

Hollow Fiber Space Suit Water Membrane Evaporator Development for Lunar Missions

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ABSTRACT

The Space Suit Water Membrane Evaporator (SWME) is a baseline heat rejection technology that was selected to develop the Constellation Program lunar suit. The Hollow Fiber (HoFi) SWME is being considered for service in the Constellation Space Suit Element Portable Life Support Subsystem to provide cooling to the thermal loop via water evaporation to the vacuum of space. Previous work [1] described the test methodology and planning that are entailed in comparing the test performance of three commercially available HoFi materials as alternatives to the sheet membrane prototype for SWME: (1) porous hydrophobic polypropylene, (2) porous hydrophobic polysulfone, and (3) ion exchange through nonporous hydrophilic-modified Nafion®. Contamination tests were performed to probe for sensitivities of the candidate SWME elements to the organic and non-volatile inorganic constituents that are expected to be found in the target feedwater source, i.e., the potable water that is provided by the vehicle.

The resulting presence of precipitate in the coolant water could plug the pores and tube channels, thus affecting SWME performance. From this prior work, a commercial porous hydrophobic HoFi was selected that will satisfy both the sensitivity question and the need to provide 800 W of heat rejection.

This paper describes the trade studies, design methodology, and HoFi test data that are used to design a full-size HoFi test article for future testing in the summer of 2009.

INTRODUCTION

A previous study describes the test methodology and planning to compare the test performance of three commercially available hollow fiber (HoFi) materials as alternatives to the sheet membrane prototype for spacesuit water membrane evaporator (SWME), which was used in turn to select the most promising HoFi material for full-size test article development [1]. Since that study, contamination tests have been performed to probe for sensitivities of the candidate SWME elements to ordinary constituents that are expected to be found in the potable water that is provided by the vehicle, which is the target feedwater source. This information is needed because at some point in the SWME mission life-cycle, as the concentrations of non-volatiles increase, the solubility limits of one or more of the constituents may be reached. The resulting presence of precipitate in the coolant water may begin to plug pores and tube channels and affect the SWME performance [2]. The selected HoFi from the commercial off-the-shelf (COTS) tests is the Membrana porous hydrophobic polypropylene configuration that is shown in Figure 1.



Figure 1. Membrana HoFi unit.

SWME Requirements

The SWME requirements to design and test various SWME concepts are taken from JSC-65684 [3].

Functional requirements for the suit thermal subsystem are to provide cooling and thermal regulation to a suited extravehicular activity (EVA) crew member for as many as 8 hours continuously during EVA in vacuum (micro-g), lunar, and Mars environments. For development design purposes, the focus shall be on the lunar design with protection for key design features for the Mars capability. The full Mars functional capability is to be demonstrated in future developments.

A summary of specific SWME requirements follows:

1. Maximum heat load of 807 W (2,754 Btu/hr) at 10°C (50°F) water outlet.
2. Minimum heat load of 81 W (276 Btu/hr) at 24°C (75°F) water outlet.
3. Water flow rate into SWME: 91 kg/hr (200 lbm/hr)
4. Water pressure into SWME: 30–69 kPa (4.2–10 psid) in vacuum EVA environment
5. SWME useful life: 100 EVAs, 8 hours each
6. SWME water quality: the portable life support subsystem shall accept potable water from the vehicle, with and without silver biocide
7. Goals for SWME mass and volume are
Volume: < 2.05 L (< 125 in³)
Mass: < 1.59 kg (< 3.5 lbm)

For the COTS scaled-down test units, the secondary test objectives for each candidate technology were to determine

1. Sensitivity and performance degradation of COTS elements to contaminants that were found in potable water over the required SWME life cycle.
2. Thermal performance of COTS elements as a function of water inlet pressure, exit vapor back-pressure, air bubbles in the inlet water, and the affect of lunar dust in the SWME water inlet.

Detailed descriptions of the tests are presented in the companion ICES paper [2].

