-, Cl^-, SO_4^{2-}, NO_3^-, NO_2^-, and PO_4^{2-}), and DOC.
4. The feed water in the feed tank was changed to groundwater samples at sampling point 2 which were adjusted to the pH of 7, 6, 5, and 4, respectively, and did the same steps as mentioned above.
5. At the end of the membrane module run with the desired feed pH values attained (step 1 to step 4), the employed membrane sheet was replaced by a new membrane sheet.
6. The membrane experiments for other operating transmembrane pressures were done by starting with the preparation of the membrane experiment step.
7. When finished all desired operating transmembrane pressures with all feed pH values of UTC-60 membrane, then UTC-70 membrane was employed and done the same steps as that of UTC-60 membrane.

The membrane experimental procedure diagram of all processes in this study is shown in Figure 3.8 and Figure 3.9 illustrates the membrane experimental apparatus. It was set for the bench scale cross-flow operation process.

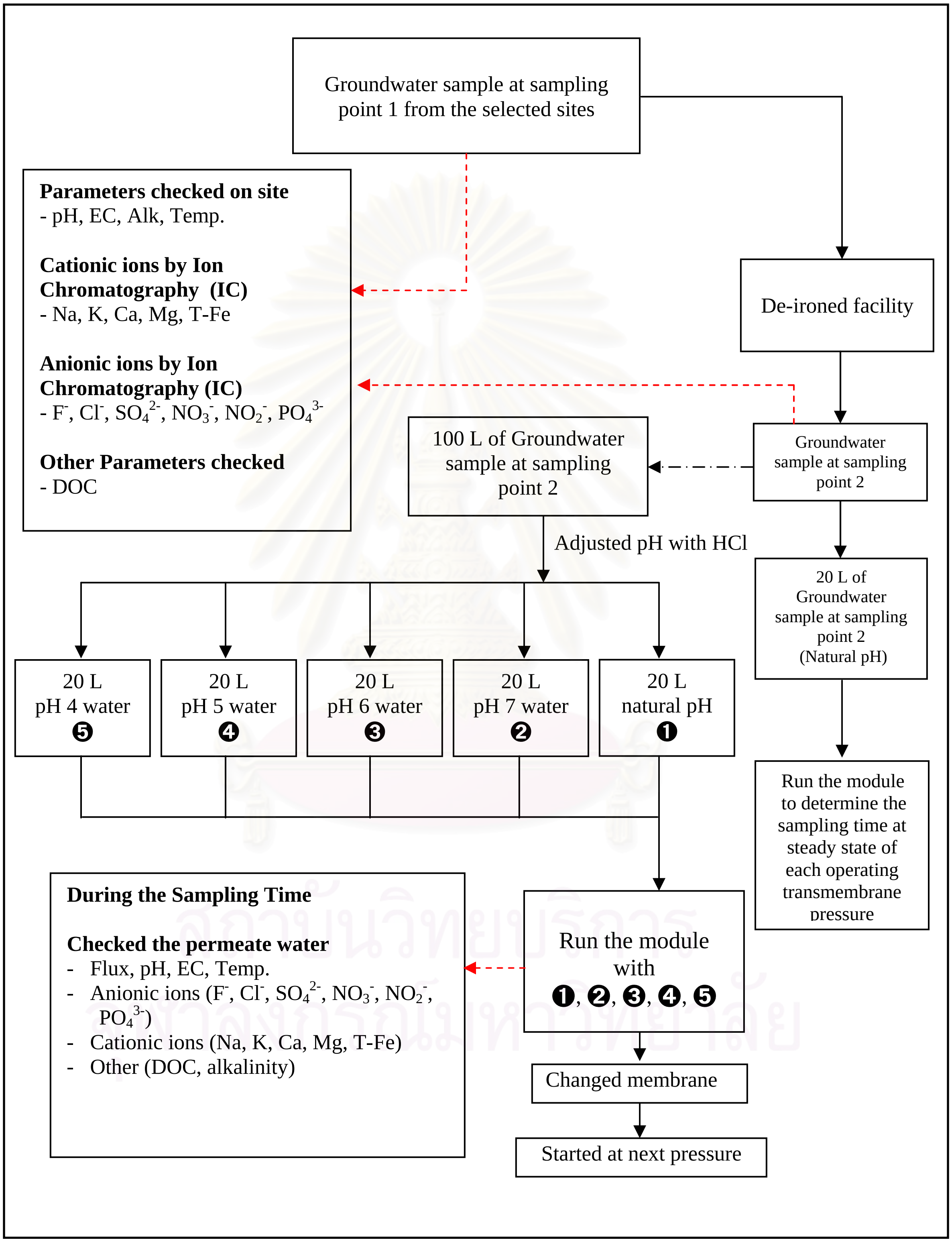
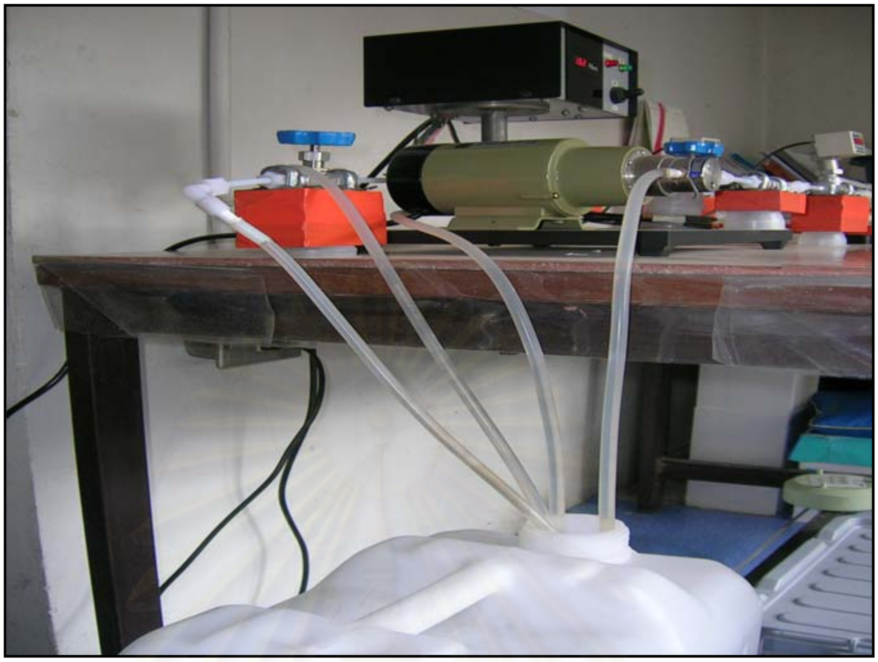
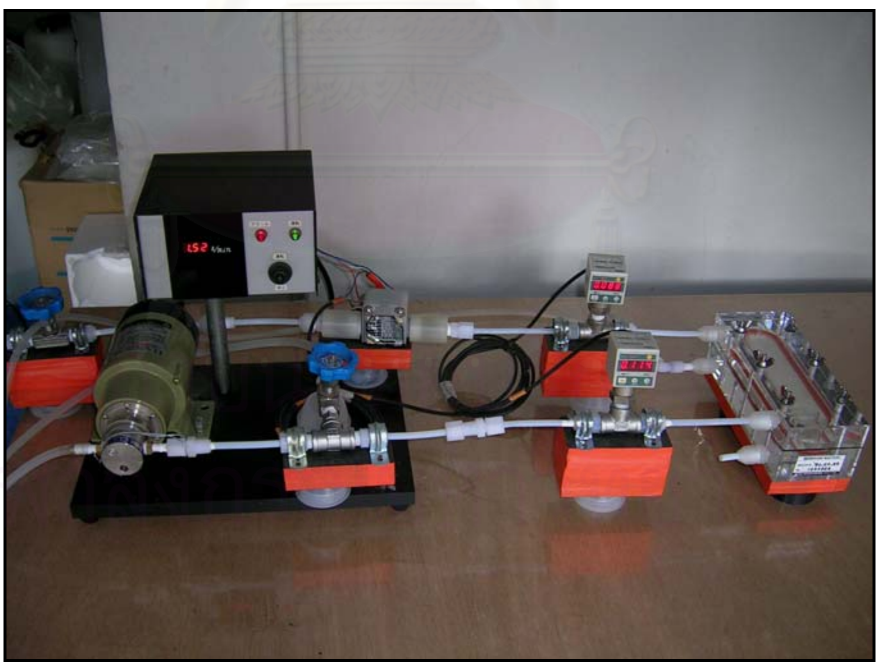


Figure 3.8 Membrane experimental procedure diagram



(a)



(b)

Figure 3.9 Membrane experimental apparatus

3.5 Analytical Methods and Instruments

3.5.1 Alkalinity

The alkalinity of the water samples was analyzed in accordance with standard method 2320 Alkalinity; section 2320B, Titration Method.

3.5.2 pH

The pH of the water samples was measured by a Horiba pH meter, Model D-13E with an accuracy of $\pm$ 0.01 pH unit.

3.5.3 Temperature

Temperature of the water samples was directly measured by using a thermometer.

3.5.4 Electrical Conductivity (EC)

The electrical conductivity (EC) of the water samples was measured by a WTW electrical conductivity meter, Model Cond 330i.

3.5.5 DOC

DOC of the water samples was measured in accordance with standard method 5310 Total Organic Carbon (TOC); section 5310 C Persulfate-Ultraviolet Oxidation Method by O.I. analytical 1010 TOC Analyzer.

3.5.6 Cationic Ions

The cationic ions included Na, K, Ca, Mg, and T-Fe were analyzed in accordance with Ion Chromatograph for cation analysis with Chemical Suppression of Eluent Conductivity.

3.5.7 Anionic Ions

The anionic ions included F^-, Cl^-, SO_4^{2-}, NO_3^-, NO_2^-, and PO_4^{2-} were analyzed in accordance with standard method 4110; section 4110B, Ion Chromatography with Chemical Suppression of Eluent Conductivity.

The water samples, analytical parameters, and analytical methods are shown in Table 3.5.

Table 3.5 Water samples, analytical parameters, and analytical methods of membrane experiment

Parameters	Groundwater sample at sampling point 1	Groundwater sample at sampling point 2	Permeate water	Analytical Method
Alkalinity	√	√	√	Standard method 2320 Alkalinity; section 2320B, Titration Method
pH	√	√	√	Direct Measurement with a Horiba pH meter, Model D-13E
Temperature	√	√	√	Direct Measurement
EC	√	√	√	Direct Measurement with a WTW electrical conductivity meter, Model Cond 330i.
DOC *	√	√	√	Standard method 5310 Total Organic Carbon (TOC); section 5310 C Persulfate-Ultraviolet Oxidation Method by O.I. analytical 1010 TOC Analyzer
Cationic Ions	√	√	√	Ion Chromatograph for cation analysis with Chemical Suppression of Eluent Conductivity
Anionic Ions	√	√	√	Standard method 4110; section 4110B, Ion Chromatography with Chemical Suppression of Eluent Conductivity

√ Analyzing in accordance with the Standard method or USEPA method

* Filtered by 1.2 μm GFC

CHAPTER IV

RESULTS AND DISCUSSION

The results from the experiments and their analysis for each topic were separately presented as followed

4.1 Groundwater quality investigation for village waterworks

4.1.1 Characteristics of groundwater from village waterworks

Groundwater from 119 wells of the village waterworks in Lamphun province were collected and analyzed for physical, chemical, and natural organic matter parameters in August 2005 and November 2005. The results of the groundwater quality investigation for 119 wells of the village waterworks were reported in Appendix A.

As mentioned in Chapter III, the main objective of the groundwater quality investigation was to investigate fluoride concentration and groundwater quality for the groundwater from village waterworks in the study area of Lamphun province. Figure 4.1, 4.2, 4.3, and 4.4 show the fluoride concentration as a function of pH, EC, alkalinity, and calcium concentration, respectively. It was observed that a high fluoride concentration in groundwater might be predicted from a high electrical conductivity, a high alkalinity, and a basic pH of groundwater. Additionally, high fluoride concentration in groundwater might be also found in a low calcium concentration of groundwater. These phenomena were agree with Kim and Jeong (2005) who indicated that the groundwater which enriched in fluoride normally found when groundwater interacted with the F-rich minerals while deeply circulating through the granitic aquifers. Thus, due to this weathering process, the increasing of pH, alkalinity whereas the decreasing of calcium concentration could be observed.

Theoretically, carbonate equilibrium predominate the groundwater quality in the weathering process of the granitic aquifers. For the groundwater in Lamphun province, Na-HCO_3 is obviously the predominant of carbonate equilibrium (Margane and Tatong, 1999) as follows

$$2NaAlSi_3O_8 + 2CO_2 + 11H_2O \longrightarrow Al_2SiO_5(OH)_4 + 2Na^+ + 2\ HCO_3^- + 4\ H_2SiO_4$$

From the above equation, HCO_3^- is released into groundwater by this weathering process. Thus, the increase in HCO_3^- resulting in the increment of the alkalinity, the pH value, and the electrical conductivity.

Additionally, the F-rich mineral in Lamphun province is a calcium fluoride (CaF_2) or is known as fluorite (Department of Mineral Resource, 2000). When groundwaters interact with the calcium fluoride (CaF_2), the weathering process of the calcium fluoride (CaF_2) is occurred as the following equation.

$$CaF_{2\,(s)} \quad \texttt{<--->} \quad Ca^{2+}_{(aq)} \; + \; 2F^-_{(aq)}$$

This weathering process become enriched in Ca^{2+} and F^-, however, Ca^{2+} is continuously precipitated as calcite ($CaCO_3$) when it is bound with CO_3^{2-} of HCO_3^- from the carbonate equilibrium equation. So, the continuous weathering process of the calcium fluoride (CaF_2) leaded to further release F^- into groundwater and Ca^{2+} further precipitated as calcite ($CaCO_3$) (Kim and Jeong, 2005).

Therefore, it could be indicated that the high fluoride concentration in groundwater was observed from the high electrical conductivity, the high alkalinity, and the basic pH value but lower in the calcium concentration.

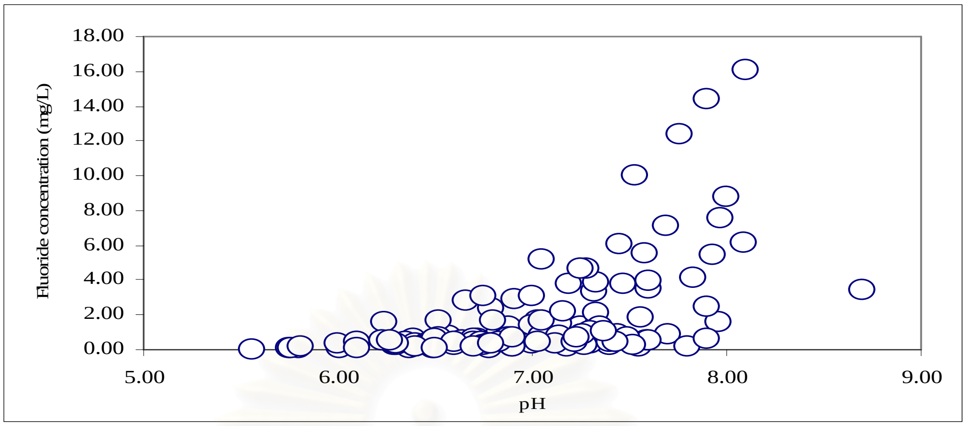


Figure 4.1 Fluoride concentration as a function of pH values

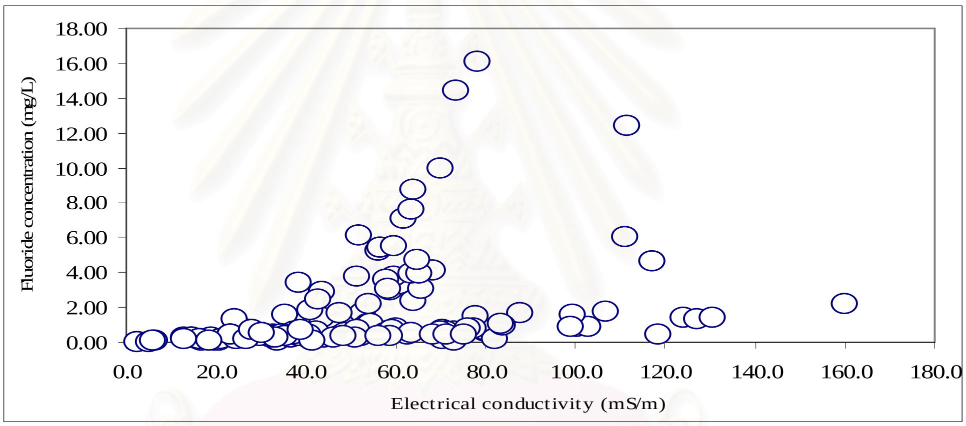


Figure 4.2 Fluoride concentration as a function of electrical conductivity

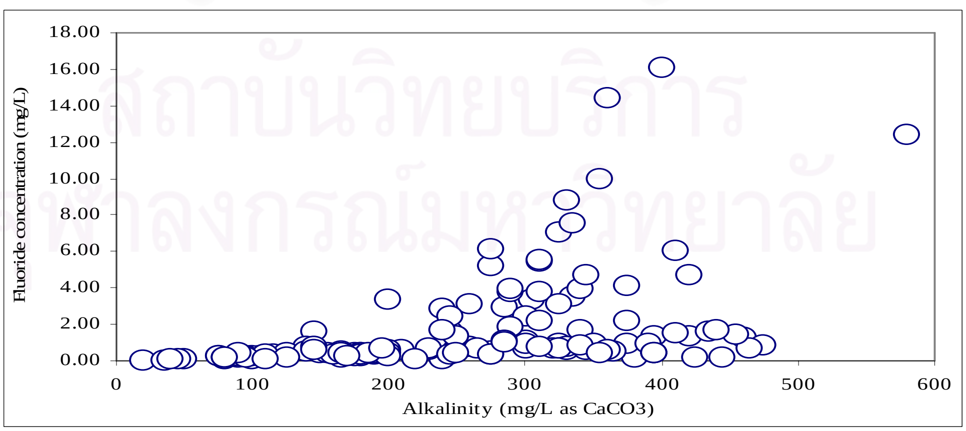


Figure 4.3 Fluoride concentration as a function of alkalinity

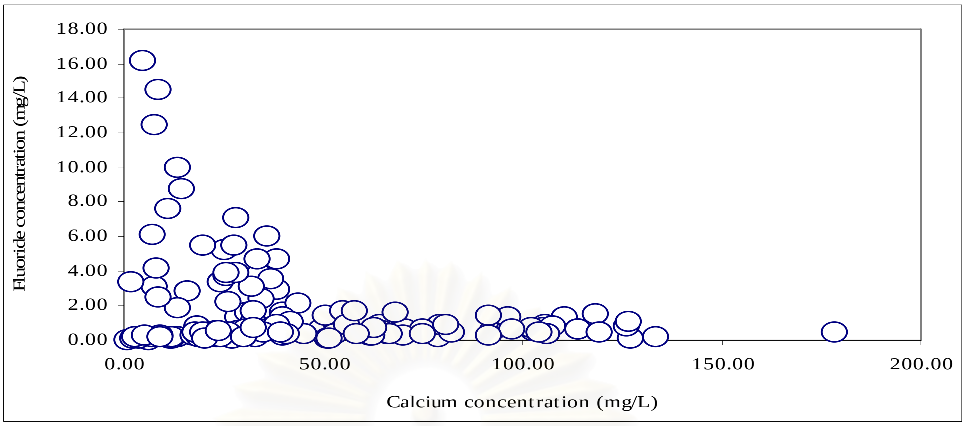


Figure 4.4 Fluoride concentration as a function of calcium concentration

4.1.2 Distribution of fluoride concentration in groundwater from the village waterworks

Figure 4.5 illustrates the distribution of the fluoride concentration in groundwater from 119 village waterworks. It was found that a high fluoride concentration in groundwater distributed in the north-eastern area of Muang district and Ban Ti district where groundwater was defined as an alkali carbonate type (occasionally found in chemical interaction between groundwater and the granitic aquifers) (Matsui, 2005).

Whereas a low fluoride concentration in groundwater distributed in the area of Pa Sang district and Mae Ta district where temporary hardness of groundwater was predominated (Matsui, 2005).

From the distribution of the fluoride concentration in groundwater from 119 village waterworks as shown in Figure 4.5, it was found that the fluoride concentration was categorized into 4 groups based on range of fluoride concentration include 0-0.7 mg/L, 0.7-3 mg/L, 3-10 mg/L, and >10 mg/L, respectively. Figure 4.6 shows a number of village waterworks in each range of fluoride concentration. It was indicated that fluoride concentration in range of 0-0.7 mg/L, 0.7-3 mg/L, 3-10 mg/L, and >10 mg/L were observed a number of village waterworks of 66, 30, 20, and 3, respectively.

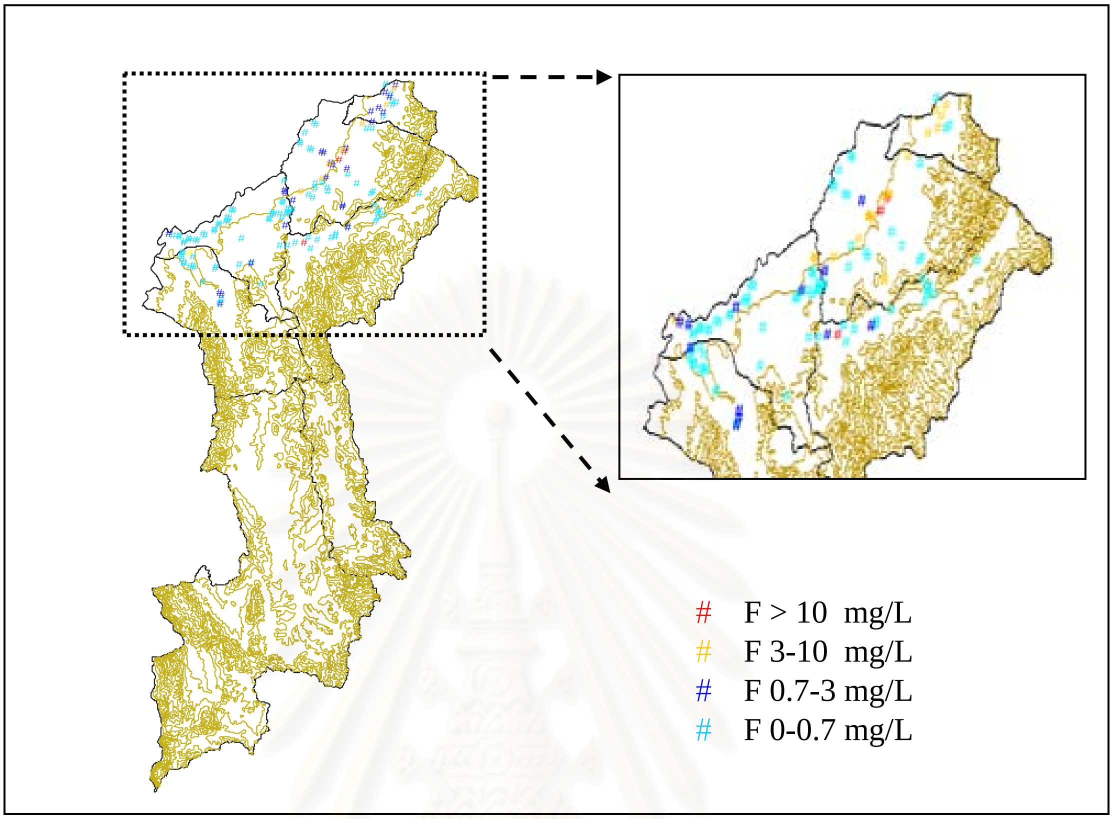


Figure 4.5 Distribution of fluoride concentration in groundwater from village waterworks

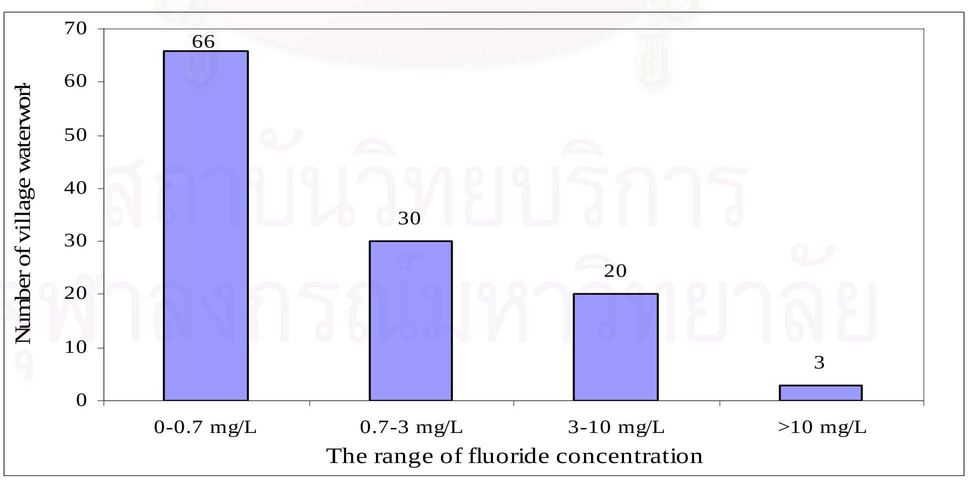


Figure 4.6 A number of village waterworks in each range of fluoride concentration in groundwater

4.1.3 Effect of the fluoride concentration in groundwater from the village waterworks

Drinking Water Limit (DWL) for the fluoride concentration in drinking water of 1.5 mg/L was established by World Health Organization (WHO, 1998). This number was not fixed and depended on climate in each region. For Thailand, the fluoride concentration in drinking water was set by many agencies. It was in the range of 0.7-1.5 mg/L. However, 0.7 mg/L of the fluoride concentration followed by the bottled drinking water standard is preferable for people in the fluorotic areas of Lamphun province because the bottled drinking water was used in their consumptions both food preparations and their drinking purposes (Ministry of Industry, 1978).

According to the results of the groundwater quality investigation for the village waterworks, it was indicated that 53 wells from the total of 119 wells (44.54 %) have fluoride concentration above 0.7 mg/L when compared with the bottled drinking water standard of Ministry of Industry. All investigated results of fluoride concentration could be categorized into 4 groups (based on its effects) given by International Program on Chemical Safety in 2002 as shown in adapted Table 4.1.

Table 4.1 Category of the effect of investigated wells

Fluoride concentration (mg/L)	Effects	Number of wells (%)
Low (< 0.7 mg/L)	Protection against dental caries	66 (55.46 %)
0.7 $\underset{\sim}{}$ 3 mg/L	An adverse effect on tooth enamel and give rise to mild dental fluorosis (prevalence: 12~33%)	30 (25.21 %)
3 $\underset{\sim}{}$ 10 mg/L	Skeletal fluorosis with adverse changes in bone structure	20 (16.81 %)
Over 10 mg/L	Crippling skeletal fluorosis	3 (2.52 %)

(Source: Adapted from International Program on Chemical Safety, 2002)

4.2 Severity of dental fluorosis investigation

The severity of dental fluorosis investigation was done in November 2005 to investigate the severity of dental fluorosis in children from both high fluoride concentration area and low fluoride concentration area. The results of the severity of dental fluorosis investigation were reported in Appendix B.

Figure 4.7 and Figure 4.8 illustrate the distribution of degree of dental fluorosis for students in high fluoride concentration area and low fluoride concentration area, respectively. It was found that 55.39 % of students in high fluoride concentration area have been observed moderate to severe dental fluorosis (level 3 - level 5). In contrast, 93.94 % of students in low fluoride concentration area have been observed none or mild dental fluorosis (level 0 - level 2).

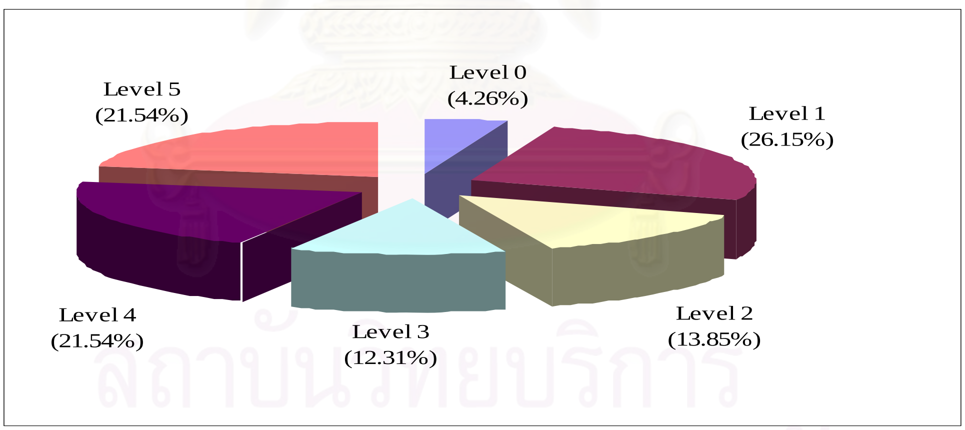


Figure 4.7 Distribution of degree of dental fluorosis for students in high fluoride concentration area

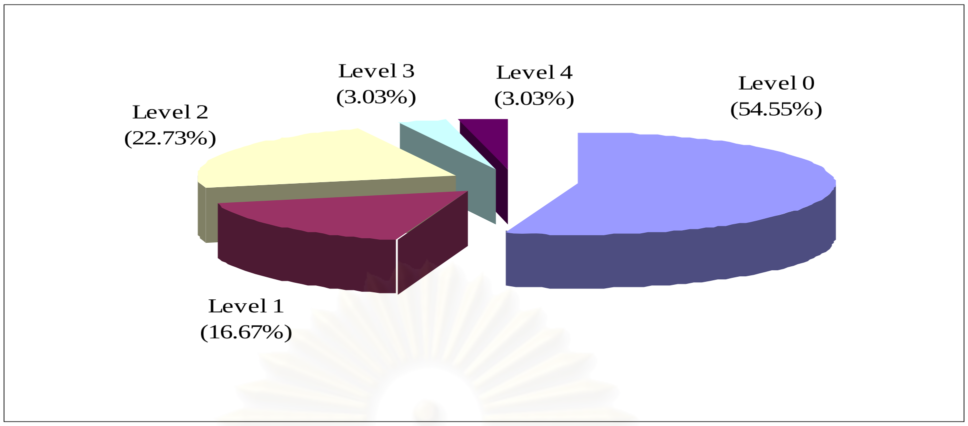


Figure 4.8 Distribution of degree of dental fluorosis for students in low fluoride concentration area

The classification criteria of dental fluorosis used the Dean's fluorosis index for categorizing the degree of dental fluorosis. The scoring of the degree of dental fluorosis is reported in Table 4.2.

Table 4.2 Scoring of the degree of dental fluorosis using the Dean's index

Degree of dental fluorosis	Criteria
0	The enamel represents the usual translucent semivitriform type of structure. The surface is smooth, glossy, and usually of a pale creamy white color.
1	The enamel discloses slight aberrations from the translucency of normal enamel, ranging from a few white flecks to occasional white spots. This classification is utilized in those instances where a definite diagnosis of the mildest form of fluorosis is not warranted and a classification of "normal" is not justified.
2	Small opaque, paper white areas scattered irregularly over the tooth but not involving as much as 25% of the tooth surface. Frequently included in this classification are teeth showing no more than about 1-2 mm of white opacity at the tip of the summit of the cusps of the bicuspids or second molars.
3	The white opaque areas in the enamel of the teeth are more extensive but do not involve as much as 50% of the tooth.
4	All enamel surfaces of the teeth are affected, and the surfaces subject to attrition show wear. Brown stain is frequently a disfiguring feature.
5	Includes teeth formerly classified as "moderately severe and severe." All enamel surfaces are affected and hypoplasia is so marked that the general form of the tooth may be affected. The major diagnostic sign of this classification is discrete or confluent pitting. Brown stains are widespread and teeth often present a corroded-like appearance.

Source: Dean, 1942

Figure 4.9 shows the comparison of severity of dental fluorosis in both areas. It was observed that in low fluoride concentration area, the severity of dental fluorosis was mostly distributed in none or mild level. In contrast, severe cases of dental fluorosis could be observed significantly in high fluoride concentration area. The severity of dental fluorosis at various levels is depicted from Figure 4.10 to Figure 4.15.

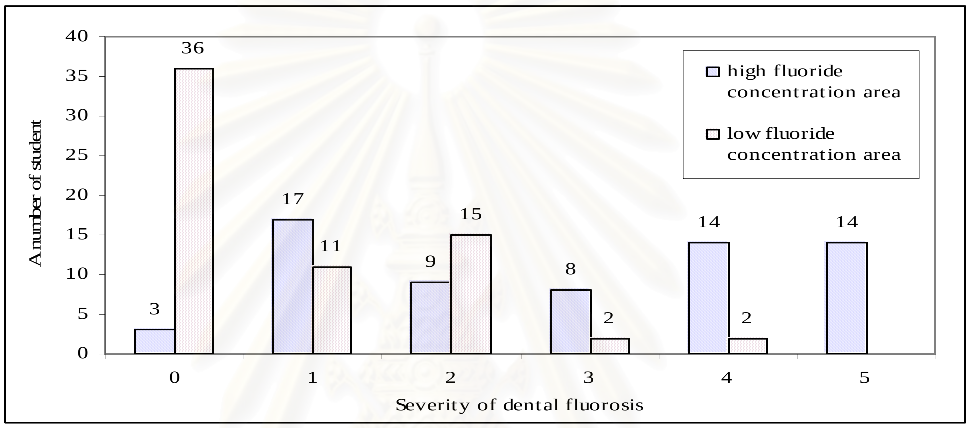


Figure 4.9 Comparison of severity of dental fluorosis in high fluoride concentration area with severity of dental fluorosis in low fluoride concentration area

Figure 4.10 Severity of dental fluorosis level 0

Figure 4.11 Severity of dental fluorosis level 1

Figure 4.12 Severity of dental fluorosis level 2

Figure 4.13 Severity of dental fluorosis level 3

Figure 4.14 Severity of dental fluorosis level 4

Figure 4.15 Severity of dental fluorosis level 5

4.3 Characteristics of groundwater from the selected sites for the membrane experiment

4.3.1 Comparison of the groundwater characteristics from the selected sites

The characteristics of the groundwater before passed through the de-ironed facility (at sampling point 1) and the groundwater which passed through the de-ironed facility (at sampling point 2) from the selected sites which located in the fluorotic area of

Lamphun province between September 2005 and December 2005 for the Pra Too Khong Bottled Drinking Water Plant (site A) which was defined as a very high fluoride concentration site and between November 2005 and January 2006 for the San Pa Hiang Membrane Plant (site B) which was defined as a high fluoride concentration site were analyzed for physical, chemical, and natural organic matter parameters as shown in Table 4.3 and Table 4.4, respectively.

4.3.1.1 Temperature

Groundwater before passed through the de-ironed facility (at sampling point 1) and groundwater which passed through the de-ironed facility (at sampling point 2) from site A and site B were measured temperature values in range from 25.2 to 30.0 °C and 22.0 to 23.8 °C, respectively, as reported in Table 4.3 and Table 4.4. Figure 4.16 illustrates the temperature values of mentioned groundwater from both of selected sites.

4.3.1.2 pH

The pH values of groundwater before passed through the de-ironed facility (at sampling point 1) and groundwater which passed through the de-ironed facility (at sampling point 2) from site A and site B were measured and reported in Table 4.3 and Table 4.4, respectively. Figure 4.17 illustrates the pH values of mentioned groundwater from both sites. In the case of the Pra Too Khong Bottled Drinking Water Plant (site A), the pH values of groundwater were mostly basic between 7.86 and 8.17 while the pH values of groundwater from the San Pa Hiang Membrane Plant (site B) were slightly acidic in range from 6.58 to 6.65.

