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Membrane Systems for the Fight against Water-Borne Contaminants in Small Communities and Remote Areas from the Developing World: Accomplishments in Thailand and Some New Development in Sénégal and Mali

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Abstract: Pressure-driven membrane processes such as microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO) are increasingly used to produce clean water for a broad range of domestic and industrial applications. This article outlines some key features of these membrane-based technologies and describes how they can be adapted to supply safe drinking water in remote communities and rural regions from the developing world. Three case studies are reported in Asia (Thailand) and Africa (Sénégal and Mali) where we investigate the feasibility of removing microorganisms and some dissolved pollutants from water with commercial pressure-driven filtration pilots. The convincing success of the Thailand study established that Pall transportable MF/UF units could help local residents meet their demand in high quality water. This case study provided some rationale for testing a similar concept in West Africa. Given the technological efficacy, robustness and modularity of these membrane systems, we see them as innovative tools for implementing a cost-effective and sustainable strategy to stop the emergence of water borne and vector borne infectious diseases not only in the developing world but also in regions severely affected by natural disasters.

Keywords: Water filtration, infections, developing countries, membranes.

I) INTRODUCTION

More than a third of the world's population does not have access to clean water or basic sanitation and nearly 1.5 million children die each year because of diarrheal diseases [1]. The United Nations Millennium Development Goals were designed to fight this crisis and reduce these numbers by 50%, until 2015.

Across West Africa, one out five children dies before reaching the age of five years, and the pathology for 80% of diseases is linked to water-borne pathogens. The main root causes of these water-borne pathogens are associated with a) the ingestion of water contaminated with pathogens such as cholera, guinea worm and diarrhea, b) some physical contact with schistosomiasis and snail-borne trematodes that are found in the water, and c) the development of parasitic vectors (malaria mosquito or onchocerciasis black fly) that breed in water [2]. Although safe clean water produced from conventional water treatment plants is supplied to some areas of Africa's largest cities, most residents living in the rural regions and remote communities drink contaminated groundwater without any further treatment.

In Sénégal, groundwater and surface water contamination is primarily attributed to dissolved species and most specifically to fluorine. Children and adults who consistently drink fluorine-contaminated water (with a fluoride ion concentration greater than 4 mg/L) often suffer from fluorosis, a dental or bone deformation disease of varying complexity [3]. However, even though excess fluorine can be detrimental to humans, it is critical to maintain its level in the range of 0.5 to 1.0 mg/L to leverage some health benefits. Moreover since Sénégal waters are mostly brackish (total mineralization > 2 g/L), it is essential to keep the amount of total dissolved species (TDS) below 500 ppm (part per million) to satisfy World Heath Organization (WHO) standards [4]. Mali drinking water is predominantly supplied by groundwater reservoirs (90%) and its non-biological contaminants are quite diverse. Water sources from the Sahelian, the semid-arid zone and north of Bamako, exhibit TDS levels greater than 1.5 mS/cm. Nitrate levels that are greater than 100 mg/L can be found in several regions where there are strong animal breeding activities. In addition, the water pollution in the Eastern Central region of Mali such as Mopti is characterized by a strong corrosiveness, some softness, and a relatively high iron concentration ranging from 1.0 to 3.3 mg/L [5].

Today, many African countries such as Sénégal and Mali have taken some actions but the outcome is still insufficient and the limited access to safe drinking water has yet to be resolved. We believe that membrane filtration technologies can provide affordable and long-lasting solutions to these problems of inadequate supply of safe drinking water to Africa's remote areas by a) purifying the contaminated groundwater to the desired level, and b) producing drinkable water from easily accessible surface water sources.

