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Small-Scale Membrane Systems for the Recovery and Purification of Water

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Abstract

The availability of high-quality membrane modules in a variety of configurations has expanded the range of potential applications for membrane systems. These expanded capabilities make it possible to use membrane systems to solve separation problems that previously could not have been addressed using membrane-based technology. This paper describes the development of three innovative membrane systems for water-recovery applications for the National Aeronautics and Space Administration and the U.S. military. For each membrane system, the separation problem is outlined, the technology and system are described, the operating data are reported, and potential spinoff applications are discussed.

INTRODUCTION

Advances in membrane performance and membrane-module design have expanded the range of potential applications for membrane systems. With the increased availability of high-quality modularized membranes in many configurations, engineers can design membrane systems to solve unique separation problems that previously could not be addressed using membrane technology. In addition, the range and quality of module configurations offers expanded flexibility in the design of hybrid systems—systems based on more than one type of unit operation. The coupling of two or more technologies can result in better performance than is possible using either unit operation individually.

This paper describes the development of three membrane systems that solve particularly challenging water-recovery problems. The systems were developed for the National Aeronautics and Space Administration (NASA) and the U.S. Army, but the technologies also have numerous industrial applications.

The membrane systems described are 1) a hybrid subsystem for NASA to recover and recycle water used for personal-hygiene purposes ("washwater"), 2) a hybrid subsystem for NASA to posttreat humidity condensate and urine distillate, and 3) a system for the Army to recover potable water from the diesel exhaust of military vehicles. In each case, we present the problem, describe the technology and system design, report operating data, and discuss commercial spinoff applications.

NASA APPLICATIONS

Work is under way to plan and design Space Station Freedom, the manned, orbiting U.S. space station. Similar efforts are progressing to design vehicles for future expeditions to the moon and, eventually, to Mars. For extended missions such as these, the water, oxygen, and food requirements of the crews must be met by extensive recycling—i.e., by recovering for reuse components from waste streams generated by the crew. Bend Research has been developing technologies that recover water from various wastewater streams (*1*, *2*). Figure 1 shows a crew mass balance for a partially closed-loop life-support system. As the figure indicates, wastewater will come from three primary sources: 1) personal-hygiene or "washwater" (effluents from hand-washing, showering, laundering, and dishwashing), 2) humidity condensate (water from perspiration and respiration), and 3) urine (*3*). Bend Research has developed membrane systems for recovering

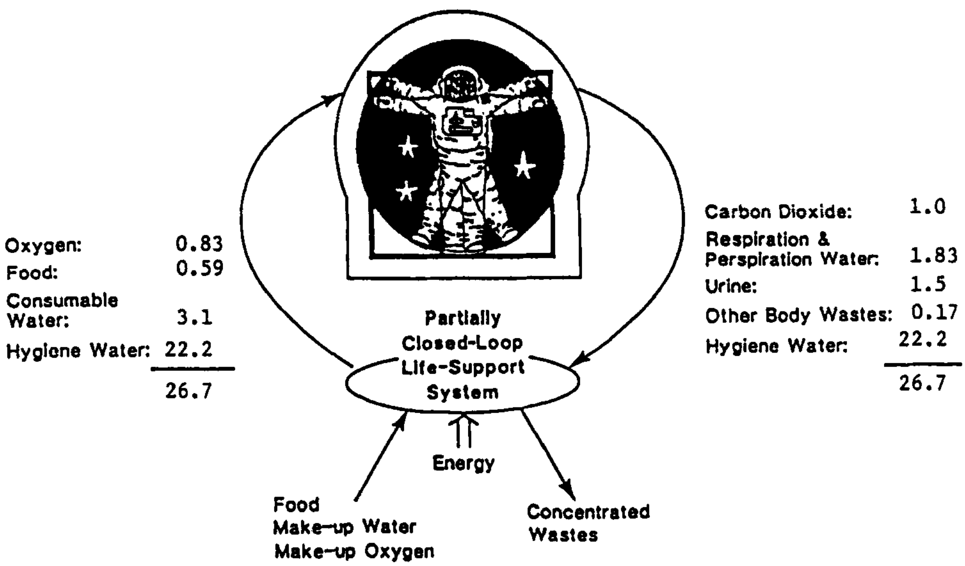

FIG. 1. Crew mass balance based on a four-person crew (units in kg/person·day).

reusable water from washwater and for posttreating humidity condensate and urine distillate. These are discussed in detail below.

Ultrafiltration/Reverse-Osmosis Hybrid Subsystem for Recovering Spacecraft Washwater

NASA commissioned Bend Research, Inc., to develop a membrane subsystem to recover and recycle wastewater generated on Space Station Freedom. The membrane subsystem was to be an alternative to the phase-change subsystems under development by NASA. The subsystem developed by Bend Research is a hybrid subsystem that combines ultrafiltration (UF) and reverse-osmosis (RO) membrane technology to recover washwater.

Of the various wastewater streams that will need to be recycled aboard the space station, washwater will be the largest. NASA estimates that each crew member aboard the space station will generate approximately 27 kg/person-day of wastewater. Of that volume, 22 kg/person-day is expected to be washwater (*3*). NASA is funding the development of at least three wastewater-reclamation subsystems that are based on a phase change of water and subsequent condensation of the purified water (*4–6*). This technology works well for the reclamation of smaller-volume wastewater streams that contain concentrated contaminants. However, the weight and complexity of subsystems based on this technology may make them less than ideal for processing larger-volume streams such as washwater.

Based on the volume of wastewater involved, the subsystem to recover washwater must 1) render a high percentage of the water reusable, 2) produce water that meets NASA's water-quality standards for recovered water, 3) be reliable, 4) use a minimum of power, and 5) be lightweight.

In designing the washwater-recovery subsystem, both water-quality goals and recovery goals must be considered. Most of the washwater generated onboard the space station will come from crew members' low-volume showers; thus, it will contain moderate concentrations of soaps and other inorganic and organic contaminants. Table 1 summarizes the composition of raw (untreated) washwater, NASA's standards for recovered washwater, and the quality of water recovered by the Bend Research UF/RO hybrid subsystem.

Our goal is to recover 90% of the raw washwater for reuse. At such a high recovery level, the concentration of soap and other contaminants can be quite high. Therefore, the membrane subsystem we designed had to be both fouling-resistant (because the soap tends to foul membranes) and capable of rejecting high percentages of other contaminants.

Through our development work, we designed a two-stage system. In the first stage, UF is used to remove suspended solids and macromolecules

TABLE 1
Composition of Typical Raw Washwater, NASA Standards for Recovered Water (7), and Quality of Water Based on 90% Recovery by the Bend Research Membrane Subsystem

	Raw washwater	NASA goals	BRI system[a]
Total organic carbon (TOC) (ppm)	230	10	10
Urea (ppm)	360	NR[b]	15
pH	5–7	5–8	6–7
Turbidity (NTU[c])	150	11	<1

[a]Average over 60-day test.
[b]NR = no requirement set by NASA.
[c]Nephelometric turbidity units.