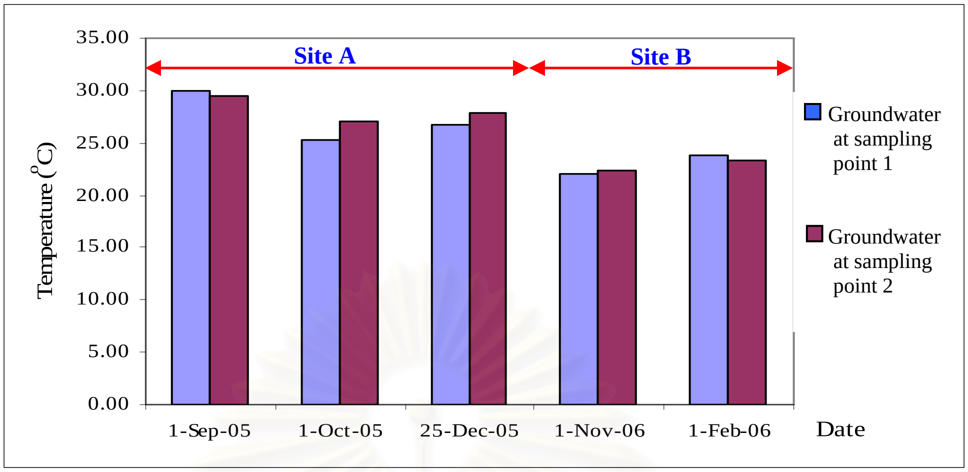


Figure 4.16 Temperature values of groundwater from site A and site B

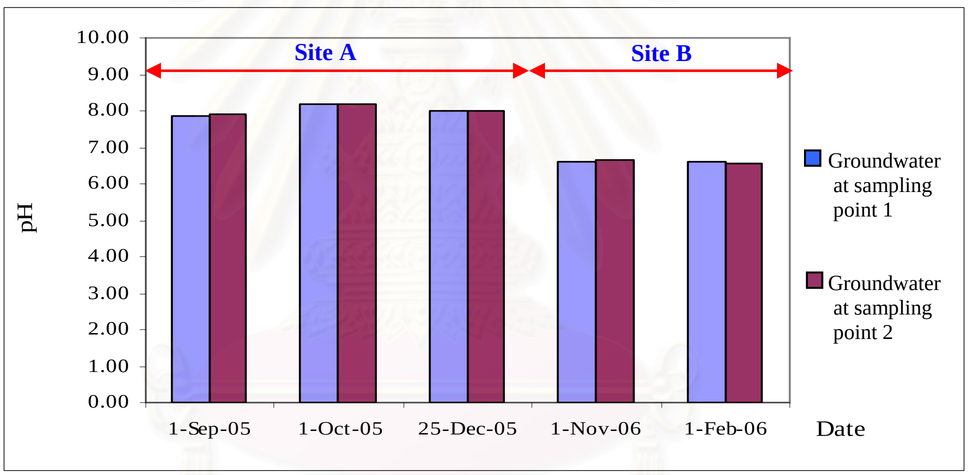


Figure 4.17 pH values of groundwater from site A and site B

4.3.1.3 Alkalinity

The alkalinity levels showed the capacity for solutes for instant carbonate, bicarbonate, and hydroxide which contained in natural water to react with acid (Jiarsirikul, 2003). Hem (1985) explained that most natural water resources contained bicarbonate as a major dissolved anion and the principle source of alkalinity. As can be seen in Table 4.3, Table 4.4, and Figure 4.18, the alkalinity level of groundwater before passed through the de-ironed facility (at sampling point 1) and groundwater which passed through the de-ironed facility (at sampling point 2) from site A in the range of 340-400 mg/L as $CaCO_3$ were observed while the alkalinity level in the range of 155-170 mg/L as $CaCO_3$ were observed from groundwater before passed through the de-ironed facility (at sampling point 1) and groundwater which passed through the de-ironed facility (at sampling point 2) from site B.

4.3.1.4 Electrical Conductivity

From Table 4.3 and Table 4.4, the electrical conductivity values of groundwater before passed through the de-ironed facility (at sampling point 1) and groundwater which passed through the de-ironed facility (at sampling point 2) of the Pra Too Khong Bottled Drinking Water Plant (site A) and the San Pa Hiang Membrane Plant (site B) were measured in the range of 760-788 µS/cm and 334-338 µS/cm, respectively. Figure 4.19 presents the electrical conductivity values of mentioned groundwater from site A and site B.

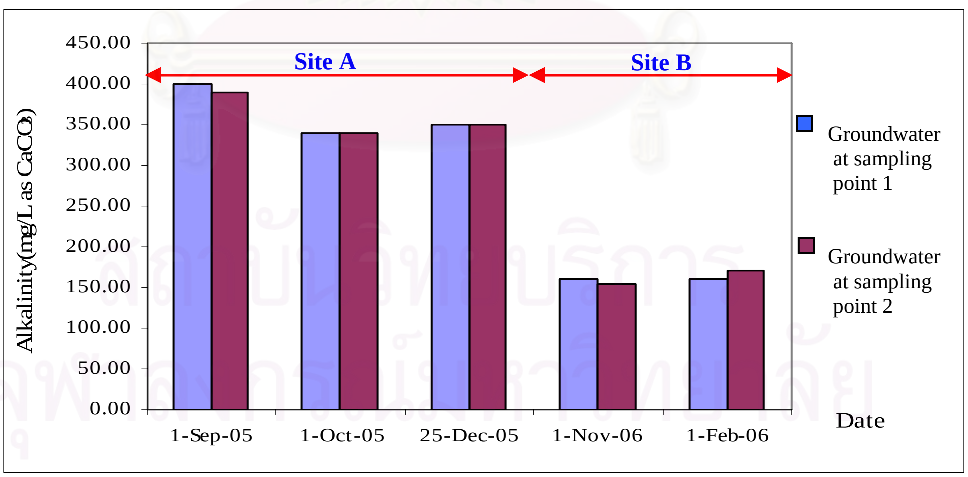


Figure 4.18 Alkalinity values of groundwater from site A and site B

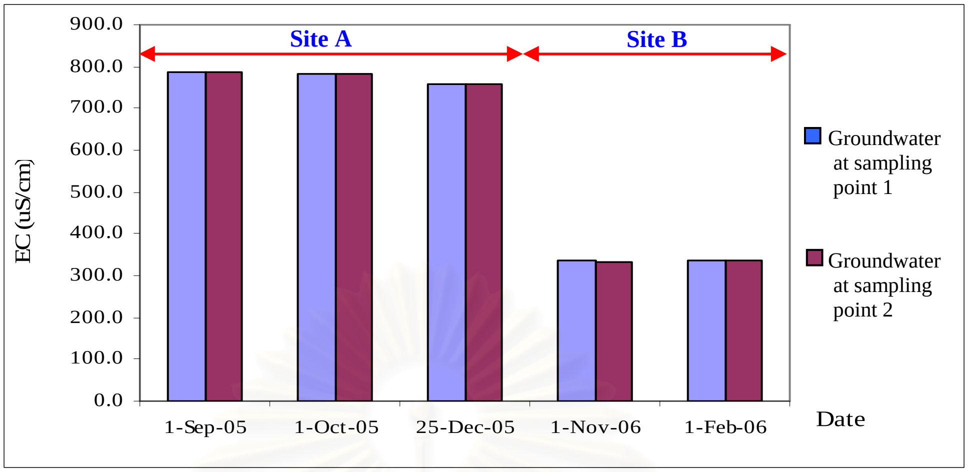


Figure 4.19 Electrical conductivity values of groundwater from site A and site B

4.3.1.5 Organic Carbon

Dissolved Organic Carbon (DOC) was also analyzed in this study. DOC of groundwater before passed through de-ironed facility (at sampling point 1) and groundwater which passed through de-ironed facility (at sampling point 2) from site A were in the range of 0.440-0.953 mg/L while DOC of groundwater before passed through de-ironed facility (at sampling point 1) and groundwater which passed through de-ironed facility (at sampling point 2) from site B were in the range of 0.570-0.686 mg/L. DOC is one of water parameters which can be a cause of the membrane fouling. Thus, membrane fouling is easily observed in high DOC water. The results of DOC from both sites were reported in Table 4.3 and Table 4.4.

Table 4.3 Characteristics of groundwater from Pra Too Khong Bottled Drinking Water Plant; site A (very high fluoride concentration site)

Water parameters	1 September 2005		1 October 2005		25 December 2005		Range of values	Average values	Remark
	Water samples at sampling point 1*	Water samples at sampling point 2**	Water samples at sampling point 1*	Water samples at sampling point 2**	Water samples at sampling point 1*	Water samples at sampling point 2**			
Temperature(° C)	30.0	29.5	25.2	27.0	26.7	27.8	25.2-30.0	27.7 $\pm$1.8	-
pH	7.86	7.92	8.17	8.17	8.00	8.01	7.86-8.17	8.02 $\pm$0.13	-
EC (µS/cm)	788	785	781	781	760	760	760-788	775 $\pm$12.5	-
Total Alkalinity (mg/L as $CaCO_3$)	400	390	340	340	350	350	340-400	361 $\pm$26.4	-
Na (mg/L)	177.6	176.4	181.3	181.4	116.2	103.8	103.8-181.4	156.1 $\pm$36.0	Cationic ion
Ca (mg/L)	6.53	6.41	6.49	6.64	6.72	6.64	6.41-6.72	6.57 $\pm$0.11	Cationic ion
K (mg/L)	4.47	4.36	4.57	4.63	4.45	4.60	4.36-4.63	4.51 $\pm$0.10	Cationic ion
Mg (mg/L)	3.51	3.44	3.82	3.86	3.10	3.03	3.03-3.86	3.46 $\pm$0.35	Cationic ion
T-Fe (mg/L)	ND	ND	0.00	0.00	0.00	0.00	0.00-0.00	0.00 $\pm$0.00	Cationic ion
Fluoride (mg/L)	16.98	16.69	14.50	13.86	12.36	12.05	12.05-16.98	14.41 $\pm$2.09	Anionic ion
Chloride (mg/L)	8.13	7.94	7.94	6.94	6.96	6.74	6.74-8.13	7.44 $\pm$0.62	Anionic ion
Nitrite (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00-0.00	0.00 $\pm$0.00	Anionic ion
Nitrate (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00-0.00	0.00 $\pm$0.00	Anionic ion
Sulfate (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00-0.00	0.00 $\pm$0.00	Anionic ion
Phosphate (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00-0.00	0.00 $\pm$0.00	Anionic ion
DOC (mg/L)	ND	0.953	0.626	0.573	0.502	0.440	0.440-0.953	0.620 $\pm$0.20	-

* Groundwater samples before passed through de-ironed facility

** Groundwater samples which passed through de-ironed facility / used as water samples for membrane experiment

Table 4.4 Characteristics of water samples from San Pa Hiang Membrane Plant; site B (high fluoride concentration site)

Water parameters	1 November 2005		1 February 2006		Range of values	Average values	Remark
	Water samples at sampling point 1*	Water samples at sampling point 2**	Water samples at sampling point 1*	Water samples at sampling point 2**			
Temperature(° C)	22.0	22.4	23.8	23.4	22.0-23.8	22.9 ±0.8	-
pH	6.60	6.65	6.62	6.58	6.58-6.65	6.61 ±0.03	-
EC (µS/cm)	335	334	336	338	334-338	335.7 ±1.7	-
Total Alkalinity (mg/L as $CaCO_3$)	160	155	160	170	155-170	161.2 ±6.3	-
Na (mg/L)	136.1	121.9	136.1	121.9	121.9-136.1	129.0 ±8.2	Cationic ion
Ca (mg/L)	14.62	11.66	14.62	11.66	11.66-14.62	13.14 ±1.71	Cationic ion
K (mg/L)	5.30	5.30	5.50	5.40	5.30-5.50	5.38 ±0.10	Cationic ion
Mg (mg/L)	7.10	7.21	7.24	7.24	7.10-7.24	7.20 ±0.07	Cationic ion
T-Fe (mg/L)	0.00	0.00	0.00	0.00	0.00-0.00	0.00 ±0.00	Cationic ion
Fluoride (mg/L)	2.88	2.84	3.06	3.12	2.84-3.12	2.98 ±0.14	Anionic ion
Chloride (mg/L)	10.50	10.45	10.70	10.70	10.45-10.70	10.59 ±0.13	Anionic ion
Nitrite (mg/L)	0.00	0.00	0.00	0.00	0.00-0.00	0.00 ±0.00	Anionic ion
Nitrate (mg/L)	0.76	0.62	0.54	0.60	0.54-0.76	0.63 ±0.09	Anionic ion
Sulfate (mg/L)	6.95	6.96	6.92	6.98	6.92-6.98	6.95 ±0.03	Anionic ion
Phosphate (mg/L)	0.00	0.00	0.00	0.00	0.00-0.00	0.00 ±0.00	Anionic ion
DOC (mg/L)	0.623	0.570	0.686	0.570	0.570-0.686	0.610 ±0.06	-

* Groundwater samples before passed through de-ironed facility

** Groundwater samples which passed through de-ironed facility / used as water samples for membrane experiment

According to the results of physical, chemical, and natural organic matter parameters of both sites, it was observed that the water quality of groundwater before passed through the de-ironed facility (at sampling point 1) and groundwater which passed through the de-ironed facility (at sampling point 2) was quite similar. The reason for this phenomenon was only Fe^{2+} and Fe^{3+} might be removed within the de-ironed facility while others ions might not be removed. For this study, Fe^{2+} and Fe^{3+} in groundwater of site A and site B were measured of 0 mg/L in both groundwater before passed through the de-ironed facility (at sampling point 1) and groundwater which passed through the de-ironed facility (at sampling point 2).

4.3.2 Characteristics of groundwater from the selected sites related to performance of the membranes on fluoride rejection

4.3.2.1 Cationic Ions

The main cationic ions which are generally found in groundwater consist of Na^{+}, K^{+}, Ca^{2+}, and Mg^{2+}. In the case of site A, the cationic ions in groundwater before passed through the de-ironed facility (at sampling point 1) and groundwater which passed through the de-ironed facility (at sampling point 2) including Na^{+}, K^{+}, Ca^{2+}, and Mg^{2+} were measured in the range of 103.8-181.4 mg/L, 4.36-4.63 mg/L, 6.41-6.72 mg/L, and 3.03-3.86 mg/L, respectively. Whereas, the cationic ions of groundwater from site B contained Na^{+}, K^{+}, Ca^{2+}, and Mg^{2+} were in the range of 121.9-136.1mg/L, 5.30-5.50 mg/L, 11.55-14.26 mg/L, and 7.10-7.24 mg/L, respectively.

4.3.2.2 Anionic Ions

The main anionic ions which are mostly found in groundwater consist of Cl^{-}, NO^{2-}, NO^{3-}, SO_4^{2-}, and PO_4^{3-}. Additionally, F^{-} is mainly found in the fluorotic area. In the case of site A, the anionic ions in groundwater before passed through the de-ironed facility (at sampling point 1) and groundwater which passed through the de-ironed facility (at sampling point 2) including $F^{-}$and Cl^{-} were measured in the range of 12.05-16.98 mg/L and 6.74-8.13 mg/L, respectively whereas NO^{2-}, NO^{3-}, SO_4^{2-}, and PO_4^{3-} were measured of 0 mg/L.

For site B, the anionic ions in groundwater before passed through the de-ironed facility (at sampling point 1) and groundwater which passed through the de-ironed facility (at sampling point 2) including F^{-}, Cl^{-}, NO^{3-}, and SO_4^{2-} were measured in the range of 2.84-3.12 mg/L, 10.45-10.70 mg/L, 0.54-0.76 mg/L, and 6.62-6.98 mg/L, respectively while NO^{2-} and PO_4^{3-} were measured of 0 mg/L.

From the Table 4.3 and Table 4.4, the characteristics of groundwater from the Pra Too Khong Bottled Drinking Water Plant (site A) and the San Pa Hiang Membrane Plant (site B) are reported. It was concluded that the Pra Too Khong Bottled Drinking Water Plant (site A) was defined as a very high fluoride concentration site within an average fluoride concentration of 14.41 mg/L while the San Pa Hiang Membrane Plant (site B) was defined as a high fluoride concentration site within an average fluoride concentration of 2.98 mg/L.

From the Table 4.5 and Table 4.6, the characteristics of groundwater from the Pra Too Khong Bottled Drinking Water Plant (site A) and the San Pa Hiang Membrane Plant (site B) in the unit of mEq/L are also reported. It was found that groundwater from the San Pa Hiang Membrane Plant (site B) has the various kinds of anionic ions which is more than that of the Pra Too Khong Bottled Drinking Water Plant (site A) so these anionic ions will have an effect on fluoride rejection in membrane experiments.

Table 4.5 Characteristics of groundwater from Pra Too Khong Bottled Drinking Water Plant (site A) in the unit of mEq/L

Water parameters	1 September 2005		1 October 2005		25 December 2005		Range of values	Average values	Remark
	Water samples at sampling point 1*	Water samples at sampling point 2**	Water samples at sampling point 1*	Water samples at sampling point 2**	Water samples at sampling point 1*	Water samples at sampling point 2**			
Temperature(° C)	30.0	29.5	25.2	27.0	26.7	27.8	25.2-30.0	27.7	-
pH	7.86	7.92	8.17	8.17	8.00	8.01	7.86-8.17	8.02	-
EC (µS/cm)	788	785	781	781	760	760	760-788	775	-
Total Alkalinity (mg/L as $CaCO_3$)	400	390	340	340	350	350	340-400	361	-
Na (mEq/L)	7.725	7.673	7.886	7.890	5.054	4.515	4.515-7.890	6.790	Cationic ion
Ca (mEq/L)	0.326	0.320	0.324	0.331	0.335	0.331	0.320-0.335	0.328	Cationic ion
K (mEq/L)	0.114	0.112	0.117	0.118	0.114	0.118	0.112-0.118	0.116	Cationic ion
Mg (mEq/L)	0.289	0.283	0.314	0.318	0.255	0.249	0.249-0.318	0.285	Cationic ion
T-Fe (mEq/L)	ND	ND	0.00	0.00	0.00	0.00	0.00-0.00	0.00	Cationic ion
Fluoride (mEq/L)	0.894	0.878	0.763	0.729	0.650	0.634	0.634-0.894	0.758	Anionic ion
Chloride (mEq/L)	0.229	0.224	0.224	0.196	0.196	0.190	0.190-0.229	0.210	Anionic ion
Nitrite (mEq/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00-0.00	0.00	Anionic ion
Nitrate (mEq/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00-0.00	0.00	Anionic ion
Sulfate (mEq/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00-0.00	0.00	Anionic ion
Phosphate (mEq/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00-0.00	0.00	Anionic ion
DOC (mg/L)	ND	0.953	0.626	0.573	0.502	0.440	0.440-0.953	0.620	-

* Groundwater samples before passed through de-ironed facility

** Groundwater samples which passed through de-ironed facility / used as water samples for membrane experiment

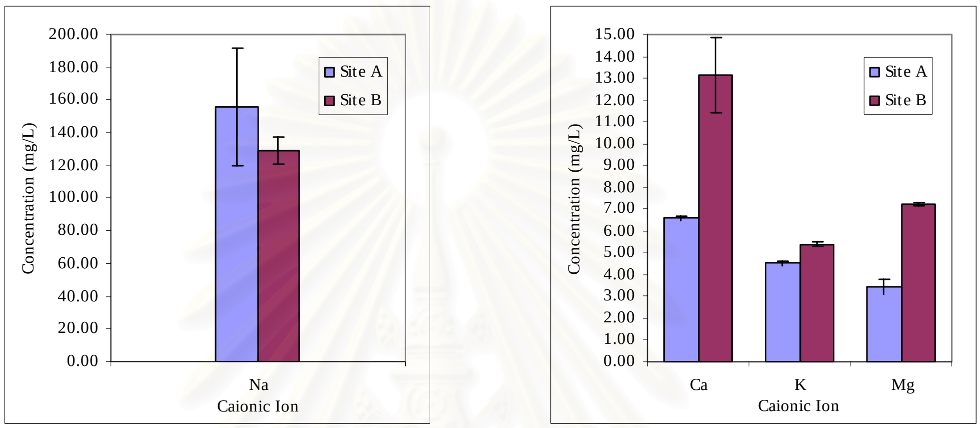
Table 4.6 Characteristics of water samples from San Pa Hiang Membrane Plant (site B) in the unit of mEq/L

Water parameters	1 November 2005		1 February 2006		Range of values	Average values	Remark
	Water samples at sampling point 1*	Water samples at sampling point 2**	Water samples at sampling point 1*	Water samples at sampling point 2**			
Temperature(° C)	22.0	22.4	23.8	23.4	22.0-23.8	22.9	-
pH	6.60	6.65	6.62	6.58	6.58-6.65	6.61	-
EC (μS/cm)	335	334	336	338	334-338	335.7	-
Total Alkalinity (mg/L as $CaCO_3$)	160	155	160	170	155-170	161.2	-
Na (mEq/L)	5.920	5.302	5.920	5.302	5.302-5.920	5.611	Cationic ion
Ca (mEq/L)	0.730	0.582	0.730	0.582	0.582-0.730	0.656	Cationic ion
K (mEq/L)	0.136	0.136	0.141	0.138	0.136-0.141	0.138	Cationic ion
Mg (mEq/L)	0.584	0.593	0.596	0.596	0.584-0.596	0.592	Cationic ion
T-Fe (mEq/L)	0.00	0.00	0.00	0.00	0.00-0.00	0.00	Cationic ion
Fluoride (mEq/L)	0.152	0.149	0.161	0.164	0.149-0.164	0.157	Anionic ion
Chloride (mEq/L)	0.296	0.295	0.302	0.302	0.295-0.302	0.299	Anionic ion
Nitrite (mEq/L)	0.00	0.00	0.00	0.00	0.00-0.00	0.00	Anionic ion
Nitrate (mEq/L)	0.012	0.010	0.009	0.010	0.009-0.012	0.010	Anionic ion
Sulfate (mEq/L)	0.144	0.144	0.144	0.146	0.114-0.146	0.145	Anionic ion
Phosphate (mEq/L)	0.00	0.00	0.00	0.00	0.00-0.00	0.00	Anionic ion
DOC (mg/L)	0.623	0.570	0.686	0.570	0.570-0.686	0.610	-

* Groundwater samples before passed through de-ironed facility

** Groundwater samples which passed through de-ironed facility / used as water samples for membrane experiment

Figure 4.20 and Figure 4.21 illustrate the average cationic ions concentration and anionic ions concentration of groundwater from the Pra Too Khong Bottled Drinking Water Plant (site A) and the San Pa Hiang Membrane Plant (site B).



(a) (b)

Figure 4.20 Average cationic ions concentration of groundwater from site A and site B

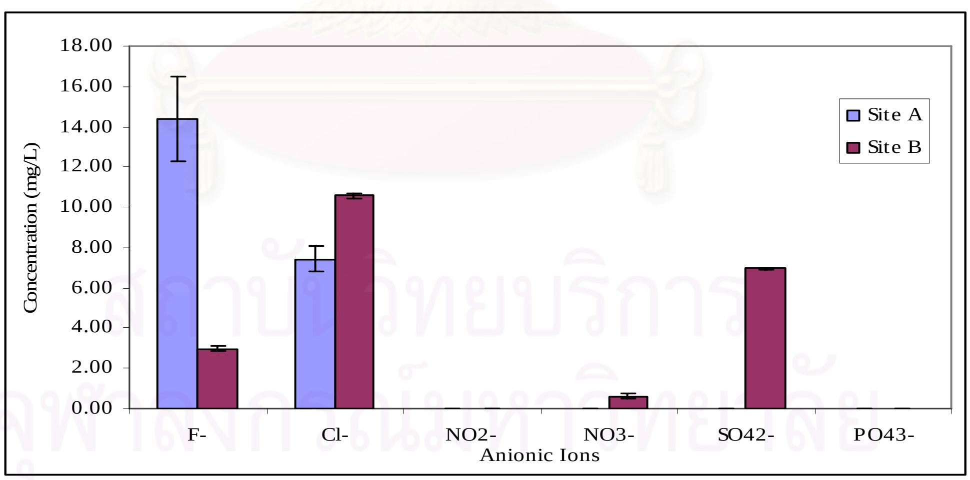


Figure 4.21 Anionic ions concentration of groundwater from site A and site B

4.3.3 The effect of electrical conductivity, alkalinity, pH, and calcium on fluoride concentration in groundwater

As mentioned previously, the high fluoride concentration in groundwater might be predicted from the high electrical conductivity, the high alkalinity, and the basic pH but low calcium concentration. Hence, to demonstrate the mentioned prediction, fluoride concentration in groundwater of site A and site B were plotted as a function of pH, alkalinity, electrical conductivity, and Ca^{2+} as depicted in Figure 4.22-Figure 4.25.

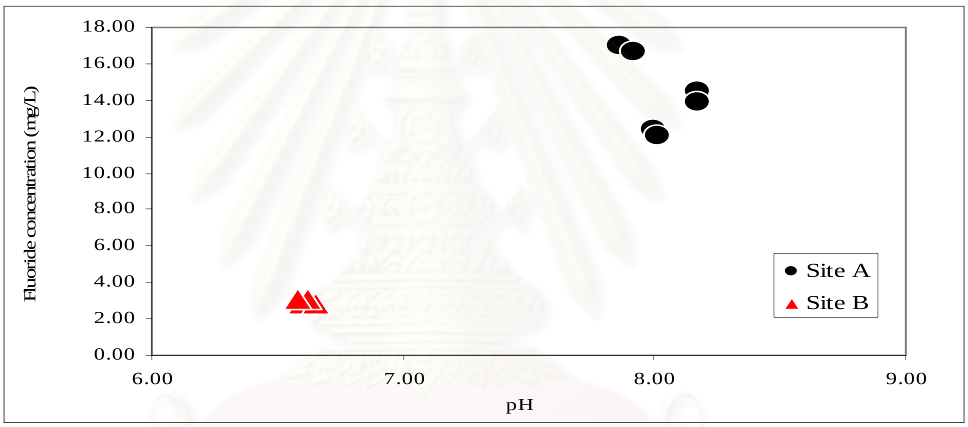


Figure 4.22 Fluoride concentration as a function of pH

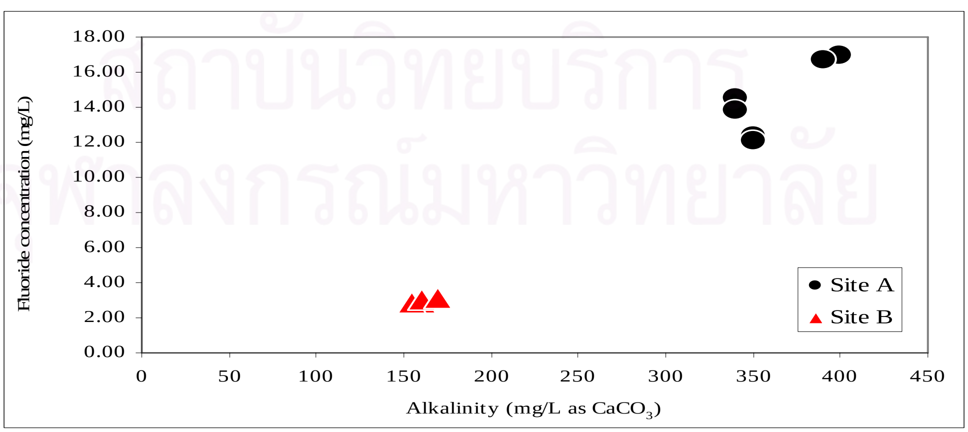


Figure 4.23 Fluoride concentration as a function of alkalinity

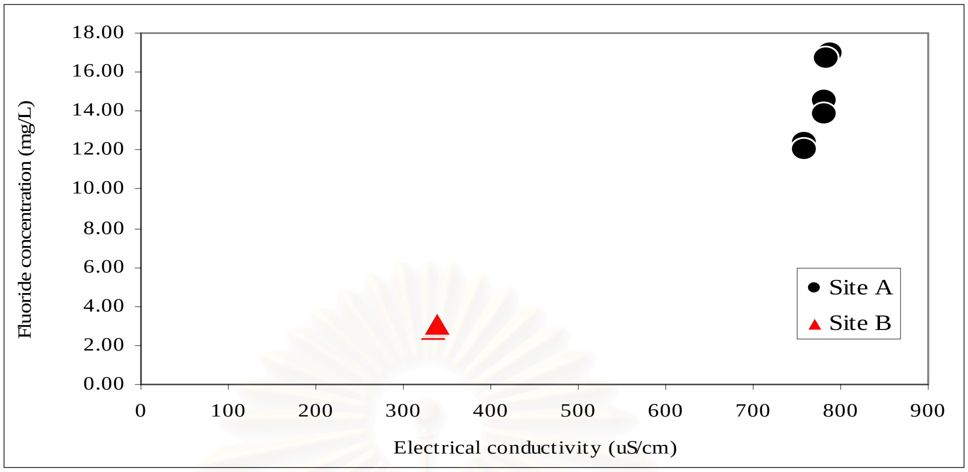


Figure 4.24 Fluoride concentration as a function of electrical conductivity

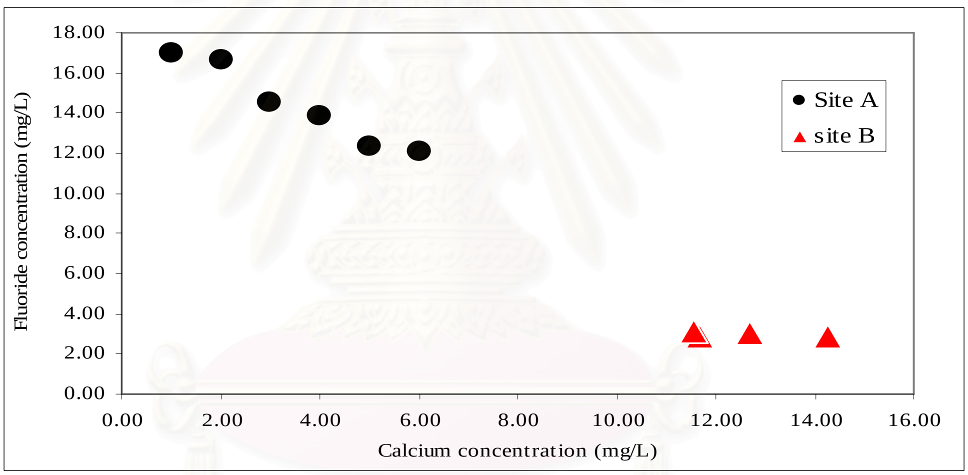


Figure 4.25 Fluoride concentration as a function of calcium concentration

From Figure 4.22 to Figure 4.25, it could be concluded that the obtained results were related to the prediction. Therefore, the high fluoride concentration in groundwater can be predicted from the high electrical conductivity, the high alkalinity, and the basic pH but low calcium concentration of groundwater. Accordingly, it should be recommended to the people in this fluorotic area which served groundwater as drinking water to avoid the high pH, the high alkalinity, and the high electrical conductivity of groundwater but low level of calcium concentration because fluoride concentration in the high level might be found in groundwater and could be a cause of fluorosis.

4.4 Membrane experimental results

4.4.1 Permeate water fluxes of NF membrane (UTC-60) and ULPRO membrane (UTC-70)

The NF membrane, namely, UTC-60 membrane and the ULPRO membrane, namely, UTC-70 membrane were developed by the Toray Company, Japan. Both of them which employed in this study were necessary to operate the membrane process at a low pressure in ranges of 0.1-0.5 MPa.

Figure 4.26 and Figure 4.27 illustrate the permeate water fluxes of the NF membrane (UTC-60) and the ULPRO membrane (UTC-70) which were investigated under steady state of each operating transmembrane pressure. The permeate water fluxes under steady state could be obtained from the sampling time determination when it reached termination as shown in Appendix C - Appendix D. The permeate water fluxes can be determined as

$$\text{Permeate water flux } (m^3/m^2 \cdot day) = \frac{\text{10 mL of permeate water}}{\text{A x (Time required for 10 mL of permeate water, min)}} \times 60 \, \frac{min}{hr} \times 24 \, \frac{hr}{day}$$

where A is Surface area of membrane sheet in cell unit, m^2 = 58.625×10^{-4} m^2

Generally, a term of operating transmembrane pressure was often used in membrane processes. Operating transmembrane pressure (OTP) is equal to $[(P_1+P_2)/2] - P_3$, where P_1 is feed pressure, P_2 is concentrated pressure, and P_3 is permeate pressure (considered negligible because of it was approximately 0). Table 4.7 gives the operating transmembrane pressure of each experiment.

The permeate water fluxes at steady state for various operating transmembrane pressure of the Pra Too Khong Bottled Drinking Water Plant (site A) and the San Pa Hiang Membrane Plant (site B) are separately reported in Table 4.8.

Table 4.7 Operating transmembrane pressure of each experiment

	NF membrane (UTC-60)			ULPRO membrane (UTC-70)		
	P_1 (MPa)	P_2 (MPa)	OTP (MPa)	P_1 (MPa)	P_2 (MPa)	OTP (MPa)
Pra Too Khong Bottled Drinking Water Plant (Site A)	0.102	0.098	0.100	0.102	0.100	0.101
	0.201	0.200	0.200	0.202	0.200	0.201
	0.290	0.290	0.290	0.291	0.290	0.290
	0.403	0.400	0.402	0.408	0.392	0.400
	0.506	0.496	0.501	0.504	0.495	0.500
San Pa Hiang Membrane Plant (Site B)	0.108	0.091	0.100	0.113	0.087	0.100
	0.209	0.192	0.200	0.212	0.187	0.199
	0.308	0.293	0.300	0.309	0.292	0.300
	0.406	0.394	0.400	0.410	0.391	0.400
	0.503	0.498	0.500	0.504	0.498	0.501

It was found that the permeate water fluxes at steady state of both membranes apparently increased with the operating transmembrane pressure. This phenomenon is agreement with the preferential sorption-capillary flow (PSCF) model (presented in Chapter II) which identified that the permeate water flux is a function of operating transmembrane pressure. Since the operating transmembrane pressure is increased, the permeate water flux will increase too.

From Figure 4.26, it was observed that the permeate water fluxes of NF membrane (UTC-60) of groundwater from site A and site B were quite the same. For the Pra Too Khong Bottled Drinking Water Plant (site A), under the operating transmembrane pressure of 0.100, 0.200, 0.290, 0.402, and 0.501 MPa, the observed permeate water fluxes at steady state were 0.314, 0.532, 0.780, 0.899, and 1.282 $m^3/m^2{\cdot}$day, respectively. In the case of the San Pa Hiang Membrane Plant (site B), under the operating transmembrane pressure of 0.100, 0.200, 0.300, 0.400, and 0.500 MPa, the observed permeate water fluxes at steady state were 0.209, 0.476, 0.734, 0.957, and 1.552 m^3/m^2·day, respectively.

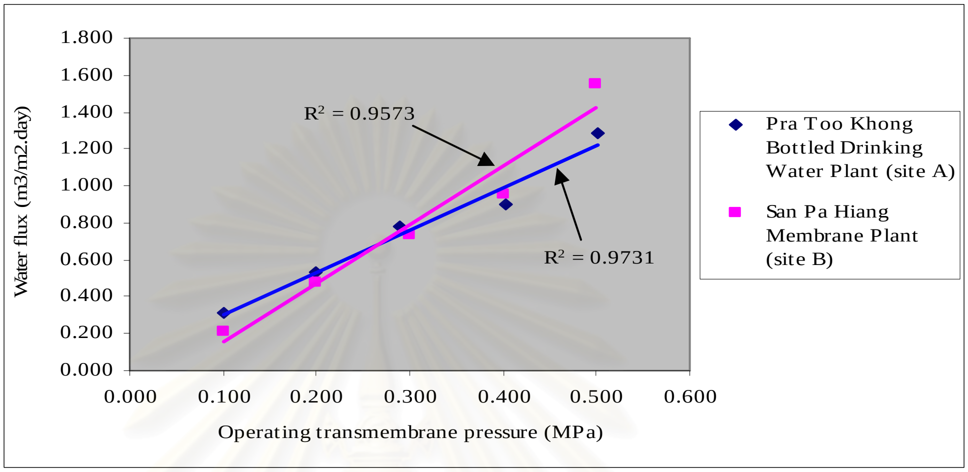


Figure 4.26 Permeate water fluxes at steady state as function of transmembrane pressure of UTC-60 membrane

In the case of the ULPRO membrane (UTC-70) as illustrated in Figure 4.27, it was also observed that the permeate water fluxes at steady state of both sites were still fairly the same. For the Pra Too Khong Bottled Drinking Water Plant (site A), under the operating transmembrane pressure of 0.101, 0.201, 0.290, 0.400, and 0.500 MPa, the observed permeate water fluxes at steady state were 0.129, 0.322, 0.481, 0.833, and 1.038 m^3/m^2·day, respectively. For the San Pa Hiang Membrane Plant (site B), under the operating transmembrane pressure of 0.100, 0.199, 0.300, 0.400, and 0.501 MPa, the observed permeate water fluxes at steady state were 0.176, 0.326, 0.507, 0.723, and 0.957 m^3/m^2·day, respectively.