Microfiltration (MF) and ultrafiltration (UF) are two examples of membrane filtration technologies that can be used to produce clean and safe drinking water. MF treatment is suitable for removing colloids in suspension as well as fine

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particles with an average size of 0.02 to 10 microns [6], while UF is used to retain and concentrate finer suspended solids and solutes, with a molecular weight in the range of 1,000 to 1,000,000 Dalton and a size of 0.001 to 0.1 micron [7]. Both MF and UF membranes are prepared from polymeric, ceramic, or metallic materials and are packaged in filters arranged as flat sheets, or spiral wound or tubular modules [8]. MF is a low-pressure filtration process, which operates within a pressure range of 1 to 3 bars and is broadly utilized for industrial water treatment, or for some applications that are linked to the biotechnology and semiconductor markets [8, 9]. MF and especially UF can function in cross-flow mode, where a portion of the feed stream flows parallel to the membrane surface at a high velocity to reduce membrane fouling, while the rest permeates through the membrane. UF systems operate at a greater pressure range (4 to 7 bars) and their main purpose is to retain fats, large proteins, polysaccharides and fine particles whereas salts, small peptides, low-molecular-weight organics and sugars can pass through the membrane [9]. In our study, the term MF/UF refers to a membrane or a filtration module whose properties fall between those of MF and UF technologies, and which can be adapted to either satisfy the MF or UF technical requirements. In addition to MF and UF, Nanofiltration (NF) units are built from membranes with an average pore size of around 1 nanometer and a molecular weight cut off in the range of 200 to 1,000 Daltons [10]. The operating pressure range for NF membranes is about 8 to 10 bars, and they are mainly designed to soften water by removing specific divalent ions such as magnesium or calcium. In contrast to specific removal of divalent ions, reverse osmosis (RO) is based on dense semi-permeable membranes that remove all ions, including sodium and chloride species, but allow water molecules to diffuse through. RO which operates at a minimum pressure of 40 bars has become the premier technology for seawater desalination because its energy consumption is smaller than that of the thermal evaporators [11]. Hence, a typical seawater RO plant requires 1.5 to 2.5 kWh of electricity per cubic meter of clean water, whereas the energy consumption for thermal distillation systems is between 4-fold and 10-fold higher [12]. The following case studies demonstrate the applicability and efficacy of Pall transportable filtration units for producing clean surface water using MF/UF processes in Thailand and Mali; and groundwater with NF and low-pressure RO (LRO) systems in Sénégal. To our knowledge, the latter study in Sénégal is a pioneering work because pilot scale NF has never been tested to remove fluoride ions from a groundwater source.

II) FIRST CASE STUDY IN THAILAND

Pall has recently developed the Aria AX membrane system that is especially designed to facilitate safe drinking water supply in small rural communities and in remote areas. The heart of this technology relies on a membrane barrier made from MF/UF hollow fibers that provide an absolute retention against microscopic pathogens such as bacteria, cysts, parasites etc. Local residents are directly responsible for the installation, maintenance and operation of the unit in order to facilitate the technology transfer. This model provides three benefits: first, the users become owners of the technology by learning to master it. Second, they have access to safe clean water whose excellent quality remains stable over time. Third, the water treatment and supply equipment are easy to operate and maintain because of their small footprint and the reduced number of cleaning steps required for maintaining the equipment in good working conditions [13]. In Thailand (Fig. **1**), these systems have provided a vital assistance to several communities in cities and villages that have demanded safe drinking water. Whenever possible, the equipment assembly or manufacturing is carried out on site, which helps minimize the capital expenses and to also support some local development.

II.1) Performance of the Pall Aria AX MF/UF System

The quality of the ARIA AX-processed water is remarkably stable and its properties are as follows: the turbidity value is below 0.1 Nephelometric Turbidity Unit (NTU), the microbial retention for Cryptosporidium and Giardia exceeds 6 log, the viral retention ranges between 0.5 and 3 log, whereas amoebas and other parasites are absolutely retained. A chemical treatment can be added upstream to the Pall MF/UF unit to precipitate various organic compounds (Total Organic Carbons) and some inorganic species (Fe, Mn, F, As).

The membranes in the AX MF/UF system are made of polyvinylidene fluoride hollow fibers that are chemically and mechanically stable when exposed to sodium hydroxide and sodium hypochlorite washing. The filter cleanability is also enhanced through a 90-second-long water backwash assisted with air bubbles and which occurs every 30 minutes. This unit operates in a quasi dead-end mode since the recovery rate is at least 95%. The recovery parameter is defined as the following Flow Rate ("FR") ratio:

[(permeate FR) / (feed FR + concentrate FR)]

Thus, 95% of the feed water is retrieved in the permeate feed (clean water), while 5% is re-circulated as concentrate, upstream of the membrane. Each unit can hold up to 36 hollow fiber modules and its full water treatment capacity is 50 m^3/hr. The electrical power consumption of Aria AX typically ranges between 0.1 and 0.2 kWh for each cubic meter of filtered water and the maximum operating pressure is equal to 3 bars. Such a low-pressure requirement makes this MF/UF technology relatively easy to implement in remote communities.

