Water Recovery in Space

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In the absence of recycling, water represents over 90% of the life-support consumables for a manned spacecraft. In addition, over 90% of the waste water generated can be classified as moderately or slightly contaminated (e.g. shower water, condensate from the air-conditioning system, etc.). The ability to recover potable water from moderately contaminated waste water hence enables significant savings to be made in resupply costs. A development model of such a water-recovery system, based on membrane technology, has been produced and tested using 'real waste water' based on used shower water. Results indicate some 95% recovery of potable water meeting ESA standards, with total elimination of microbial contaminants such as bacteria, spores and viruses.

Introduction

'Life support' covers the theory and practice of sustaining life in environments or situations in which the human body is incapable of sustaining its own natural functions. There are essentially only three practical, non-exclusive ways to ensure the biological autonomy of man when isolated from his original biosphere: provide all required consumables at the start of the mission or resupply them, regenerate life-support materials during the mission, or utilise in-situ resources (in the case of manned missions on planets).

Historically, air, water and food were taken on board and the waste stored and returned to Earth. This was a completely open-loop life-support system used successfully for short-duration space missions. As space missions get longer, however, supply loads get heavier and soon prohibitive, effectively limiting the duration of such missions, however exciting and potentially important they may be. It becomes crucial then to close some vital loops to permit longer missions.

When we consider the three vital loops of a life-support system, i.e. air, water and food/solid waste, the most demanding in terms of mass constraints is the water loop. Indeed, water represents approximately 92% by mass of the total life-support consumables (see Table 1). Closing the water loop by recovering potable water from waste water will therefore already provide for 92% of human needs, i.e. a 92% autonomy of man in space.

Background

Waste water can be roughly classified according to its degree of contamination. It is now generally accepted that highly contaminated water, such as urine, must be subjected to a process involving phase change before it will be regarded as suitable for re-use. Such phase-change systems have been studied for several years, notably in Russia and the USA, and include techniques such as AES (Air Evaporation System), TIMES (Thermo-electric Integrated Membrane Evaporation System) and VCD (Vapour Compression Distillation). Moderately or slightly contaminated water, such as hygiene (washing, showering) water, condensate recovered from the air-conditioning system, product water from the air-revitalisation (oxygen recovery) system and possibly also the product water from the urine processing system, can be treated in other ways which promise to be less complex, consume less power and provide a higher percentage recovery rate.

From Table 1 it can be seen that over 90% of the expected waste water can be classified as 'moderately contaminated'. If, in addition, the product water from the processing of the highly contaminated waste stream is regarded as 'moderately contaminated', the need, as a first priority, for an effective, reliable and efficient 'core water recycling system' for processing moderately contaminated water becomes evident.

Core water recycling system

Based on the conclusions of past studies financed by the Agency, a core water recycling system was designed, aimed at recovering potable water from hygiene water, typified by shower water. The system, shown schematically in Figure1, uses a combination of filtration and reverse-osmosis units in successive stages to eliminate solids, organic and inorganic molecules, including micro-organisms, from the product stream. The aim is to produce water meeting the ESA quality standards for potable water defined in ESA PSS-03-402.

To validate the technology, a development model has been designed, built and tested. This development model water-recovery unit (Fig. 1) is contained in a rack approximately 2 m wide, 2.1 m high and 0.6 m deep, and consists of four successive membrane units: one ultra-filtration (UF) unit based on a mineral membrane, and three successive reverse-osmosis (RO) units. It is sized to produce approximately 2 litres of drinking water per hour (Fig. 2). The role of the first (ultra-filtration) unit is to reduce the turbidity of water, i.e. to exclude particulate materials and high-molecular-weight macromolecules. Elimination of low-molecular-weight organic molecules as well as ionic compounds (salts) is the task of the three successive reverse-osmosis units. The test bed operates nearly automatically, controlled by software specifically designed for that purpose, the main exception being the periodic purges needed to maintain membrane performance, which are done manually.

The UF unit consists of a cartridge containing seven tubular 'Carbosep M1' ultra-filtration membranes (zirconium and titanium on a carbon support), connected in parallel. These membranes have a molecular weight cut-off of 150 x 10^3 dalton, and a total filter surface area of 0.16 m^2. The operating pressure is typically 2 – 4 bar.