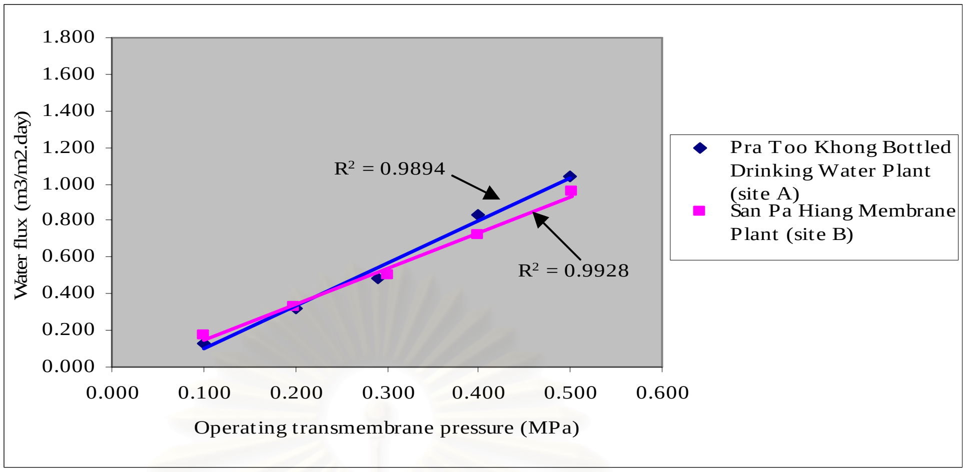


Figure 4.27 Permeate water fluxes at steady state as function of transmembrane pressure of UTC-70 membrane

Figure 4.28 and Figure 4.29 illustrate the comparison of the permeate water fluxes at steady state of both membranes for site A and site B, respectively. It was found that under the same operating transmembrane pressure, the permeate water fluxes of UTC-60 membrane are always higher than that of UTC-70 membrane. The reason of this phenomenon is due to the difference in the pore size of membranes and their permeability. UTC-60 membrane is categorized into nanofiltration membrane type whereas UTC-70 membrane is categorized into reverse osmosis membrane type thus permeability of UTC-60 membrane is higher than UTC-70 membrane.

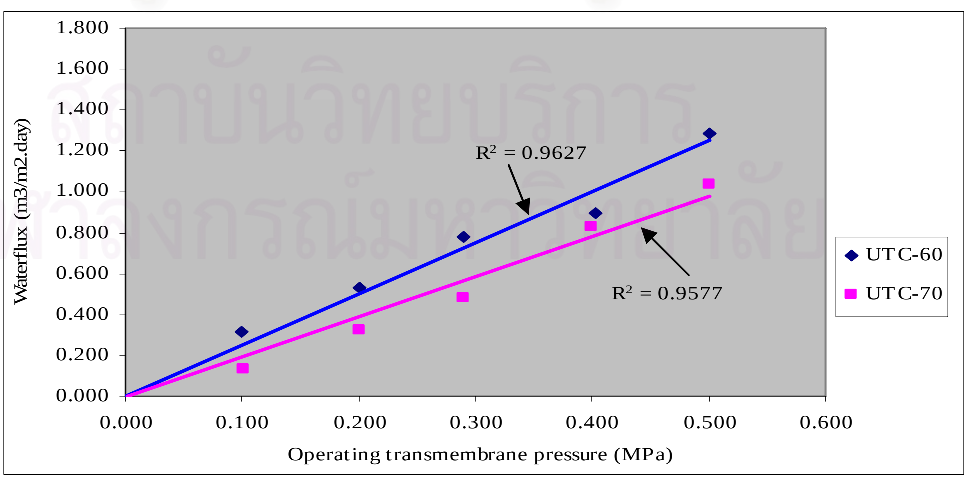


Figure 4.28 Permeate water fluxes at steady state as function of OTP of UTC-60 membrane and UTC-70 membrane at the Pra Too Khong Bottled Drinking Water Plant

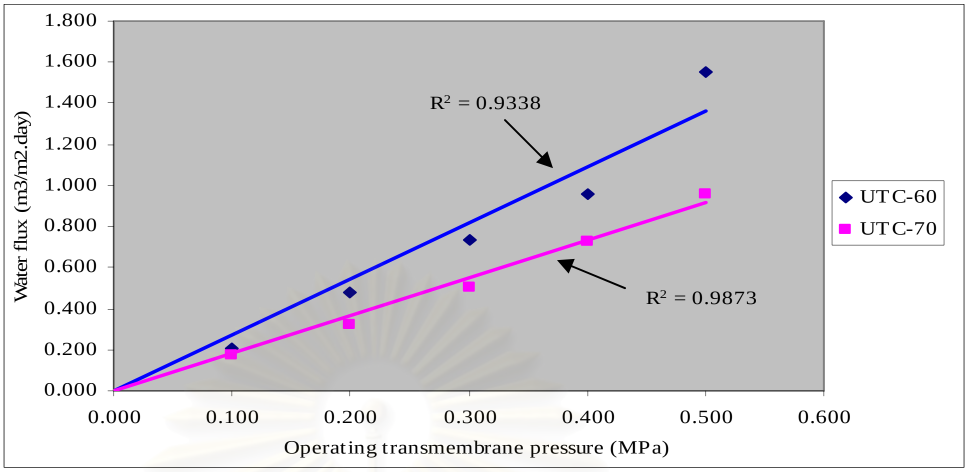


Figure 4.29 Permeate water fluxes at steady state as function of OTP of UTC-60 membrane and UTC-70 membrane at the San Pa Hiang Membrane Plant

Table 4.8 Permeate water fluxes at steady state of various operating transmembrane pressure

	NF membrane (UTC-60)			ULPRO membrane (UTC-70)		
	OTP (MPa)	Permeate water flux at steady state ($m^3/m^2 \cdot day$)	Sampling time (hr)	OTP (MPa)	Permeate water flux at steady state ($m^3/m^2 \cdot day$)	Sampling time (hr)
Pra Too Khong Bottled Drinking Water Plant (site A)	0.100	0.314	20	0.101	0.129	24
	0.200	0.532	9	0.201	0.322	15
	0.290	0.780	5	0.290	0.481	8
	0.402	0.899	5	0.400	0.833	7
	0.501	1.282	5	0.500	1.038	6
San Pa Hiang Membrane Plant (site B)	0.100	0.209	15	0.100	0.176	27
	0.200	0.476	10	0.199	0.326	24
	0.300	0.734	6	0.300	0.507	12
	0.400	0.957	4	0.400	0.723	9
	0.500	1.552	3	0.501	0.957	6

The results of membrane experiment of groundwater from the Pra Too Khong Botttled Drinking Water Plant (site A) and the San Pa Hiang Membrane Plant (site B) were reported in Appendix C - Appendix D. The effect of the operating transmembrane pressure and the feed pH value on fluoride rejection was discussed as followed.

4.4.2 Fluoride rejection by membranes

4.4.2.1 NF membrane (UTC-60) experiments

a) The experiment using groundwater from the Pra Too Khong Bottled Drinking Water Plant (site A)

Figure 4.30 illustrates the performance of UTC-60 membrane on fluoride rejection at steady state condition for the very high fluoride concentration groundwater (14.41 mg/L) from the Pra Too Khong Bottled Drinking Water Plant (site A).

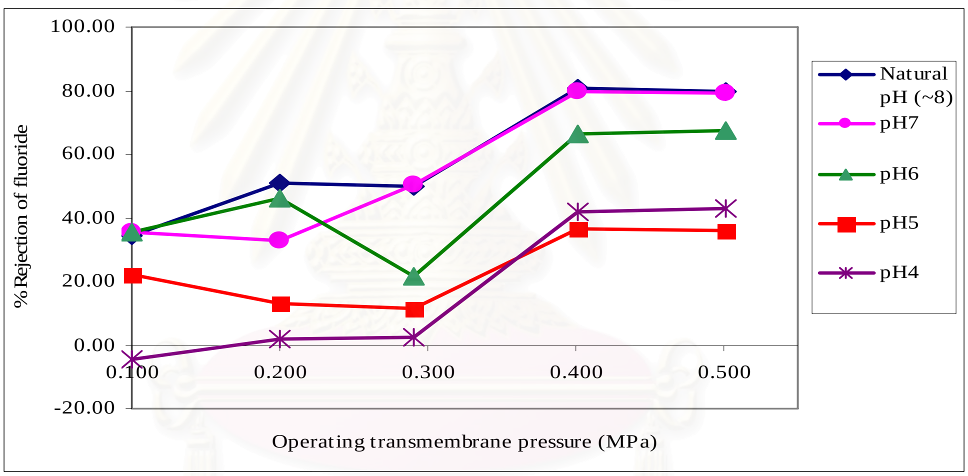


Figure 4.30 Percent fluoride rejection as a function of operating transmembrane pressure at different feed pH of very high fluoride concentration groundwater (14.41 mg/L) from Pra Too Khong Bottled Drinking Water Plant (site A) by NF membrane (UTC-60)

As shown in Figure 4.30, the effect of the operating transmembrane pressure of UTC-60 membrane process on fluoride rejection was observed. In the case of the feed pH values were natural pH and 7, the percentage fluoride rejection increased with the operating transmembrane pressure rose from 0.1 to 0.5 MPa. This is attributed to the reasons that the increasing in operating transmembrane pressure resulting in the increment of driving force for water but only a few affects the driving force for fluoride.

The increase in the operating transmembrane pressure increased the water flux of permeate water whereas the solute flux can be thought to be less affected by the increment of the operating transmembrane pressure when compared with the increase in water flux (Ratanatamskul, 1996; Arora et al., 2004). By these reasons, higher fluoride concentration in permeate water at the lower operating transmembrane pressure than that of at the higher operating transmembrane pressure could be noticed in the experiment which leads to the results that the percent fluoride rejection at the lower operating transmembrane pressure were lower than the percent fluoride rejection at the higher operating transmembrane pressure.

Besides, the effects of pH of the feed water on the percent fluoride rejection by UTC-60 membrane were also found as can be seen in Figure 4.30. Under the UTC-60 membrane process operated with the feed water of pH ranged from approximately 4 to 8, it could be noted that the percent fluoride rejection obtained at the lower feed pH conditions have a tendency to be lower than that of those obtained at the higher feed pH conditions. This is due to the ineffectiveness of electric repulsion for monovalent anions at low pH in feed water (Ratanatamskul, 1996). As the results, fluoride concentration in permeate water at the lower feed pH was greater than those of at the higher feed pH and was the cause of the percent fluoride rejection at the lower feed pH being lower than those of at the higher feed pH. By this above reason, the fluctuation of the percent fluoride rejection was observed when using the feed pH values of 5 and 6. However, the effects of the feed pH on the fluoride rejection will be discussed more in term of isoelectric point in section 4.4.3.

In addition, the negative value of fluoride rejection was observed in the experiment of pH of the feed water at 4 (low pH) under the operating transmembrane pressure of 0.1 MPa. The reasons that could be used to support this phenomenon are similar to the above mentioned discussions which are the effects of operating transmembrane pressure and pH on percent fluoride rejection.

b) The experiment using groundwater from the San Pa Hiang Membrane Plant (site B)

Figure 4.31 illustrates the performance of UTC-60 membrane on the fluoride rejection at steady state condition for the high fluoride concentration groundwater (2.98 mg/L) from the San Pa Hiang Membrane Plant (site B).

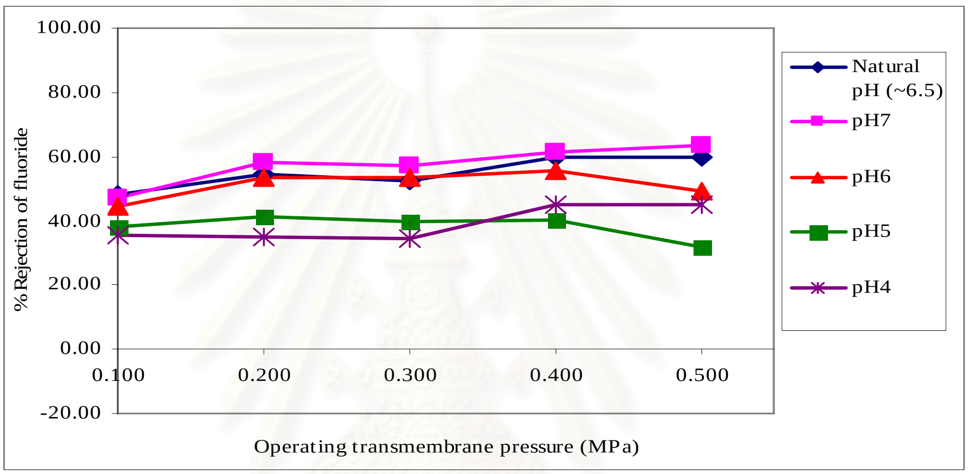


Figure 4.31 Percent fluoride rejection as a function of operating transmembrane pressure at different feed pH of high fluoride concentration groundwater (2.98 mg/L) from San Pa Hiang Membrane Plant (site B) by NF membrane (UTC-60)

As shown in Figure 4.31, the effect of the operating transmembrane pressure of UTC-60 membrane process on the fluoride rejection for the high fluoride concentration groundwater (2.98 mg/L) from the San Pa Hiang Membrane Plant (site B) was observed. These results showed that the percentage of fluoride rejection has a tendency to be increased with the increasing of operating transmembrane pressure. This phenomenon is similar to that of groundwater from the Pra Too Khong Bottled Drinking Water Plant (site A). Thus the mechanism of this phenomenon could be explained in the same way as in the case of the Pra Too Khong Bottled Drinking Water Plant (site A). However, it was found that the percentage of the fluoride rejection was not increased significantly with the increasing of the operating transmembrane pressure. A reason of this matter was due to the ineffectiveness of electric repulsion for monovalent anions in the presence of multivalent anions (Ratanatamskul, 1996). It means that when fluoride ions were presented in multivalent anionic water, the multivalent anions likely to be repulsed from the membrane more effective than fluoride ions. As can be seen in Table 4.5 and Table 4.6, the anionic ions in groundwater from the San Pa Hiang Membrane Plant (site B) contains higher Cl^-, NO_3^-, and SO_4^{2-} than those of the Pra Too Khong Bottled Drinking Water Plant (site A) thus the presence of these anionic ions in groundwater from the San Pa Hiang Membrane Plant (site B) might have an higher effect on the percent fluoride rejection compared to groundwater from the Pra Too Khong Bottled Drinking Water Plant (site A).

The effects of pH of feed water on the percent fluoride rejection by UTC-60 membrane were also observed as shown in Figure 4.31. Under the UTC-60 membrane process operated with the feed pH ranges from approximately 4 to 7, it could be observed that the percent fluoride rejection obtained at lower feed pH conditions have a tendency to be lower than that of those obtained at higher feed pH conditions. This phenomena could be described as same as that of the Pra Too Khong Bottled Drinking Water Plant (site A). The fluctuation of the percent fluoride rejection was still observed when using the feed pH values of 5 and 6. However, the effects of the feed pH on the fluoride rejection will be discussed more in term of isoelectric point in section 4.4.3.

Additionally, the negative value of fluoride rejection was not observed at the lower pH of feed water under the lower operating transmembrane pressure as can be seen in the case of groundwater from the Pra Too Khong Bottled Drinking Water Plant (site A). It might be explained that in this condition, the solute flux of fluoride ions in the permeate water of groundwater from the San Pa Hiang Membrane Plant (site B) might be less than that of the Pra Too Khong Bottled Drinking Water Plant (site A). Even though the permeate water flux under lower operating transmembrane pressure was poor, fluoride concentration in the mentioned permeate water was not higher than fluoride concentration in feed water. Thus, the negative value of fluoride rejection was not observed.

4.4.2.2 ULPRO membrane (UTC-70) experiments

Figure 4.32 and Figure 4.33 illustrate the performance of UTC-70 membrane in the fluoride rejection under steady state condition for the very high fluoride concentration groundwater (14.41 mg/L) from the Pra Too Khong Bottled Drinking Water Plant (site A) and for the high fluoride concentration groundwater (2.98 mg/L) from the San Pa Hiang Membrane Plant (site B), respectively.

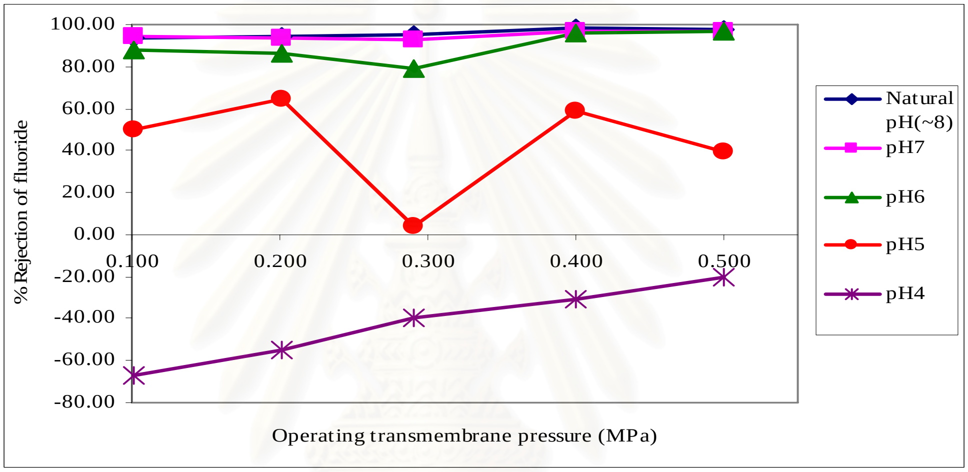


Figure 4.32 Percent fluoride rejection as a function of OTP at the different feed pH of very high fluoride concentration groundwater (14.41 mg/L) from the Pra Too Khong Bottled Drinking Water Plant (site A) by UTC-70 membrane

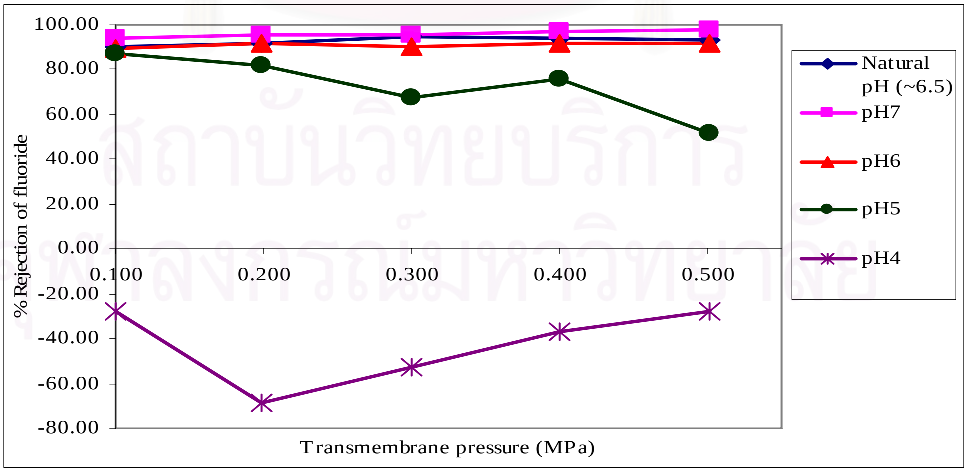


Figure 4.33 Percent fluoride rejection as a function of OTP at different feed pH of the high fluoride concentration groundwater (2.98 mg/L) from the San Pa Hiang Membrane Plant (site B) by UTC-70 membrane

As shown in Figure 4.32 and Figure 4.33, the effect of the operating transmembrane pressure of UTC-70 membrane process on the fluoride rejection from groundwater from both selected sites was observed. It was found that the performance of UTC-70 membrane on fluoride rejection of groundwater from both selected sites was quite the same. These phenomena are different from that of UTC-60 membrane thus it means that there is no effect of ions selectivity on UTC-70 membrane. This is attributed to the reasons that the mechanisms of UTC-70 membrane on fluoride ion and other ions rejection were considerably different from that of UTC-60 membrane. The mechanisms of UTC-60 membrane on fluoride ion and other ions rejection were size exclusion and electric repulsion while the mechanisms of UTC-70 membrane on fluoride ion and other ions rejection were electric repulsion, solution diffusion, and molecular interaction, respectively.

Moreover, the effects of pH of feed water on the percent fluoride rejection by UTC-70 membrane were also observed in groundwater from both selected sites as can be seen in Figure 4.32 and Figure 4.33. Under the UTC-70 membrane process, it was operated with the feed water of pH ranged from approximately 4 to 8, the fluctuation of percentage of fluoride rejection can be observed from the under feed pH water of 6. This phenomenon will be explained more in section 4.4.3.

In the case of UTC-70 membrane, at the feed pH value of 4, the negative rejection of fluoride ion was significantly observed under the operating transmembrane pressure ranges from 0.1 to 0.5 MPa. This is due to the ineffectiveness of electric repulsion for monovalent anions at low pH in feed water of UTC-70 membrane and another reason was the permeate water fluxes of UTC-70 membrane under the operating transmembrane pressure ranges from 0.1 to 0.5 MPa were low. Thus, fluoride concentration in permeate water under this condition might be more than fluoride concentration in the feed water.

4.4.3 Estimated pH values at isoelectric points of UTC-60 and UTC-70 membranes

From the membrane experimental results of UTC-60 and UTC-70 membranes, it was found that at the approximate feed pH values of 5 for UTC-60 membrane and 6 for UTC-70 membrane, the fluctuation of fluoride rejection performances were significantly observed. These phenomena may be caused by the effect of the isoelectric point which related to the pH values of the feed water on charged surface property.

4.4.3.1 An isoelectric point of UTC-60 membrane

The estimation of pH value at an isoelectric point of UTC-60 membrane obtained from the experimental results of groundwater from Pra Too Khong Bottled Drinking Water Plant (site A) and San Pa Hiang Membrane Plant (site B) are shown in Figure 4.34 and Figure 4.35.

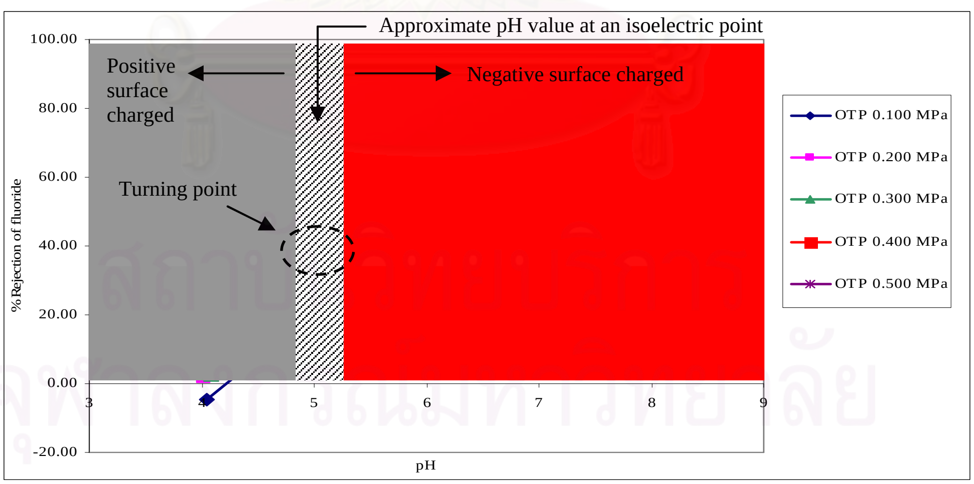


Figure 4.34 The approximate pH value at an isoelectric point of UTC-60 membrane for groundwater from Pra Too Khong Bottled Drinking Water Plant (site A)

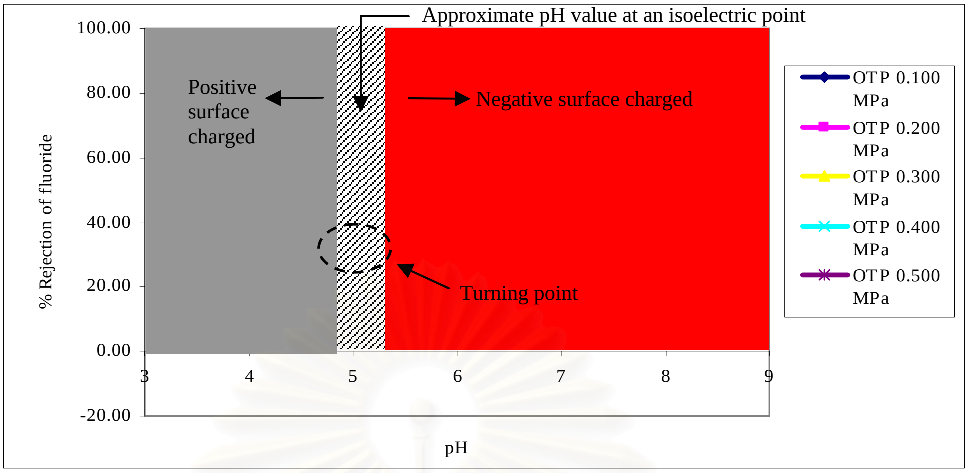


Figure 4.35 The approximate pH value at an isoelectric point of UTC-60 membrane for groundwater from San Pa Hiang Membrane Plant (site B)

Szoke et al. (2002) proposed that an isoelectric point of nano membrane could be roughly estimated at the feed pH value at which the turning point of ion rejection was observed. At this point, membrane surface charge is nearly zero and named as “isoelectric point”.

From Figure 4.34 and Figure 4.35, it was found that the turning points of fluoride rejection could be significantly observed at the approximate feed pH of 5 under 0.4-0.5 MPa operating transmembrane pressure in both experiments of using groundwater from the Pra Too Khong Bottled Drinking Water Plant (site A) and the San Pa Hiang Membrane Plant (site B). While the turning point of fluoride rejection of the other condition experiments were not clearly noticed because other condition experiments may have the effects from both feed pH values and operating transmembrane pressures. Hence, only the results obtained from the experiments of under 0.4-0.5 MPa were considered so as to predict the isoelectric point and it can be roughly stated that the isoelectric point of UTC-60 membrane is occurred at the pH of about 5.

As previously mentioned in Figure 2.8 and Figure 2.9 in section 2.2.3, UTC-60 and UTC-70 membrane surfaces are polyamides which consist of 2 functional groups; carboxylate group and amine group. Therefore, it can be concluded that the charge on UTC-60 and UTC-70 membranes surface are negatively charge when the feed pH value is higher than that of at the isoelectric point, whereas the feed pH value is lower than that of at the isoelectric point, the charge on membrane surface are positive.

4.4.3.2 An isoelectric point of UTC-70 membrane

The estimation of pH value at an isoelectric point of UTC-70 membrane obtained from the experimental results of groundwater from Pra Too Khong Bottled Drinking Water Plant (site A) and San Pa Hiang Membrane Plant (site B) are shown in Figure 4.36 and Figure 4.37.

The determination of pH value at an isoelectric point of UTC-70 membrane used to be done with the titration method by Mr. Matsui, a doctoral degree student at the Department of Urban Engineering, The University of Tokyo, Japan. From his study, it was found that the pH value at an isoelectric point of UTC-70 membrane was around the pH of 6.

It was observed that at an isoelectric point of UTC-70 membrane, the performance of nearly complete rejection of fluoride at the feed pH of 7 and decreased and down to nearly 80 % rejection of fluoride at the feed pH of 6.

Because of the membrane structure of UTC-60 membrane and UTC-70 membrane is the same thus the explanation of pH value at an isoelectric point of UTC-70 membrane is similar to that of UTC-60 membrane.

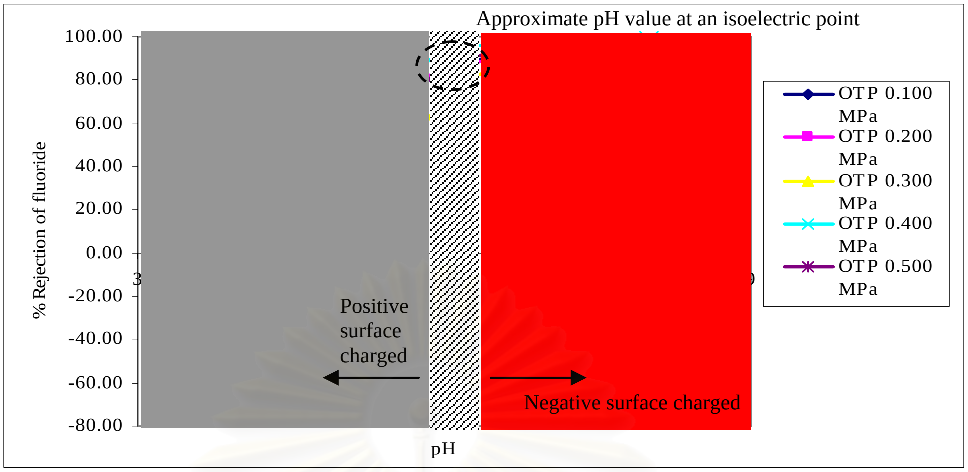


Figure 4.36 The approximate pH value at an isoelectric point of UTC-70 membrane for groundwater from Pra Too Khong Bottled Drinking Water Plant (site A)

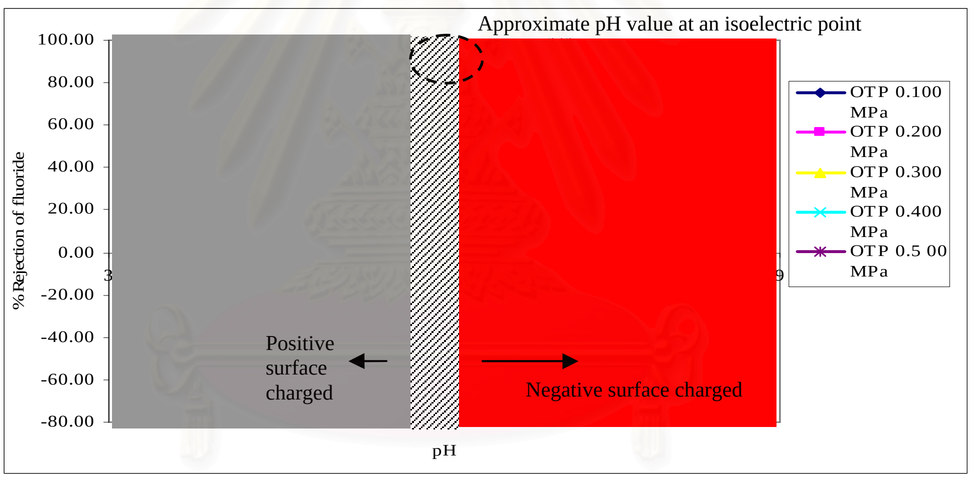


Figure 4.37 The approximate pH value at an isoelectric point of UTC-70 membrane for groundwater from San Pa Hiang Membrane Plant (site B)

4.4.4 Comparison of ULPRO membrane (UTC-70) and NF membrane (UTC-60) results

One of the objectives of this study was to compare the performance of the ULPRO membrane (UTC-70) and the NF membrane (UTC-60) on the defluoridation of fluorotic groundwater. Hence, the comparison of the ULPRO membrane (UTC-70) and the NF membrane (UTC-60) results was reported in Table 4.9 and Table 4.10.

Table 4.9 Comparison of ULPRO membrane (UTC-70) and NF membrane (UTC-60) results

	UTC-60 membrane	UTC-70 membrane
Pra Too Khong Bottled Drinking Water Plant (site A)		
Maximum OTP at steady state	0.5 MPa*	0.5 MPa*
Permeate water flux at steady state of OTP under 0.5 MPa	1.282	1.038
% Rejection of fluoride at feed pH of natural pH under 0.5 MPa	80.75 %	98.17 %
% Rejection of fluoride at feed pH of 7 under 0.5 MPa	79.67 %	96.93 %
% Rejection of fluoride at feed pH of 6 under 0.5 MPa	67.39 %	95.77 %
% Rejection of fluoride at feed pH of 5 under 0.5 MPa	36.76 %	58.76 %
% Rejection of fluoride at feed pH of 4 under 0.5 MPa	42.74 %	-20.08 %
Estimated pH at isoelectric point	5	6
San Pa Hiang Membrane Plant (site B)		
Maximum OTP at steady state	0.5 MPa*	0.5 MPa*
Permeate water flux at steady state of OTP under 0.5 MPa	1.552	0.957
% Rejection of fluoride at feed pH of 7 under 0.5 MPa	63.38 %	97.44 %
% Rejection of fluoride at feed pH of natural pH under 0.5 MPa	59.86 %	93.59 %
% Rejection of fluoride at feed pH of 6 under 0.5 MPa	55.63 %	91.67 %
% Rejection of fluoride at feed pH of 5 under 0.5 MPa	40.14 %	75.64 %
% Rejection of fluoride at feed pH of 4 under 0.5 MPa	45.07 %	-27.88 %
Estimated pH at isoelectric point	5	6

* Based on the experimental results, the highest defluoridation by membranes obtained under OTP in this study (0.5 MPa)

From Table 4.8, it was indicated that the maximum performance of fluoride rejection of groundwater from the Pra Too Khong Bottled Drinking Water Plant (site A) and the San Pa Hiang Membrane Plant (site B) was observed under the operating transmembrane pressure of 0.5 MPa from both UTC-60 and UTC-70 membranes.

For the membrane experimental results of groundwater from the Pra Too Khong Bottled Drinking Water Plant (site A), the maximum percent fluoride rejection of UTC-

60 and UTC-70 membranes at the feed pH of natural pH were 80.75 % and 98.17 %, respectively. For the membrane experimental results of groundwater from the San Pa Hiang Membrane Plant (site B), the maximum percent fluoride rejection of UTC-60 and UTC-70 membranes at the feed pH of neutral pH were 63.38 % and 97.44, respectively. Therefore, it can be concluded that the maximum percent fluoride rejection of UTC-70 membrane was higher than that of UTC-60 membrane. Additionally, it was found that in the case of UTC-60 membrane on the maximum percent fluoride rejection of groundwater from both selected sites was greatly different. The result of this phenomenon was groundwater from the San Pa Hiang Membrane Plant (site B) has many kinds of anionic ions which is more than that of the Pra Too Khong Bottled Drinking Water Plant (site A). It leads to the ineffectiveness of electric repulsion for fluoride ion compared with multivalent anionic ions. Therefore, the maximum percent fluoride rejection of groundwater from the San Pa Hiang Membrane Plant (site B) was less than that of the Pra Too Khong Bottled Drinking Water Plant (site A) when UTC-60 membrane was employed in the experiments.

Moreover, the negative rejection of fluoride from groundwater from both selected sites was significantly observed from UTC-70 membrane experimental results at the maximum percent fluoride rejection. So, it should be avoided the feed groundwater at pH of 4 when UTC-70 membrane is employed in the membrane experiments.

However, the advantages of UTC-60 membrane on defluoridation from groundwater were higher of permeate water flux could be obtained and negative percent fluoride rejection could not be observed.

Finally, the estimated pH value at isoelectric point which obtained from the membrane experimental results were noticed at pH of 5 and pH of 6 for UTC-60 membrane and UTC-70 membrane, respectively.

Table 4.10 shows the Fluoride concentration in the permeate water from the ULPRO membrane (UTC-70) and the NF membrane (UTC-60). It was observed that groundwater from the Pra Too Khong Bottled Drinking Water Plant (site A) at the maximum performance of NF membrane (UTC-60) for fluoride removal, the fluoride concentration in the permeate water was 2.41 mg/L. Whereas groundwater from the San Pa Hiang Membrane Plant (site B) at the maximum performance of NF membrane (UTC-60) for fluoride removal, the fluoride concentration in the permeate water was 1.04 mg/L. It was found that fluoride concentration in the permeate water from both sites was higher than 0.7 mg/L of the bottled drinking water standard of Ministry of Industry.