II.2) Technology Validation

A feasibility study was recently carried out in Thailand to validate the Aria AX system. In 2006, a one-module (hollow fiber) pilot was operated for several months in the town of Pranon to cover both the dry and monsoon seasons. The feed water properties varied within the following range: 1.2-2007 NTU (turbidity), 0.9 -3.3 mg/L for iron, and 0.6-0.18 mg/L for manganese. Upon MF/UF treatment, the clean water exhibited turbidity below 0.1 NTU, while the iron and manganese content was less than 0.2 mg/L. Such numbers are lower than those of the Thailand Industrial Standards Institute 257 norm (TISI 257) that are recommended for drinking water. Water turbidity was monitored in real time during the full length of the testing period. Even when the starting raw water turbidity exceeded 100 NTU, the filtered water (permeate) always remained below 0.1 NTU. Bacteri-

Fig. (1). Pall MF/UF Membrane unit in the village of Pranon, Thailand, with a capacity of 10 m^3/h.

ological analyses of the water permeate were frequently conducted and its quality was always compliant with TISI 257 norm (i.e. bacterial counts far below 500 colony forming units/mL), despite some sharp variability in the feed water composition, especially during the flood season. Likewise, the average recovery rate was always maintained at 95%.

II.3) Manufacturing, Operation and Maintenance of These Units

Today nearly 30 Aria AX systems can be found in the villages of Thailand. The long-term goal is to assemble and build these filtration skids locally, which will keep both the manufacturing cost and selling price to a minimum. These units are operated and maintained by a qualified team that provides a full range of services to villages and municipalities. Some of the services include: the replacement of fouled modules, and their chemical cleaning at a dedicated filter processing site, monthly maintenance visits, and fast troubleshooting interventions. The service contract cost estimate is between 0.10 and 0.20 US dollar per cubic meter of processed water, excluding the cost of electricity. For Thailand, one individual can maintain 25 MF/UF units in a 35 mile-radius.

II.4) Necessary Skill-Set for Maintenance and Monitoring Operations

The staff responsible for monitoring and maintaining these systems must accomplish the following tasks:

- Control the water quality.
- Dismantle and assemble-back the modules, and conduct all integrity tests.
- Perform the chemical cleaning at a dedicated processing site.
- Maintain all accessories, which comprise of the pumps, air compressor, automated valves, strainer and instrumentation.

In addition the staff can be hired, trained and certified locally, and thus contribute to reinforce the value chain by implementing this new technology.

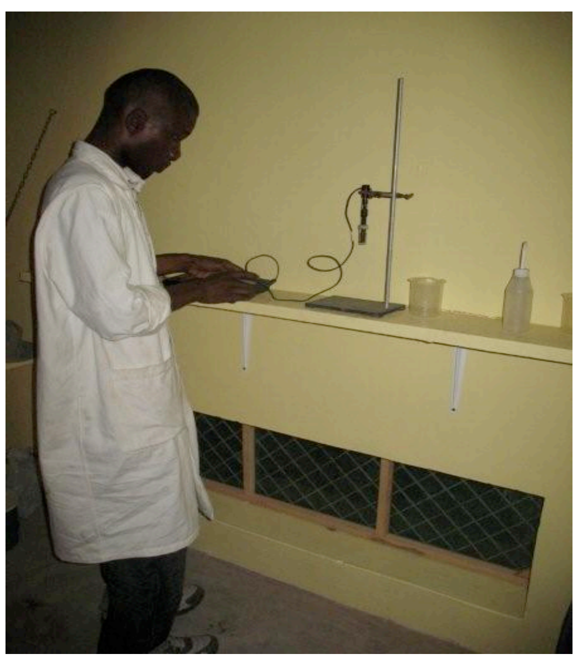
III) SECOND CASE STUDY: FILTRATION SYSTEM INSTALLED IN THE VILLAGE OF NDIAFFATE, FROM THE REGION OF KAOLAK IN SÉNÉGAL