(soap and microbes); in the second stage, RO is used to remove dissolved contaminants. Figure 2 is a schematic of this two-stage UF/RO hybrid system. The first stage employs "inside feed" hollow-fiber UF modules developed at Bend Research. The configuration of these modules is shown in Fig. 3.

The inside-feed flow pattern of these UF modules creates high shear-stress gradients that make the module fouling-resistant. The applied feed-side pressure varies down the length of the first-stage hollow-fiber module due to pressure drop, as shown in Fig. 4. The permeate side of the module in this system is kept at a constant pressure of about 620 kPa (90 psi). Thus, the transmembrane pressure—the driving force for the transport of water across the UF membrane—also varies down the length of the module. This variation is also shown in Fig. 4. Notice that transmembrane pressure is positive at the feed inlet to the module and negative at the reject outlet of the module. This means that water flows through the membrane from the inside of the fibers to the shell side at the entrance to the module and in the opposite direction at the exit from the module. Near the middle of the module, the transmembrane pressure is zero. At this point there is no net transport of fluid across the membrane.

Membrane fouling occurs only where transmembrane pressure is positive. This simple fact has an important implication in designing a UF module system that resists fouling: by reversing the direction of feed flow down the fiber lumen—i.e., by switching the module so the feed and reject ports are reversed—the part of the membrane that was previously subject to fouling now has a negative transmembrane pressure and is cleaned by backflushing. Through flow-reversal, fouling in the first-stage UF modules can be nearly eliminated.

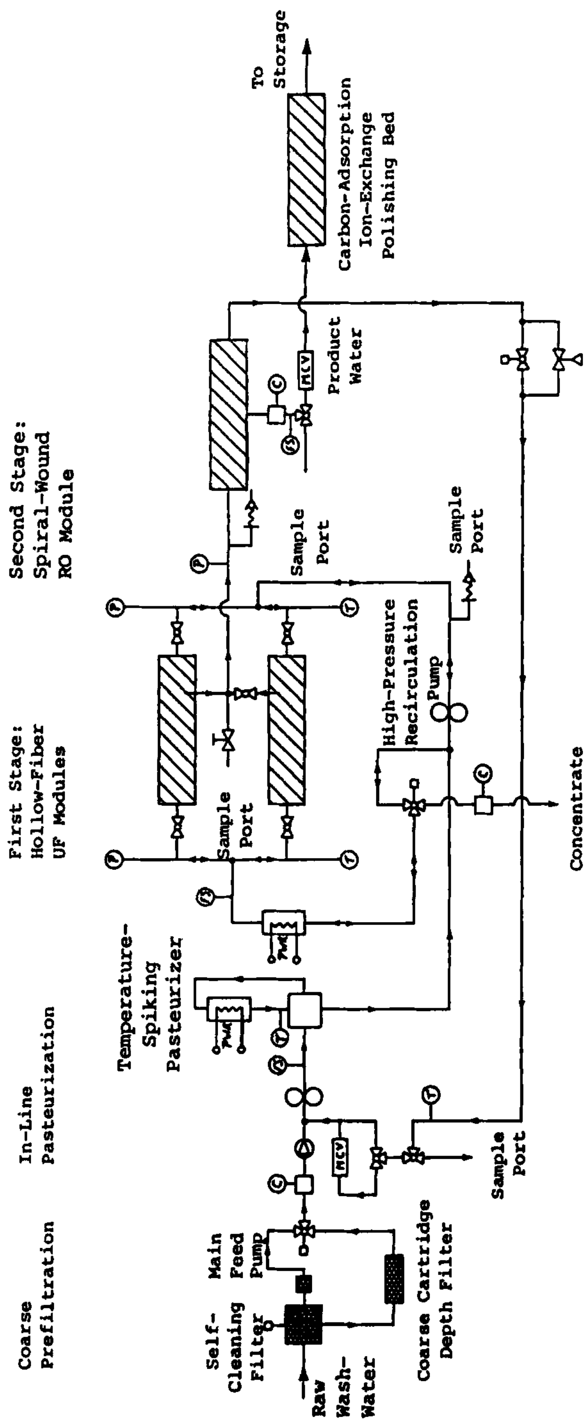

FIG. 2. Final design the Bend Research UF/RO hybrid system for washwater recovery.

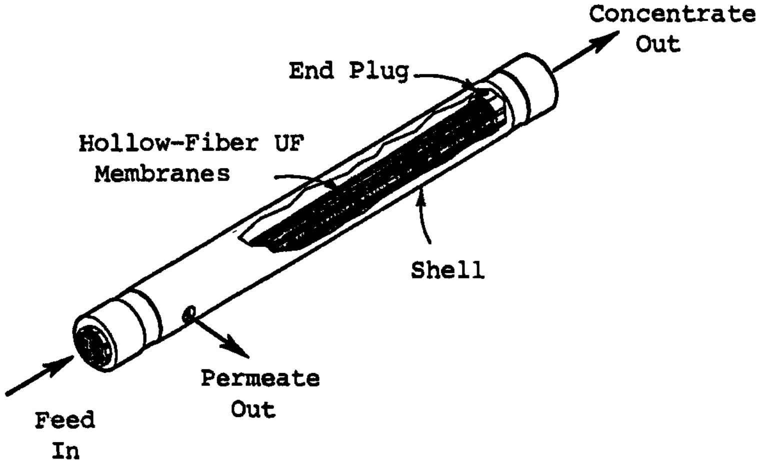

FIG. 3. Inside-feed hollow-fiber UF membrane module developed at Bend Research.