The RO units consist of Filmtec SW30 (first unit) and Filmtec SW30HR (second and third units) membranes, made from polysulfone on polyester support, each about 6.4 cm in diameter and 36.5 cm in length. Each has a total membrane area of 0.9 m^2 and typically operates at a pressure of about 55 bar.

Table 1. Average human requirements per person per day

Consumables		**Waste**	
Type	Mass (in kg)	Type	Mass (in kg)
Gaseous state		**Gaseous state**	
Metabolic oxygen	0.83	Metabolic carbon dioxide	1.00
Sub-total (gaseous)	*0.83*	*Sub-total (gaseous)*	*1.00*
Liquid state		**Liquid state**	
Water for:		Water from:	
- food re-hydration	1.15	- metabolic perspiration and respiration	2.28
- food preparation	0.79	- urine	1.50
- drinking	1.62	- faeces	0.09
- dishwashing	5.46	- dishwashing	5.46
- hand/face washing	1.82	- personal hygiene	7.27
- shower	5.45	- laundry	12.50
- laundry	12.50	- toilet flushing	0.50
- toilet flushing	0.50		
Sub-total (liquid)	*29.29*	*Sub-total (liquid)*	*29.60*
Solid state			**Solid state**
Solids for:		Solids from:	
- Dry food	0.62	- sweat	0.02
- Packaging, bags, paper	0.89	- urine	0.03
		- faeces	0.09
		- packaging	0.89
Sub-total (solid)	*1.51*	*Sub-total (solid)*	*1.03*
TOTAL	**31.63**	**TOTAL**	**31.63**

During operation, the incoming waste water is pre-filtered and stabilised by the addition of biocide (0.2% oxone solution). Sulphuric acid is then added, if necessary, to obtain a pH of 4. After processing through the ultra-filtration unit (UF1) and the first two reverse-osmosis units (RO1 and RO2), sodium hydroxide is added to the permeate to raise its pH to 7, before the final reverse-osmosis stage (RO3).

Test plan

The test campaign, illustrated in Table 2, was conducted in three stages:
(i) Test-bed commissioning, consisting essentially of system verification and preliminary testing at subsystem and system level.
(ii) Performance during a short-duration (24 h) test with reference water.
(iii) Performance during three long-duration (100 h) tests with real waste water.