Table 4.10 Fluoride concentration in the permeate water from the ULPRO membrane (UTC-70) and the NF membrane (UTC-60)

	UTC-60 membrane	UTC-70 membrane
Pra Too Khong Bottled Drinking Water Plant (site A)		
Maximum OTP at steady state	0.5 MPa*	0.5 MPa*
Fluoride concentration in the permeate water using the feed pH of natural pH under 0.5 MPa	2.41 mg/L	0.27 mg/L
Fluoride concentration in the permeate water using the feed pH of 7 under 0.5 MPa	2.50 mg/L	0.39 mg/L
Fluoride concentration in the permeate water using the feed pH of 6 under 0.5 MPa	3.93 mg/L	1.38 mg/L
Fluoride concentration in the permeate water using the feed pH of 5 under 0.5 MPa	7.76 mg/L	7.27 mg/L
Fluoride concentration in the permeate water using the feed pH of 4 under 0.5 MPa	6.90 mg/L	14.47 mg/L
San Pa Hiang Membrane Plant (site B)		
Maximum OTP at steady state	0.5 MPa*	0.5 MPa*
Fluoride concentration in the permeate water using the feed pH of 7 under 0.5 MPa	1.04 mg/L	0.08 mg/L
Fluoride concentration in the permeate water using the feed pH of natural pH under 0.5 MPa	1.14 mg/L	0.21 mg/L
Fluoride concentration in the permeate water using the feed pH of 6 under 0.5 MPa	1.44 mg/L	0.26 mg/L
Fluoride concentration in the permeate water using the feed pH of 5 under 0.5 MPa	1.94 mg/L	1.50 mg/L
Fluoride concentration in the permeate water using the feed pH of 4 under 0.5 MPa	1.56 mg/L	3.99 mg/L

* Based on the experimental results, the highest defluoridation by membranes obtained under OTP in this study (0.5 MPa)

In the case of UTC-70 membrane, fluorotic groundwater from both the Pra Too Khong Bottled Drinking Water Plant (site A) and the San Pa Hiang Membrane Plant (site B) were experimented and their results showed that the operating condition of the ULPRO membrane (UTC-70) for fluoride removal was obtained under the operating transmembrane pressure of 0.5 MPa within the feed pH value of natural pH. At this desired condition, fluoride concentration in the permeate water of 0.08 mg/L was achieved from the membrane experiment using groundwater from the San Pa Hiang Membrane Plant (site B) and fluoride concentration in the permeate water of 0.27 mg/L was achieved from the membrane experiment using groundwater from the Pra Too Khong Bottled Drinking Water Plant (site A). It was found that fluoride concentration in the permeate water from both sites was lower than 0.7 mg/L of the bottled drinking water standard of Ministry of Industry.

It can be concluded that the fluoride concentration in permeate water which was obtained from the UTC-70 membrane experiments met the bottled drinking water standard of Ministry of Industry when the operating condition of the ULPRO membrane (UTC-70) for fluoride removal was set under the operating transmembrane pressure of 0.5 MPa within the feed pH value of natural pH (7-8).

CHAPTER V

CONCLUSIONS

Based on the experimental results, the following conclusion can be drawn.

1. From the groundwater quality investigation for 119 village waterworks, the high fluoride concentration in groundwater distributed in the north-eastern area of Muang district and Ban Ti district where groundwater was defined as an alkali carbonate type (occasionally found in chemical interaction between groundwater and the granitic aquifers) while the low fluoride concentration in groundwater distributed in the area of Pa Sang district and Mae Ta district where temporary hardness of groundwater was predominated.

2. It was observed that the high fluoride concentration in groundwater might be predicted from the high electrical conductivity, the high alkalinity, and the basic pH of groundwater. Additionally, the high fluoride concentration in groundwater might be also found in the low calcium concentration of groundwater.

3. The results of the groundwater quality investigation for the village waterworks, it was indicated that 53 wells from the total of 119 wells (44.54 %) have fluoride concentration above 0.7 mg/L when compared with the bottled drinking water standard of Ministry of Industry.

4. The results of the severity of dental fluorosis indicated that in the low fluoride concentration area, the severity of dental fluorosis was mostly distributed in none or mild

level. In contrast, severe cases of dental fluorosis could be observed significantly in the high fluoride concentration area.

5. For the membrane experimental results, it was found that the permeate water fluxes of both membranes apparently increased with the operating transmembrane pressure. Under the same operating transmembrane pressure, the permeate water flux of UTC-60 membrane is always higher than that of UTC-70 membrane. The reason is due to the difference in the pore size of membranes and their permeability.

6. Groundwater from the selected sites in fluorotic area for the membrane experiments includes groundwater from the Pra Too Khong Bottled Drinking Water Plant (site A) and groundwater from the San Pa Hiang Membrane Plant (site B). The surprising site, namely, the Pra Too Khong Bottled Drinking Water Plant (site A) which is defined as the very high fluoride concentration site (>5 mg/L) was observed the fluoride concentration in the range of 12.05-16.98 mg/L while the San Pa Hiang Membrane Plant (site B) which is defined as the high fluoride concentration site (1-5 mg/L) was observed the fluoride concentration in the range of 2.84-3.12 mg/L. Groundwater in both sites were highly recommended to be defluoridated before drinking.

7. For groundwater from the Pra Too Khong Bottled Drinking Water Plant (site A), the maximum performance of NF membrane (UTC-60) for fluoride removal was reported about 80 % rejection (fluoride concentration in the permeate water was 2.41 mg/L) can be obtained under the operating transmembrane pressure of 0.5 MPa within the feed pH value of natural pH ($\underset{\sim}{}$ 8) whereas groundwater from the San Pa Hiang Membrane Plant (site B), the maximum performance of NF membrane (UTC-60) for fluoride removal was noted about 60 % rejection (fluoride concentration in the permeate water was 1.04 mg/L) can be obtained at the operating transmembrane pressure of 0.5 MPa within the feed pH value of neutral pH. It was found that fluoride concentration in the permeate water from both sites was higher than 0.7 mg/L of the bottled drinking water standard of Ministry of Industry. It was also observed that the performances of

UTC-60 membrane on the maximum percent fluoride rejection of groundwater from both of selected sites were greatly different. This result of this phenomenon was groundwater from the San Pa Hiang Membrane Plant (site B) has many kinds of anionic ions which is more than that of the Pra Too Khong Bottled Drinking Water Plant (site A), it leads to the ineffectiveness of electric repulsion for fluoride ion compared with multivalent anionic ions of groundwater from the San Pa Hiang Membrane Plant (site B).

8. In the case of the ULPRO membrane (UTC-70), fluorotic groundwater from both the Pra Too Khong Bottled Drinking Water Plant (site A) and the San Pa Hiang Membrane Plant (site B) were experimented and their results showed that the operating condition of the ULPRO membrane (UTC-70) for fluoride removal was obtained under the operating transmembrane pressure of 0.5 MPa within the feed pH value of natural pH. At this desired condition, 97 % of the fluoride rejection (fluoride concentration in the permeate water was 0.08 mg/L) was achieved from the membrane experiment using groundwater from the San Pa Hiang Membrane Plant (site B) and 98 % of the fluoride rejection (fluoride concentration in the permeate water was 0.27 mg/L) was achieved from the membrane experiment using groundwater from the Pra Too Khong Bottled Drinking Water Plant (site A). It was found that fluoride concentration in the permeate water from both sites was lower than 0.7 mg/L of the bottled drinking water standard of Ministry of Industry.

9. It was concluded that the performance of the ULPRO membrane, namely, UTC-70 membrane for fluoride removal was higher than that of the NF membrane, namely, UTC-60 membrane. Additionally, UTC-70 membrane could be operated under wide range of the operating transmembrane pressure.

10. Negative rejection of fluoride of groundwater from both selected sites was significantly observed from UTC-70 membrane experimental results. So, it should be avoided the feed pH of groundwater of 4 when UTC-70 membrane is employed in membrane processes.

11. The pH value at an isoelectric point for the NF membrane (UTC-60) was about 5 while the pH value at an isoelectric point for the ULPRO membrane (UTC-70) was about 6.

12. According to the membrane experimental results of this study, the UTC-70 membrane should be considered to employ instead of typical RO membrane. The supported reason was UTC-70 membrane can be operated under 0.100-0.500 MPa which lower than typical operating pressure of 4-5 MPa but provide more permeate water. Nevertheless, this membrane should be experimented in the larger scale to confirm their performance.

CHAPTER VI

RECOMMENDATIONS FOR FUTURE WORKS

Based on the results of this study, some recommendations for future studies can be proposed.

1. In this study, the geological conditions were not taken into account. Thus, a comparison of the performance of ULPRO membrane in the different geological conditions may be an interesting topic for the future study.

2. As stated previously, the various conditions including operating transmembrane pressure, pH of feed water, and the concentration of fluoride in groundwater were studied. Thus, more studies on the effects of other parameters (for instance temperature and feed flow rate) should be done.

3. The effects of an individual ion and combined ions on the performance of membrane for defluoridation should be studied.

4. The implementation of a new method to measure the actual charge on membrane surface should be done.

5. A health Risk Assessment should be done in this region, not only in Lamphun province but also in other surrounding provinces.

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APPENDICES

APPENDIX A

GROUNDWATER QUALITY INVESTIGATION FOR VILLAGE WATERWORKS

Table A-1 Results of site investigation in August 2005 from site no.1 to site no.40

Site	UTM X	UTM Y	A.S.L. (m)	Depth (m)	Temp. (^oC)	pH	EC mS/m	Alk. (mg/L) as CaCO3
1	494457	2042017	342	> 50	28.7	6.1	21.3	110
2	494894	2041686	314	88	27.9	6.5	23.4	125
3	495320	2041987	311	> 80	29.0	6.0	30.0	110
4	495251	2042512	310	> 90	30.0	6.7	42.3	265
5	493888	2043969	308	> 70	29.0	6.5	37.7	200
6	492057	2041627	301	55	30.0	7.3	54.4	285
7	491289	2040560	315	87	28.5	6.1	33.0	140
8	491673	2041475	310	54.9	28.2	7.0	52.4	155
9	493302	2041779	312	15	27.5	6.3	26.0	75
10	493736	2041045	317	60	32.4	6.9	24.6	125
11	483787	2042312	296	> 190	27.8	7.1	58.1	230
12	482811	2040765	301	> 150	28.1	6.9	71.3	325
13	482569	2040075	301	> 180	33.0	7.1	59.1	320
14	480928	2039382	299	-	29.7	7.7	99.2	350
15	479974	2038265	292	> 50	29.0	7.6	63.8	360
16	506979	2054505	304	> 200	28.0	7.5	111.2	410
17	506437	2053985	315	-	34.0	7.9	73.6	360
18	505397	2052607	309	-	29.3	8.1	78.3	400
19	503979	2051482	305	>90	28.8	7.6	65.5	340
20	503608	2051491	301	>100	29.8	8.0	64.2	330
21	502151	2053781	296	-	28.7	7.9	43.0	245
22	499694	2054424	293	48	29.4	6.3	14.9	90
23	497544	2055689	293	>40	27.2	7.8	41.3	165
24	498324	2057996	295	50	27.2	6.9	16.3	95
25	500591	2059538	296	44	27.5	6.4	13.0	80
26	477895	2037369	310	-	27.6	7.9	70.0	325
27	476328	2036353	298	80	25.8	7.3	38.6	180
28	474793	2036430	294	-	27.8	6.3	33.1	160
29	472847	2037133	291	96	27.2	7.0	130.5	455
30	470402	2037757	291	120	28.4	8.7	38.6	200
31	471366	2037445	289	48	27.8	7.1	77.3	340
32	473700	2035953	291	-	27.2	6.7	40.7	190
33	473572	2036083	292	>100	27.0	7.3	58.8	275
34	475391	2033056	305	80	27.5	6.7	37.2	200
35	474774	2034124	297	>120	27.6	6.6	34.5	165
36	473128	2034159	288	>80	26.3	7.1	76.2	310
37	473342	2033931	291	>80	26.4	7.5	51.5	230
38	473092	2033445	289	>110	25.9	7.4	118.5	395
39	473597	2032120	290	>100	26.0	7.5	51.0	200
40	473566	2031703	291	>100	26.9	6.8	46.2	180

Table A-1 Results of site investigation in August 2005 from site no.1 to site no.40 (Continue)

Site	F^-	Cl^-	NO_2^-	NO_3^-	SO_4^{2-}	Na^+	Mg^{2+}	K^+	Ca^{2+}	T-Fe
	mg/L									
1	0.16	2.33	0.00	0.00	1.96	8.67	9.73	3.41	23.57	2.05
2	0.41	2.41	0.00	0.00	6.61	14.61	8.74	7.82	21.32	0.05
3	0.36	16.20	0.00	14.92	17.55	15.18	13.44	10.57	20.36	0.04
4	0.64	10.59	0.00	5.93	21.84	17.49	15.64	11.17	36.06	0.23
5	0.58	3.45	0.00	0.00	1.11	27.68	14.30	10.58	30.93	0.02
6	1.05	6.91	0.00	0.00	6.50	34.20	21.22	11.95	41.80	0.81
7	0.48	16.21	0.00	0.00	15.46	15.63	14.22	11.37	26.29	4.67
8	0.39	64.41	0.00	22.03	51.63	40.22	25.24	14.99	34.29	0.40
9	0.27	16.78	0.00	14.20	40.98	17.77	8.91	6.82	17.37	0.00
10	0.19	2.32	0.00	0.00	2.81	5.39	9.63	4.85	24.61	10.32
11	0.56	3.23	0.00	0.00	8.88	8.49	19.34	2.44	103.10	0.80
12	0.65	36.24	0.00	0.00	35.94	24.16	23.42	9.47	114.20	1.52
13	0.67	1.02	0.00	0.00	0.81	9.01	18.66	7.32	102.60	1.43
14	0.91	31.37	0.00	0.00	225.23	159.82	22.72	6.56	38.30	1.51
15	0.55	1.96	0.00	0.00	2.94	10.48	38.38	4.70	64.80	1.06
16	6.04	88.20	0.00	47.79	51.08	153.80	31.16	12.78	36.14	0.02
17	14.43	17.14	0.00	2.04	0.75	198.78	4.44	3.06	8.79	0.03
18	16.11	8.33	0.00	0.00	0.91	239.20	3.45	2.93	5.01	0.09
19	3.92	10.14	0.00	115.00	5.10	149.80	9.06	1.07	25.85	0.01
20	8.75	6.20	0.00	32.82	0.81	161.60	6.43	0.82	14.55	0.01
21	2.46	1.28	0.00	0.75	0.00	97.66	8.10	1.32	8.71	0.73
22	0.23	0.47	0.00	15.78	0.00	9.70	3.13	5.78	5.56	5.42
23	0.20	29.03	0.32	0.41	32.92	36.54	12.43	6.40	33.39	6.88
24	0.18	4.21	0.00	0.00	4.07	4.85	3.76	4.87	19.08	6.00
25	0.20	0.88	0.00	0.00	0.00	5.68	2.75	2.19	9.29	7.26
26	0.65	38.88	0.00	0.38	33.79	42.88	38.78	5.49	97.80	0.36
27	0.39	12.88	0.00	0.00	19.19	8.17	14.32	6.20	18.90	0.85
28	0.32	8.38	0.00	0.00	10.50	8.46	9.61	4.96	40.84	4.44
29	1.43	76.54	0.00	0.00	300.39	133.58	65.04	7.04	91.90	0.35
30	3.39	4.69	0.00	0.47	11.30	101.86	0.00	0.70	1.85	0.00
31	0.82	50.87	4.95	2.28	31.21	73.68	12.76	7.89	107.70	0.23
32	0.41	8.25	0.00	0.00	17.84	10.62	12.28	7.62	35.00	1.76
33	0.32	19.37	0.00	0.00	30.41	17.97	15.81	8.02	106.40	0.35
34	0.41	4.01	0.00	0.00	13.08	9.36	13.81	5.27	17.90	2.51
35	0.42	6.71	0.00	0.00	29.08	8.38	12.08	5.83	39.55	3.62
36	0.78	64.00	0.00	0.00	61.74	25.26	33.22	4.73	126.10	0.07
37	0.66	13.15	0.00	0.00	41.40	9.44	16.70	7.96	114.00	1.38
38	0.42	101.27	0.00	1.31	197.84	63.62	35.76	36.99	201.80	1.00
39	0.25	20.58	0.00	1.38	77.49	14.70	11.53	5.32	91.80	0.26
40	0.30	20.18	0.00	1.57	73.06	10.27	10.23	5.39	61.80	1.06

Table A-2 Results of site investigation in November 2005 from site no.1 to site no.40

Site	UTM X	UTM Y	A.S.L. (m)	Depth (m)	Temp. (^{o}C)	pH	EC mS/m	Alk. (mg/L) as CaCO3
1	494452	2039355	311	70	27.6	6.91	59.0	285
2	499036	2037081	339	100	28.0	6.92	80.0	390
3	498224	2035908	340	79	29.0	7.76	111.7	580
4	504745	2037708	364	12	27.5	6.01	20.1	100
5	507243	2039113	372	60	27.9	6.39	38.4	195
6	507150	2039041	373	60	27.5	6.24	35.4	145
7	513278	2041074	400	72	28.8	4.85	2.5	20
8	513276	2041072	401	42	28.4	5.56	5.3	35
9	506829	2050616	308	-	27.5	6.66	43.7	240
10	509061	2047670	327	-	27.6	6.35	42.3	175
11	507246	2049467	315	>80	27.4	6.81	57.2	275
12	511782	2045708	370	-	27.3	7.55	70.7	380
13	512319	2046157	372	80	27.9	6.92	44.8	250
14	513775	2042385	417	54	26.9	5.75	6.7	50
15	513151	2042235	404	>80	30.1	6.37	33.6	240
16	512646	2043312	401	100	27.0	5.80	5.9	45
17	514311	2041313	401	-	25.4	5.76	20.7	40
18	506014	2043141	345	40	25.7	7.32	61.1	305
19	505921	2043188	345	67	29.2	7.19	59.8	310
20	503104	2046239	323	60	24.3	6.40	18.4	105
21	502961	2046787	316	72	28.9	6.49	16.9	80
22	499957	2044794	306	108	29.1	5.81	16.0	90
23	499165	2045554	297	95	28.8	7.15	60.2	260
24	500451	2046611	299	120	29.5	6.57	25.8	140
25	516708	2067287	311	90	28.7	6.79	64.1	300
26	516698	2066598	311	>100	29.0	7.05	56.4	275
27	515901	2065497	310	60	29.0	7.25	45.5	250
28	515679	2065164	314	42	25.5	7.47	51.7	290
29	514736	2065946	314	80	30.1	7.60	58.0	335
30	514775	2067448	317	80	27.4	6.72	26.6	195
31	515026	2063462	318	90	29.6	8.09	52.0	275
32	513351	2062762	312	90	29.3	6.75	58.3	325
33	514240	2061850	317	80	29.1	7.03	52.9	245
34	514373	2060974	322	75	28.5	7.08	54.1	300
35	516424	2063535	327	90	27.1	6.40	39.0	190
36	517015	2063866	328	-	30.0	7.59	41.8	250
37	516240	2064130	324	32	27.1	7.34	124.3	420
38	511850	2062253	308	36	28.0	6.52	87.7	340
39	512156	2060164	306	200	29.9	7.00	65.8	260
40	512089	2058805	308	120	30.9	6.88	47.5	275

Table A-2 Results of site investigation in November 2005 from site no.1 to site no.40 (continue)

Site	F^-	Cl^-	NO_2^-	NO_3^-	SO_4^{2-}	Na^+	Mg^{2+}	K^+	Ca^{2+}	T-Fe
	mg/L									
1	2.94	11.50	0.00	0.00	15.30	64.30	9.90	7.00	38.50	0.50
2	0.60	12.10	0.00	0.90	37.90	78.00	22.60	5.60	49.80	0.00
3	12.40	6.40	0.00	0.00	0.50	237.30	1.90	4.60	7.60	0.00
4	0.10	5.90	0.00	0.00	1.30	4.20	2.60	2.60	27.20	0.20
5	0.61	6.60	0.00	0.00	10.40	20.30	6.20	3.20	36.90	6.30
6	1.57	7.40	0.00	0.20	31.40	15.60	5.00	4.20	40.00	0.10
7	0.00	1.20	0.00	0.80	0.00	0.80	0.50	1.20	0.90	0.00
8	0.00	1.30	0.00	0.30	0.30	0.80	0.50	1.80	6.30	0.10
9	2.85	2.00	0.00	0.00	0.80	45.90	15.70	5.40	15.90	0.00
10	0.44	2.50	0.00	0.00	54.40	12.30	13.20	1.00	41.60	5.50
11	0.50	23.80	0.00	0.00	12.70	16.00	13.80	3.00	67.90	1.40
12	0.17	1.70	0.00	0.00	30.00	38.10	17.00	2.00	79.00	0.00
13	0.62	0.80	0.00	0.00	8.10	11.40	24.10	3.10	35.80	0.20
14	0.10	0.70	0.00	0.00	0.50	0.70	4.60	2.10	2.60	0.20
15	0.12	2.20	0.00	0.60	0.90	9.30	8.80	3.90	51.00	1.00
16	0.07	0.50	0.00	0.00	0.30	1.20	2.70	1.10	3.80	0.10
17	0.06	42.30	0.00	2.50	0.40	15.70	2.90	1.80	11.50	0.00
18	3.35	7.70	0.00	1.20	23.10	96.80	4.10	7.10	24.20	0.00
19	3.75	2.40	0.00	0.00	19.20	88.70	3.20	7.50	25.80	0.10
20	0.21	1.30	0.00	0.00	0.80	4.90	9.20	2.80	13.60	0.00
21	0.10	9.90	0.00	0.20	4.90	6.60	3.10	10.40	12.40	0.10
22	0.19	2.10	0.00	0.00	2.80	17.00	3.30	9.00	2.70	0.60
23	0.76	36.70	0.00	9.50	12.10	28.70	12.20	12.50	53.60	0.00
24	0.78	2.90	0.00	0.00	0.70	5.70	9.30	12.40	18.70	0.00
25	2.40	22.40	0.00	0.00	36.80	47.90	27.90	1.00	34.80	0.00
26	5.20	16.30	0.00	0.00	12.50	76.10	6.90	3.60	25.40	0.00
27	1.35	3.70	0.00	0.00	2.40	39.70	10.00	6.60	28.90	0.20
28	3.80	2.10	0.00	0.50	1.40	59.10	5.80	7.60	34.00	0.00
29	3.55	3.00	0.00	0.00	2.10	65.30	9.30	9.10	37.20	0.00
30	0.54	18.40	0.00	5.10	49.40	20.70	23.90	4.70	28.70	0.00
31	6.12	2.40	0.00	0.00	0.00	101.70	1.30	2.70	7.10	0.00
32	3.10	2.10	0.00	0.30	0.70	111.20	3.10	4.20	7.80	0.00
33	1.63	27.20	0.00	1.50	5.10	52.60	8.30	9.60	31.40	0.00
34	1.07	7.30	0.00	0.00	0.40	34.40	6.10	8.80	32.60	32.50
35	0.35	20.80	0.00	1.40	2.80	27.10	6.40	6.50	30.80	1.00
36	0.51	1.00	0.00	0.00	0.00	52.50	4.30	5.10	23.40	0.00
37	1.38	122.84	0.20	30.80	53.30	165.20	16.70	8.90	50.60	0.00
38	1.65	56.61	0.00	51.90	12.70	96.80	11.30	4.50	55.10	0.00
39	3.10	4.00	0.00	0.00	1.60	94.70	5.60	7.00	32.10	0.00
40	0.32	1.60	0.00	0.00	1.80	32.00	6.20	12.40	45.20	0.40

Table A-3 Results of site investigation in November 2005 from site no.41 to site no.79

Site	UTM X	UTM Y	A.S.L. (m)	Depth (m)	Temp. (^oC)	pH	EC mS/m	Alk. (mg/L) as CaCO3
41	511073	2058677	306	>100	28.1	6.83	100.4	325
42	510175	2059716	303	137	27.5	7.93	56.6	310
43	502584	2048967	301	-	32.7	7.33	53.9	310
44	501659	2048715	302	-	29.7	7.58	59.5	310
45	502038	2048058	305	97	29.5	6.88	43.7	250
46	500351	2047754	305	80	28.4	6.64	48.8	165
47	497430	2046218	310	60	29.9	7.69	61.9	325
48	483435	2042615	282	190	26.7	6.96	57.1	330
49	482484	2041071	289	150	27.9	6.52	70.4	330
50	482237	2040386	291	180	29.4	6.72	52.2	300
51	480637	2039693	289	70	28.3	7.36	103.1	375
52	479641	2038574	285	90	27.8	7.41	62.6	365
53	477550	2037683	282	100	27.8	7.20	73.2	345
54	476020	2036632	287	79	24.3	7.01	31.5	150
55	474483	2036743	283	100	28.2	6.29	32.3	165
56	472525	2037455	287	53	27.4	7.06	127.1	460
57	473256	2032424	292	82	24.7	7.40	44.1	180
58	475406	2031263	300	--	25.8	7.15	34.9	180
59	480884	2025934	329	100	26.2	7.96	99.7	435
60	480825	2023945	322	100	31.0	6.92	41.0	190
61	480059	2030656	332	100	28.9	7.44	79.2	475
62	480124	2031062	335	-	27.6	6.88	79.7	465
63	484954	2031686	386	100	27.0	6.78	73.0	425
64	487385	2032007	356	-	29.4	7.35	24.3	395
65	487443	2031788	358	100	25.3	7.14	77.7	410
66	489401	2027533	407	200	27.9	7.18	82.4	445
67	490952	2040860	310	87	30.4	6.46	27.2	115
68	491726	2041916	301	55	29.9	7.26	53.4	300
69	494891	2042838	305	80	29.4	6.89	19.0	100
70	493560	2044251	300	70	28.5	6.23	37.0	210
71	494021	2046380	296	200	29.7	7.33	63.7	290
72	506646	2054801	309	-	28.7	7.28	117.4	420
73	506108	2054287	302	-	32.3	7.53	70.2	355
74	503642	2051776	299	116	31.1	7.83	68.5	375
75	503267	2051805	297	-	30.0	7.97	63.5	335
76	501823	2054092	296	-	27.1	7.56	40.9	290
77	499355	2054735	297	48	29.6	6.46	14.5	95
78	497223	2056004	298	-	26.1	6.73	36.6	175
79	500232	2059838	298	-	27.6	6.60	12.8	75

Table A-3 Results of site investigation in November 2005 from site no.41 to site no.79 (continue)

Site	F^-	Cl^-	NO_2^-	NO_3^-	SO_4^{2-}	Na^+	Mg^{2+}	K^+	Ca^{2+}	T-Fe
	mg/L									
41	0.88	88.40	0.10	40.10	44.50	90.30	17.30	19.30	79.30	0.00
42	5.43	3.70	0.00	0.70	0.00	97.70	4.40	6.60	19.80	0.00
43	2.15	3.80	0.00	0.00	0.50	44.20	16.50	7.10	44.00	0.20
44	5.50	10.50	0.00	0.90	1.70	82.40	11.80	4.50	27.60	0.00
45	1.36	4.00	0.00	0.30	1.10	24.50	14.50	6.80	39.90	0.00
46	0.54	56.50	0.00	7.40	1.30	28.40	14.60	8.60	37.10	0.00
47	7.07	6.30	0.00	0.00	0.50	93.50	7.90	7.30	28.40	0.00
48	0.57	3.40	0.00	0.00	8.80	7.20	13.70	3.10	92.70	0.40
49	0.72	27.80	0.00	0.00	27.80	18.20	17.00	12.00	96.90	1.20
50	0.63	2.90	0.00	0.00	0.60	8.00	10.60	7.40	70.80	1.80
51	0.89	26.90	0.00	0.00	186.20	130.60	18.20	8.50	64.60	0.00
52	0.48	1.40	0.00	0.00	2.50	8.40	26.60	6.10	82.30	0.00
53	0.60	32.70	0.00	0.00	28.50	33.20	28.00	7.70	75.20	0.00
54	0.43	7.10	0.00	0.00	14.10	5.50	8.20	7.50	40.40	0.00
55	0.23	6.70	0.00	0.00	8.40	6.50	6.80	7.10	39.90	4.30
56	1.29	63.20	0.00	0.00	203.20	102.00	46.20	9.60	96.40	0.40
57	0.25	13.20	0.00	0.00	46.20	8.10	6.60	3.70	70.00	0.00
58	0.38	4.40	0.00	0.00	8.20	5.30	7.90	2.50	53.40	0.00
59	1.57	52.10	0.00	23.30	40.20	97.00	31.80	4.90	68.10	0.00
60	0.39	8.20	0.00	0.00	28.70	5.80	6.80	2.20	66.10	0.80
61	0.84	1.10	0.00	0.00	0.80	22.40	30.30	6.20	105.70	0.00
62	0.71	0.90	0.00	0.00	1.80	19.40	32.10	6.00	105.30	0.00
63	0.13	2.90	0.00	5.20	4.50	1.00	21.70	1.50	127.30	0.00
64	1.34	9.40	0.00	11.70	22.10	5.50	29.30	2.20	110.80	0.00
65	1.52	8.90	0.00	11.00	22.30	5.80	29.50	2.40	118.70	0.00
66	0.20	3.30	0.00	0.00	37.60	3.30	30.00	3.70	133.70	0.00
67	0.33	10.50	0.00	0.00	15.40	11.80	8.70	12.00	20.30	0.00
68	0.90	6.00	0.00	0.00	6.10	27.30	15.90	11.60	56.10	0.00
69	0.22	3.00	0.00	0.40	3.40	6.80	5.20	11.10	12.30	1.90
70	0.56	2.90	0.00	0.00	1.00	20.50	10.50	9.80	32.90	2.70
71	3.90	3.50	0.00	0.30	3.80	91.60	8.20	14.70	28.10	0.00
72	4.67	88.40	0.00	0.00	49.20	158.40	24.70	17.80	38.40	0.00
73	9.99	15.40	0.00	1.90	1.40	131.30	6.90	3.40	13.50	0.00
74	4.13	5.20	0.00	0.00	2.10	140.30	5.00	1.30	8.50	0.00
75	7.57	5.10	0.00	0.60	0.70	124.40	5.00	1.20	11.20	0.00
76	1.83	1.20	0.00	0.00	0.30	67.40	6.60	2.20	13.70	0.00
77	0.22	0.60	0.00	0.00	0.30	8.70	2.80	7.80	7.40	5.40
78	0.23	18.70	0.50	1.50	21.40	25.70	8.60	8.80	31.20	0.00
79	0.24	0.80	0.00	0.00	0.00	5.10	2.50	3.20	9.50	7.00

APPENDIX B
SEVERITY OF DENTAL FLUOROSIS INVESTIGATION

Table B-1 Severity of dental fluorosis investigation in high fluorotic area

Sample no.	Age (yr.)	Residence Time (yr.)	Source of drinking water	Level of dental fluorosis	Fluoride in urine (mg/L)	Fluoride in drinking water (mg/L)
1	13	14	VW	5	2.5	14.41
2	14	14	VW	4	3	5.10
3	16	16	VW	1	4.6	12.75
4	16	16	VW	1	5.5	4.63
5	14	14	SW	5	4	0.00
6	14	14	VW	5	2.8	14.48
7	15	15	SW	3	2.3	0.06
8	15	15	VW	5	11	9.08
9	15	15	VW	5	1.55	5.87
10	14	14	SW	2	1.02	9.03
11	14	14	SW	4	1.5	0.00
12	14	14	VW	5	4.5	0.00
13	14	14	SW	1	1.4	0.34
14	14	14	VW	1	0.82	0.00
15	14	14	DW	3	0.33	0.87
16	15	15	VW	1	1.04	0.81
17	15	15	SW	4	0.53	0.00
18	14	14	VW	0	1.85	4.96
19	13	13	VW	5	3.3	6.68
20	13	13	VW	3	0.85	7.42
21	13	13	VW	1	2.5	0.25
22	13	13	VW	3	0.15	0.28
23	13	13	SW	4	1.5	0.00
24	13	13	SW	5	3.9	0.00
25	14	14	SW	4	1.3	1.07
26	15	15	VW	5	0.68	6.17
26	15	15	VW	2	1.61	0.34
28	14	14	VW	2	2.9	0.36
29	15	15	VW	5	4.2	1.84
30	15	15	VW	4	1.8	5.01
31	16	16	VW	5	9	6.11
32	15	15	VW	4	3.3	7.33
33	13	13	VW	1	5	14.25
34	14	14	SW	1	2.7	14.69
35	15	15	VW	5	10.2	0.31
36	15	15	VW	2	1.45	0.33
37	13	13	SW	4	6	0.47
38	13	13	SW	4	2.8	6.15
39	15	15	VW	4	2.9	0.83

Note: DW = Deep Well, SW = Shallow Well, VW = Village Water Work

Table B-1 Severity of dental fluorosis investigation in high fluorotic area (continue)

Sample no.	Age (yr.)	Residence Time (yr.)	Source of drinking water	Level of dental fluorosis	Fluoride in urine (mg/L)	Fluoride in drinking water (mg/L)
40	15	15	SW	3	1.73	4.98
41	15	15	VW	5	7.3	0.46
42	13	13	VW	1	2.3	0.16
43	13	13	VW	2	2.3	6.79
44	13	13	VW	4	5.7	9.50
45	13	13	VW	3	4.5	1.10
46	14	14	SW	2	2.6	0.00
47	14	14	SW	3	3.4	0.39
48	13	10	SW	4	1.2	0.21
49	14	10	VW	3	0.25	0.00
50	14	10	VW	4	0.35	7.20
51	14	10	VW	1	2	0.44
52	14	9	VW	5	1.8	5.96
53	13	7	VW	1	2.6	0.47
54	15	7	VW	2	3	7.26
55	14	6	VW	1	3.7	3.91
56	15	6	VW	2	1.3	6.23
57	14	2	SW	2	1	0.38
58	15	3	SW	0	0.31	0.40
59	13	1	SW	1	2.5	1.01
60	15	2.5	VW	1	0.7	0.00
61	13	0.25	VW	4	1.26	3.76
62	14	1	VW	1	11.6	0.33
63	15	1.5	VW	1	0.5	0.38
64	15	1	SW	1	1.3	0.38
65	17	0.08	VW	0	1.67	0.00

Note: DW = Deep Well, SW = Shallow Well, VW = Village Water Work

Table B-2 Severity of dental fluorosis investigation in low fluorotic area

Sample no.	Age (yr.)	Residence Time (yr.)	Source of drinking water	Level of dental fluorosis	Fluoride in urine (mg/L)	Fluoride in drinking water (mg/L)
1	16	16	VW	2	0.13	0.6
2	14	14	VW	1	0.16	0.5
3	14	14	VW	0	0.17	0.2
4	17	17	VW	2	0.15	0.3
5	14	14	VW	0	0.24	0.5
6	14	14	VW	1	0.1	0.5
7	14	14	VW	2	1	3.9
8	13	13	VW	2	0.72	0.8
9	13	13	VW	0	1.03	0.7
10	13	13	VW	1	0.3	0.5
11	17	17	DW	2	0.87	0.9
12	14	14	VW	2	0.73	1.2
13	15	15	VW	0	0.55	0.6
14	16	16	VW	0	0.1	0.7
15	17	17	VW	1	0.33	0.5
16	16	16	VW	0	0.87	0.6
17	17	17	VW	4	0.12	1.1
18	17	17	VW	0	2.1	0.8
19	17	17	VW	2	0.35	0.6
20	16	16	VW	2	0.38	0.5
21	16	16	VW	4	1.03	1.0
22	16	16	VW	1	0.63	0.8
23	14	14	DW	1	0.31	0.9
24	14	14	DW	0	1.52	0.9
25	14	14	DW	2	0.09	1.2
26	13	13	VW	0	2.3	0.7
27	15	15	VW	2	1.32	1.4
28	14	14	DW	0	2.2	0.4
29	13	13	VW	0	0.6	0.7
30	14	14	VW	2	0.63	0.3
31	16	16	DW	0	1.45	0.7
32	15	15	VW	0	1.09	0.7
33	14	14	VW	3	1.16	0.9
34	14	14	VW	2	0.74	0.9
35	15	15	VW	3	1.89	1.0
36	13	13	VW	1	0.46	0.7
38	13	13	VW	0	1.34	0.6
38	13	13	VW	0	1.1	0.8
39	16	16	VW	0	0.75	0.7
40	15	15	VW	0	1.22	0.6