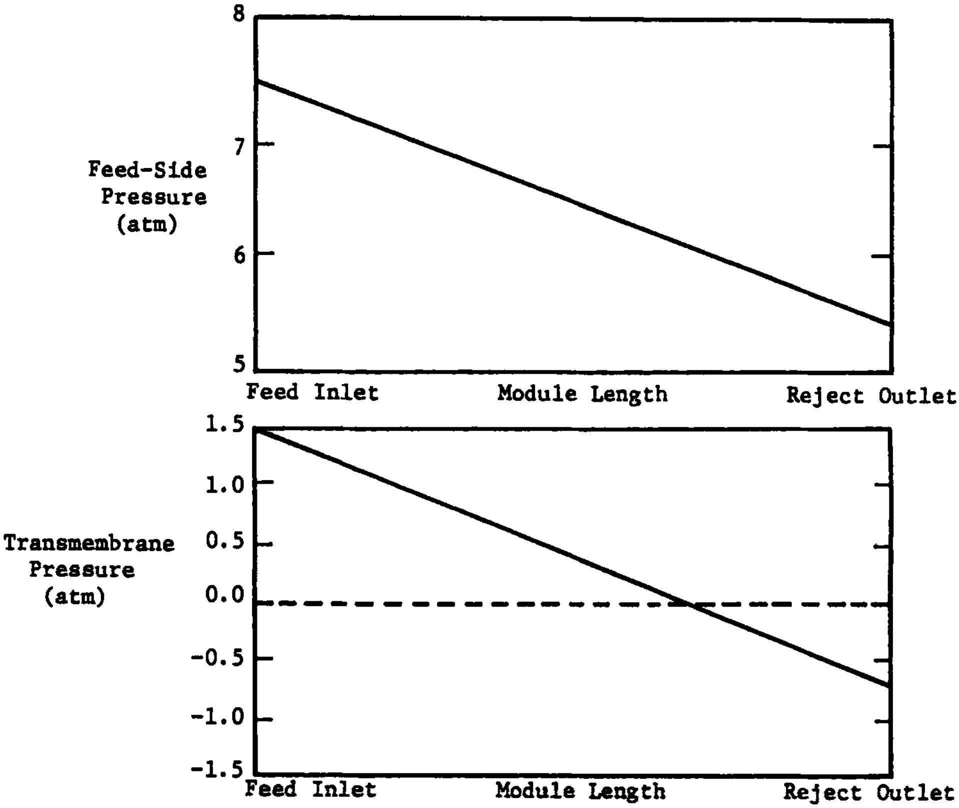

FIG. 4. Pressure profiles in the first-stage UF module.

The spiral-wound RO module in the second stage of the two-stage membrane system is used to remove the dissolved contaminants from the permeate of the first-stage UF modules. Figure 5 is a drawing of a spiral-wound RO module. Such modules can be fouling-prone because of the various spacers used and because of the tortuousity of the feed path. However, because the contaminants that tend to foul membranes have been removed from the feed by the first-stage UF modules, a spiral-wound RO module is ideal for removing the dissolved contaminants that remain in the first-stage permeate. Thus, our two-stage design capitalizes on the best characteristics of each type of module and allows each to be optimized separately. The water produced by the hybrid UF/RO subsystem contains only trace contaminants, which are removed by a polishing bed that contains activated carbon and ion-exchange resins. Table 1 shows the quality of water the membrane system produces before the water is polished.

This UF/RO hybrid subsystem was designed, tested, and optimized. A long-term test at Bend Research demonstrated the system could treat batches of raw washwater every day for as long as a year. The system was shipped to NASA's Johnson Space Center (NASA-JSC, Houston, Texas) for further testing. The test, which ran for 60 days, was managed for NASA by Hamilton Standard (a division of United Technologies, Inc., Windsor Locks, Connecticut); the water quality was monitored by NASA personnel. Washwater for the test was actual shower water supplied from an experimental program conducted by NASA.

Figure 6 shows the permeate-flow rate (productivity) of the system during that test. As these data indicate, the productivity of the unit remained

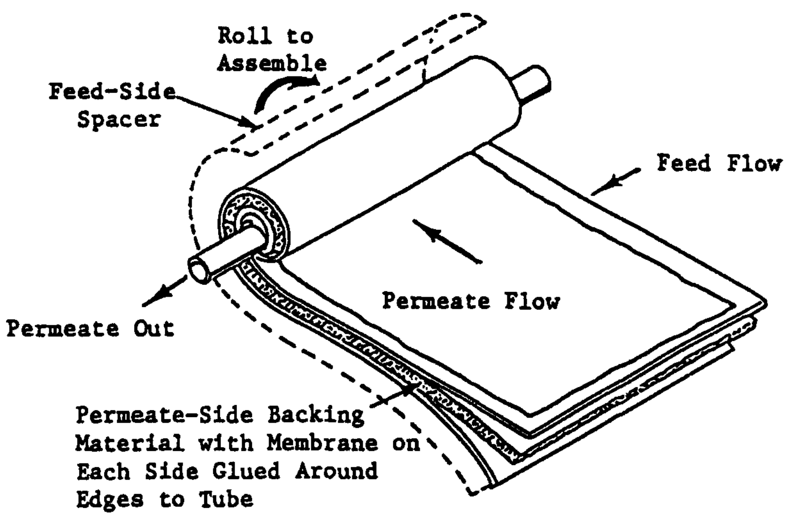

FIG. 5. Spiral-wound RO module.

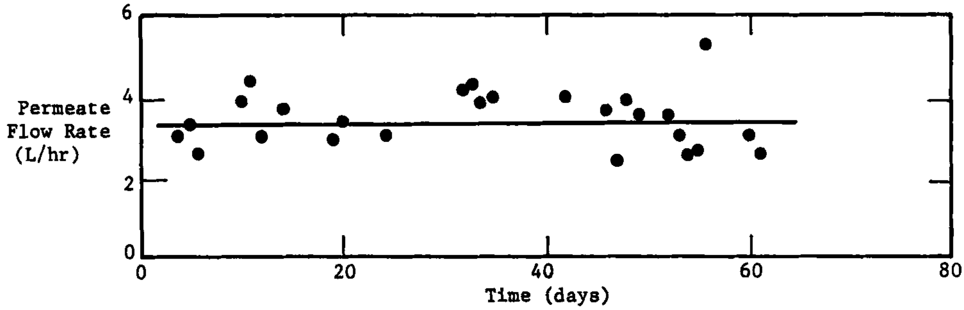

FIG. 6. Permeate flow rate as a function of time. Test conditions: Actual washwater generated at NASA-JSC, 95% recovery.

within the same range for the entire 60 days, implying that any fouling that did occur did not significantly affect productivity. During the long-term test, flow-reversal was used to continuously backflush the modules, minimizing fouling.