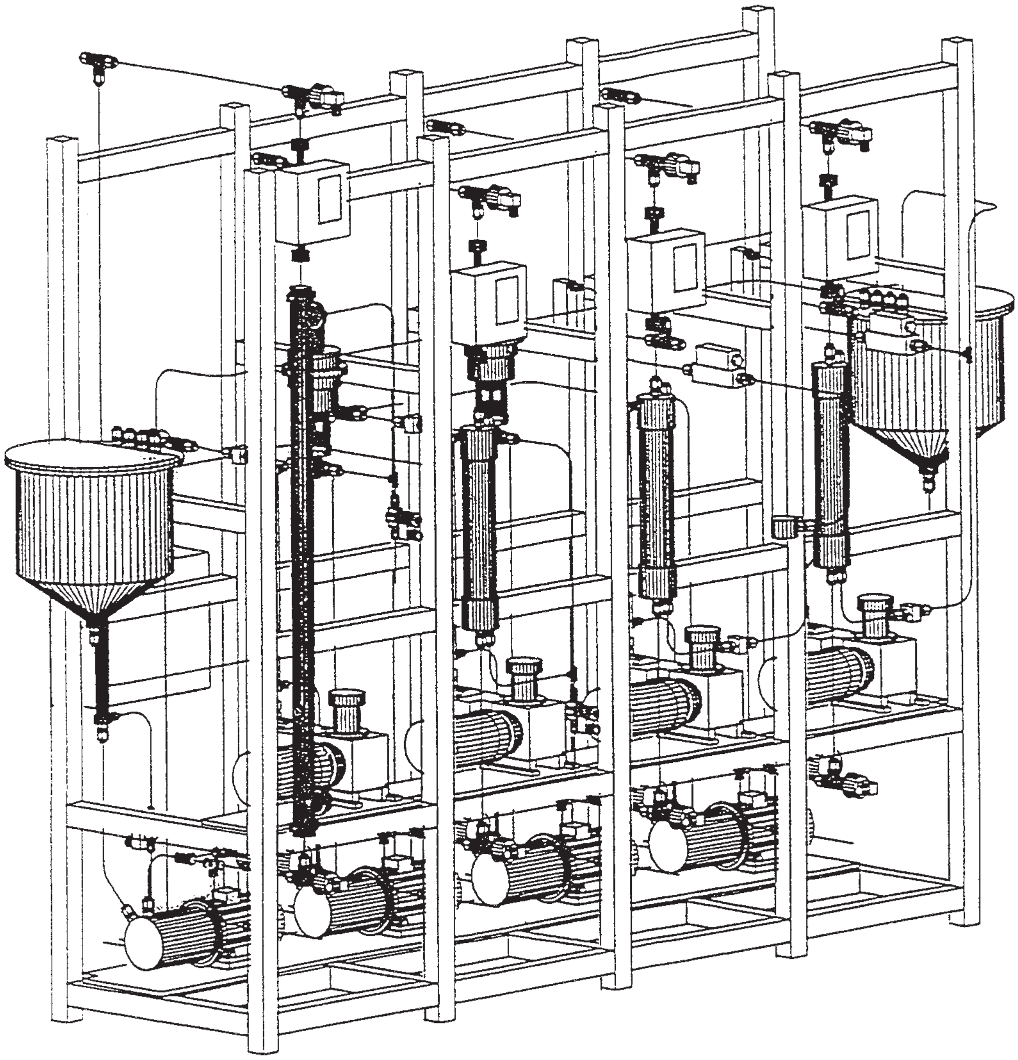
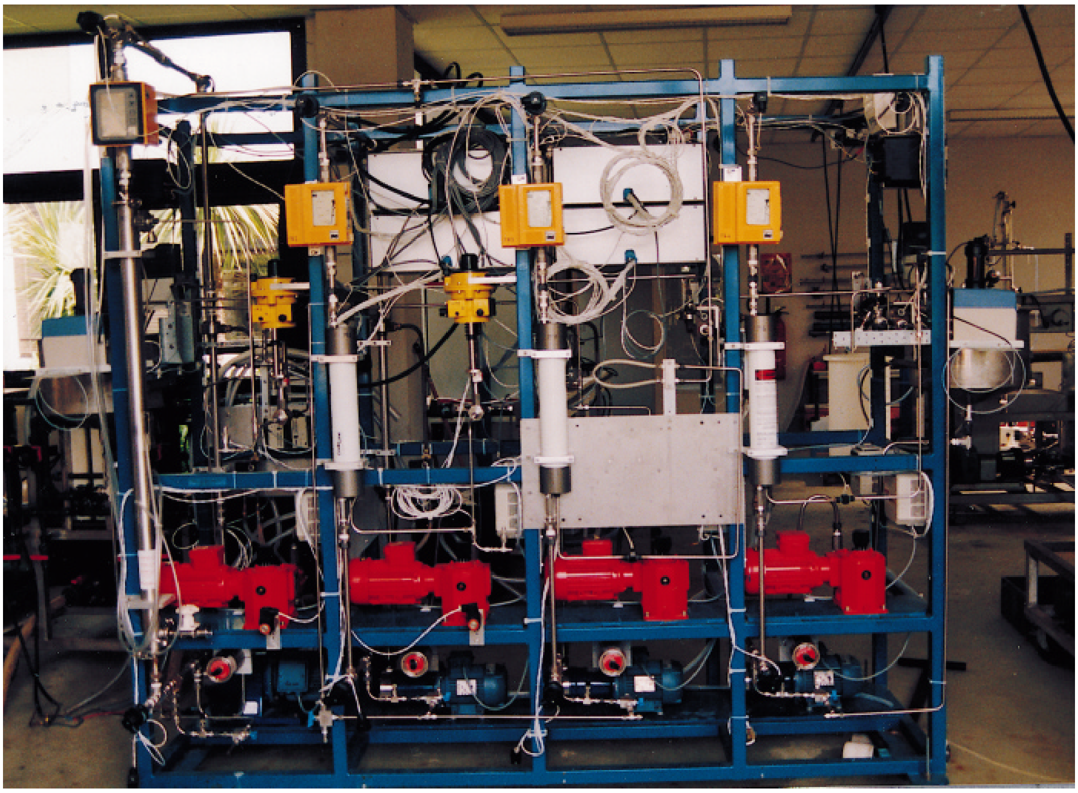