Note: DW = Deep Well, SW = Shallow Well, VW = Village Water Work

Table B-2 Severity of dental fluorosis investigation in low fluorotic area (continue)

Sample no.	Age (yr.)	Residence Time (yr.)	Source of drinking water	Level of dental fluorosis	Fluoride in urine (mg/L)	Fluoride in drinking water (mg/L)
41	14	14	VW	0	0.66	1.0
42	13	13	VW	0	0.2	0.3
43	17	17	VW	1	0.17	0.5
44	16	16	VW	0	0.93	0.0
45	18	18	VW	0	0.47	0.6
46	16	16	VW	0	0.23	0.4
47	13	13	VW	2	0.2	0.1
48	16	16	VW	0	0.22	0.2
49	16	16	SW	1	0.23	0.0
50	16	15	DW	2	0.05	0.4
51	16	15	VW	0	0.33	0.6
52	14	12	VW	0	0.3	0.5
53	15	13	VW	0	1.21	0.6
54	13	10	VW	0	1.2	0.5
55	16	10	VW	0	0.36	1.4
56	13	6	VW	0	0.13	0.8
57	13	6	DW	0	0.38	0.4
58	16	8	VW	0	0.36	0.8
59	15	7	VW	2	1.34	0.9
60	15	7	VW	1	0.3	0.7
61	14	4	VW	0	0.24	0.6
62	14	3	VW	0	0.11	0.4
63	15	3	VW	0	0.24	0.7
64	14	2	VW	0	0.4	0.7
65	13	1	VW	1	1.08	0.4
66	15	2.5	VW	0	0.86	0.6

Note: DW = Deep Well, SW = Shallow Well, VW = Village Water Work

APPENDIX C

MEMBRANE EXPERIMENTAL RESULTS OF NF MEMBRANE (UTC-60)

APPENDIX C-1

MEMBRANE EXPERIMENTAL RESULTS OF NF MEMBRANE (UTC-60) OF GROUNDWATER FROM PRA TOO KHONG BOTTLED DRINKING WATER PLANT (SITE A)

Table C-1.1 Determination of sampling time of NF membrane (UTC-60) of groundwater from Pra Too Khong Bottled Drinking Water Plant under OTP = 0.100 MPa

Time	Permeate water					Concentrated water				Feed tank	
	pH	EC	Temp.	Flow rate	Flux	pH	EC	Temp.	Flow rate	Temp.	EC
(Min.)		(μS/cm)	(° C)	(m^3/day)	(m^3/m^2.day)		(μS/cm)	(° C)	(m^3/day)	(° C)	(μS/cm)
0	8.35	536	26.9	0.00213	0.363	8.25	778	27.2	2.189	27.0	779
20	8.39	542	26.6	0.00209	0.356	8.27	780	27.2	2.189	27.2	780
40	8.39	541	27.0	0.00204	0.349	8.31	781	27.3	2.189	27.4	781
60	8.44	535	26.8	0.00206	0.351	8.34	780	27.4	2.189	27.5	780
130	8.49	529	26.6	0.00200	0.341	8.36	782	27.8	2.189	27.9	780
240	8.51	523	26.5	0.00193	0.329	8.42	782	27.8	2.189	28.2	780
360	-	-	-	0.00186	0.317	-	-	-	2.189	-	-
600	-	-	-	0.00183	0.313	-	-	-	2.189	-	-
840	-	-	-	0.00183	0.312	-	-	-	2.189	-	-
960	-	-	-	0.00183	0.312	-	-	-	2.189	-	-
1100	-	-	-	0.00183	0.313	-	-	-	2.189	-	-
1200	-	-	-	0.00184	0.314	-	-	-	2.189	-	-
1320	-	-	-	0.00183	0.313	-	-	-	2.189	-	-

Table C-1.2 Determination of sampling time of NF membrane (UTC-60) of groundwater from Pra Too Khong Bottled Drinking Water Plant under OTP = 0.200 MPa

Time	Permeate water					Concentrated water				Feed tank	
(Min.)	pH	EC (µS/cm)	Temp. (° C)	Flow rate (m^3/day)	Flux (m^3/m^2.day)	pH	EC (µS/cm)	Temp. (° C)	Flow rate (m^3/day)	Temp. (° C)	EC (µS/cm)
0	8.20	426	27.1	0.00325	0.554	8.13	783	27.5	2.131	26.8	778
20	8.21	413	26.9	0.00320	0.546	8.14	785	27.4	2.131	27.1	779
40	8.19	411	27.3	0.00320	0.546	8.14	785	27.6	2.131	27.4	780
60	8.20	411	26.7	0.00316	0.540	8.14	786	27.6	2.131	27.6	780
120	8.33	403	26.2	0.00315	0.538	8.29	784	27.7	2.131	28.1	780
180	8.40	403	26.1	0.00313	0.534	8.31	788	27.7	2.131	28.3	780
240	8.42	403	26.4	0.00314	0.536	8.37	788	28.0	2.131	28.5	780
300	8.46	403	26.0	0.00313	0.534	8.37	788	27.9	2.131	28.6	781
360	8.50	400	25.8	0.00312	0.532	8.38	791	27.9	2.131	28.6	783
1080	8.61	411	25.8	0.00301	0.514	8.42	798	27.3	2.131	28.3	787

Table C-1.3 Determination of sampling time of NF membrane (UTC-60) of groundwater from Pra Too Khong Bottled Drinking Water Plant under OTP = 0.300 MPa

Time	Permeate water					Concentrated water				Feed tank	
	pH	EC	Temp.	Flow rate	Flux	pH	EC	Temp.	Flow rate	Temp.	EC
(Min.)		(µS/cm)	(° C)	(m^3/day)	(m^3/m^2.day)		(µS/cm)	(° C)	(m^3/day)	(° C)	(µS/cm)
0	-	-	29.0	0.00416	0.710	-	-	-	-	-	-
20	-	-	28.0	0.00428	0.730	-	-	-	-	-	-
40	-	-	28.5	0.00434	0.740	-	-	-	-	-	-
60	-	-	29.0	0.00445	0.760	-	-	-	-	-	-
90	-	-	29.0	0.00445	0.760	-	-	-	-	-	-
120	-	-	29.0	0.00457	0.780	-	-	-	-	-	-
180	-	-	29.0	0.00463	0.790	-	-	-	-	-	-
360	-	326	29.0	0.00451	0.770	-	804	-	-	-	786
840	-	311	29.0	0.00445	0.760	-	806	-	-	-	786
1080	-	320	30.0	0.00463	0.790	-	809	-	-	-	787

Table C-1.4 Determination of sampling time of NF membrane (UTC-60) of groundwater from Pra Too Khong Bottled Drinking Water Plant under OTP = 0.400 MPa

Time	Permeate water					Concentrated water				Feed tank	
(Min.)	pH	EC (μS/cm)	Temp. (° C)	Flow rate (m^3/day)	Flux (m^3/m^2.day)	pH	EC (μS/cm)	Temp. (° C)	Time (Min.)	pH	EC (μS/cm)
0	7.87	165.6	27.3	0.00465	0.793	8.13	783	27.5	1.843	26.8	778
20	7.87	176.8	27.0	0.00470	0.801	8.14	785	27.4	1.843	27.1	779
40	7.91	188.3	27.5	0.00491	0.838	8.14	785	27.6	1.843	27.4	780
60	7.98	191.2	26.8	0.00502	0.857	8.14	786	27.6	1.843	27.6	780
120	8.09	192.6	27.1	0.00511	0.872	8.29	784	27.7	1.843	28.1	780
180	8.10	194.7	27.0	0.00517	0.883	8.31	788	27.7	1.843	28.3	780
240	8.16	196.7	26.4	0.00524	0.894	8.37	788	28.0	1.843	28.5	780
300	8.21	197.6	26.9	0.00527	0.899	8.37	788	27.9	1.843	28.6	781
360	8.25	197.2	27.2	0.00527	0.899	8.38	791	27.9	1.843	28.6	783
540	8.41	196.6	26.5	0.00524	0.894	8.42	798	27.3	1.843	28.3	787

Table C-1.5 Determination of sampling time of NF membrane (UTC-60) of groundwater from Pra Too Khong Bottled Drinking Water Plant under OTP = 0.500 MPa

Time (Min.)	Permeate water					Concentrated water				Feed tank	
	pH	EC (µS/cm)	Temp. (° C)	Flow rate (m^3/day)	Flux (m^3/m^2.day)	pH	EC (µS/cm)	Temp. (° C)	Time (Min.)	pH	EC (µS/cm)
0	7.88	225	25.1	0.00675	1.152	7.98	770	24.7	1.037	22.3	760
20	7.87	232	24.7	0.00675	1.152	7.98	770	25.1	1.037	22.4	761
40	7.90	224	25.6	0.00680	1.161	8.00	770	25.6	1.037	25.1	761
60	7.87	217	26.9	0.00691	1.180	8.01	771	26.1	1.037	25.8	763
120	7.93	215	26.4	0.00720	1.229	8.01	773	26.3	1.037	27.7	763
180	7.95	212	26.7	0.00751	1.282	8.03	774	26.2	1.037	27.8	765
240	7.96	214	27.1	0.00745	1.271	8.06	776	26.8	1.037	28.4	766
300	8.01	210	26.8	0.00751	1.282	8.08	776	27.1	1.037	27.9	767
360	8.06	211	26.8	0.00751	1.282	8.13	776	27.4	1.037	27.5	767
540	8.16	210	27.2	0.00745	1.271	8.15	778	27.9	1.037	28.2	768

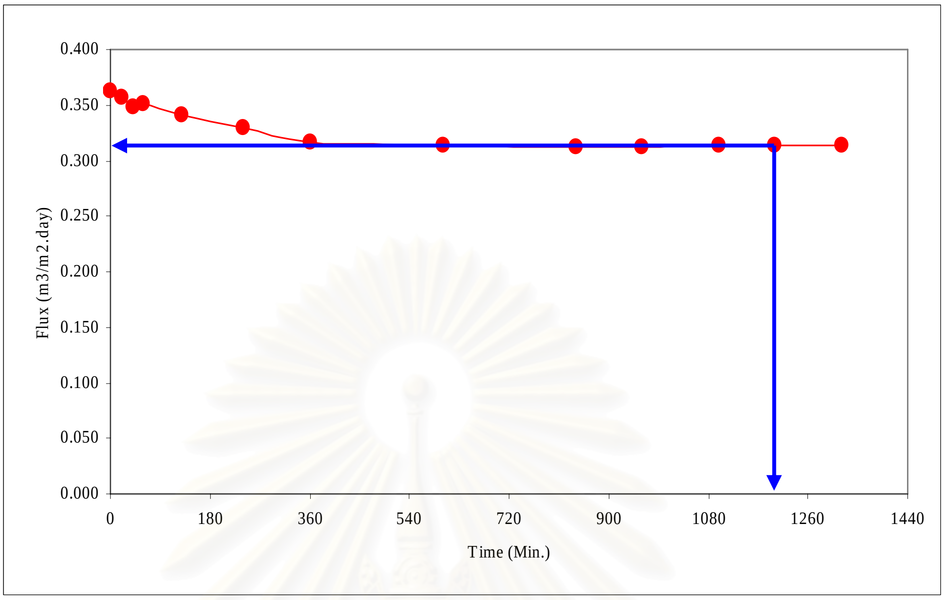

Figure C-1.1 Determination of sampling time of UTC-60 membrane of groundwater from Pra Too Khong Bottled Drinking Water Plant under OTP = 0.100 MPa

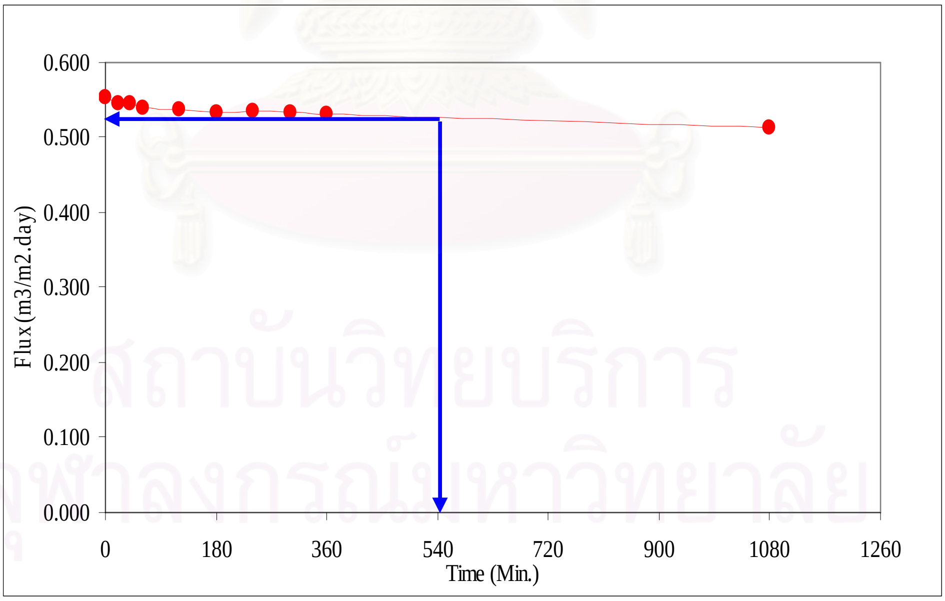

Figure C-1.2 Determination of sampling time of UTC-60 membrane of groundwater from Pra Too Khong Bottled Drinking Water Plant under OTP = 0.200 MPa

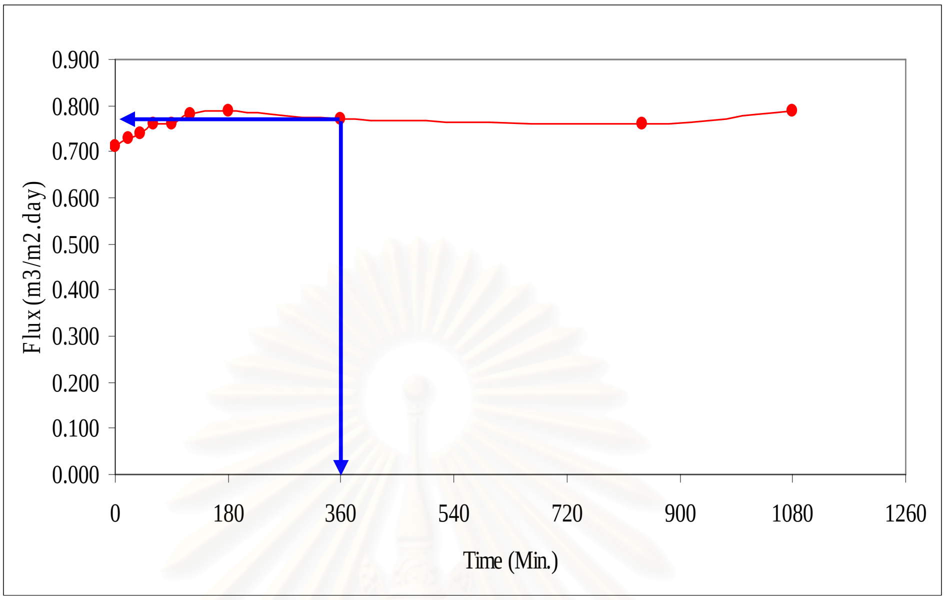

Figure C-1.3 Determination of sampling time of UTC-60 membrane of groundwater from Pra Too Khong Bottled Drinking Water Plant under OTP = 0.300 MPa

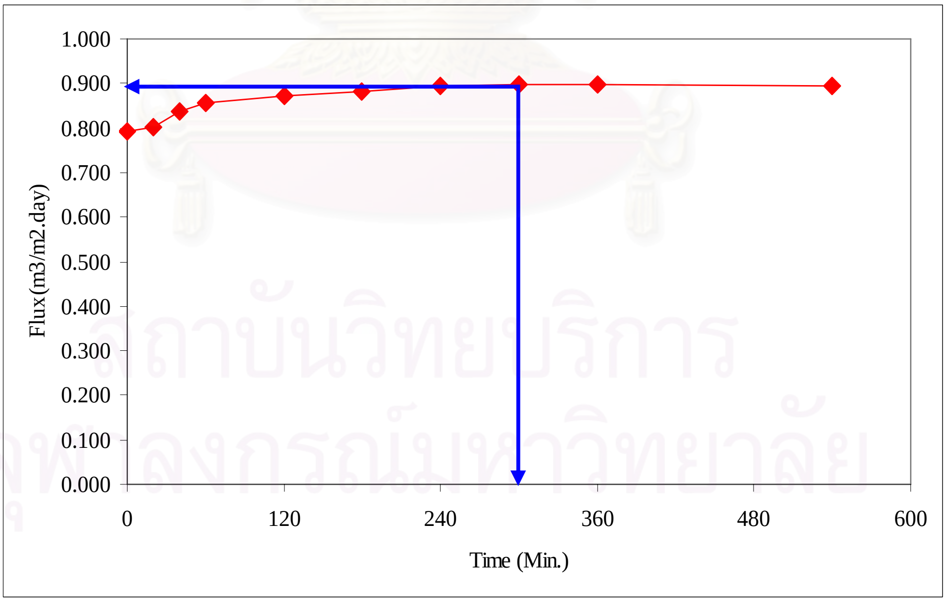

Figure C-1.4 Determination of sampling time of UTC-60 membrane of groundwater from Pra Too Khong Bottled Drinking Water Plant under OTP = 0.400 MPa

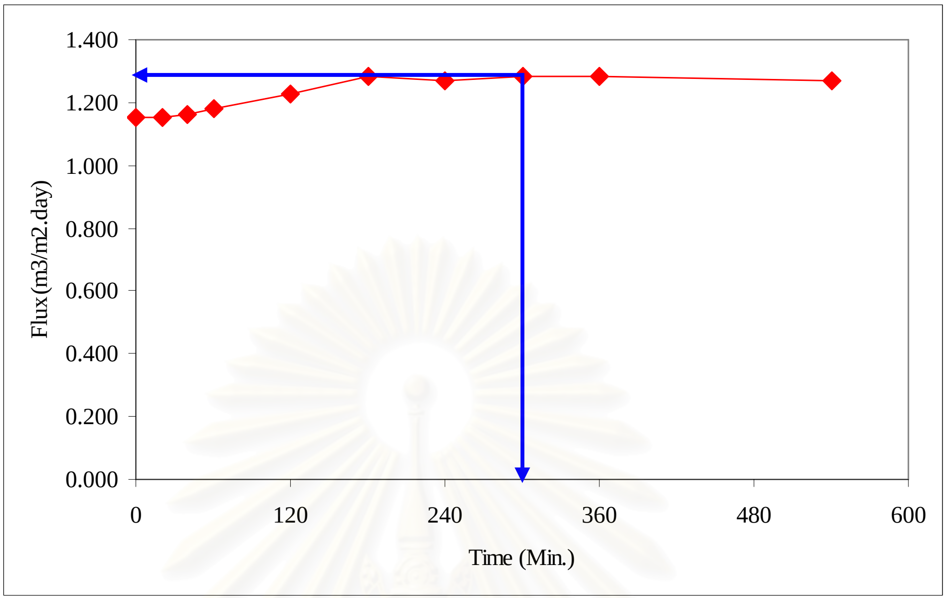

Figure C-1.5 Determination of sampling time of UTC-60 membrane of groundwater from Pra Too Khong Bottled Drinking Water Plant under OTP = 0.500 MPa

Table C-1.6 Membrane experimental results of NF membrane (UTC-60) of groundwater from Pra Too Khong Bottled Drinking Water Plant under OTP = 0.100 MPa

Water parameters	Groundwater at sampling point 1	Groundwater at sampling point 2	Permeate water under OTP of 0.100 MPa (sampling time = 20 hours)				
			Feed pH 8.23	Feed pH 7.07	Feed pH 6.09	Feed pH 5.05	Feed pH 4.05
Temperature(° C)	30.0	29.5	27.9	27.1	26.6	26.1	26.5
pH	7.86	7.92	8.62	8.36	7.9	7.07	4.35
EC (µS/cm)	788.0	785.0	503.0	587.0	773.0	871.0	897.0
Total Alkalinity (mg/L as $CaCO_3$)	400.0	390.0	245.0	185.0	75.0	18.0	NA
Na (mg/L)	177.61	176.45	119.17	129.42	149.57	164.25	163.00
Ca (mg/L)	6.53	6.41	2.86	3.63	4.41	4.68	2.47
K (mg/L)	4.47	4.36	2.86	3.20	3.65	3.95	5.23
Mg (mg/L)	3.51	3.44	1.04	1.41	1.77	1.65	0.84
Fluoride (mg/L)	16.98	16.69	10.94	10.81	10.76	13.00	17.44
Chloride (mg/L)	8.13	7.94	6.56	50.22	155.77	204.33	214.70
Nitrite (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nitrate (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sulfate (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Phosphate (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DOC (mg/L)	NA	0.953	0.534	0.350	0.145	0.000	0.000

Table C-1.7 Membrane experimental results of NF membrane (UTC-60) of groundwater from Pra Too Khong Bottled Drinking Water Plant under OTP = 0.200 MPa

Water parameters	Groundwater at sampling point 1	Groundwater at sampling point 2	Permeate water under OTP of 0.200 MPa (sampling time = 9 hours)				
			Feed pH 8.10	Feed pH 7.08	Feed pH 6.08	Feed pH 5.06	Feed pH 4.02
Temperature(° C)	30.0	29.5	25.8	25.8	25.8	25.5	25.5
pH	7.86	7.92	8.54	8.00	6.87	6.12	4.56
EC (µS/cm)	788.0	785.0	400.0	652.0	728.0	832.0	814.0
Total Alkalinity (mg/L as $CaCO_3$)	400.0	390.0	190.0	210.0	70.0	22.0	4.0
Na (mg/L)	177.61	176.45	98.66	144.78	148.72	164.84	150.15
Ca (mg/L)	6.53	6.41	2.00	4.48	4.18	3.35	0.68
K (mg/L)	4.47	4.36	2.29	3.37	3.45	3.83	3.71
Mg (mg/L)	3.51	3.44	0.48	1.91	1.38	0.46	0.00
Fluoride (mg/L)	16.98	16.69	8.21	11.23	8.95	14.54	16.41
Chloride (mg/L)	8.13	7.94	6.02	6.07	48.39	179.92	185.03
Nitrite (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nitrate (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sulfate (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Phosphate (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DOC (mg/L)	NA	0.953	0.330	0.468	0.066	0.000	0.000

Table C-1.8 Membrane experimental results of NF membrane (UTC-60) of groundwater from Pra Too Khong Bottled Drinking Water Plant under OTP = 0.300 MPa

Water parameters	Groundwater at sampling point 1	Groundwater at sampling point 2	Permeate water under OTP of 0.300 MPa (sampling time = 5 hours)				
			Feed pH 7.92	Feed pH 7.09	Feed pH 6.05	Feed pH 5.00	Feed pH 4.08
Temperature(° C)	30.0	29.5	26.0	26.7	25.9	25.9	25.9
pH	7.86	7.92	8.05	7.58	6.62	5.53	4.39
EC (µS/cm)	788.0	785.0	190.0	514.0	839.0	866.0	819.0
Total Alkalinity (mg/L as $CaCO_3$)	400.0	390.0	402.0	180.0	100.0	20.0	5.4
Na (mg/L)	177.61	176.45	103.14	115.28	167.51	169.76	157.92
Ca (mg/L)	6.53	6.41	2.48	3.09	6.35	3.49	1.69
K (mg/L)	4.47	4.36	2.44	2.70	4.16	12.02	3.90
Mg (mg/L)	3.51	3.44	0.62	0.84	2.59	0.37	0.00
Fluoride (mg/L)	16.98	16.69	8.41	8.26	13.07	14.80	16.30
Chloride (mg/L)	8.13	7.94	5.75	42.50	56.80	106.50	98.30
Nitrite (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nitrate (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sulfate (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Phosphate (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DOC (mg/L)	NA	0.953	0.484	0.369	0.263	0.000	0.000

Table C-1.9 Membrane experimental results of NF membrane (UTC-60) of groundwater from Pra Too Khong Bottled Drinking Water Plant under OTP = 0.400 MPa

Water parameters	Groundwater at sampling point 1	Groundwater at sampling point 2	Permeate water under OTP of 0.400 MPa (sampling time = 5 hours)				
			Feed pH 8.01	Feed pH 7.04	Feed pH 6.02	Feed pH 5.02	Feed pH 4.04
Temperature(° C)	26.7	27.8	26.2	25.6	24.2	25.9	26.4
pH	8.00	8.01	8.06	7.88	7.81	7.29	4.12
EC (µS/cm)	760.0	760.0	194.9	301.0	494.0	666.0	582.0
Total Alkalinity (mg/L as $CaCO_3$)	350.0	350.0	90.0	80.0	50.0	25.0	10.0
Na (mg/L)	116.20	103.80	53.55	59.05	68.00	76.10	67.30
Ca (mg/L)	6.72	6.64	2.11	3.02	4.67	2.50	1.08
K (mg/L)	4.45	4.60	1.42	1.98	3.66	4.97	4.02
Mg (mg/L)	3.10	3.03	0.06	0.08	0.18	0.16	0.13
Fluoride (mg/L)	12.36	12.05	2.32	2.45	4.06	7.62	7.01
Chloride (mg/L)	6.96	6.74	4.20	35.08	113.41	178.74	153.88
Nitrite (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nitrate (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sulfate (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Phosphate (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DOC (mg/L)	0.502	0.440	0.233	0.209	0.214	0.254	0.215

Table C-1.10 Membrane experimental results of NF membrane (UTC-60) of groundwater from Pra Too Khong Bottled Drinking Water Plant under OTP = 0.500 MPa

Water parameters	Groundwater at sampling point 1	Groundwater at sampling point 2	Permeate water under OTP of 0.500 MPa (sampling time = 5 hours)				
			Feed pH 8.05	Feed pH 7.02	Feed pH 6.06	Feed pH 5.03	Feed pH 4.02
Temperature(° C)	26.7	27.8	25.5	26.2	23.5	26.7	27.3
pH	8.00	8.01	8.10	7.80	7.49	6.73	4.07
EC (µS/cm)	760.0	760.0	205.0	262.0	491.0	654.0	590.0
Total Alkalinity (mg/L as $CaCO_3$)	350.0	350.0	100.0	92.0	50.0	22.0	10.0
Na (mg/L)	116.20	103.80	43.00	47.75	77.30	97.30	114.60
Ca (mg/L)	6.72	6.64	2.34	2.62	5.85	3.48	2.55
K (mg/L)	4.45	4.60	1.46	1.89	3.54	4.87	4.04
Mg (mg/L)	3.10	3.03	0.07	0.08	0.18	0.15	0.12
Fluoride (mg/L)	12.36	12.05	2.41	2.50	3.93	7.70	6.90
Chloride (mg/L)	6.96	6.74	4.08	25.61	116.59	172.76	154.69
Nitrite (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nitrate (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sulfate (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Phosphate (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DOC (mg/L)	0.502	0.440	0.250	0.220	0.219	0.217	0.170

Table C-1.11 Data analysis for membrane experiment of NF membrane (UTC-60) of groundwater from Pra Too Khong Bottled Drinking Water Plant

Sample \ Permeate water Parameters		Temp. (° C)	pH	EC (µS/cm)	T-Alk. (mg/L as $CaCO_3$)	Na (mg/L)	% remove Na	Ca (mg/L)	% remove Ca	K (mg/L)	% remove K	Mg (mg/L)	% remove Mg
Groundwater at sampling point 1		30.0	7.86	788	400	177.61		6.53		6.53		3.51	
Groundwater at sampling point 2		29.5	7.92	785	390	176.45		6.41		4.36		3.44	
Permeate under operating pressure of 0.100 MPa at the feed pH of …..	pH 8.23	27.9	8.62	503	245	119.17	32.46	2.86	55.38	2.86	34.40	1.04	69.77
	pH 7.07	27.1	8.36	587	185	129.42	26.65	3.63	43.37	3.20	26.61	1.41	59.01
	pH 6.09	26.6	7.90	773	75	149.57	15.23	4.41	31.20	3.65	16.28	1.77	48.55
	pH 5.05	26.1	7.07	871	18	164.25	6.91	4.68	26.99	3.95	9.40	1.65	52.03
	pH 4.05	26.5	4.35	897	NA	163.00	7.62	2.47	61.47	5.23	-19.95	0.84	75.58
Permeate under operating pressure of 0.200 MPa at the feed pH of …..	pH 8.10	25.8	8.54	400	190	98.66	44.09	2.00	68.80	2.29	47.48	0.48	86.05
	pH 7.08	25.8	8.00	652	210	144.78	17.95	4.48	30.11	3.37	22.71	1.91	44.48
	pH 6.08	25.8	6.87	728	70	148.72	15.72	4.18	34.79	3.45	20.87	1.38	59.88
	pH 5.06	25.5	6.12	832	22	164.84	6.58	3.35	47.74	3.83	12.16	0.46	86.63
	pH 4.02	25.5	4.56	814	4	150.15	14.91	0.68	89.39	3.71	14.91	0.00	100.00
Permeate under operating pressure of 0.300 MPa at the feed pH of …..	pH 7.92	26.0	8.05	190	402	103.14	41.55	2.48	61.31	2.44	44.04	0.62	81.98
	pH 7.09	26.7	7.58	514	180	115.28	34.67	3.09	51.79	2.70	38.07	0.84	75.58
	pH 6.05	25.9	6.62	839	100	167.51	5.07	6.35	0.94	4.16	4.59	2.59	24.71
	pH 5.00	25.9	5.53	866	20	169.76	3.79	3.49	45.55	12.02	-175.69	0.37	89.24
	pH 4.08	25.9	4.39	819	5.4	157.92	10.50	1.69	73.63	3.90	10.55	0.00	100.00

Table C-1.11 Data analysis for membrane experiment of NF membrane (UTC-60) of groundwater from Pra Too Khong Bottled Drinking Water Plant (continue)

Sample \ Permeate water Parameter		F^- (mg/L)	% remove F^-	NO_2^- (mg/L)	% remove NO_2^-	NO_3^- (mg/L)	% remove NO_3^-	SO_4^{2-} (mg/L)	% remove SO_4^{2-}	PO_4^{2-} (mg/L)	% remove PO_4^{2-}	Cl^- (mg/L)	DOC (mg/L)	% remove DOC
Groundwater at sampling point 1		16.98		0.00		0.00		0.00		0.00		8.13	NA	
Groundwater at sampling point 2		16.69		0.00		0.00		0.00		0.00		7.94	0.953	
Permeate under OTP of 0.100 MPa at the feed pH of …..	pH 8.23	10.94	34.45	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6.56	0.534	43.97
	pH 7.07	10.81	35.23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	50.22	0.350	63.27
	pH 6.09	10.76	35.53	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	155.77	0.145	84.78
	pH 5.05	13.00	22.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	204.33	0.000	100.00
	pH 4.05	17.44	-4.49	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	214.70	0.000	100.00
Permeate under OTP of 0.200 MPa at the feed pH of …..	pH 8.10	8.21	50.81	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6.02	0.330	65.37
	pH 7.08	11.23	32.71	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6.07	0.468	50.89
	pH 6.08	8.95	46.38	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	48.39	0.066	93.07
	pH 5.06	14.54	12.88	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	179.92	0.000	100.00
	pH 4.02	16.41	1.68	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	185.03	0.000	100.00
Permeate under OTP of 0.300 MPa at the feed pH of …..	pH 7.92	8.41	49.61	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5.75	0.484	49.21
	pH 7.09	8.26	50.51	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	42.50	0.369	61.28
	pH 6.05	13.07	21.69	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	56.80	0.265	72.19
	pH 5.00	14.80	11.32	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	106.50	0.000	100.00
	pH 4.08	16.30	2.34	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	98.30	0.000	100.00

Table C-1.11 Data analysis for membrane experiment of NF membrane (UTC-60) of groundwater from Pra Too Khong Bottled Drinking Water Plant (continue)

Sample \ Permeate water Parameters		Temp. (° C)	pH	EC (µS/cm)	T-Alk. (mg/L as $CaCO_3$)	Na (mg/L)	% remove Na	Ca (mg/L)	% remove Ca	K (mg/L)	% remove K	Mg (mg/L)	% remove Mg
Groundwater at sampling point 1		26.7	8.00	760	350	116.20		6.72		4.45		3.10	
Groundwater at sampling point 2		27.8	8.01	760	350	103.80		6.64		4.60		3.03	
Permeate under OTP of 0.400 MPa at the feed pH of …..	pH 8.01	26.2	8.06	194.9	90	53.55	48.41	2.11	68.22	1.42	69.13	0.06	98.02
	pH 7.04	25.6	7.88	301	80	59.05	43.11	3.02	54.52	1.98	56.96	0.08	97.36
	pH 6.02	24.2	7.81	494	50	68.00	34.49	4.67	29.67	3.66	20.43	0.18	94.06
	pH 5.02	25.9	7.29	666	25	76.10	26.69	2.50	62.35	4.97	-8.04	0.16	94.72
	pH 4.04	26.4	4.12	582	10	67.30	35.16	1.08	83.73	4.02	12.61	0.13	95.71
Permeate under OTP of 0.500 MPa at the feed pH of …..	pH 8.05	25.5	8.10	205	100	43.00	58.57	2.34	64.76	1.46	68.26	0.07	97.69
	pH 7.02	26.2	7.80	262	92	47.75	54.00	2.62	60.54	1.89	58.91	0.08	97.36
	pH 6.06	23.5	7.49	491	50	77.30	25.53	5.85	11.90	3.54	23.04	0.18	94.06
	pH 5.03	26.7	6.73	654	22	97.30	6.26	3.48	47.59	4.87	-5.87	0.15	95.05
	pH 4.02	27.3	4.07	590	10	114.60	-10.40	2.55	61.60	4.04	12.17	0.12	96.04

Table C-1.11 Data analysis for membrane experiment of NF membrane (UTC-60) of groundwater from Pra Too Khong Bottled Drinking Water Plant (continue)

Sample \ Permeate water Parameters		F^- (mg/L)	% remove F^-	NO_2^- (mg/L)	% remove NO_2^-	NO_3^- (mg/L)	% remove NO_3^-	SO_4^{2-} (mg/L)	% remove SO_4^{2-}	PO_4^{2-} (mg/L)	% remove PO_4^{2-}	Cl^- (mg/L)	DOC (mg/L)	% remove DOC
Groundwater at sampling point 1		12.36		0.00		0.00		0.00		0.00		6.69	0.502	
Groundwater at sampling point 2		12.05		0.00		0.00		0.00		0.00		6.74	0.440	
Permeate under OTP of 0.400 MPa at the feed pH of …..	pH 8.01	2.32	80.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.20	0.233	47.05
	pH 7.04	2.45	79.67	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	35.08	0.209	52.50
	pH 6.02	4.06	66.31	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	113.41	0.214	51.36
	pH 5.02	7.62	36.76	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	178.74	0.254	42.27
	pH 4.04	7.01	41.83	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	153.88	0.215	51.14
Permeate under OTP of 0.500 MPa at the feed pH of …..	pH 8.05	2.41	80.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.08	0.250	43.18
	pH 7.02	2.50	79.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	25.61	0.220	50.00
	pH 6.06	3.93	67.39	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	116.59	0.219	50.23
	pH 5.03	7.70	36.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	172.76	0.217	50.68
	pH 4.02	6.90	42.74	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	154.69	0.170	61.36

APPENDIX C-2
MEMBRANE EXPERIMENTAL RESULTS OF NF MEMBRANE (UTC-60) OF GROUNDWATER FROM SAN PA HIANG MEMBRANE PLANT (SITE B)

Table C-2.1 Determination of sampling time of NF membrane (UTC-60) of groundwater from San Pa Hiang Membrane Plant under OTP = 0.100 MPa