High-quality water was produced by the two-stage system throughout the test, as indicated by the data summarized in Table 1 and the plots of TOC and conductivity shown in Figs. 7 and 8. As Table 1 indicates, the

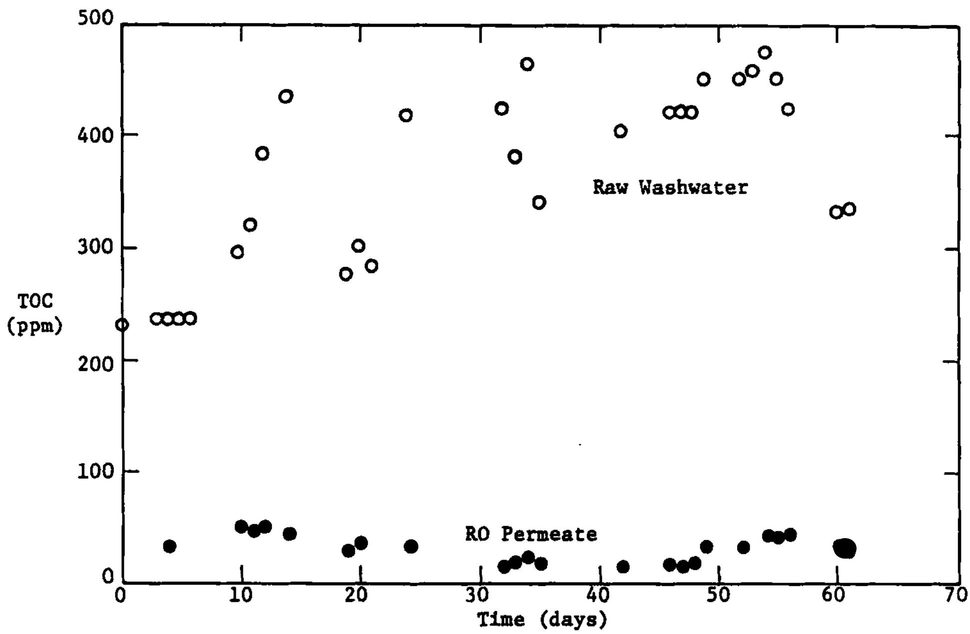

FIG. 7. TOC of the raw washwater and the RO permeate throughout NASA's 60-day test. Test conditions: Actual washwater generated at NASA-JSC, 95% recovery.

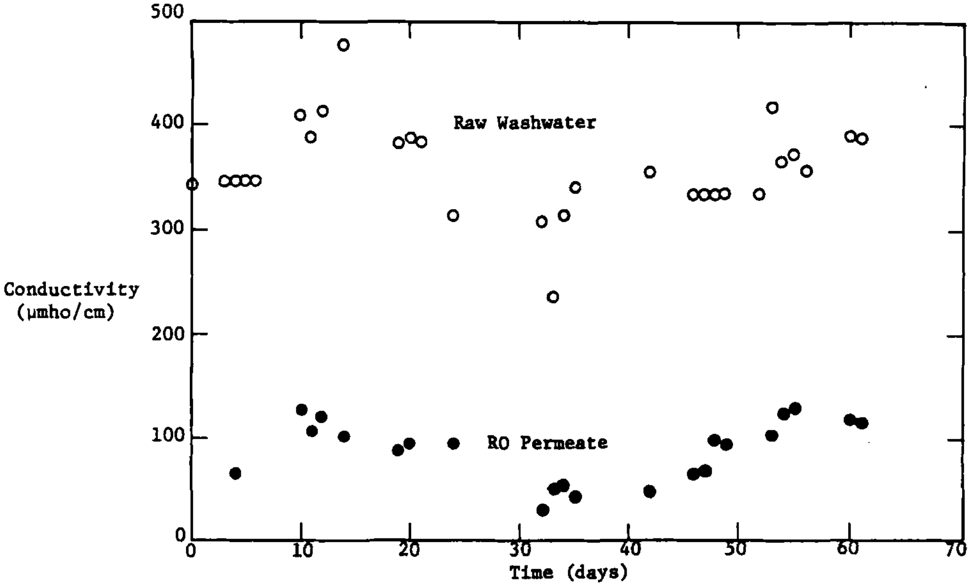

FIG. 8. Conductivities of the raw washwater and the RO permeate throughout NASA's 60-day test. Test conditions: Actual washwater generated at NASA-JSC, 95% recovery.

system met the water-quality standards set by NASA for reusable washwater. In fact, as part of the test at NASA, water produced by the system was reused as shower water three times, each time meeting NASA's water-quality standards.

In addition to meeting design requirements for water quality and fouling-resistance, the Bend Research UF/RO subsystem proved superior to competing subsystems in terms of weight and energy consumption. Table 2 compares the weight and power requirements for the Bend Research

TABLE 2
Estimated System Weights and Power Requirements for Subsystems to Recover Washwater

Subsystem	Estimated system weight (kg)	Estimated power requirements (W·h/kg)
Thermoelectric integrated membrane evaporation subsystem (TIMES) (*8*)	55	180
Vapor compression distillation (VCD) subsystem (*9*)	36	80
Bend Research UF/RO hybrid subsystem	40	18

subsystem to those of the flight-qualified subsystems developed by NASA for which equivalent information is available.

Based on the results of these tests, on the estimates for weight and power requirements, and on the results of other tests performed after these original studies, NASA has designated this system as a "baseline" system for use in the Space Station Freedom. We continue to receive funding from NASA to improve the components of the system and to optimize the procedures for long-term system operation.

A Membrane Posttreatment System for Production of Potable Water

In addition to washwater, wastewater generated aboard the space station will come from two other main sources: humidity condensate and urine distillate. These two wastewater streams will be generated by the subsystems NASA has selected to control humidity (produced by respiration and perspiration) and to treat urine. Bend Research has developed a hybrid membrane system to produce potable water from the water produced by these two subsystems.

Typical compositions of humidity condensate and phase-change distillate are shown in Table 3. Also shown in the table are NASA's goals for potable water. Systems for treating humidity condensate and phase-change distillate must be lightweight, efficient, capable of recovering a high percentage of the wastewater, and must require a minimum of consumables and expendable components.

NASA is developing a conventional posttreatment system that is based on sorption of the contaminants in humidity condensate and phase-change distillate onto various solid sorbents. Although this "multifiltration" sorbent system is effective, the sorbents must be resupplied. The system developed at Bend Research combines the use of a membrane and sorbent beds. The resulting hybrid system uses less sorbent than is used by the conventional multifiltration system. In this section, background informa-

TABLE 3
Composition of Typical Humidity Condensate and Phase-Change Distillate and NASA's Goals for Potable Water (*3*)

Item	Humidity condensate	Phase-change distillate	NASA's potable-water goals
TOC (ppb)	200,000	40,000	<500
Conductivity	Variable	Variable	NR
pH	3	3	6–8

tion is provided on the performance of these sorption beds and the operation of the membrane-based hybrid system is described, allowing comparison of the two systems.

Figure 9 is a schematic of the "unibed" sorbent bed that is being developed by Umpqua Research Co. (Myrtle Creek, Oregon) for the multifiltration system. A unibed is a single module containing all of the necessary sorbent media in optimum proportions and sequence. The disadvantage of this sorbent-based concept is that when the sorbent beds become saturated with contaminants, they must be replaced. New beds must be supplied periodically, imposing a resupply or storage burden (*10*).