Figure 1. The water-recovery test bed



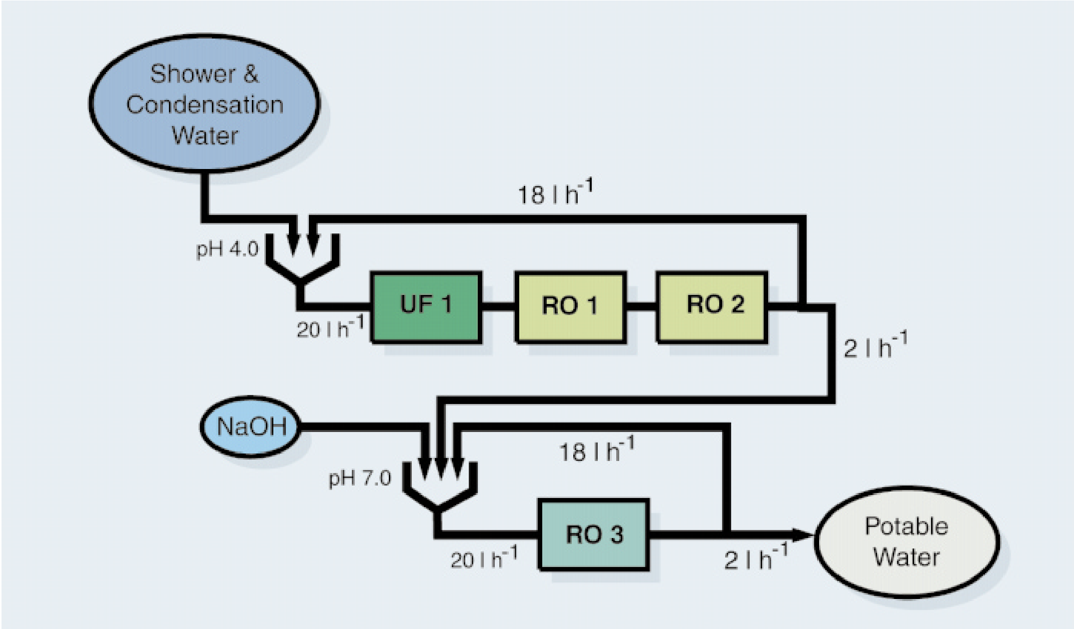


Figure 2. Water production cyc le inside the recovery unit

Experimental tests were performed using real waste water based on:

– shower water (10 litres of commercial mineral water to which had been added 2.5 g of soap)
– condensation water (2 litres of demineralised water)
– bactericide (oxonia at 0.2% concentration by volume)
– sulphuric acid, as required to provide a pH of 4.0.

Achievement of a recovered water quality compliant with the ESA standards for potable water (ESA PSS-03-402) was considered as the major success/failure criterion, especially regarding the system's ability to prevent any microbial (bacterial or viral) risk. The second major criterion was the percentage of water recovered.

Test performance and results

During the testing, particular emphasis was placed on the following aspects:

– quality of the recovered water
– elimination of any microbial contamination
– performance of the membranes
– performance in terms of the percentage of water recovered.

The recovered water complied with the ESA standards for drinking water (see Table 3), with one exception, namely the TOC (Total Organic Carbon) concentration. This was due to the addition of oxonia to the waste water.