This project is a partnership between Pall and the university Cheikh Anta Diop (UCAD) of Dakar in Sénégal. The goal is to evaluate the defluorination of deep bore well water *via* NF and low-pressure reverse osmosis (LRO). NF technology can remove multivalent ions and molecular species with a molecular weight greater than 200 Dalton. Fluoride ions can be removed by NF but the rejection mechanism is not yet fully elucidated [14]. It is hypothesized that the large electronic density surrounding the fluorine nucleus affects its removal while being transported across the membrane [15]. RO too can reject fluorine, but this process requires a minimum operating pressure of 40 bars, whereas the NF transmembrane pressure does not exceed 10 bars. In fact, not only does NF consume less energy than RO but it can be tuned to adjust the water taste and odor by controlling the operational parameters – i.e. set the levels of monovalent and divalent salts in the permeate. The Pall Disc-Tube (DT) system can accommodate either NF or LRO filters dependent on the fluoride content of the raw material and the level of removal required. LRO membrane can treat contaminated water at an operating pressure (varying from 11 to 15 bars), which is greater than the NF range but much below that of standard RO [16]. Alternative methods such as resin adsorption, chemical precipitation, electro-deionization or capacitive deionization are either not adequate to adjust the fluorine concentration to the desirable level, or they are too costly or not sufficiently established (scalability, robustness, cost) to be operational in a remote environment. The DT system currently installed in Ndiaffate comprises 1 filtration module, which is very robust and well adapted to operate in a remote environment. This module contains several dozens of circular NF (or LRO) membranes packed in a vertical arrangement. The following points highlight some major attributes of this technology:

- Dirty filters plugged with contaminants can be reused after a simple chemical cleaning.
- The pilot can be dismantled and repaired on-site.
- Disposable parts such as the membranes, joints and flexible hoses need to be replaced, but all other parts can last for at least 10 years without any significant damage.

a

b



c

Fig. (2). (**a**) Pall DT arrival at the bore well, (**b**) DT pilot in the testing room, (**c**) Preliminary trials.

III.1) Performance of Pall "DT" Pilot (NF and LRO Membranes)

The preliminary filtration tests were conducted in Europe by Pall on a 100-liter water sample from Ndiaffate's deep bore well. The fluorine content in the raw water was 3 ppm. The feed stream was concentrated 8 times in volume during the NF treatment. The fluorine content in the collected permeate (7 volumes) was 1 ppm, which is in compliance with WHO standards of 1 ppm. The NF water concentrate exhibited a fluorine content of 15 ppm, although this unfiltered fraction is not used for consumption.

III.2) Technology Validation

Since June 2008, a Pall "DT" pilot has been installed in Ndiaffate with a processing capacity of a 1,000 L/hr (Fig. **2**). This NF system can be operated entirely manually, which is very convenient for a location where automated parts are difficult to find. The objectives of this test were to:

- Verify the filtration results obtained earlier with the 100-liter sample, in terms of partial and controlled removal of fluorine via NF.
- Determine the length of NF treatment operation between two chemical cleaning steps and validate the cleaning protocol.
- Study the effect of an increased recovery rate on the permeate fluorine content (cleaned water), the length of the filtration cycles, and the frequency of the chemical cleaning steps.

More recently, LRO membranes were also tested because their water permeability and salt rejection properties fall between those of NF and standard RO. Hence, LRO membranes offer some additional choice flexibility in terms of performance control. LRO is typically used in field applications when the feed stream contains a high concentration of dissolved contaminants (e.g.: fluorine) that must be sharply reduced, while NF is more suited when the incoming water is less polluted and the rejection for divalent salts is not too stringent – e.g. less than 95%.