Sorption of contaminants on sorbents in a unibed (or on other forms of solid sorbent) is governed by isotherms unique to each sorbent. Generally, the loading of a contaminant on a sorbent increases as the concentration of the contaminant in the liquid phase increases; the higher the concentration of the contaminant in the stream to be treated, the greater the mass of contaminant that is adsorbed onto a given mass of sorbent. The maximum loading or "saturation" of a unibed therefore increases as the concentration of contaminants increases. Thus, a unibed that has reached saturation during treatment of a dilute stream can be reused to treat a stream in which contaminants are more concentrated. The unibed will then sorb contaminants until a new higher saturation level, corresponding to a higher concentration of contaminants, is reached.

Unibeds are typically connected in series. Because the concentration of contaminants is greatest when the feed stream enters the unibed series, the sorbent bed that is first in the series (at the influent end) will operate at the maximum loading level. When this bed reaches saturation, it will be removed from the series. The second bed will then be moved to the first position, and all other beds will be advanced accordingly. A new bed will then be installed in the last position in the series (at the effluent end). In this "countercurrent" replacement pattern, the useful life of each bed is prolonged by periodically moving the bed progressively toward the influent end of the series to treat portions of the feed stream in which contaminants are more concentrated. In this method, each bed in the series becomes saturated with progressively higher concentrations of contaminants. The beds at the effluent end of the series remove lower concentrations of contaminants, but the removal of these residual contaminants improves the quality of the water to meet NASA standards.

Since the concentrations of contaminants in the humidity condensate and phase-change distillate will be low, the amount of contaminants removed by the unibeds will also be low. The membrane/sorption-bed hybrid system developed by Bend Research is designed to increase the concentration of contaminants in the streams fed to the unibeds to increase the saturation

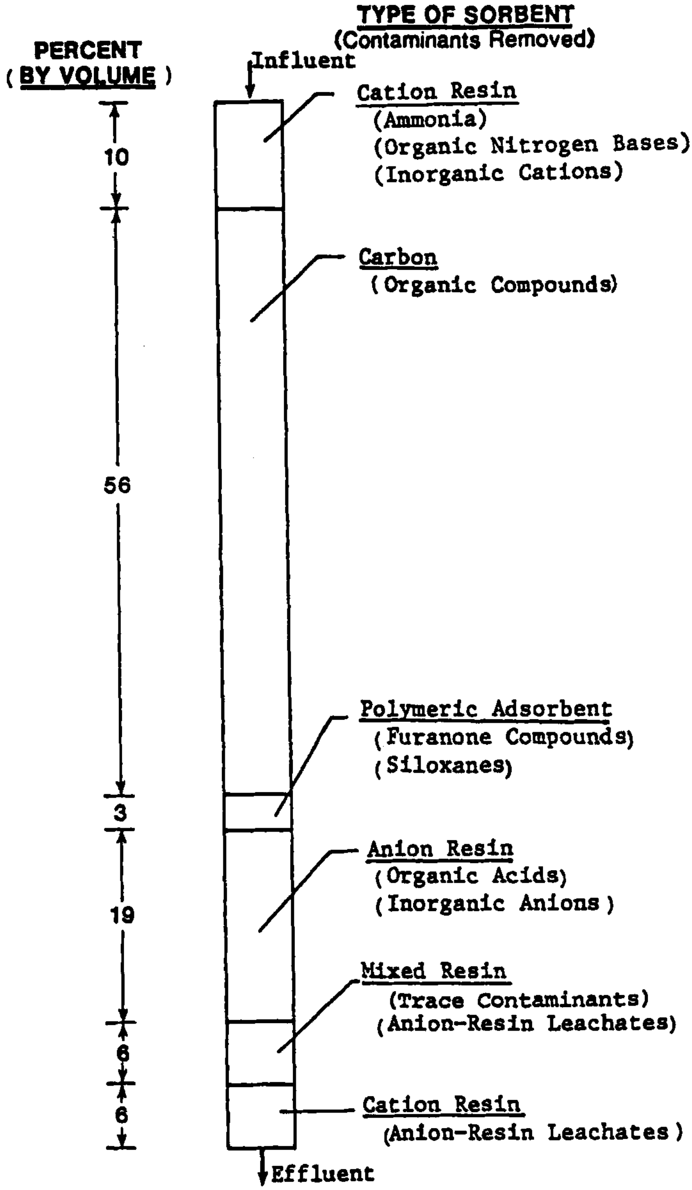

FIG. 9. Optimum unibed configuration for phase-change distillate.

levels of the unibeds. In this way, the unibeds will be used more efficiently and fewer will be needed for a given mission.

Figure 10 shows a schematic of the membrane/sorption-bed hybrid subsystem developed by Bend Research. In this hybrid system, a spiral-wound RO membrane module is used to concentrate contaminants to optimize sorption of contaminants in the unibeds. As the figure shows, the humidity condensate and phase-change distillate are fed to a feedwater accumulation tank, where pH levels and other feedwater characteristics can be adjusted. The feedwater is then brought to operating pressure by a high-pressure pump and fed to the RO module. The retentate from the RO module is recycled to the feedwater accumulation tank and then is recirculated through the RO module. The permeate from the RO module is "polished" by a permeate unibed to produce potable water that meets NASA's current standards.

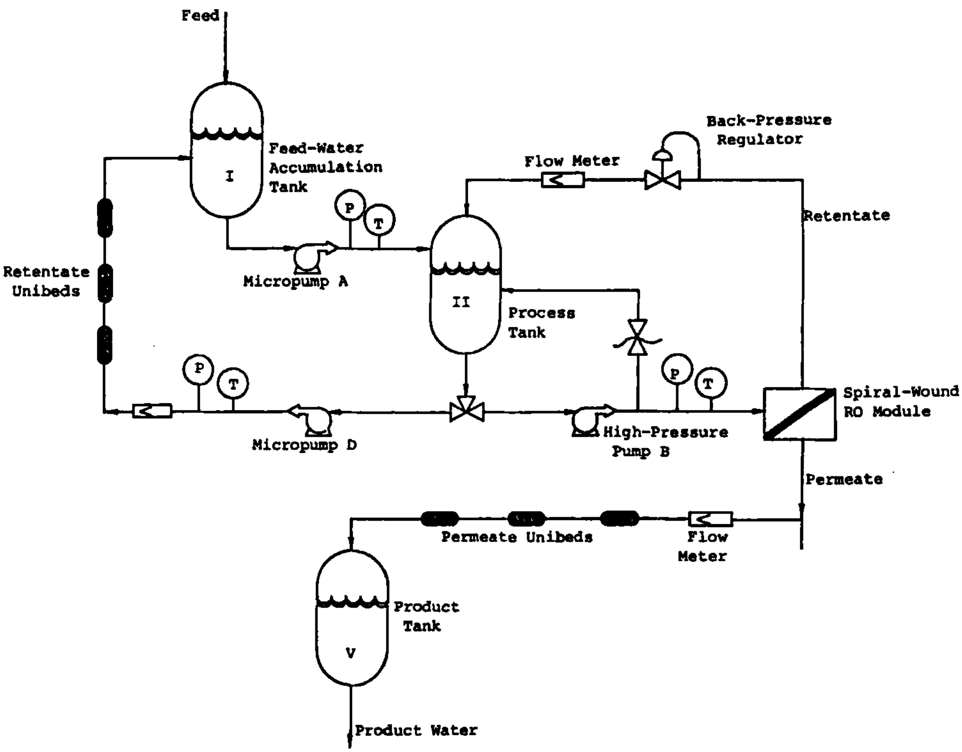

FIG. 10. Bend Research membrane/sorption-bed hybrid subsystem for posttreatment of humidity condensate and phase-change distillate.