The ability of the Water Recovery System to eliminate all microbial contamination was tested four times:

Table 2. Overall flow of the test campaign

VERIFICATION AND PRE-TEST	
CHOICE OF REGULATION PARAMETERS	
FUNCTIONAL TEST	- Verification at component level - Verification of automated mode
SYSTEM VERIFICATION	- Ultrafiltration membrane permeability - NaCl retention by RO membranes
PERFORMANCE TEST WITH REFERENCE WATER	
- During test	- Data collection - Permeate & retentate sampling - Compounds & microbial analysis - Purging operations
- After test	- Cleaning operations - Performance synthesis
PERFORMANCE TEST WITH REAL WASTE WATER	
- During test	1st Run - Data collection - Permeate & retentate sampling - Compounds & microbial analysis - Purging operations
- After test	- Cleaning operations - Performance synthesis
- During test	2nd Run - Idem as 1st run - Microbial overload on day 4
- After test	- Idem as 1st run
- During test	3rd Run - Idem as 1st run - No oxonia added to waste water after day 2 - Microbial overload on day 4
- After test	- Idem as 1st run

Table 3. Quality of recovered water compared to ESA standards

Parameters		Drinking Water ESA Standard	Hygiene Water ESA	Standard Recovered Water
pH		6.5-8.5	5-8.5	6.2-7.8
Conductivity	($mS.cm^{-1}$)	0.75	3	<0.01
Turbidity	(NTU)	2.5	10	<0.25
TOC	(ppm)	0.5	10	1.3-2.7
Oxidative power	(ppm)	-	-	230
F^-	(ppm)	1	10	<0.8
Cl^-	(ppm)	200	1000	<1.1
NO_3^-	(ppm)	25	50	<0.4
PO_4^{2-}	(ppm)	5	50	<0.2
SO_4^{2-}	(ppm)	250	TBD	<1.1
Na^+	(ppm)	150	750	<1.8
K^+	(ppm)	12	120	<0.1
NH_4^+	(ppm)	0.5	0.5	<0.1

(i) test of microbial retention by the UF unit alone during test-bed commissioning
(ii) monitoring of microbial elimination during the first long-duration test
(iii) simulation of a 'microbial accident' (serious microbial contamination) during the second long-duration test
(iv) simulation of two simultaneous microbial accidents (serious microbial contamination coupled with a failure in the bactericide [oxonia] delivery) during the third long-duration test.

Microbial contamination was induced by the addition to the waste water of the following micro-organisms:
- *Escherichia coli* ATCC 10536 bacteria at a final concentration of 5 x10^6 $CFU.ml^{-1}$
- *Bacillus subtilis* ATCC 6633 spores at a final concentration of 1 x 10^6 $CFU.ml^{-1}$
- Bacteriophage MS2 virus at a final concentration of 2 x 10^9 $BFU.ml^{-1}$.

In the first three tests, the presence of oxonia alone was responsible for the complete elimination of the microbes (bacteria and viruses). In the fourth test, the presence of microbes was observed in the first tank before the ultra-filtration unit, but none was found after that unit.

In all cases, neither bacteria nor viruses were detected after the ultra-filtration unit, assuring the complete decontamination of waste water and protection for the down-stream reverse-osmosis membranes against bacterial contamination and bio-film development.

The performance of the membranes was according to specification and remained constant throughout the tests. Table 4 shows the membrane performance from test run number 3, but these results are typical and varied very little from run to run. The water-recovery yield was always above 95%.

These 100 h tests demonstrated the correct functioning of a water-recovery system based on membranes. It also validated the control software allowing an automated mode of functioning. The purging procedure during testing and the cleaning procedure between tests, performed manually during this test campaign, were also validated. In order to support extended testing, the next logical step in development, to explore performance over periods of months rather than days, the control software needs to be upgraded to enable purging and cleaning to be carried out automatically.

Conclusions

The ability of current membrane techniques to recover potable water from moderately-contaminated waste water has been demonstrated. The associated control system and purging/cleaning procedures have also been verified. The design has proven to be very robust in the face of simulated 'microbial accidents'. Although the design appears to protect the membranes efficiently against risks from, for example, bio-degradation or bio-film development, continuous testing has so far been limited to only a few days. The next logical step, prior to testing in space conditions, is to explore the long-term (months rather than days) performance of the system. esa

Table 4. Membrane performance during long-duration test number 3

Membrane Type	Flux	Salt Retention
UF1	85.0 $l.h^{-1}.m^{-2}.bar^{-1}$	-
RO1 (SW30)	8.8 $l.h^{-1}$-$1.m^{-2}$	99.4%
RO2 (SW30HR)	12.2 $l.h^{-1}$-$1.m^{-2}$	99.6%
RO3 (SW30HR)	13.0 $l.h^{-1}$-$1.m^{-2}$	99.5%