Time (Min.)	Permeate water					Concentrated water				Feed tank	
	pH	EC (μS/cm)	Temp. (° C)	Flow rate (m^3/day)	Flux (m^3/m^2.day)	pH	EC (μS/cm)	Temp. (° C)	Flow rate (m^3/day)	Temp (° C)	EC (μS/cm)
0	6.80	168.7	21.4	0.00114	0.194	6.64	331.0	20.1	2.189	19.5	328.0
30	6.81	209.0	21.7	0.00115	0.196	6.69	332.0	20.5	2.189	20.2	330.0
60	6.84	210.0	21.6	0.00118	0.201	6.71	333.0	20.9	2.189	20.8	330.0
120	6.87	212.0	21.8	0.00120	0.204	6.84	333.0	21.3	2.189	21.3	331.0
180	6.97	214.0	22.0	0.00121	0.206	7.01	334.0	22.1	2.189	22.4	331.0
240	7.20	212.0	22.4	0.00122	0.209	7.23	333.0	21.0	2.189	22.2	332.0
300	7.45	207.0	23.0	0.00125	0.214	7.43	334.0	20.6	2.189	21.2	332.0
360	7.61	210.0	23.4	0.00126	0.214	7.38	334.0	20.8	2.189	21.5	331.0
540	7.83	204.0	24.1	0.00123	0.210	7.67	334.0	20.2	2.189	21.8	333.0
720	8.12	204.0	23.4	0.00122	0.209	7.88	335.0	20.5	2.189	22.7	332.0
780	8.16	207.0	22.0	0.00123	0.209	7.94	334.0	20.4	2.189	22.5	332.0
900	8.23	205.0	22.2	0.00122	0.209	8.25	336.0	20.9	2.189	21.6	332.0
1080	8.53	213.0	22.6	0.00121	0.206	8.36	336.0	22.3	2.189	22.5	333.0

Table C-2.2 Determination of sampling time of NF membrane (UTC-60) of groundwater from San Pa Hiang Membrane Plant under OTP = 0.200 MPa

Time	Permeate water					Concentrated water				Feed tank	
	pH	EC	Temp.	Flow rate	Flux	pH	EC	Temp.	Flow rate	Temp.	EC
(Min.)		(µS/cm)	(° C)	(m^3/day)	(m^3/m^2.day)		(µS/cm)	(° C)	(m^3/day)	(° C)	(µS/cm)
0	6.55	163.9	21.3	0.00257	0.439	6.63	332.0	20.9	2.131	20.4	331.0
20	6.57	178.7	21.6	0.00258	0.440	6.58	334.0	21.0	2.131	20.8	331.0
40	6.53	180.0	21.4	0.00258	0.440	6.62	335.0	21.3	2.131	21.2	332.0
60	6.58	177.9	21.8	0.00262	0.447	6.64	335.0	22.1	2.131	21.5	331.0
120	6.62	171.3	21.5	0.00266	0.454	6.73	336.0	21.8	2.131	21.8	332.0
180	6.67	172.4	22.1	0.00272	0.464	6.81	337.0	21.4	2.131	22.3	333.0
240	6.71	168.5	22.4	0.00273	0.467	6.84	336.0	21.2	2.131	22.6	332.0
300	6.73	174.4	21.8	0.00277	0.473	6.93	338.0	21.5	2.131	23.1	334.0
360	6.77	165.3	21.5	0.00279	0.476	7.02	335.0	21.8	2.131	23.3	334.0
540	6.94	166.8	21.4	0.00279	0.476	7.11	336.0	22.2	2.131	23.5	334.0
720	7.15	172.2	21.4	0.00279	0.476	7.17	334.0	22.6	2.131	22.9	335.0
900	7.26	169.5	21.3	0.00277	0.473	7.27	335.0	22.8	2.131	23.9	336.0
1080	7.31	174.2	22.6	0.00268	0.458	7.35	336.0	23.0	2.131	22.4	335.0

Table C-2.3 Determination of sampling time of NF membrane (UTC-60) of groundwater from San Pa Hiang Membrane Plant under OTP = 0.300 MPa

Time	Permeate water					Concentrated water				Feed tank	
(Min.)	pH	EC (μS/cm)	Temp. (° C)	Flow rate (m^3/day)	Flux (m^3/m^2.day)	pH	EC (μS/cm)	Temp. (° C)	Flow rate (m^3/day)	Temp. (° C)	EC (μS/cm)
0	6.47	166.4	20.1	0.00485	0.828	6.59	324.0	20.3	2.074	20.1	323.0
20	6.54	179.8	20.0	0.00455	0.776	6.61	327.0	20.5	2.074	20.5	325.0
40	6.59	174.9	19.9	0.00448	0.764	6.61	327.0	20.9	2.074	20.8	326.0
60	6.57	171.8	20.0	0.00445	0.760	6.66	327.0	21.6	2.074	21.1	325.0
120	6.66	166.2	20.3	0.00436	0.745	6.84	327.0	22.0	2.074	21.7	325.0
180	6.79	162.9	20.4	0.00434	0.741	6.96	328.0	21.7	2.074	22.3	326.0
240	6.88	157.9	20.6	0.00432	0.737	7.04	327.0	21.5	2.074	22.5	326.0
300	6.95	153.4	20.9	0.00432	0.737	7.18	326.0	22.0	2.074	22.9	327.0
360	7.06	155.8	20.5	0.00430	0.734	7.24	325.0	22.2	2.074	22.4	326.0
540	7.21	150.7	20.1	0.00430	0.734	7.31	327.0	22.7	2.074	22.1	327.0
720	7.35	151.0	20.3	0.00426	0.726	7.39	325.0	22.5	2.074	22.0	327.0

Table C-2.4 Determination of sampling time of NF membrane (UTC-60) of groundwater from San Pa Hiang Membrane Plant under OTP = 0.400 MPa

Time	Permeate water					Concentrated water				Feed tank	
(Min.)	pH	EC (µS/cm)	Temp. (° C)	Flow rate (m^3/day)	Flux (m^3/m^2.day)	pH	EC (µS/cm)	Temp. (° C)	Flow rate (m^3/day)	Temp. (° C)	EC (µS/cm)
0	6.50	170.9	20.3	0.00588	1.003	6.66	335.0	20.9	1.843	20.3	327.0
20	6.49	167.5	20.5	0.00572	0.976	6.65	334.0	21.4	1.843	21.3	332.0
40	6.54	165.5	20.4	0.00568	0.970	6.65	335.0	21.6	1.843	21.6	334.0
60	6.60	163.3	20.7	0.00565	0.964	6.69	336.0	21.7	1.843	21.9	333.0
120	6.62	160.9	20.7	0.00565	0.964	6.81	336.0	22.0	1.843	22.3	333.0
180	6.00	158.2	20.7	0.00565	0.964	6.84	337.0	22.3	1.843	22.6	333.0
240	6.66	155.4	20.6	0.00561	0.957	6.87	337.0	22.2	1.843	22.7	333.0
300	6.68	156.1	20.8	0.00561	0.957	6.93	337.0	22.6	1.843	22.9	333.0
360	6.74	157.4	20.9	0.00561	0.957	6.98	336.0	22.4	1.843	23.0	334.0
540	6.92	155.2	21.3	0.00550	0.939	7.01	337.0	21.9	1.843	22.5	334.0
720	7.13	156.7	20.2	0.00537	0.916	7.08	338.0	22.0	1.843	22.1	333.0

Table C-2.5 Determination of sampling time of NF membrane (UTC-60) of groundwater from San Pa Hiang Membrane Plant under OTP = 0.500 MPa

Time	Permeate water					Concentrated water				Feed tank	
(Min.)	pH	EC (µS/cm)	Temp. (° C)	Flow rate (m^3/day)	Flux (m^3/m^2.day)	pH	EC (µS/cm)	Temp. (° C)	Flow rate (m^3/day)	Temp. (° C)	EC (µS/cm)
0	6.77	191.5	22.5	0.01016	1.735	6.85	337.0	23.0	1.037	21.8	334.0
20	6.85	181.3	22.5	0.00960	1.638	6.89	337.0	23.0	1.037	23.0	334.0
40	6.87	175.7	22.6	0.00939	1.603	6.79	336.0	23.5	1.037	23.5	336.0
60	6.88	171.7	22.3	0.00919	1.569	6.85	337.0	23.4	1.037	23.6	335.0
120	6.96	165.8	22.1	0.00909	1.552	6.87	337.0	24.1	1.037	24.4	334.0
180	6.97	164.3	22.6	0.00909	1.552	6.89	338.0	24.7	1.037	25.0	335.0
240	6.99	163.4	22.7	0.00909	1.552	6.92	337.0	24.5	1.037	24.9	335.0
300	7.01	162.6	22.8	0.00909	1.552	6.95	338.0	24.8	1.037	25.2	336.0
360	7.05	160.1	22.9	0.00909	1.552	6.97	338.0	24.9	1.037	25.5	335.0
540	7.09	153.8	23.1	0.00891	1.520	7.03	339.0	24.6	1.037	25.4	335.0
720	7.15	150.5	23.6	0.00864	1.474	7.05	339.0	25.3	1.037	25.7	336.0

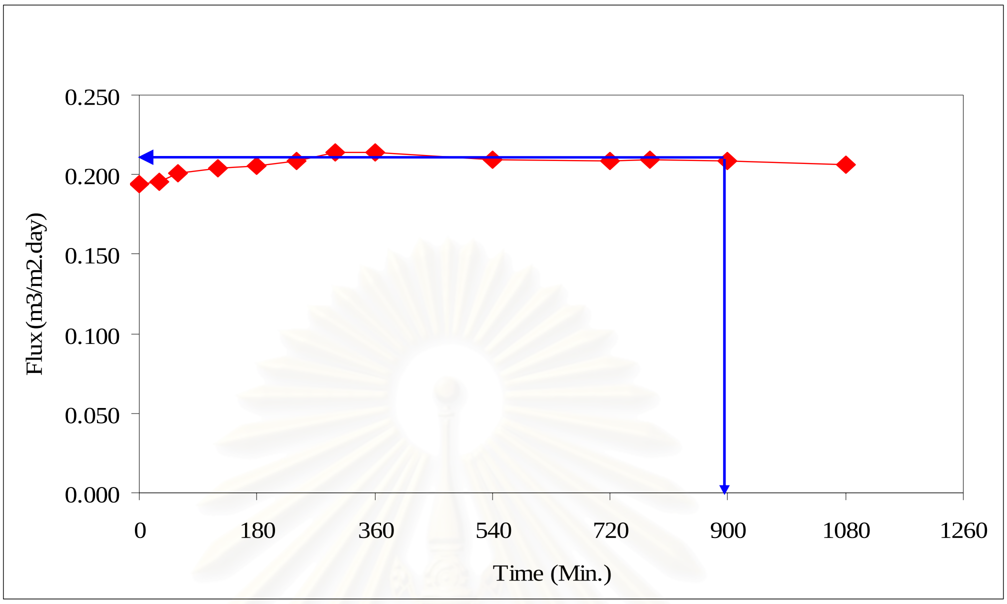

Figure C-2.1 Determination of sampling time of UTC-60 membrane of groundwater from San Pa Hiang Membrane Plant under OTP = 0.100 MPa

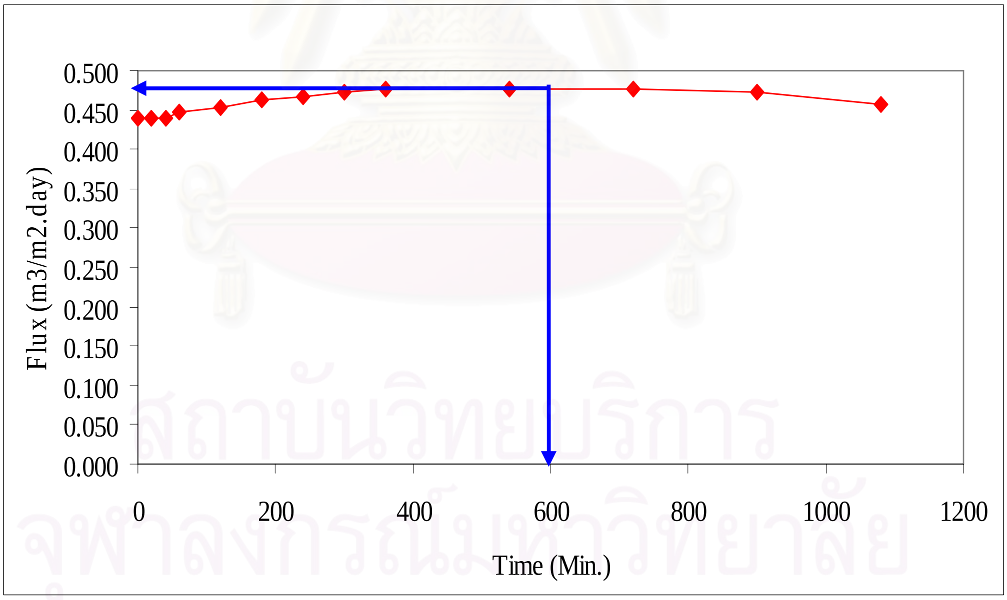

Figure C-2.2 Determination of sampling time of UTC-60 membrane of groundwater from San Pa Hiang Membrane Plant under OTP = 0.200 MPa

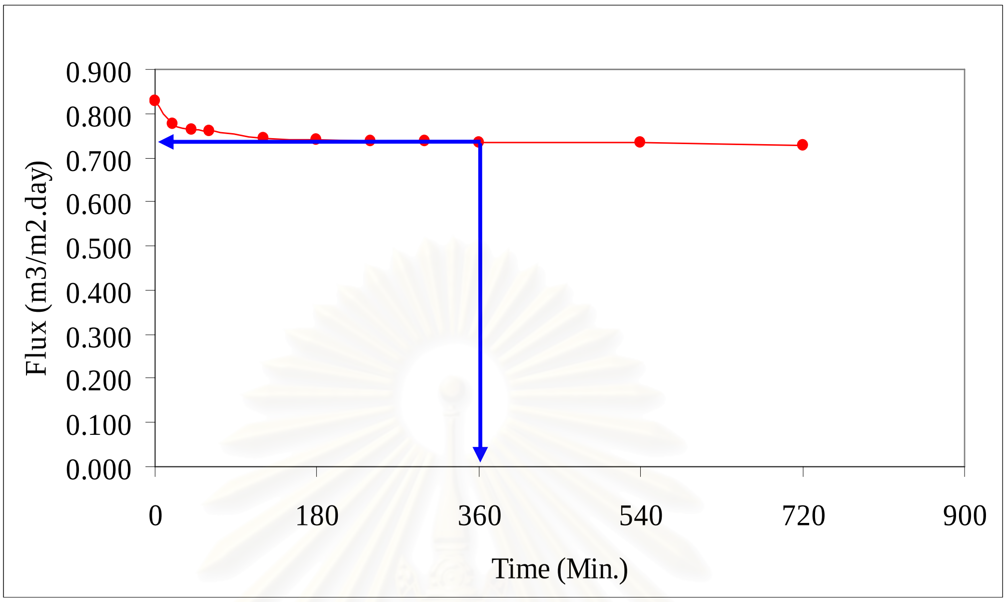

Figure C-2.3 Determination of sampling time of UTC-60 membrane of groundwater from San Pa Hiang Membrane Plant under OTP = 0.300 MPa

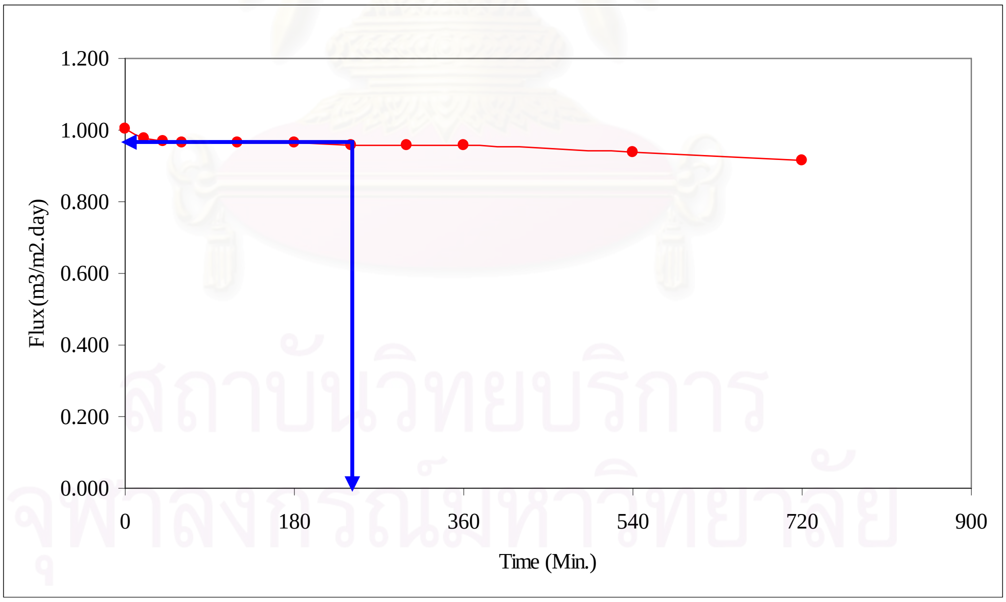

Figure C-2.4 Determination of sampling time of UTC-60 membrane of groundwater from San Pa Hiang Membrane Plant under OTP = 0.400 MPa

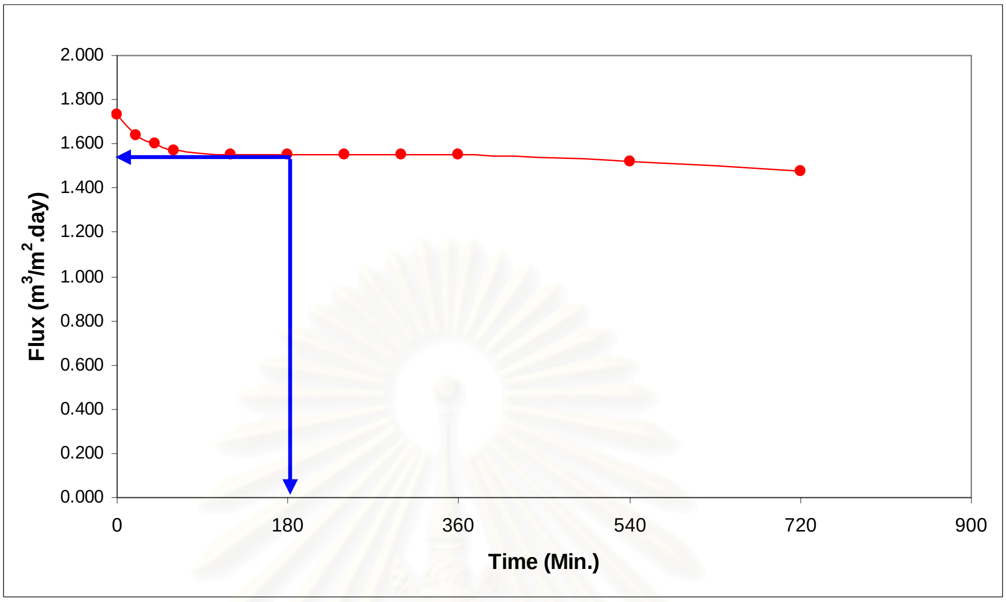

Figure C-2.5 Determination of sampling time of UTC-60 membrane of groundwater from San Pa Hiang Membrane Plant under OTP = 0.500 MPa

Table C-2.6 Membrane experimental results of NF membrane (UTC-60) of groundwater from San Pa Hiang Membrane Plant under OTP = 0.100 MPa

Water parameters	Groundwater at sampling point 1	Groundwater at sampling point 2	Permeate water under OTP of 0.100 MPa (sampling time = 15 hours)				
			Feed pH 7.03	Feed pH 6.65	Feed pH 6.01	Feed pH 5.04	Feed pH 4.02
Temperature(° C)	22.0	22.4	23.2	24.1	22.4	22.7	23.6
pH	6.60	6.65	8.42	8.12	7.74	7.01	4.12
EC (µS/cm)	335.0	334.0	385.0	204.0	271.0	325.0	286.0
Total Alkalinity (mg/L as $CaCO_3$)	160.0	155.0	160.0	60.0	50.0	10.0	4.0
Na (mg/L)	136.10	121.90	56.80	25.75	33.30	41.85	48.45
Ca (mg/L)	14.62	11.66	8.52	8.15	11.20	14.43	4.57
K (mg/L)	5.30	5.30	7.09	6.18	7.16	8.55	7.89
Mg (mg/L)	7.10	7.21	1.42	1.64	2.15	2.40	0.87
Fluoride (mg/L)	2.88	2.84	1.50	1.47	1.58	1.76	1.83
Chloride (mg/L)	10.50	10.45	10.21	9.57	45.57	87.98	130.90
Nitrite (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nitrate (mg/L)	0.76	0.62	0.42	0.40	0.28	0.27	0.15
Sulfate (mg/L)	6.95	6.96	0.37	0.47	0.45	0.55	0.72
Phosphate (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DOC (mg/L)	0.623	0.570	0.286	0.261	0.267	0.273	0.292

Table C-2.7 Membrane experimental results of NF membrane (UTC-60) of groundwater from San Pa Hiang Membrane Plant under OTP = 0.200 MPa

Water parameters	Groundwater at sampling point 1	Groundwater at sampling point 2	Permeate water under OTP of 0.200 MPa (sampling time = 10 hours)				
			Feed pH 7.05	Feed pH 6.62	Feed pH 6.01	Feed pH 5.02	Feed pH 4.05
Temperature(° C)	22.0	22.4	24.5	23.7	22.8	24.1	23.8
pH	6.60	6.65	8.4	7.99	7.5	7.12	4.1
EC (µS/cm)	335.0	334.0	313.0	166.8	246.0	281.0	254.0
Total Alkalinity (mg/L as $CaCO_3$)	160.0	155.0	160.0	64.0	22.0	10.0	4.0
Na (mg/L)	136.10	121.90	35.40	30.45	34.90	44.85	70.85
Ca (mg/L)	14.62	11.66	2.85	4.52	8.45	8.19	2.54
K (mg/L)	5.30	5.30	5.24	5.25	6.80	8.04	7.12
Mg (mg/L)	7.10	7.21	0.71	1.02	1.53	1.34	0.57
Fluoride (mg/L)	2.88	2.84	1.19	1.29	1.32	1.66	1.84
Chloride (mg/L)	10.50	10.45	11.02	13.11	52.71	76.64	65.80
Nitrite (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nitrate (mg/L)	0.76	0.62	0.51	0.46	0.37	0.28	0.20
Sulfate (mg/L)	6.95	6.96	0.35	0.49	0.49	0.47	0.62
Phosphate (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DOC (mg/L)	0.623	0.570	0.222	0.247	0.213	0.205	0.225

Table C-2.8 Membrane experimental results of NF membrane (UTC-60) of groundwater from San Pa Hiang Membrane Plant under OTP = 0.300 MPa

Water parameters	Groundwater at sampling point 1	Groundwater at sampling point 2	Permeate water under OTP of 0.300 MPa (sampling time = 6 hours)				
			Feed pH 7.02	Feed pH 6.61	Feed pH 6.02	Feed pH 5.01	Feed pH 4.02
Temperature(° C)	22.0	22.4	24.3	22.7	22.6	23.3	24.5
pH	6.60	6.65	7.98	7.86	7.62	7.17	4.29
EC (µS/cm)	335.0	334.0	262.0	152.4	221.0	273.0	263.0
Total Alkalinity (mg/L as $CaCO_3$)	160.0	155.0	120.0	64.0	40.0	8.0	4.0
Na (mg/L)	136.10	121.90	55.95	22.50	29.65	31.35	30.65
Ca (mg/L)	14.62	11.66	2.58	3.74	6.60	7.42	4.18
K (mg/L)	5.30	5.30	4.51	3.96	5.99	7.59	6.65
Mg (mg/L)	7.10	7.21	0.72	1.06	1.44	1.44	0.94
Fluoride (mg/L)	2.88	2.84	1.22	1.35	1.32	1.71	1.86
Chloride (mg/L)	10.50	10.45	9.40	8.79	44.22	73.46	69.18
Nitrite (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nitrate (mg/L)	0.76	0.62	0.52	0.32	0.38	0.27	0.18
Sulfate (mg/L)	6.95	6.96	0.66	1.08	0.88	0.86	0.88
Phosphate (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DOC (mg/L)	0.623	0.570	0.190	0.229	0.243	0.199	0.210

Table C-2.9 Membrane experimental results of NF membrane (UTC-60) of groundwater from San Pa Hiang Membrane Plant under OTP = 0.400 MPa

Water parameters	Groundwater at sampling point 1	Groundwater at sampling point 2	Permeate water under OTP of 0.400 MPa (sampling time = 4 hours)				
			Feed pH 7.01	Feed pH 6.59	Feed pH 6.03	Feed pH 5.01	Feed pH 4.01
Temperature(° C)	22.0	22.4	22.6	22.6	23.1	22.1	22.8
pH	6.60	6.65	8.15	7.99	7.60	7.29	4.02
EC (µS/cm)	335.0	334.0	218.0	152.5	203.0	252.0	245.0
Total Alkalinity (mg/L as $CaCO_3$)	160.0	155.0	100.0	48.0	32.0	8.0	4.0
Na (mg/L)	136.10	121.90	42.25	20.80	25.55	30.10	26.75
Ca (mg/L)	14.62	11.66	2.46	3.94	5.33	6.43	5.43
K (mg/L)	5.30	5.30	4.19	3.85	5.44	7.00	5.78
Mg (mg/L)	7.10	7.21	1.06	0.72	1.44	1.44	0.94
Fluoride (mg/L)	2.88	2.84	1.10	1.14	1.26	1.70	1.56
Chloride (mg/L)	10.50	10.45	8.36	8.03	38.92	68.81	60.90
Nitrite (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nitrate (mg/L)	0.76	0.62	0.48	0.43	0.40	0.27	0.17
Sulfate (mg/L)	6.95	6.96	0.71	1.22	0.92	0.89	0.93
Phosphate (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DOC (mg/L)	0.623	0.570	0.208	0.252	0.215	0.209	0.195

Table C-2.10 Membrane experimental results of NF membrane (UTC-60) of groundwater from San Pa Hiang Membrane Plant under OTP=0.500 MPa

Water parameters	Groundwater at sampling point 1	Groundwater at sampling point 2	Permeate water under OTP of 0.500 MPa (sampling time = 3 hours)				
			Feed pH 7.02	Feed pH 6.64	Feed pH 6.05	Feed pH 5.02	Feed pH 4.05
Temperature(° C)	22.0	22.4	22.5	23.4	24.8	24.1	24.7
pH	6.60	6.65	8.02	8.02	7.40	7.40	4.15
EC (µS/cm)	335.0	334.0	168.3	159.0	227.0	252.0	243.0
Total Alkalinity (mg/L as $CaCO_3$)	160.0	155.0	60.0	64.0	24.0	8.0	4.0
Na (mg/L)	136.10	121.90	25.25	22.25	23.00	26.40	23.45
Ca (mg/L)	14.62	11.66	3.03	4.39	7.46	6.69	4.42
K (mg/L)	5.30	5.30	3.48	4.54	6.23	7.50	5.88
Mg (mg/L)	7.10	7.21	0.69	1.12	1.29	1.28	1.02
Fluoride (mg/L)	2.88	2.84	1.04	1.14	1.44	1.94	1.56
Chloride (mg/L)	10.50	10.45	8.07	8.28	45.52	70.27	61.31
Nitrite (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nitrate (mg/L)	0.76	0.62	0.23	0.40	0.32	0.25	0.16
Sulfate (mg/L)	6.95	6.96	1.11	1.03	1.04	1.15	0.94
Phosphate (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DOC (mg/L)	0.623	0.570	0.237	0.247	0.252	0.281	0.287

Table C-2.11 Data analysis for membrane experiment of NF membrane (UTC-60) of groundwater from San Pa Hiang Membrane Plant

Permeate water Parameters / Sample		Temp. (° C)	pH	EC (µS/cm)	T-Alk. (mg/L as $CaCO_3$)	Na (mg/L)	% remove Na	Ca (mg/L)	% remove Ca	K (mg/L)	% remove K	Mg (mg/L)	% remove Mg
Groundwater at sampling point 1		22.0	6.60	335	160	136.10		14.62		10.60		7.10	
Groundwater at sampling point 2		22.4	6.65	334	155	121.90		11.66		10.60		7.21	
Permeate under OTP of 0.100 MPa at the feed pH of …..	pH 7.03	23.2	8.42	385.0	160	56.80	53.40	8.52	26.93	7.09	33.11	1.42	80.31
	pH 6.65	24.1	8.12	204.0	60	25.75	78.88	8.15	30.10	6.18	41.70	1.64	77.25
	pH 6.01	22.4	7.74	271.0	50	33.30	72.68	11.20	3.95	7.16	32.45	2.15	70.18
	pH 5.04	22.7	7.01	325.0	10	41.85	65.67	14.43	-23.76	8.55	19.34	2.40	66.71
	pH 4.02	23.6	4.12	286.0	4	48.45	60.25	4.57	60.81	7.89	25.57	0.87	87.93
Permeate under OTP of 0.200 MPa at the feed pH of …..	pH 7.05	24.5	8.40	313	160	35.40	70.96	2.85	75.56	5.24	50.57	0.71	90.15
	pH 6.62	23.7	7.99	166.8	64	30.45	75.02	4.52	61.23	5.25	50.47	1.02	85.85
	pH 6.01	22.8	7.50	246	22	34.90	71.37	8.45	27.53	6.80	35.85	1.53	78.78
	pH 5.02	24.1	7.12	281	10	44.85	63.21	8.19	29.76	8.04	24.15	1.34	81.41
	pH 4.05	23.8	4.10	254	4	70.85	41.88	2.54	78.22	7.12	32.83	0.57	92.09
Permeate under OTP of 0.300 MPa at the feed pH of …..	pH 7.02	24.3	7.98	262	120	55.95	54.10	2.58	77.87	4.51	57.45	0.72	90.01
	pH 6.61	22.7	7.86	152.4	64	22.50	81.54	3.74	67.92	3.96	62.64	1.06	85.30
	pH 6.02	22.6	7.62	221	40	29.65	75.68	6.60	43.40	5.99	43.49	1.44	80.03
	pH 5.01	23.3	7.17	273	8	31.35	74.28	7.42	36.36	7.59	28.40	1.44	80.03
	pH 4.02	24.4	4.29	263	4	30.65	74.86	4.18	64.15	6.65	37.26	0.94	86.96
Permeate under OTP of 0.400 MPa at the feed pH of …..	pH 7.01	22.6	8.15	218	100	42.25	65.34	2.46	78.90	4.19	60.47	1.06	85.30
	pH 6.59	22.6	7.99	152.2	48	20.80	82.94	3.94	66.21	3.85	63.68	0.72	90.01
	pH 6.03	23.1	7.60	203	32	25.55	79.04	5.33	54.29	5.44	48.68	1.44	80.03
	pH 5.01	22.1	7.29	252	8	30.10	75.31	6.43	44.85	7.00	33.96	1.44	80.03
	pH 4.01	22.8	4.02	245	4	26.75	78.06	5.43	53.43	5.78	45.47	0.94	86.96
Permeate under OTP of 0.500 MPa at the feed pH of …..	pH 7.02	22.5	8.02	168.3	60	25.25	79.29	3.03	74.01	3.48	67.17	0.69	90.43
	pH 6.64	23.4	8.02	159	64	22.25	81.75	4.39	62.35	4.54	57.17	1.12	84.47
	pH 6.05	24.8	7.40	227	24	23.00	81.13	7.46	36.02	6.23	41.23	1.29	82.11
	pH 5.02	24.1	7.40	252	8	26.40	78.34	6.69	42.62	7.50	29.25	1.28	82.25
	pH 4.05	24.7	4.15	243	4	23.45	80.76	4.42	62.09	5.88	44.53	1.02	85.85

Table C-2.11 Data analysis for membrane experiment of NF membrane (UTC-60) of groundwater from San Pa Hiang Membrane Plant (continue)

Sample \ Permeate water Parameters		F^- (mg/L)	% remove F^-	NO_2^- (mg/L)	% remove NO_2^-	NO_3^- (mg/L)	% remove NO_3^-	SO_4^{2-} (mg/L)	% remove SO_4^{2-}	PO_4^{2-} (mg/L)	% remove PO_4^{2-}	Cl^- (mg/L)	DOC (mg/L)	% remove DOC
Groundwater at sampling point 1		2.88		0.00		0.38		6.95		0.00		10.50	0.623	
Groundwater at sampling point 2		2.84		0.00		0.31		6.96		0.00		10.45	0.570	
Permeate under OTP of 0.100 MPa at the feed pH of …..	pH 7.03	1.50	47.18	0.00	0.00	0.42	-35.48	0.37	94.68	0.00	0.00	10.21	0.286	49.82
	pH 6.65	1.47	48.24	0.00	0.00	0.40	-29.03	0.47	93.25	0.00	0.00	9.57	0.261	54.21
	pH 6.01	1.58	44.37	0.00	0.00	0.28	9.68	0.45	93.53	0.00	0.00	45.57	0.267	53.16
	pH 5.04	1.76	38.03	0.00	0.00	0.27	12.90	0.55	92.10	0.00	0.00	87.98	0.273	52.11
	pH 4.02	1.83	35.56	0.00	0.00	0.15	51.61	0.72	89.66	0.00	0.00	130.90	0.292	48.77
Permeate under OTP of 0.200 MPa at the feed pH of …..	pH 7.05	1.19	58.10	0.00	0.00	0.51	-64.52	0.35	94.97	0.00	0.00	11.02	0.222	61.05
	pH 6.62	1.29	54.58	0.00	0.00	0.46	-48.39	0.49	92.96	0.00	0.00	13.11	0.247	56.67
	pH 6.01	1.32	53.52	0.00	0.00	0.37	-19.35	0.49	92.96	0.00	0.00	52.71	0.213	62.63
	pH 5.02	1.66	41.55	0.00	0.00	0.28	9.68	0.47	93.25	0.00	0.00	76.64	0.205	64.04
	pH 4.05	1.84	35.21	0.00	0.00	0.20	35.48	0.62	91.09	0.00	0.00	65.80	0.225	60.53
Permeate under OTP of 0.300 MPa at the feed pH of …..	pH 7.02	1.22	57.04	0.00	0.00	0.52	-67.74	0.66	90.52	0.00	0.00	9.40	0.190	66.67
	pH 6.61	1.35	52.46	0.00	0.00	0.32	-3.23	1.08	84.48	0.00	0.00	8.79	0.229	59.82
	pH 6.02	1.32	53.52	0.00	0.00	0.38	-22.58	0.88	87.36	0.00	0.00	44.22	0.243	57.37
	pH 5.01	1.71	39.79	0.00	0.00	0.27	12.90	0.86	87.64	0.00	0.00	73.46	0.199	65.09
	pH 4.02	1.86	34.51	0.00	0.00	0.18	41.94	0.88	87.36	0.00	0.00	69.18	0.210	63.16
Permeate under OTP of 0.400 MPa at the feed pH of …..	pH 7.01	1.10	61.27	0.00	0.00	0.48	-54.84	0.71	89.80	0.00	0.00	8.36	0.208	63.51
	pH 6.59	1.14	59.86	0.00	0.00	0.43	-38.71	1.22	82.47	0.00	0.00	8.03	0.252	55.79
	pH 6.03	1.26	55.63	0.00	0.00	0.40	-29.03	0.92	86.78	0.00	0.00	38.92	0.215	62.28
	pH 5.01	1.70	40.14	0.00	0.00	0.27	12.90	0.89	87.21	0.00	0.00	68.81	0.209	63.33
	pH 4.01	1.56	45.07	0.00	0.00	0.17	45.16	0.93	86.64	0.00	0.00	60.90	0.195	65.79
Permeate under OTP of 0.500 MPa at the feed pH of …..	pH 7.02	1.04	63.38	0.00	0.00	0.23	25.81	1.11	84.04	0.00	0.00	8.07	0.237	58.42
	pH 6.64	1.14	59.86	0.00	0.00	0.40	-29.03	1.03	85.20	0.00	0.00	8.28	0.247	56.67
	pH 6.05	1.44	49.30	0.00	0.00	0.32	-3.23	1.04	85.06	0.00	0.00	45.52	0.252	55.79
	pH 5.02	1.94	31.69	0.00	0.00	0.25	19.35	1.15	83.48	0.00	0.00	70.27	0.281	50.70
	pH 4.05	1.56	45.07	0.00	0.00	0.16	48.39	0.94	86.49	0.00	0.00	61.31	0.287	49.65