After about 95% of the water has been removed from the feedwater accumulation tank and processed, the concentrated solution in the holding tank is passed to a series of retentate unibeds. Because the concentration of contaminants in this stream is about 10 times higher than that of the raw feed, the saturation levels of the retentate unibeds will be much higher than would be possible if the RO module was not used, minimizing the amount of sorbent used to remove a given quantity of contaminant from the feed stream.

When a retentate unibed becomes saturated, it is removed from the system and the remaining retentate unibeds are moved up in sequence. The empty position in the retentate-unibed sequence is filled with a saturated permeate unibed. The permeate unibeds are likewise advanced, and an unused unibed is used to fill the empty position in the permeate-unibed sequence.

This membrane/sorption-bed system was tested for 90 days using an ersatz solution designed to simulate humidity condensate and phase-change distillate. We processed 2052 liters of solution—the volume expected to be generated by a four-person crew in 100 days. Figure 11 shows the TOC concentration of the feed, RO permeate, and overall permeate throughout the test. These data indicate that the system performed consistently over the test period. However, the water produced by the system contained about 10 ppm TOC—higher than the 500-ppb goal set by NASA. The addition of unibeds to the permeate-unibed series and further optimization

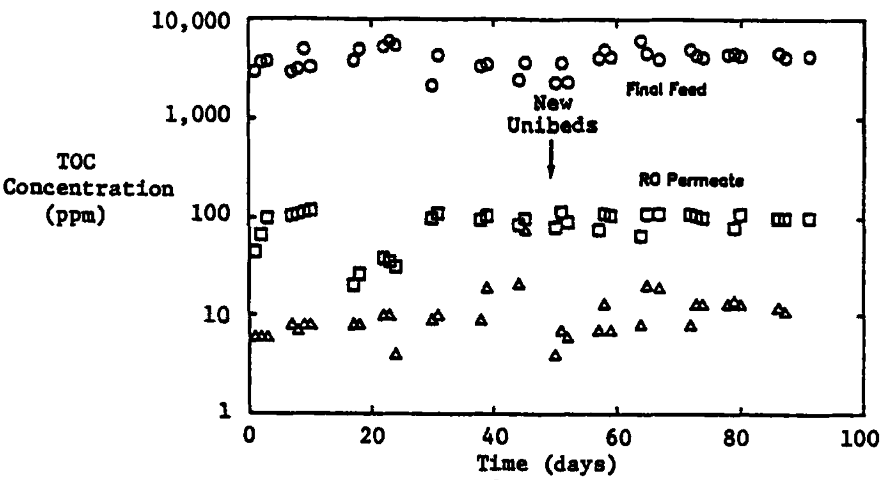

FIG. 11. TOC concentration as a function of time during the long-term test.

of the hybrid system will be required to improve the water quality to meet NASA goals.

Using data from this test, we compared our hybrid design with that of NASA's current multifiltration system. The results of this comparison are summarized in Table 4. As the table indicates, the membrane/sorption-bed hybrid system would require only half as many unibeds as a conventional multifiltration system during a 1-year mission. The hybrid system does use more power, which is factored into the comparison by calculating the system's equivalent weight. A 35% reduction in equivalent weight is estimated if our hybrid system is used.

Future work on this system will include the design of membrane modules with very low operating pressures and low feedside pressure drops to minimize the power requirement. In addition, the unibeds will be optimized for the hybrid application to increase the total loading of the unibeds.

ONBOARD WATER GENERATION FROM MILITARY VEHICLES

Ensuring adequate supplies of water for troops in the field is a formidable problem, given that today's armies must be highly mobile and capable of sustained operation in arid or contaminated environments. It is difficult to carry sufficient water aboard military vehicles to supply troops with adequate supplies of drinking water and hygiene water.

The U.S. Army needs a practical method of producing water in the field, ideally as near the point of consumption as possible. One solution to this critical troop-support problem is to recover water from the exhaust of military vehicles.

Heavy military vehicles burn high-grade fuels such as diesel. Diesel exhaust contains nitrogen, oxygen, carbon dioxide, and water vapor; smaller amounts of carbon monoxide, unburned hydrocarbons, and other impurities are also present (*11*). Slightly more than 1 pound of water vapor is

TABLE 4
Comparison of the Membrane/Sorption-Bed Hybrid Subsystem with Multifiltration

Item	Hybrid subsystem	Multifiltration
Sorbent requirement[a] (kg)	53	105
Power requirement (W)	~50	~0.1
Equivalent weight[b] (kg)	68	106

[a]Based on a 1-year mission duration.
[b]Based on 0.3 kg/W of power.

produced for each pound of fuel consumed by the diesel engine. The idealized reaction is

$$C_{12}H_{26} + 18.5\ O_2 \rightarrow 12\ CO_2 + 13\ H_2O$$

$$(320\ \text{lb diesel/h} \rightarrow 440\ \text{lb}\ H_2O/\text{h})$$

Heavy military vehicles can consume as much as 320 lb/h of fuel (*12*), so recovery of only a small fraction of the water vapor from the diesel exhaust stream could supply enough potable water for a typical crew.

In the early 1960s, the Army conducted a series of experiments that proved the feasibility of using a refrigeration system to condense water vapor from the exhaust gas of internal-combustion engines (*13*). However, the condensate produced was a smelly, oily, turbid fluid that would have required extensive purification to make it potable. The Army abandoned further investigation of this water-generation method, deciding the required purification equipment would be too bulky to carry onboard military vehicles.

Since June of 1984, Bend Research has been working to develop a membrane system for the recovery of water from diesel exhaust. The patented Bend Research process, shown schematically in Fig. 12, solves problems associated with earlier attempts at water generation (*14*). In the Bend Research process, the humid exhaust stream contacts one side of a membrane that is permeable to water vapor and relatively impermeable to other components in the exhaust stream. A vacuum applied to the opposite side of the membrane provides the driving force for transport of the water vapor through the membrane, leaving behind the other gaseous and particulate components of the exhaust stream. The water vapor is then compressed, condensed, and stored in a tank on the vehicle.