The encouraging results of this field study (in progress) are summarized in Table **1**:

SO far, the water treated *via* NF/LRO module meets WHO quality standards and the filtration process is quite reliable and reproducible. NF technology is more suited when the feed water fluoride content is below 4 ppm, while LRO can handle more polluted water – i.e. the fluoride concentration can be as high as 20 mg/L. The early NF operating cost estimate for Sénégal is between 0.10 and 0.20 US dollar per cubic meter of processed water, which is more affordable than the chemical processes (5-fold) and than electro-deionization (2-fold) [17].

IV) PRELIMINARY STAGE OF A FEASIBILITY STUDY IN MALI

A WHO study established that the morbidity rate in Mali was reduced by 16% when local residents had access to safe drinking water and by 22% when the quantity and quality of water were simultaneously raised [18]. Pall MF/UF systems are ideally suited to meet such requirements. This membrane technology offers a valuable alternative to clean water from Mali's groundwater sources – which accounts for over 90% of the country drinking water. Despite an easy access, surface water has been under-exploited mainly because of its poor quality and the potential risks for new disease cases. Hence, the performance versatility and water cleaning efficacy of Pall MF/UF should help address critical issues reported by the WHO (*i.e.* surface water treatment; low energy consumption and scalable process; efficient removal of suspended solids, turbidity, pathogens, ionic complexes and iron species etc.) and thereby lower the morbidity rate.

IV.1) Partners

The Ecole Nationale d'Ingénieurs (ENI) of Bamako and Pall Corporation have partnered to evaluate the feasibility of producing safe clean water by filtering contaminated water through the Aria AX MF/UF technology. This work will be conducted at the "Energie du Mali" water utility in Bamako where surface water is directly accessible from the Niger River.

IV.2) Project Planning and Critical Milestones

The conceptual stage of this project was recently finished and the experimentation will start during winter 2009. The overall scope of this research will focus on:

- Assessing the robustness, sustainability, quality, affordability and efficacy of membrane technologies to supply small communities in Mali with safe clean water;
- Adapting these modern filtration tools to the local environment;

Table 1. Merit Assessment for Pall NF and LRO Technology Based on the Treatment of Ndiaffate's Contaminated Water

	NF	LRO
Operating pressure	< 8 bars	14 bars
Total running hours	400	350
Highest fluoride content in the contaminated water	</= 4 mg/L	</= 20 mg/L
Fluoride removal efficiency	75%	98%
Salinity removal efficiency	55%	98%
Full performance recovery After chemical cleaning	yes	yes

- Adopting a sustainable strategy for providing remote communities in Mali with some affordable, low cost, clean water in full compliance with WHO standards;
- Determining the feasibility of electrically powering the MF/UF equipment with a renewable source of energy, such as solar photovoltaics or non-edible biofuels – e.g., oil derived from the Jatropha plant, which is increasingly developed in Mali [19].

The completion of the above goals will be conducted in three successive phases:

Phase 1: Installation and operation of a MF/UF Pall Aria AX unit at the main water utility in Bamako. At this early stage, the filtration equipment will receive its energy directly from the city electric grid.

Phase 2: Coupling of the MF/UF pilot with a source of renewable energy; and parameterization study: – i.e. achieve the highest volume of processed water per kWh, while preserving high quality standards.

Phase 3: Testing the above concept in the field, in a remote region where surface water is readily available.

IV.3) Targeted Outcome

This study is expected to generate a local expertise in the field of filtration, separation processes, and membrane science and technology. Each project milestone is critical because it will enable participants to assess the progress made in terms of greater water quality, chemical cleaning efficacy and length, reduced energy consumption, enhanced MF/UF treatment operation as a function of daily solar irradiance, pilot maintenance and operation, system robustness and sustainability. We anticipate that a) acquiring the resulting technology will involve some capital spending but its longevity will make it very cost attractive; b) the financial support will come from the local governments, some non governmental organizations, and through loans or donations from international institutions [20, 21].

V) CONCLUSION

Pressure-driven membrane processes are well suited to produce clean water (out of groundwater or surface water) that meets the highest drinking quality standards. Projects that are carried out in Sénégal and Mali should help better assess the merit of transportable filtration systems based on their reliability, ease of implementation, cost competitiveness and suitability for supplying clean water in rural communities and in small remote areas across the globe.

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