APPENDIX D
MEMBRANE EXPERIMENTAL RESULTS OF ULPRO MEMBRANE (UTC-70)

APPENDIX D-1

MEMBRANE EXPERIMENTAL RESULTS OF ULPRO MEMBRANE (UTC-70) OF GROUNDWATER FROM PRA TOO KHONG BOTTLED DRINKING WATER PLANT (SITE A)

Table D-1.1 Determination of sampling time of ULPRO membrane (UTC-70) of groundwater from Pra Too Khong Bottled Drinking Water Plant under OTP = 0.100 MPa

Time	Permeate water					Concentrated water				Feed tank	
(Min.)	pH	EC (µS/cm)	Temp. (° C)	Flow rate (m^3/day)	Flux (m^3/m^2.day)	pH	EC (µS/cm)	Temp. (° C)	Flow rate (m^3/day)	Temp. (° C)	EC (µS/cm)
0	7.74	61.0	25.9	0.0006874	0.117	8.06	776	26.2	2.304	25.5	775
30	7.83	67.6	25.8	0.0007030	0.120	8.14	780	26.5	2.246	26.5	777
60	7.84	67.6	26.1	0.0007088	0.121	8.17	780	26.7	2.304	27.1	776
120	7.86	67.7	26.0	0.0007140	0.122	8.24	781	27.1	2.304	27.2	777
240	7.85	64.0	26.3	0.0007435	0.127	8.23	782	27.4	2.304	27.9	778
360	7.89	63.5	26.5	0.0007500	0.128	8.27	783	27.9	2.246	28.3	778
540	7.92	62.7	26.2	0.0007533	0.129	8.31	785	28.3	2.246	28.5	779
720	7.96	62.9	26.6	0.0007559	0.129	8.35	789	28.0	2.304	28.9	782
900	7.91	60.4	26.3	0.0007533	0.129	8.42	791	28.1	2.304	28.7	783
1200	7.80	61.3	26.4	0.0007533	0.129	8.51	789	27.6	2.246	27.8	785
1440	7.74	60.9	26.5	0.0007533	0.129	8.57	792	27.7	2.304	28.2	789
1620	7.82	61.1	26.1	0.0007481	0.128	8.62	793	27.9	2.304	28.6	787

Table D-1.2 Determination of sampling time of ULPRO membrane (UTC-70) of groundwater from Pra Too Khong Bottled Drinking Water Plant under OTP = 0.200 MPa

Time (Min.)	Permeate water					Concentrated water				Feed tank	
	pH	EC (µS/cm)	Temp. (° C)	Flow rate (m^3/day)	Flux (m^3/m^2.day)	pH	EC (µS/cm)	Temp. (° C)	Flow rate (m^3/day)	Temp. (° C)	EC (µS/cm)
0	7.84	57.5	26.6	0.00172	0.294	8.10	775	25.8	2.246	25.1	775
20	7.86	54.8	25.6	0.00175	0.298	8.13	781	26.2	2.189	25.6	776
40	7.85	54.3	25.3	0.00176	0.300	8.17	781	26.1	2.246	25.9	777
60	7.87	53.8	25.4	0.00178	0.303	8.20	783	26.3	2.189	26.2	777
120	7.90	52.7	25.3	0.00182	0.310	8.22	785	26.8	2.189	26.8	777
240	7.85	50.9	25.7	0.00190	0.324	8.48	785	27.3	2.189	27.8	778
360	7.91	49.5	26.2	0.00194	0.331	8.40	785	27.7	2.189	28.4	780
540	7.92	49.3	26.2	0.00193	0.330	8.43	785	27.6	2.246	28.7	782
900	7.95	50.2	26.1	0.00189	0.322	8.46	787	27.9	2.246	28.5	782
1320	7.88	49.8	26.3	0.00187	0.319	8.51	788	28.5	2.246	28.3	781
1620	7.93	50.1	26.2	0.00193	0.330	8.50	789	28.7	2.246	28.7	784

Table D-1.3 Determination of sampling time of ULPRO membrane (UTC-70) of groundwater from Pra Too Khong Bottled Drinking Water Plant under OTP = 0.300 MPa

Time	Permeate water					Concentrated water				Feed tank	
	pH	EC	Temp.	Flow rate	Flux	pH	EC	Temp.	Flow rate	Temp.	EC
(Min.)		(μS/cm)	(° C)	(m^3/day)	(m^3/m^2.day)		(μS/cm)	(° C)	(m^3/day)	(° C)	(μS/cm)
0	7.74	47.4	26.5	0.00253	0.431	8.25	789	27.5	2.131	25.7	778
30	7.89	45.5	26.3	0.00263	0.448	8.30	788	27.7	2.189	26.4	777
60	7.83	47.3	26.2	0.00260	0.444	8.30	796	27.9	2.189	26.8	777
120	7.72	44.0	26.6	0.00270	0.461	8.33	792	28.6	2.131	27.5	778
180	7.81	43.8	26.7	0.00276	0.471	8.32	794	28.8	2.131	28.2	779
240	7.95	43.8	26.7	0.00279	0.476	8.33	797	29.0	2.189	28.5	779
300	7.90	44.3	26.7	0.00278	0.474	8.33	798	29.0	2.131	28.8	780
360	7.75	42.2	26.8	0.00283	0.483	8.33	795	29.1	2.189	28.9	782
540	7.86	43.0	26.2	0.00281	0.480	8.43	806	28.7	2.189	29.2	784
720	7.92	39.1	26.4	0.00285	0.487	8.50	800	28.9	2.131	28.8	786
840	7.88	41.5	26.7	0.00283	0.483	8.55	802	28.4	2.131	28.8	787

Table D-1.4 Determination of sampling time of ULPRO membrane (UTC-70) of groundwater from Pra Too Khong Bottled Drinking Water Plant under OTP = 0.400 MPa

Time	Permeate water					Concentrated water				Feed tank	
(Min.)	pH	EC (µS/cm)	Temp. (° C)	Flow rate (m^3/day)	Flux (m^3/m^2.day)	pH	EC (µS/cm)	Temp. (° C)	Flow rate (m^3/day)	Temp. (° C)	EC (µS/cm)
0	7.35	29.9	26.0	0.00354	0.604	8.05	765	24.0	1.843	22.3	754
30	7.37	25.4	26.0	0.00376	0.641	8.08	765	24.5	1.843	23.5	754
60	7.38	24.3	26.3	0.00389	0.664	8.12	766	25.1	1.843	23.9	755
120	7.41	22.7	25.8	0.00450	0.768	8.17	767	25.7	1.843	24.6	757
180	7.44	20.5	25.5	0.00462	0.788	8.24	767	26.4	1.843	25.2	758
240	7.47	19.5	26.1	0.00477	0.815	8.27	768	27.1	1.843	26.5	760
300	7.52	21.4	26.4	0.00483	0.824	8.25	769	26.9	1.843	26.8	764
360	7.55	19.5	25.7	0.00485	0.828	8.30	769	28.2	1.843	27.7	765
420	7.59	19.9	26.5	0.00488	0.833	8.33	771	29.8	1.843	28.5	767
480	7.63	18.6	26.2	0.00488	0.833	8.38	770	28.7	1.843	28.1	768
540	7.69	20.3	26.0	0.00488	0.833	8.39	770	27.3	1.843	28.4	770
720	7.85	19.2	26.7	0.00485	0.828	8.46	772	27.5	1.843	28.0	771

Table D-1.5 Determination of sampling time of ULPRO membrane (UTC-70) of groundwater from Pra Too Khong Bottled Drinking Water Plant under OTP = 0.500 MPa

Time (Min.)	Permeate water					Concentrated water				Feed tank	
	pH	EC (µS/cm)	Temp. (° C)	Flow rate (m^3/day)	Flux (m^3/m^2.day)	pH	EC (µS/cm)	Temp. (° C)	Flow rate (m^3/day)	Temp. (° C)	EC (µS/cm)
0	7.15	27.5	25.2	0.00497	0.847	8.02	764	25.5	1.037	25.0	762
30	7.22	24.8	25.7	0.00511	0.872	8.03	769	26.3	1.037	25.5	765
60	7.27	23.5	26.0	0.00524	0.894	8.06	771	26.8	1.037	26.7	766
120	7.32	22.1	26.3	0.00547	0.933	8.10	772	27.2	1.037	27.1	768
180	7.38	20.9	26.1	0.00568	0.970	8.13	775	27.7	1.037	27.2	768
240	7.41	20.4	26.7	0.00561	0.996	8.15	776	27.5	1.037	26.8	771
300	7.49	19.5	26.6	0.00608	1.038	8.20	777	26.6	1.037	27.1	772
360	7.58	19.0	26.4	0.00617	1.053	8.22	779	26.9	1.037	27.4	774
420	7.66	19.2	26.0	0.00613	1.046	8.27	779	26.5	1.037	27.8	775
480	7.69	20.1	25.8	0.00617	1.053	8.33	780	26.1	1.037	27.8	776
540	7.75	18.7	25.5	0.00613	1.046	8.35	781	25.5	1.037	26.5	777

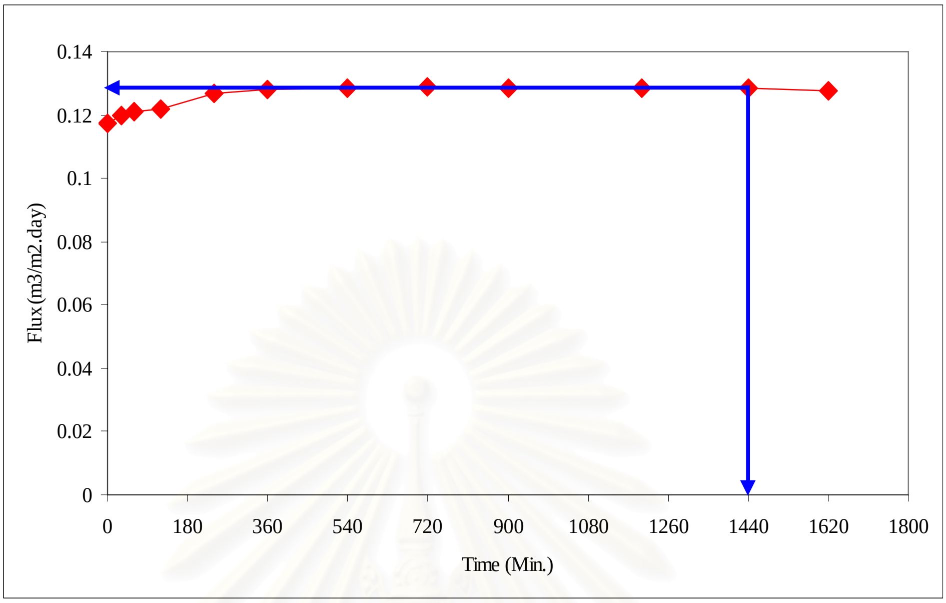

Figure D-1.1 Determination of sampling time of UTC-70 membrane of groundwater from Pra Too Khong Bottled Drinking Water Plant under OTP = 0.100 MPa

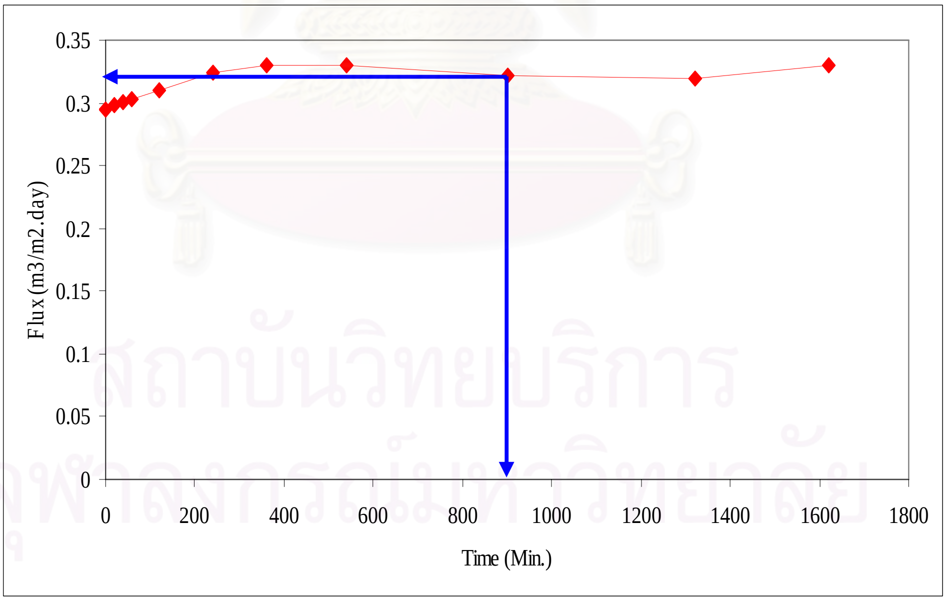

Figure D-1.2 Determination of sampling time of UTC-70 membrane of groundwater from Pra Too Khong Bottled Drinking Water Plant under OTP = 0.200 MPa

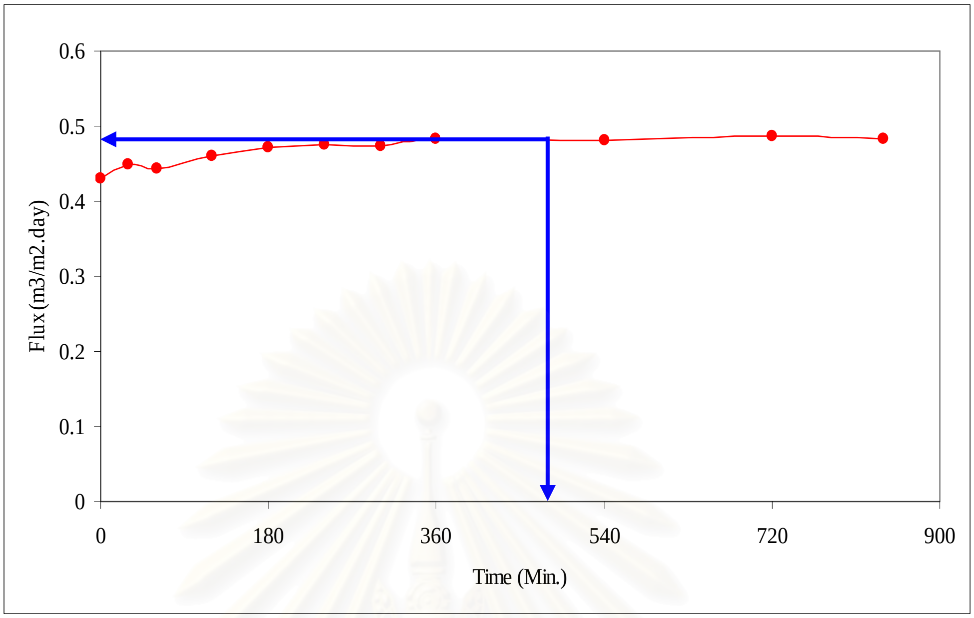

Figure D-1.3 Determination of sampling time of UTC-70 membrane of groundwater from Pra Too Khong Bottled Drinking Water Plant under OTP = 0.300 MPa

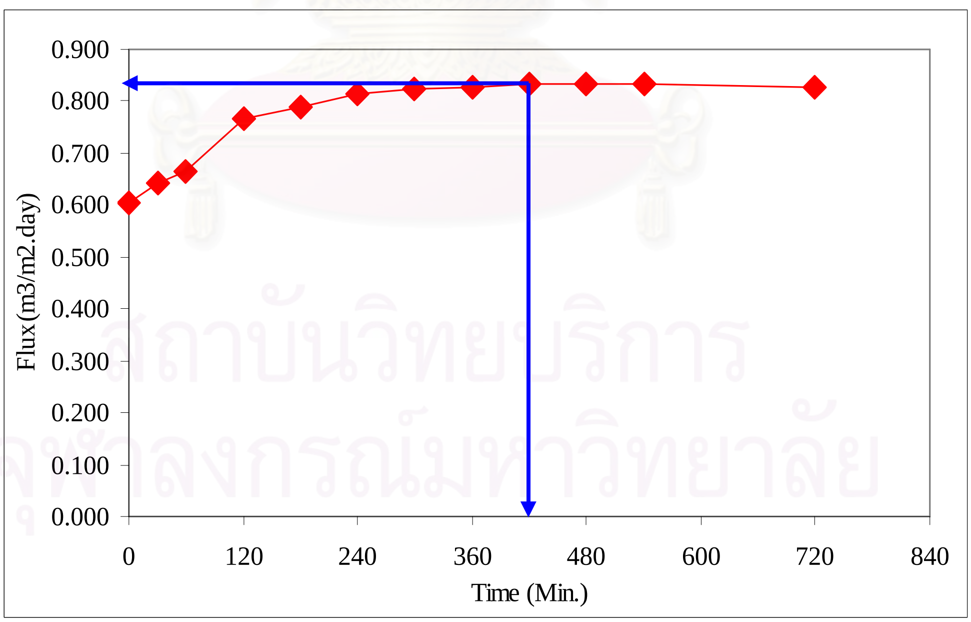

Figure D-1.4 Determination of sampling time of UTC-70 membrane of groundwater from Pra Too Khong Bottled Drinking Water Plant under OTP = 0.400 MPa

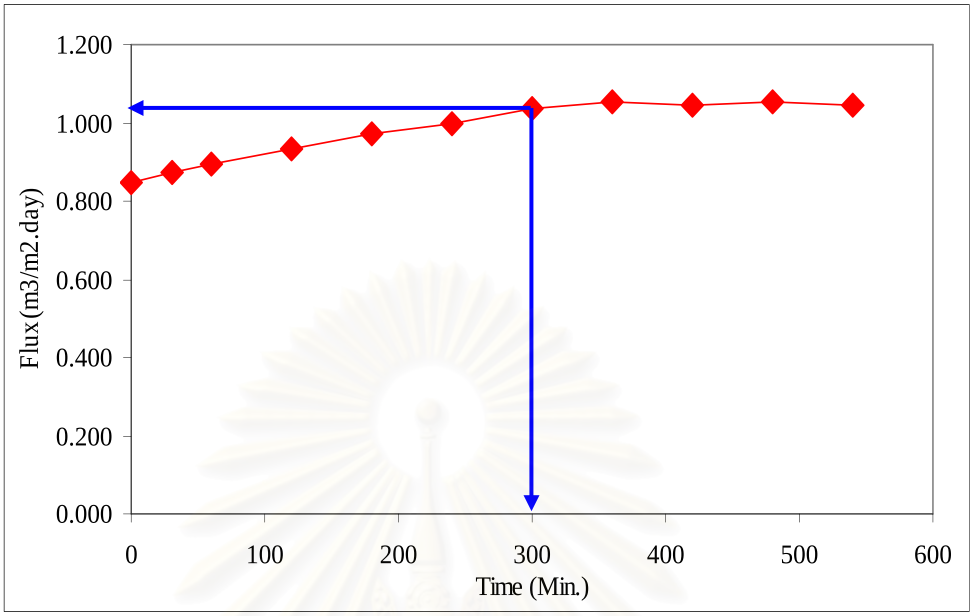

Figure D-1.5 Determination of sampling time of UTC-70 membrane of groundwater from Pra Too Khong Bottled Drinking Water Plant under OTP = 0.500 MPa

Table D-1.6 Membrane experimental results of ULPRO membrane (UTC-70) of groundwater from Pra Too Khong Bottled Drinking Water Plant under OTP = 0.100 MPa

Water parameters	Groundwater at sampling point 1	Groundwater at sampling point 2	Permeate water under OTP of 0.100 MPa (sampling time = 24 hours)				
			Feed pH 7.90	Feed pH 7.07	Feed pH 6.06	Feed pH 5.05	Feed pH 4.03
Temperature(° C)	25.2	27	26.6	26.4	26.3	26.3	26.2
pH	8.17	8.17	7.74	7.59	7.44	7.28	4.71
EC (µS/cm)	781.0	781.0	60.9	65.0	90.9	130.1	279.0
Total Alkalinity (mg/L as $CaCO_3$)	340.0	340.0	36.0	30.0	24.0	20.0	10.0
Na (mg/L)	181.31	181.39	14.06	15.14	18.69	26.43	74.65
Ca (mg/L)	6.49	6.64	0.04	0.11	0.07	0.14	0.24
K (mg/L)	4.57	4.63	0.34	0.36	0.46	0.65	2.42
Mg (mg/L)	3.82	3.86	0.04	0.04	0.05	0.09	0.17
Fluoride (mg/L)	14.50	13.86	0.85	0.83	1.65	6.89	23.20
Chloride (mg/L)	7.94	6.94	0.64	4.46	16.00	22.71	43.11
Nitrite (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nitrate (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sulfate (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Phosphate (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DOC (mg/L)	0.626	0.573	0.296	0.183	0.293	0.311	0.311

Table D-1.7 Membrane experimental results of ULPRO membrane (UTC-70) of groundwater from Pra Too Khong Bottled Drinking Water Plant under OTP = 0.200 MPa

Water parameters	Groundwater at sampling point 1	Groundwater at sampling point 2	Permeate water under OTP of 0.200 MPa (sampling time = 15 hours)				
			Feed pH 8.08	Feed pH 7.07	Feed pH 6.06	Feed pH 4.97	Feed pH 4.09
Temperature(° C)	25.2	27	26.5	26.5	26.2	26.4	26.0
pH	8.17	8.17	8.02	7.43	7.52	7.03	5.58
EC (µS/cm)	781.0	781.0	50.3	57.9	80.5	109.4	228.0
Total Alkalinity (mg/L as $CaCO_3$)	340.0	340.0	20.0	22.0	18.0	12.0	10.0
Na (mg/L)	181.31	181.39	11.40	13.22	16.12	20.66	44.64
Ca (mg/L)	6.49	6.64	0.08	0.06	0.13	0.14	1.41
K (mg/L)	4.57	4.63	0.25	0.29	0.39	0.53	0.65
Mg (mg/L)	3.82	3.86	0.05	0.07	0.08	0.12	0.33
Fluoride (mg/L)	14.50	13.86	0.74	0.88	1.92	4.92	21.44
Chloride (mg/L)	7.94	6.94	0.48	3.89	13.65	22.31	31.00
Nitrite (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nitrate (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sulfate (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Phosphate (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DOC (mg/L)	0.626	0.573	0.191	0.265	0.279	0.190	0.199

Table D-1.8 Membrane experimental results of ULPRO membrane (UTC-70) of groundwater from Pra Too Khong Bottled Drinking Water Plant under OTP = 0.300 MPa

Water parameters	Groundwater at sampling point 1	Groundwater at sampling point 2	Permeate water under OTP of 0.300 MPa (sampling time = 8 hours)				
			Feed pH 8.21	Feed pH 7.07	Feed pH 6.08	Feed pH 5.03	Feed pH 4.02
Temperature(° C)	25.2	27	26.4	26.2	26.3	26.5	26.4
pH	8.17	8.17	7.83	7.05	6.64	6.25	5.51
EC (µS/cm)	781.0	781.0	41.7	52.7	86.8	160.4	192.8
Total Alkalinity (mg/L as $CaCO_3$)	340.0	340.0	24.0	22.0	20.0	14.0	10.0
Na (mg/L)	181.31	181.39	9.98	11.68	18.30	32.93	37.13
Ca (mg/L)	6.49	6.64	0.05	0.07	0.10	0.30	0.40
K (mg/L)	4.57	4.63	0.24	0.29	0.45	0.84	1.22
Mg (mg/L)	3.82	3.86	0.06	0.07	0.09	0.18	0.27
Fluoride (mg/L)	14.50	13.86	0.64	1.00	2.90	13.36	19.33
Chloride (mg/L)	7.94	6.94	0.38	0.35	10.07	18.10	23.82
Nitrite (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nitrate (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sulfate (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Phosphate (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DOC (mg/L)	0.626	0.573	0.215	0.276	0.249	0.240	0.203

Table D-1.9 Membrane experimental results of ULPRO membrane (UTC-70) of groundwater from Pra Too Khong Bottled Drinking Water Plant under OTP = 0.400 MPa

Water parameters	Groundwater at sampling point 1	Groundwater at sampling point 2	Permeate water under OTP of 0.400 MPa (sampling time = 7 hours)				
			Feed pH 8.01	Feed pH 7.03	Feed pH 6.02	Feed pH 5.03	Feed pH 4.04
Temperature(° C)	26.7	27.8	26.5	27.3	26.9	26.0	26.4
pH	8.00	8.01	7.59	7.22	7.12	6.94	4.56
EC (µS/cm)	760	760	19.9	21.7	28.0	69.1	147.8
Total Alkalinity (mg/L as $CaCO_3$)	350	350	12.0	4.0	12.0	8.0	12.0
Na (mg/L)	116.20	103.80	26.0	25.0	14.00	22.00	25.05
Ca (mg/L)	6.72	6.64	0.00	0.00	0.00	0.00	0.10
K (mg/L)	4.45	4.60	0.08	0.08	0.11	0.49	1.41
Mg (mg/L)	3.10	3.03	0.06	0.08	0.18	0.16	0.13
Fluoride (mg/L)	12.36	12.05	0.22	0.37	0.51	4.97	15.80
Chloride (mg/L)	6.96	6.74	0.29	1.48	4.36	6.64	11.36
Nitrite (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nitrate (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sulfate (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Phosphate (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DOC (mg/L)	0.502	0.440	0.170	0.162	0.178	0.143	0.181

Table D-1.10 Membrane experimental results of ULPRO membrane (UTC-70) of groundwater from Pra Too Khong Bottled Drinking Water Plant under OTP = 0.500 MPa

Water parameters	Groundwater at sampling point 1	Groundwater at sampling point 2	Permeate water under OTP of 0.500 MPa (sampling time = 6 hours)				
			Feed pH 8.00	Feed pH 7.01	Feed pH 6.02	Feed pH 5.02	Feed pH 4.03
Temperature(° C)	26.7	27.8	26.5	26.2	27.2	26.9	26.7
pH	8.00	8.01	7.58	6.65	5.97	5.93	5.15
EC (µS/cm)	760	760	19.0	21.8	41.3	90.0	130.3
Total Alkalinity (mg/L as $CaCO_3$)	350	350	12.0	12.0	8.0	12.0	12.0
Na (mg/L)	116.20	103.80	9.00	29.10	14.40	24.05	19.55
Ca (mg/L)	6.72	6.64	0.00	0.00	0.00	0.00	0.06
K (mg/L)	4.45	4.60	0.07	0.07	0.23	0.73	1.26
Mg (mg/L)	3.10	3.03	0.07	0.08	0.18	0.15	0.12
Fluoride (mg/L)	12.36	12.05	0.27	0.39	1.38	7.27	14.47
Chloride (mg/L)	6.96	6.74	0.33	1.21	4.22	6.73	8.74
Nitrite (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nitrate (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sulfate (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Phosphate (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DOC (mg/L)	0.502	0.440	0.172	0.158	0.182	0.126	0.217

Table D-1.11 Data analysis for membrane experiment of ULPRO membrane (UTC-70) of groundwater from Pra Too Khong Bottled Drinking Water Plant

Sample \ Permeate water Parameters		Temp. (° C)	pH	EC (μS/cm)	T-Alk. (mg/L as $CaCO_3$)	Na (mg/L)	% remove Na	Ca (mg/L)	% remove Ca	K (mg/L)	% remove K	Mg (mg/L)	% remove Mg
Groundwater at sampling point 1		25.2	8.17	781	340	181.31		6.49		4.57		3.82	
Groundwater at sampling point 2		27.0	8.17	781	340	181.39		6.64		4.62		3.86	
Permeate under OTP of 0.100 MPa at the feed pH of …..	pH 7.90	26.6	7.74	60.9	36	14.06	92.25	0.04	99.40	0.34	92.64	0.04	98.96
	pH 7.07	26.4	7.59	65.0	30	15.14	91.65	0.11	98.34	0.36	92.21	0.04	98.96
	pH 6.06	26.3	7.44	90.9	24	18.69	89.70	0.07	98.95	0.46	90.04	0.05	98.70
	pH 5.05	26.3	7.28	130.1	20	26.43	85.43	0.14	97.89	0.65	85.93	0.09	97.67
	pH 4.03	26.2	4.71	279.0	10	74.65	58.85	0.24	96.39	2.42	47.62	0.17	95.60
Permeate under OTP of 0.200 MPa at the feed pH of …..	pH 8.08	26.5	8.02	50.3	20	11.40	93.72	0.08	98.80	0.25	94.59	0.05	98.70
	pH 7.07	26.5	7.43	57.9	22	13.22	92.71	0.06	99.10	0.29	93.72	0.07	98.19
	pH 6.06	26.2	7.52	80.5	18	16.12	91.11	0.13	98.04	0.39	91.56	0.08	97.93
	pH 4.97	26.4	7.03	109.4	12	20.66	88.61	0.14	97.89	0.53	88.53	0.12	96.89
	pH 4.09	26.0	5.58	228	10	44.64	75.39	1.41	78.77	0.65	85.93	0.33	91.45
Permeate under OTP of 0.300 MPa at the feed pH of …..	pH 8.21	26.4	7.83	41.7	24	9.98	94.50	0.05	99.25	0.24	94.81	0.06	98.45
	pH 7.07	26.2	7.05	52.7	22	11.68	93.56	0.07	98.95	0.29	93.72	0.07	98.19
	pH 6.08	26.3	6.64	86.8	20	18.30	89.91	0.10	98.49	0.45	90.26	0.09	97.67
	pH 5.03	26.5	6.25	160.4	14	32.93	81.85	0.30	95.48	0.84	81.82	0.18	95.34
	pH 4.02	26.4	5.51	192.8	10	37.13	79.53	0.40	93.98	1.22	73.59	1.22	68.39

Table D-1.11 Data analysis for membrane experiment of ULPRO membrane (UTC-70) of groundwater from Pra Too Khong Bottled Drinking Water Plant (continue)

Sample \ Permeate water Parameters		F^- (mg/L)	% remove F^-	NO_2^- (mg/L)	% remove NO_2^-	NO_3^- (mg/L)	% remove NO_3^-	SO_4^{2-} (mg/L)	% remove SO_4^{2-}	PO_4^{2-} (mg/L)	% remove PO_4^{2-}	Cl^- (mg/L)	DOC (mg/L)	% remove DOC
Groundwater at sampling point 1		14.5		0.00		0.00		0.00		0.00		7.94	0.626	
Groundwater at sampling point 2		13.86		0.00		0.00		0.00		0.00		6.94	0.573	
Permeate under OTP of 0.100 MPa at the feed pH of …..	pH 7.90	0.85	93.87	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.64	0.296	48.34
	pH 7.07	0.83	94.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.46	0.183	68.06
	pH 6.06	1.65	88.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	16.00	0.293	48.87
	pH 5.05	6.89	50.29	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	22.71	0.311	45.72
	pH 4.03	23.20	-67.39	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	43.11	0.311	45.72
Permeate under OTP of 0.200 MPa at the feed pH of …..	pH 8.08	0.74	94.66	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.48	0.191	66.67
	pH 7.07	0.88	93.65	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.89	0.265	53.75
	pH 6.06	1.92	86.15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	13.65	0.279	51.31
	pH 4.97	4.92	64.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	22.31	0.190	66.84
	pH 4.09	21.44	-54.69	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	31.00	0.199	65.27
Permeate under OTP of 0.300 MPa at the feed pH of …..	pH 8.21	0.64	95.38	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.38	0.215	62.48
	pH 7.07	1.00	92.78	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.35	0.276	51.83
	pH 6.08	2.90	79.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	10.07	0.249	56.54
	pH 5.03	13.36	3.61	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	18.10	0.240	58.12
	pH 4.02	19.33	-39.47	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	23.82	0.203	64.57

Table D-1.11 Data analysis for membrane experiment of ULPRO membrane (UTC-70) of groundwater from Pra Too Khong Bottled Drinking Water Plant (continue)

Sample \ Permeate water Parameters		Temp. (° C)	pH	EC (µS/cm)	T-Alk. (mg/L as $CaCO_3$)	Na (mg/L)	% remove Na	Ca (mg/L)	% remove Ca	K (mg/L)	% remove K	Mg (mg/L)	% remove Mg
Groundwater at sampling point 1		26.7	8.00	760	350	116.20		6.72		4.45		3.10	
Groundwater at sampling point 2		27.8	8.01	760	350	103.80		6.64		4.60		3.03	
Permeate under OTP of 0.400 MPa at the feed pH of …..	pH 8.01	26.5	7.59	19.9	12	26.00	74.95	0.00	100.00	0.08	98.26	0.06	98.02
	pH 7.03	27.3	7.22	21.7	4	25.00	75.92	0.00	100.00	0.08	98.26	0.08	97.36
	pH 6.02	26.9	7.12	28	12	14.00	86.51	0.00	100.00	0.11	97.61	0.18	94.06
	pH 5.03	26	6.94	69.1	8	22.00	78.81	0.00	100.00	0.49	89.35	0.16	94.72
	pH 4.04	26.4	4.56	147.8	12	25.05	75.87	0.10	98.49	1.41	69.35	0.13	95.71
Permeate under OTP of 0.500 MPa at the feed pH of …..	pH 8.00	26.5	7.58	19	12	9.00	91.33	0.00	100.00	0.07	98.48	0.07	97.69
	pH 7.01	26.2	6.65	21.8	12	29.10	71.97	0.00	100.00	0.07	98.48	0.08	97.36
	pH 6.02	27.2	5.97	41.3	8	14.40	86.13	0.00	100.00	0.23	95.00	0.18	94.06
	pH 5.02	26.9	5.93	90	12	24.05	76.83	0.00	100.00	0.73	84.13	0.15	95.05
	pH 4.03	26.7	5.15	130.3	12	19.55	81.17	0.06	99.10	1.26	72.61	0.12	96.04

Table D-1.11 Data analysis for membrane experiment of ULPRO membrane (UTC-70) of groundwater from Pra Too Khong Bottled Drinking Water Plant (continue)

Sample \ Permeate water Parameters		F^- (mg/L)	% remove F^-	NO_2^- (mg/L)	% remove NO_2^-	NO_3^- (mg/L)	% remove NO_3^-	SO_4^{2-} (mg/L)	% remove SO_4^{2-}	PO_4^{2-} (mg/L)	% remove PO_4^{2-}	Cl^- (mg/L)	DOC (mg/L)	% remove DOC
Groundwater at sampling point 1		12.36		0.00		0.00		0.00		0.00		6.69	0.502	
Groundwater at sampling point 2		12.05		0.00		0.00		0.00		0.00		6.74	0.440	
Permeate under OTP of 0.400 MPa at the feed pH of …..	pH 8.01	0.22	98.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.29	0.170	61.36
	pH 7.03	0.37	96.93	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.48	0.162	63.18
	pH 6.02	0.51	95.77	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.36	0.178	59.55
	pH 5.03	4.97	58.76	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6.64	0.143	67.50
	pH 4.04	15.80	-31.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	11.36	0.181	58.86
Permeate under OTP of 0.500 MPa at the feed pH of …..	pH 8.00	0.27	97.76	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.172	60.91
	pH 7.01	0.39	96.76	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.21	0.158	64.09
	pH 6.02	1.38	88.55	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.22	0.182	58.64
	pH 5.02	7.27	39.67	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6.73	0.126	71.36
	pH 4.03	14.47	-20.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.74	0.217	50.68

APPENDIX D-2

MEMBRANE EXPERIMENTAL RESULTS OF ULPRO MEMBRANE (UTC-70) OF GROUNDWATER FROM SAN PA HIANG MEMBRANE PLANT (SITE B)

Table D-2.1 Determination of sampling time of ULPRO membrane (UTC-70) of groundwater from San Pa Hiang Membrane Plant under OTP=0.100 MPa