The recovered water must undergo a posttreatment step before it meets standards for potable water. However, because most of the contaminants in the exhaust stream do not permeate the membrane, the posttreatment process required is much simpler—and the required equipment is much less cumbersome—than that required for the water-generation system the Army investigated during the 1960s.

The performance requirements for a membrane module for use in this system are formidable. Such a module must have the following characteristics: 1) a high permeability to water vapor, because the available driving force for water-vapor transport is low; 2) a high selectivity for water vapor over the noncondensable gases and the condensable organic contaminants in diesel exhaust; 3) the capability to withstand the high temperatures of exhaust from an internal-combustion engine; 4) a low pressure drop to

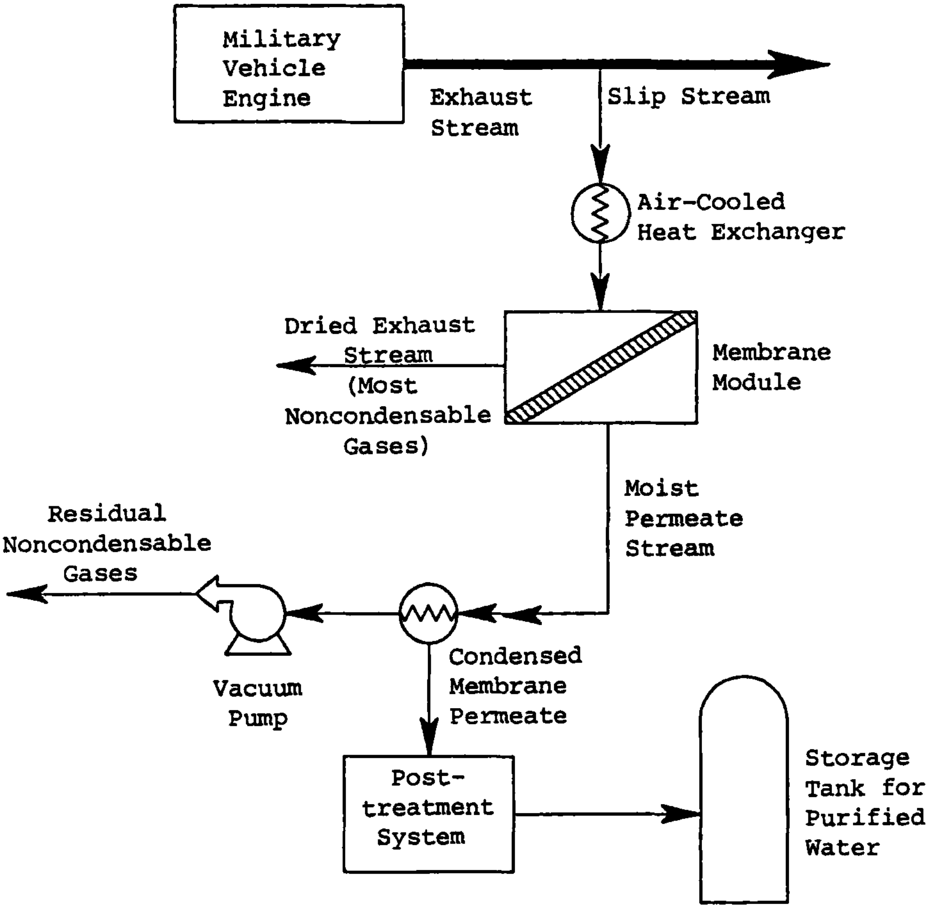

FIG. 12. Schematic of the membrane-based onboard water-generation subsystem.

prevent excessive back-pressure on the engine; and 5) high resistance to fouling by the various particulates and condensates that form in the cooling diesel-engine exhaust.

No commercially available modules were identified that fulfilled these criteria, although we investigated spiral-wound, plate-and-frame, and hollow-fiber modules from many sources. We therefore undertook a module-development program based on adapting our inside-feed UF hollow fibers for this application. The adapted fibers are larger in diameter than are typical UF fibers, and the lumens of the fibers are coated with an interfacially formed, crosslinked polymeric film. A scanning-electron micrograph (SEM) of such a membrane is shown as Fig. 13. When these hollow-

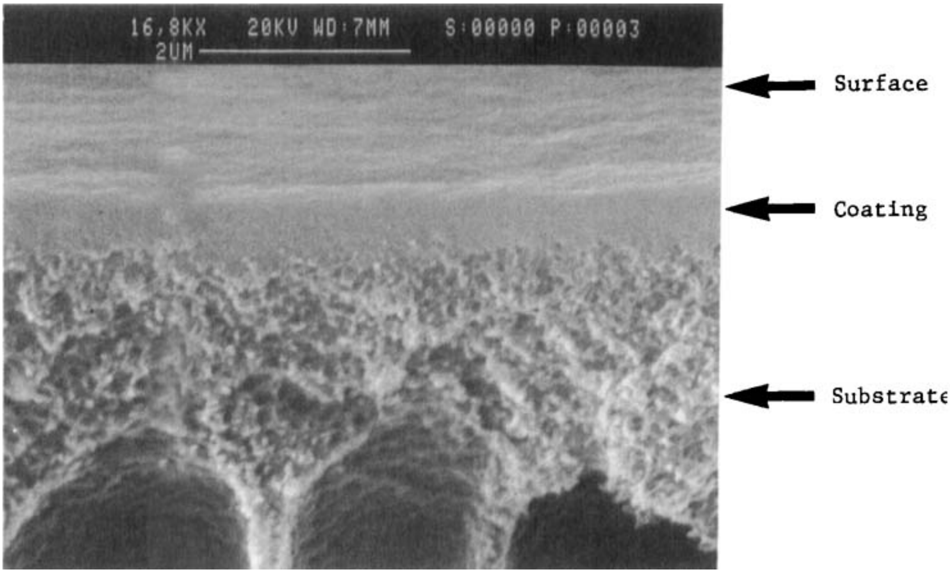

FIG. 13. SEM showing coating layer on top of substrate.

fiber membranes are modularized in the configuration shown in Fig. 3, the resulting modules meet most of the criteria listed above. The inside diameter of these fibers is about 1.5 mm, which is large enough to maintain low back-pressure on the diesel engine when the exhaust stream is fed down the fiber lumens. The relatively high shear stresses on the lumen side of the fibers make them fouling-resistant; temperature- and chemical-resistant materials can be used to give the module at least a two-week lifetime when operated on the hot diesel exhaust. Finally, the support fiber and the coating film can be optimized separately to achieve maximum water flux.