Time (Min.)	Permeate water					Concentrated water				Feed tank	
	pH	EC (µS/cm)	Temp. (° C)	Flow rate (m^3/day)	Flux (m^3/m^2.day)	pH	EC (µS/cm)	Temp. (° C)	Flow rate (m^3/day)	Temp. (° C)	EC (µS/cm)
0	6.34	34.2	23.5	0.000957	0.163	6.76	342	24.3	2.304	23.1	341
60	6.37	33.6	24.4	0.000969	0.165	6.81	344	24.8	2.304	24.5	343
120	6.42	33.3	23.4	0.000991	0.169	6.88	347	24.6	2.304	24.7	345
180	6.46	32.5	23.7	0.000993	0.169	6.93	350	24.5	2.304	24.5	348
240	6.54	32.1	24.6	0.000997	0.170	7.02	351	25.2	2.304	25.3	348
300	6.60	31.7	25.2	0.001000	0.171	7.14	352	24.9	2.304	26.7	348
360	6.66	31.4	24.8	0.001003	0.171	7.19	354	25.1	2.304	26.1	348
540	6.73	30.7	24.5	0.001011	0.172	7.25	354	24.7	2.304	25.5	349
720	6.81	29.8	24.2	0.001014	0.173	7.36	356	24.6	2.304	25.0	350
900	6.95	30.1	24.3	0.001019	0.174	7.42	358	24.7	2.304	24.2	352
1080	7.11	30.4	24.1	0.001027	0.175	7.53	361	25.3	2.304	23.9	353
1440	7.23	30.8	24.5	0.001031	0.176	7.57	360	24.1	2.304	21.3	355
1620	7.36	31.5	25.2	0.001033	0.176	7.64	362	24.0	2.304	22.4	356
1800	7.54	32.1	23.1	0.001032	0.176	7.70	361	24.4	2.304	24.5	358

Table D-2.2 Determination of sampling time of ULPRO membrane (UTC-70) of groundwater from San Pa Hiang Membrane Plant under OTP=0.200 MPa

Time (Min.)	Permeate water					Concentrated water				Feed tank	
	pH	EC (µS/cm)	Temp. (° C)	Flow rate (m^3/day)	Flux (m^3/m^2.day)	pH	EC (µS/cm)	Temp. (° C)	Flow rate (m^3/day)	Temp. (° C)	EC (µS/cm)
0	6.48	22.4	22.4	0.00185	0.316	6.63	341	24.1	2.246	23.7	336
30	6.52	22.1	23.5	0.00187	0.318	6.68	343	24.8	2.246	24.4	337
60	6.58	21.5	22.1	0.00188	0.321	6.74	345	25.7	2.246	24.9	337
120	6.65	21.0	23.6	0.00189	0.323	6.85	346	25.6	2.246	25.2	338
180	6.70	20.3	24.6	0.00191	0.325	6.92	348	24.9	2.246	25.3	339
240	6.76	19.5	22.6	0.00192	0.328	6.98	349	26.3	2.246	25.7	339
300	6.83	19.2	22.7	0.00195	0.332	7.06	349	26.7	2.246	25.2	339
360	6.88	18.7	23.1	0.00196	0.334	7.14	350	26.0	2.246	25.0	340
540	6.95	18.0	23.2	0.00199	0.339	7.23	351	24.2	2.246	24.8	341
720	7.07	17.4	22.0	0.00200	0.342	7.26	352	25.8	2.246	24.7	342
900	7.24	17.8	22.5	0.00204	0.349	7.35	352	24.1	2.246	24.6	344
1080	7.35	17.5	24.3	0.00207	0.353	7.44	353	24.7	2.246	23.9	345
1260	7.49	18.0	23.0	0.00211	0.360	7.57	354	23.6	2.246	23.0	346
1440	7.67	18.1	23.3	0.00212	0.361	7.68	354	23.1	2.246	23.5	346
1620	7.72	18.8	23.4	0.00209	0.357	7.82	354	23.4	2.246	24.4	346
1800	7.81	17.9	22.6	0.00211	0.360	7.90	356	24.4	2.246	25.3	348

Table D-2.3 Determination of sampling time of ULPRO membrane (UTC-70) of groundwater from San Pa Hiang Membrane Plant under OTP=0.300 MPa

Time	Permeate water					Concentrated water				Feed tank	
(Min.)	pH	EC (µS/cm)	Temp. (° C)	Flow rate (m^3/day)	Flux (m^3/m^2.day)	pH	EC (µS/cm)	Temp. (° C)	Flow rate (m^3/day)	Temp. (° C)	EC (µS/cm)
0	6.52	24.4	20.5	0.00279	0.476	6.71	340	20.9	2.131	20.8	333
30	6.54	32.1	20.5	0.00281	0.480	6.70	340	20.7	2.131	20.2	335
60	6.55	30.8	20.5	0.00286	0.488	6.72	341	21.4	2.131	21.4	335
120	6.63	29.1	20.5	0.00294	0.501	6.78	342	21.8	2.131	20.5	338
180	6.74	26.7	21.4	0.00296	0.505	6.84	342	22.5	2.131	21.3	340
240	6.79	23.2	22.2	0.00300	0.512	6.88	343	23.5	2.131	22.5	340
300	6.83	24.9	21.4	0.00301	0.514	6.90	344	23.3	2.131	23.4	341
360	6.88	23.3	20.8	0.00303	0.517	6.93	345	24.1	2.131	24.1	342
540	6.92	23.5	23.5	0.00298	0.508	6.98	346	23.1	2.131	25.7	343
720	7.01	22.0	24.5	0.00297	0.507	7.04	347	23.6	2.131	23.5	343
900	7.16	22.6	22.1	0.00298	0.508	7.28	349	22.9	2.131	22.6	344

Table D-2.4 Determination of sampling time of ULPRO membrane (UTC-70) of groundwater from San Pa Hiang Membrane Plant under OTP=0.400 MPa

Time (Min.)	Permeate water					Concentrated water				Feed tank	
	pH	EC (µS/cm)	Temp. (° C)	Flow rate (m^3/day)	Flux (m^3/m^2.day)	pH	EC (µS/cm)	Temp. (° C)	Flow rate (m^3/day)	Temp. (° C)	EC (µS/cm)
0	6.34	20.1	22.2	0.00402	0.686	6.70	337	23.2	1.843	21.6	335
20	6.36	19.8	23.1	0.00402	0.686	6.72	338	23.5	1.843	21.9	335
40	6.41	19.7	22.7	0.00409	0.699	6.72	339	23.7	1.843	22.4	336
60	6.43	19.5	22.4	0.00413	0.705	6.76	340	24.2	1.843	23.4	337
120	6.48	18.7	22.6	0.00419	0.716	6.82	340	24.3	1.843	23.2	338
180	6.52	18.4	23.6	0.00424	0.723	6.87	341	23.6	1.843	24.6	337
240	6.54	17.6	24.1	0.00430	0.734	6.94	342	23.2	1.843	24.4	337
300	6.61	17.1	23.5	0.00426	0.726	6.99	344	22.7	1.843	23.8	338
360	6.77	17.6	23.7	0.00424	0.723	7.01	344	23.5	1.843	25.2	339
540	6.98	17.7	24.2	0.00424	0.723	7.10	346	24.8	1.843	23.7	340
720	7.09	17.4	22.5	0.00424	0.723	7.18	348	25.7	1.843	24.5	345

Table D-2.5 Determination of sampling time of ULPRO membrane (UTC-70) of groundwater from San Pa Hiang Membrane Plant under OTP=0.500 MPa

Time	Permeate water					Concentrated water				Feed tank	
(Min.)	pH	EC (µS/cm)	Temp. (° C)	Flow rate (m^3/day)	Flux (m^3/m^2.day)	pH	EC (µS/cm)	Temp. (° C)	Flow rate (m^3/day)	Temp. (° C)	EC (µS/cm)
0	6.23	18.7	20.2	0.00505	0.862	6.64	339	22.4	1.037	21.9	336
20	6.26	18.5	20.5	0.00514	0.878	6.70	338	23.1	1.037	22.2	335
40	6.31	18.2	21.0	0.00514	0.878	6.73	338	23.7	1.037	22.2	335
60	6.40	17.3	21.7	0.00530	0.905	6.79	338	24.2	1.037	22.6	336
120	6.48	16.6	22.5	0.00540	0.922	6.84	339	23.6	1.037	23.4	337
180	6.54	15.4	21.9	0.00554	0.945	6.89	340	24.8	1.037	24.1	339
240	6.63	15.0	21.5	0.00557	0.951	6.91	341	24.2	1.037	24.7	340
300	6.69	14.9	22.0	0.00557	0.951	6.95	340	24.5	1.037	24.0	340
360	6.80	14.5	22.4	0.00561	0.957	7.03	342	23.8	1.037	23.5	341
540	6.95	14.4	23.6	0.00554	0.945	7.12	345	23.9	1.037	23.7	343
720	7.05	15.0	24.9	0.00547	0.933	7.24	346	24.7	1.037	24.6	343

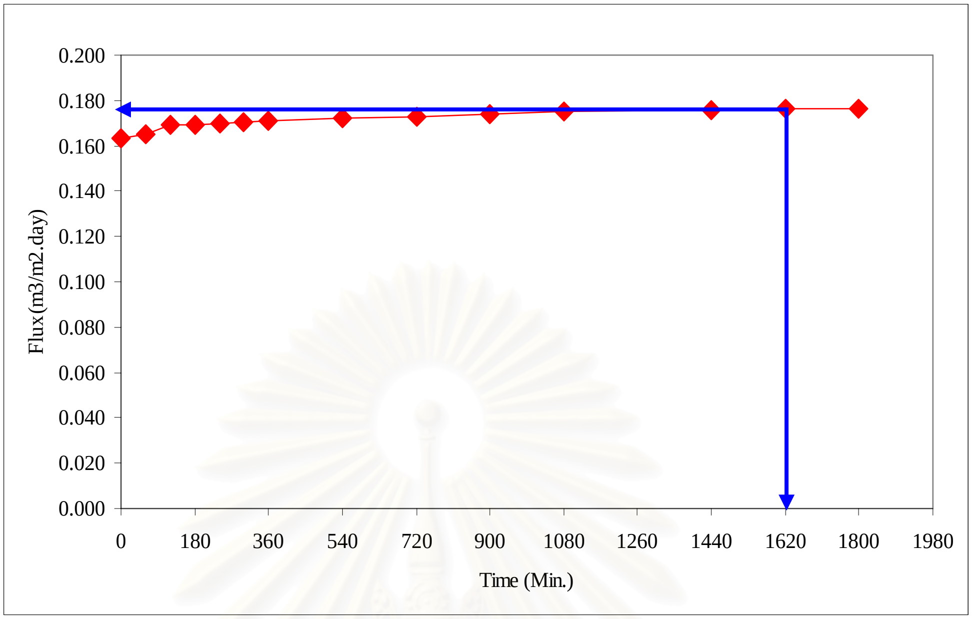

Figure D-2.1 Determination of sampling time of UTC-70 membrane of groundwater from San Pa Hiang Membrane Plant under OTP = 0.100 MPa

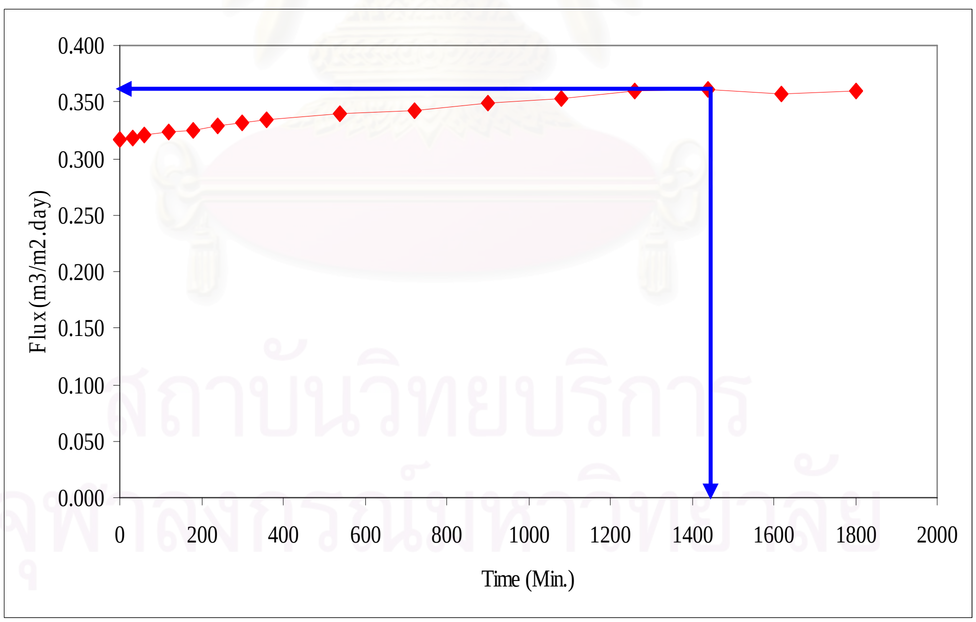

Figure D-2.2 Determination of sampling time of UTC-70 membrane of groundwater from San Pa Hiang Membrane Plant under OTP = 0.200 MPa

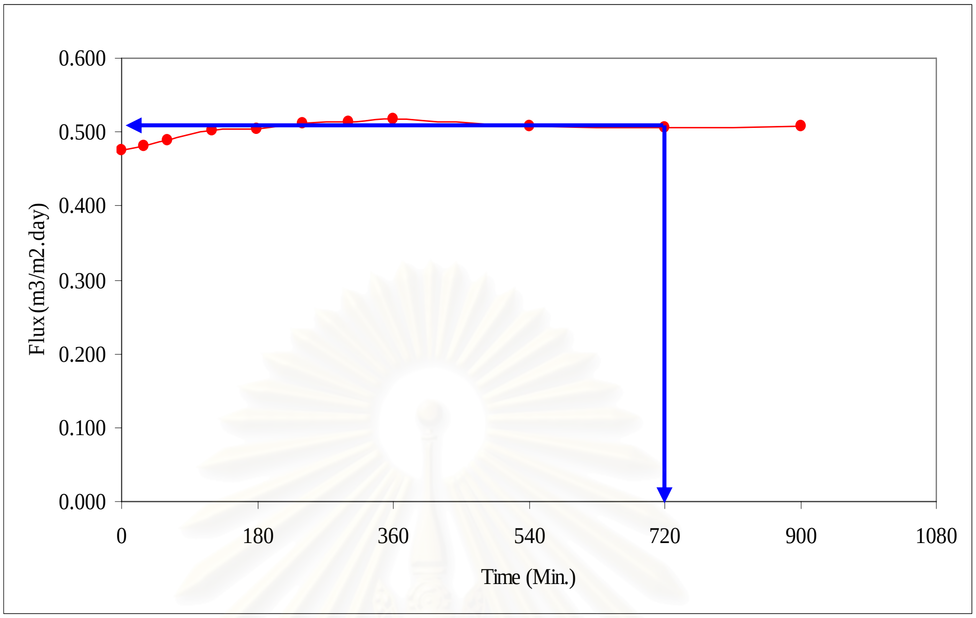

Figure D-2.3 Determination of sampling time of UTC-70 membrane of groundwater from San Pa Hiang Membrane Plant under OTP = 0.300 MPa

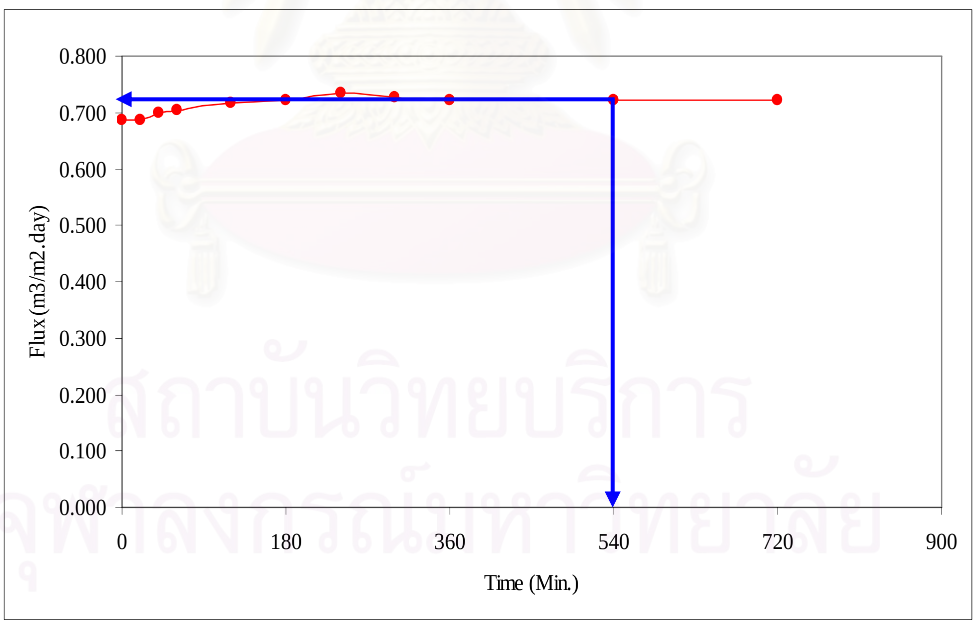

Figure D-2.4 Determination of sampling time of UTC-70 membrane of groundwater from San Pa Hiang Membrane Plant under OTP = 0.400 MPa

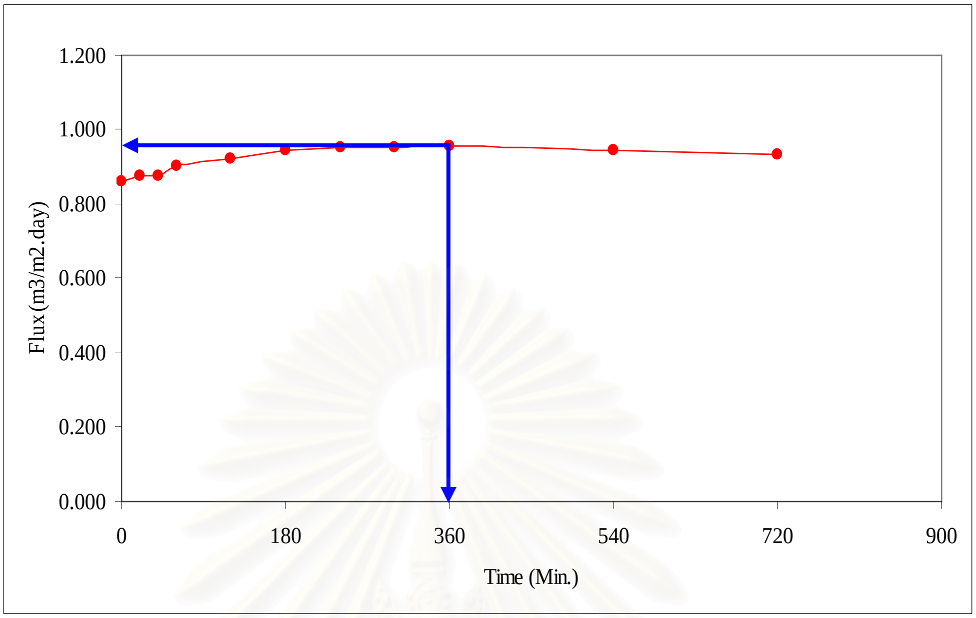

Figure D-2.5 Determination of sampling time of UTC-70 membrane of groundwater from San Pa Hiang Membrane Plant under OTP = 0.500 MPa

Table D-2.6 Membrane experimental results of ULPRO membrane (UTC-70) of groundwater from San Pa Hiang Membrane Plant under OTP = 0.100 MPa

Water parameters	Groundwater at sampling point 1	Groundwater at sampling point 2	Permeate water under OTP of 0.100 MPa (sampling time = 27 hours)				
			Feed pH 7.01	Feed pH 6.56	Feed pH 6.03	Feed pH 5.02	Feed pH 4.00
Temperature(° C)	23.8	23.4	24.9	25.2	23.7	22.3	23.5
pH	6.62	6.58	7.54	7.36	6.75	6.54	4.96
EC (µS/cm)	336.0	338.0	25.6	31.5	45.8	52.0	91.0
Total Alkalinity (mg/L as $CaCO_3$)	160.0	170.0	12.0	10.0	8.0	6.0	2.0
Na (mg/L)	112.09	108.39	10.50	6.10	6.10	3.70	2.95
Ca (mg/L)	12.67	11.55	0.23	0.38	0.58	0.90	0.62
K (mg/L)	5.50	5.40	1.00	1.23	1.47	0.99	1.82
Mg (mg/L)	7.24	7.24	0.08	0.14	0.23	0.30	0.52
Fluoride (mg/L)	3.06	3.12	0.18	0.30	0.34	1.40	3.98
Chloride (mg/L)	10.70	10.70	1.19	1.46	9.42	18.81	20.60
Nitrite (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nitrate (mg/L)	0.54	0.60	0.00	0.06	0.00	0.04	0.10
Sulfate (mg/L)	6.92	6.98	0.10	0.17	0.15	0.10	0.13
Phosphate (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DOC (mg/L)	0.686	0.570	0.284	0.286	0.304	0.309	0.267

Table D-2.7 Membrane experimental results of ULPRO membrane (UTC-70) of groundwater from San Pa Hiang Membrane Plant under OTP = 0.200 MPa

Water parameters	Groundwater at sampling point 1	Groundwater at sampling point 2	Permeate water under OTP of 0.200 MPa (sampling time = 24 hours)				
			Feed pH 7.02	Feed pH 6.6	Feed pH 6.04	Feed pH 5.05	Feed pH 4.05
Temperature(° C)	23.8	23.4	22.5	23.1	24.6	23.8	22.2
pH	6.62	6.58	7.84	7.67	7.29	6.89	5.7
EC (µS/cm)	336.0	338.0	13.3	18.1	19.4	24.3	39.0
Total Alkalinity (mg/L as $CaCO_3$)	160.0	170.0	8.0	8.0	4.0	6.0	2.0
Na (mg/L)	112.09	108.39	12.50	4.55	4.94	6.38	3.81
Ca (mg/L)	12.67	11.55	0.06	0.20	0.16	0.23	0.58
K (mg/L)	5.50	5.40	0.32	0.61	0.59	0.78	1.33
Mg (mg/L)	7.24	7.24	0.02	0.08	0.08	0.12	0.24
Fluoride (mg/L)	3.06	3.12	0.15	0.26	0.27	0.57	5.26
Chloride (mg/L)	10.70	10.70	0.15	1.23	6.27	5.27	7.37
Nitrite (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nitrate (mg/L)	0.54	0.60	0.03	0.00	0.04	0.03	0.03
Sulfate (mg/L)	6.92	6.98	0.09	0.18	0.13	0.07	0.07
Phosphate (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DOC (mg/L)	0.686	0.570	0.235	0.252	0.220	0.197	0.274

Table D-2.8 Membrane experimental results of ULPRO membrane (UTC-70) of groundwater from San Pa Hiang Membrane Plant under OTP = 0.300 MPa

Water parameters	Groundwater at sampling point 1	Groundwater at sampling point 2	Permeate water under OTP of 0.300 MPa (sampling time = 12 hours)				
			Feed pH 7.05	Feed pH 6.58	Feed pH 6.01	Feed pH 5.02	Feed pH 4.03
Temperature(° C)	23.8	23.4	22.8	24.5	24.7	23.3	24.1
pH	6.62	6.58	7.06	7.01	6.97	6.64	5.75
EC (µS/cm)	336.0	338.0	24.8	22.0	31.8	38.3	50.2
Total Alkalinity (mg/L as $CaCO_3$)	160.0	170.0	12.0	8.0	8.0	6.0	4.0
Na (mg/L)	112.09	108.39	5.50	2.85	2.25	3.55	4.65
Ca (mg/L)	12.67	11.55	0.14	0.34	0.49	0.66	1.04
K (mg/L)	5.50	5.40	0.44	0.74	1.00	1.15	1.52
Mg (mg/L)	7.24	7.24	0.08	0.14	0.22	0.28	0.45
Fluoride (mg/L)	3.06	3.12	0.15	0.16	0.30	1.02	4.76
Chloride (mg/L)	10.70	10.70	0.68	0.77	4.99	7.94	10.23
Nitrite (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nitrate (mg/L)	0.54	0.60	0.03	0.02	0.03	0.03	0.50
Sulfate (mg/L)	6.92	6.98	0.10	0.14	0.14	0.15	0.15
Phosphate (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DOC (mg/L)	0.686	0.570	0.257	0.244	0.194	0.263	0.232

Table D-2.9 Membrane experimental results of ULPRO membrane (UTC-70) of groundwater from San Pa Hiang Membrane Plant under OTP = 0.400 MPa

Water parameters	Groundwater at sampling point 1	Groundwater at sampling point 2	Permeate water under OTP of 0.400 MPa (sampling time = 9 hours)				
			Feed pH 7.02	Feed pH 6.63	Feed pH 6.03	Feed pH 5.00	Feed pH 4.02
Temperature(° C)	23.8	23.4	24.5	24.2	23.6	23.1	23.8
pH	6.62	6.58	6.91	6.98	6.8	6.69	5.95
EC (µS/cm)	336.0	338.0	19.6	17.7	24.1	30.6	41.7
Total Alkalinity (mg/L as $CaCO_3$)	160.0	170.0	10.0	12.0	8.0	6.0	4.0
Na (mg/L)	112.09	108.39	10.70	1.60	1.90	2.75	0.80
Ca (mg/L)	12.67	11.55	0.06	0.17	0.25	0.40	0.85
K (mg/L)	5.50	5.40	0.31	0.59	0.80	0.95	1.32
Mg (mg/L)	7.24	7.24	0.04	0.09	0.13	0.21	0.39
Fluoride (mg/L)	3.06	3.12	0.09	0.20	0.27	0.76	4.26
Chloride (mg/L)	10.70	10.70	0.49	0.59	3.22	5.88	8.12
Nitrite (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nitrate (mg/L)	0.54	0.60	0.01	0.02	0.02	0.03	0.04
Sulfate (mg/L)	6.92	6.98	0.06	0.10	0.08	0.11	0.12
Phosphate (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DOC (mg/L)	0.686	0.570	0.247	0.219	0.231	0.226	0.208

Table D-2.10 Membrane experimental results of ULPRO membrane (UTC-70) of groundwater from San Pa Hiang Membrane Plant under OTP = 0.500 MPa

Water parameters	Groundwater at sampling point 1	Groundwater at sampling point 2	Permeate water under OTP of 0.500 MPa (sampling time = 6 hours)				
			Feed pH 7.05	Feed pH 6.67	Feed pH 6.04	Feed pH 5.01	Feed pH 4.02
Temperature(° C)	23.8	23.4	22.1	22.4	23.1	23.6	23.0
pH	6.62	6.58	7.14	6.80	6.83	6.53	6.45
EC (µS/cm)	336.0	338.0	15.7	14.5	19.8	29.7	34.2
Total Alkalinity (mg/L as $CaCO_3$)	160.0	170.0	6.0	6.0	12.0	8.0	4.0
Na (mg/L)	112.09	108.39	7.75	2.95	4.33	5.51	2.15
Ca (mg/L)	12.67	11.55	0.04	0.14	0.21	0.48	0.71
K (mg/L)	5.50	5.40	0.19	0.45	0.63	1.02	1.25
Mg (mg/L)	7.24	7.24	0.04	0.09	0.13	0.21	0.39
Fluoride (mg/L)	3.06	3.12	0.08	0.21	0.26	1.5	3.99
Chloride (mg/L)	10.70	10.70	0.32	0.37	1.96	3.98	5.58
Nitrite (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nitrate (mg/L)	0.54	0.60	0.00	0.00	0.01	0.02	0.03
Sulfate (mg/L)	6.92	6.98	0.07	0.07	0.07	0.10	0.12
Phosphate (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DOC (mg/L)	0.686	0.570	0.168	0.169	0.181	0.158	0.207

Table D-2.11 Data analysis for membrane experiment of ULPRO membrane (UTC-70) of groundwater from San Pa Hiang Membrane Plant

Sample \ Permeate water Parameters		Temp. (° C)	pH	EC (μS/cm)	T-Alk. (mg/L as $CaCO_3$)	Na (mg/L)	% remove Na	Ca (mg/L)	% remove Ca	K (mg/L)	% remove K	Mg (mg/L)	% remove Mg
Groundwater at sampling point 1		23.8	6.62	336	160	136.10		14.62		5.50		7.24	
Groundwater at sampling point 2		23.4	6.58	338	170	121.90		11.66		5.40		7.24	
Permeate under OTP of 0.100 MPa at the feed pH of …..	pH 7.01	24.9	7.54	25.6	12	10.50	91.39	0.23	98.03	1.00	81.48	0.08	98.90
	pH 6.56	25.2	7.36	31.5	10	6.10	95.00	0.38	96.74	1.23	77.22	0.14	98.07
	pH 6.03	23.7	6.75	45.8	8	6.10	95.00	0.58	95.03	1.47	72.78	0.23	96.82
	pH 5.02	22.3	6.54	52.0	6	3.70	96.96	0.90	92.28	0.99	81.67	0.30	95.86
	pH 4.00	23.5	4.96	91.1	2	2.95	97.58	0.62	94.68	1.82	66.30	0.52	92.82
Permeate under OTP of 0.200 MPa at the feed pH of …..	pH 7.02	22.5	7.84	13.3	8	12.50	89.75	0.06	99.49	0.32	94.07	0.02	99.72
	pH 6.60	23.1	7.67	18.1	8	4.55	96.27	0.20	98.28	0.61	88.70	0.08	98.90
	pH 6.04	24.6	7.29	19.4	4	4.94	95.95	0.16	98.63	0.59	89.07	0.08	98.90
	pH 5.05	23.8	6.89	24.3	6	6.38	94.77	0.23	98.03	0.78	85.56	0.12	98.34
	pH 4.05	22.2	5.7	39	2	3.81	96.87	0.58	95.03	1.33	75.37	0.24	96.69
Permeate under OTP of 0.300 MPa at the feed pH of …..	pH 7.05	22.8	7.06	24.8	12	5.50	95.49	0.14	98.80	0.44	91.85	0.08	98.90
	pH 6.58	24.5	7.01	22	8	2.85	97.66	0.34	97.08	0.74	86.30	0.14	98.07
	pH 6.01	24.7	6.97	31.8	8	2.25	98.15	0.49	95.80	1.00	81.48	0.22	96.96
	pH 5.02	23.3	6.64	38.3	6	3.55	97.09	0.66	94.34	1.15	78.70	0.28	96.13
	pH 4.03	24.1	5.75	50.2	4	4.65	96.19	1.04	91.08	1.52	71.85	0.45	93.78
Permeate under OTP of 0.400 MPa at the feed pH of …..	pH 7.02	24.5	6.91	19.6	10	10.70	91.22	0.06	99.49	0.31	94.26	0.04	99.45
	pH 6.63	24.2	6.98	17.7	12	1.60	98.69	0.17	98.54	0.59	89.07	0.09	98.76
	pH 6.03	23.6	6.8	24.1	8	1.90	98.44	0.25	97.86	0.80	85.19	0.13	98.20
	pH 5.00	23.1	6.69	30.6	6	2.75	97.74	0.40	96.57	0.95	82.41	0.21	97.10
	pH 4.02	23.8	5.95	41.7	4	0.80	99.34	0.85	92.71	1.32	75.56	0.39	94.61
Permeate under OTP of 0.500 MPa at the feed pH of …..	pH 7.05	22.1	7.14	15.7	6	7.75	93.64	0.04	99.66	0.19	96.48	0.04	99.45
	pH 6.67	22.4	6.80	14.5	6	2.95	97.58	0.14	98.80	0.45	91.67	0.09	98.76
	pH 6.04	23.1	6.83	19.8	12	4.33	96.45	0.21	98.20	0.63	88.33	0.13	98.20
	pH 5.01	23.6	6.53	29.7	8	5.51	95.48	0.48	95.88	1.02	81.11	0.21	97.10
	pH 4.02	23	6.45	34.2	4	2.15	98.24	0.71	93.91	1.25	76.85	0.39	94.61

Table D-2.11 Data analysis for membrane experiment of ULPRO membrane (UTC-70) of groundwater from San Pa Hiang Membrane Plant (continue)

Sample \ Permeate water Parameters		F^- (mg/L)	% remove F^-	NO_2^- (mg/L)	% remove NO_2^-	NO_3^- (mg/L)	% remove NO_3^-	SO_4^{2-} (mg/L)	% remove SO_4^{2-}	PO_4^{2-} (mg/L)	% remove PO_4^{2-}	Cl^- (mg/L)	DOC (mg/L)	% remove DOC
Groundwater at sampling point 1		3.06		0.00		0.27		6.92		0.00		10.70	0.686	
Groundwater at sampling point 2		3.12		0.00		0.30		6.98		0.00		10.70	0.570	
Permeate under OTP of 0.100 MPa at the feed pH of …..	pH 7.01	0.18	94.23	0.00	0.00	0.00	100.00	0.10	98.57	0.00	0.00	1.19	0.284	50.18
	pH 6.56	0.30	90.38	0.00	0.00	0.06	80.00	0.17	97.56	0.00	0.00	1.46	0.286	49.82
	pH 6.03	0.34	89.10	0.00	0.00	0.00	100.00	0.15	97.85	0.00	0.00	9.42	0.304	46.67
	pH 5.02	0.40	87.18	0.00	0.00	0.04	86.67	0.10	98.57	0.00	0.00	18.81	0.309	45.79
	pH 4.00	3.98	-27.56	0.00	0.00	0.10	66.67	0.13	98.14	0.00	0.00	20.60	0.267	53.16
Permeate under OTP of 0.200 MPa at the feed pH of …..	pH 7.02	0.15	95.19	0.00	0.00	0.03	90.00	0.09	98.71	0.00	0.00	0.15	0.235	58.77
	pH 6.60	0.26	91.67	0.00	0.00	0.00	100.00	0.18	97.42	0.00	0.00	1.23	0.252	55.79
	pH 6.04	0.27	91.35	0.00	0.00	0.04	86.67	0.13	98.14	0.00	0.00	6.27	0.220	61.40
	pH 5.05	0.57	81.73	0.00	0.00	0.03	90.00	0.07	99.00	0.00	0.00	5.27	0.197	65.44
	pH 4.05	5.26	-68.59	0.00	0.00	0.03	90.00	0.07	99.00	0.00	0.00	7.37	0.274	51.93
Permeate under OTP of 0.300 MPa at the feed pH of …..	pH 7.05	0.15	95.19	0.00	0.00	0.03	90.00	0.10	98.57	0.00	0.00	0.68	0.257	54.91
	pH 6.58	0.16	94.87	0.00	0.00	0.02	93.33	0.14	97.99	0.00	0.00	0.77	0.244	57.19
	pH 6.01	0.30	90.38	0.00	0.00	0.03	90.00	0.14	97.99	0.00	0.00	4.99	0.194	65.96
	pH 5.02	1.02	67.31	0.00	0.00	0.03	90.00	0.15	97.85	0.00	0.00	7.94	0.263	53.86
	pH 4.03	4.76	-52.56	0.00	0.00	0.50	-66.67	0.15	97.85	0.00	0.00	10.23	0.232	59.30
Permeate under OTP of 0.400 MPa at the feed pH of …..	pH 7.02	0.09	97.12	0.00	0.00	0.01	96.67	0.06	99.14	0.00	0.00	0.49	0.247	56.67
	pH 6.63	0.20	93.59	0.00	0.00	0.02	93.33	0.10	98.57	0.00	0.00	0.59	0.219	61.58
	pH 6.03	0.27	91.35	0.00	0.00	0.02	93.33	0.08	98.85	0.00	0.00	3.22	0.231	59.47
	pH 5.00	0.76	75.64	0.00	0.00	0.03	90.00	0.11	98.42	0.00	0.00	5.88	0.226	60.35
	pH 4.02	4.26	-36.54	0.00	0.00	0.04	86.67	0.12	98.28	0.00	0.00	8.12	0.208	63.51
Permeate under OTP of 0.500 MPa at the feed pH of …..	pH 7.05	0.08	97.44	0.00	0.00	0.00	100.00	0.07	99.00	0.00	0.00	0.32	0.168	70.53
	pH 6.67	0.21	93.27	0.00	0.00	0.00	100.00	0.07	99.00	0.00	0.00	0.37	0.169	70.35
	pH 6.04	0.26	91.67	0.00	0.00	0.01	96.67	0.07	99.00	0.00	0.00	1.96	0.181	68.25
	pH 5.01	1.50	51.92	0.00	0.00	0.02	93.33	0.10	98.57	0.00	0.00	3.98	0.158	72.28
	pH 4.02	3.99	-27.88	0.00	0.00	0.03	90.00	0.12	98.28	0.00	0.00	5.58	0.207	63.68

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