Figure 14 shows the results of a test of membrane modules containing these hollow fibers; the modules were operated for more than 90 h on the exhaust stream from a military-vehicle diesel engine. As the figure shows, the performance of the module is relatively stable, despite the fact that in this test we had little control over the inlet temperature to the module (the feed was cooled by an air-to-air heat exchanger with ambient air). As Fig. 14 also shows, the membrane module produced about 0.2 L water/h/m^2 of membrane—half our ultimate water-production goal of 0.4 L/h·m^2. We are concentrating our current research efforts on increasing the productivity of our fibers.

A comparison of direct diesel-exhaust condensate and membrane permeate indicates that the membrane rejects about 85% of the measur-

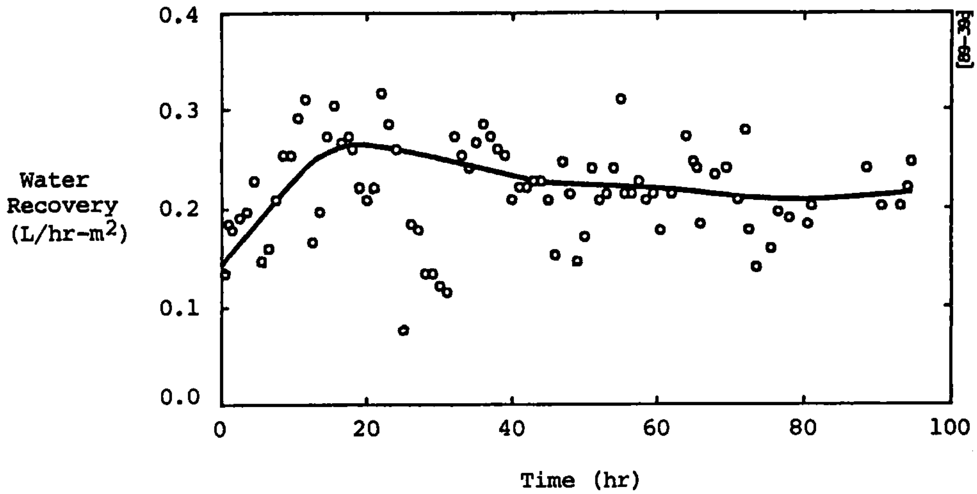

FIG. 14. Water recovery of a hollow-fiber membrane module operating on diesel exhaust.

able organics. Figure 15 shows high-performance liquid-chromatography (HPLC) traces of three water samples. Trace A is that of direct condensate, Trace B is that of condensed membrane permeate, and Trace C is that of Sample B after it has passed through simple posttreatment. The concentration of organics in Trace C is essentially as low as tap water in Bend, Oregon.

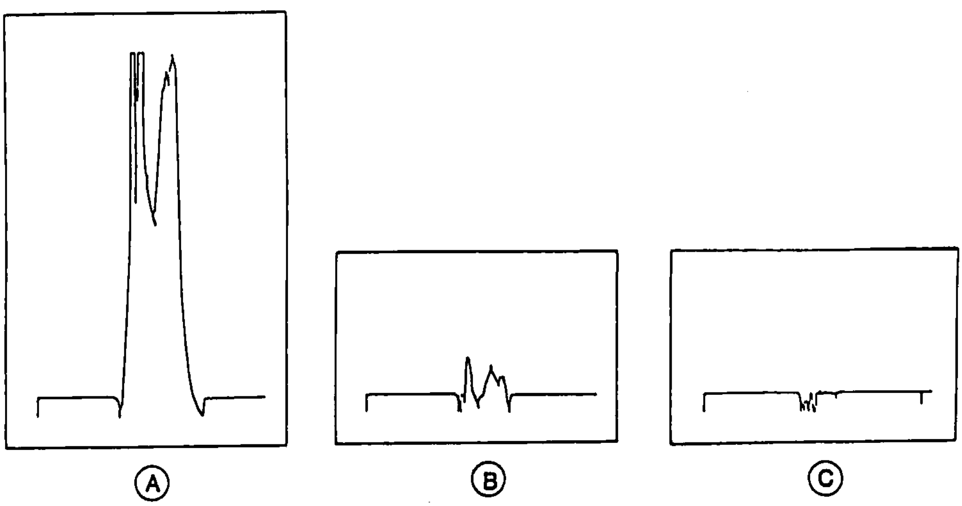

FIG. 15. HPLC traces of (A) direct condensate (diluted 10 times), (B) condensed membrane permeate, and (C) condensed membrane permeate after simple carbon filtration.

Phase III of this program is under way. In this phase, we are optimizing the performance of our hollow-fiber membranes and building a preprototype system for long-term field tests on an actual vehicle. At the end of Phase III, we plan to build a prototype for further testing before the system is procured by the Army.

COMMERCIAL APPLICATIONS

The technologies developed in these three programs and in related programs for other government agencies are adaptable to many commercial separation problems. Table 5 shows a partial list of these applications as they relate to the technologies discussed here.

The hollow-fiber technology used in the washwater-recovery system for NASA has allowed us to solve various wastewater-treatment problems for numerous private clients and several government agencies. Several of these applications are listed in Table 5. We are currently seeking private-sector funding to begin manufacturing hollow-fiber modules commercially for nanofiltration and RO applications. Furthermore, as indicated in Table 5, we hold several U.S. patents in this area.

The posttreatment system designed for NASA is a synergistic hybrid system—i.e., a system in which at least two different kinds of unit operations are coupled in a way that results in much better performance by the hybrid system than can be achieved by either unit operation alone. We have applied this concept to a system for achieving the separation of a natural product, and have delivered an operating pilot plant to a client for use in generating engineering data for the design of a full-scale system. Also, we have developed membranes for treating various wastewater streams, for which this system design makes a given separation possible with an economically viable amount of membrane. A U.S. patent on this hybrid system concept has been allowed.

Our work on the onboard water-generation system has spawned development of a series of hollow-fiber membranes that are ideal for use in dehydrating various gas streams. We are well on our way to introducing our first commercial products in this area.

CONCLUSIONS

At Bend Research, we have solved several challenging and unique separations problems posed by NASA and the U.S. military using novel membranes and innovative membrane systems. The technologies developed in these programs have been applied to several key industrial-processing and waste-treatment problems. Several patents have been issued based on this work.

TABLE 5
Partial List of Spinoff Applications

System	Base technology	Commercial applications	Comments
Washwater recovery	Hollow fibers	Treatment of oilfield wastewater, chemical-plant wastewater, corn steep water, potato processing water, seawater, brackish water, and synfuel wastewater	Fibers covered by U.S. Patent 4,772,391; pertinent coating patents
Posttreatment system	Membrane-based hybrid systems	Production of fine chemicals, separation of natural products, and removal of organics from wastewaters	Hybrid-systems patent allowed
Onboard water generation	Hollow fibers; permselective gas-separation coatings	Dehydration of compressed gas, room dehumidification, and removal of dissolved oxygen from water	Onboard process covered by U.S. Patent 4,725,359

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