Selected HoFi Element from COTS Test Candidates

Figure 2 shows a typical schematic representation of a tubular HoFi unit. For the SWME test application, a vacuum, rather than a dry sweep gas, is pulled on the shell side. Four COTS HoFi units were tested at the NASA Johnson Space Center (JSC) in 2008 [8]. A hydrophobic test article that was made by Membrana [4] was selected for further development as a SWME prototype. This configuration contains polypropylene HoFis with a porosity of 40%. These HoFi units are primarily used to degas water, but they are also used as humidifiers, by evaporation of water through the porous polypropylene fiber. The Membrana unit that was selected is shown in Figure 3, with the outer polycarbonate cover removed for testing to maximize water evaporation to vacuum.

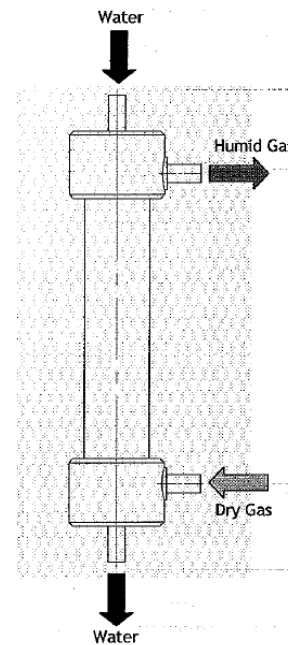


Figure 2. Schematic of an HoFi unit.



Figure 3. Membrana unit with outer cover removed.

To summarize, a Membrana unit with 2,300 HoFi tubes of 40% porosity provided a cooling load of 388 Btu/hr at a flow rate of 28 lbs/hr with no load degradation after 100 simulated EVA cycles using potable water.

DESIGN METHODOLOGY

For the basic HoFi structure, and based on the previous COTS element tests, a Membrana 1.7x5.5 MiniModule baseline fiber COTS source, Celgard X50-215 microporous HoFi membrane, was selected.

Fibers were arranged linearly in a fabric that was spaced 50 per inch (see Figure 4): (a) polypropylene HoFi, 40% nominal porosity, 220- μm internal diameter (b) 40- μm wall thickness, burst strength (min) 400 psi (15.5 kg/cm²) (c) 0.04x0.10- μm pore size.

Fiber was obtained from COTS hardware as an altered item that was, limited to a 7.0-in. exposed fiber length.

Prototype Designs Considered

A brainstorming activity was conducted that made use of the de Bono Six Thinking Hat Method [8]. This process generated 22 SWME arrangement concepts as well as the 19 fiber arrangement concepts.

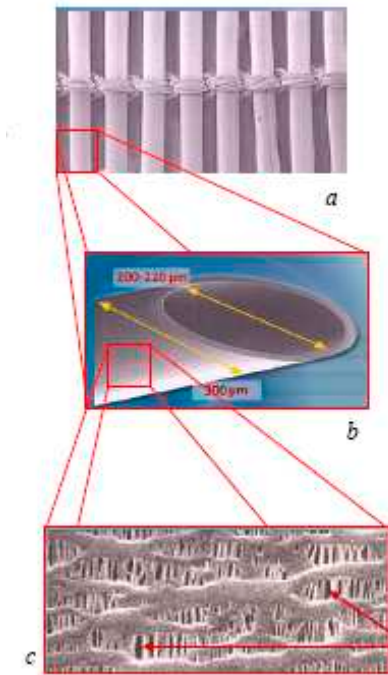


Figure 4. Membrana basic structure.

The major concepts that were generated were broken down into canister layouts and fiber packaging categories. The major canister layout concepts were

- Cylindrical – axial water flow/axial vapor vent (see Figure 5a)
- Cylindrical – axial water flow/tee vapor vent (see Figure 5b)
- Spherical – spherical/radial water and vapor vent (see Figure 5c)
- Inverted Flow – water in a shell, vapor in fibers (see Figure 5d)

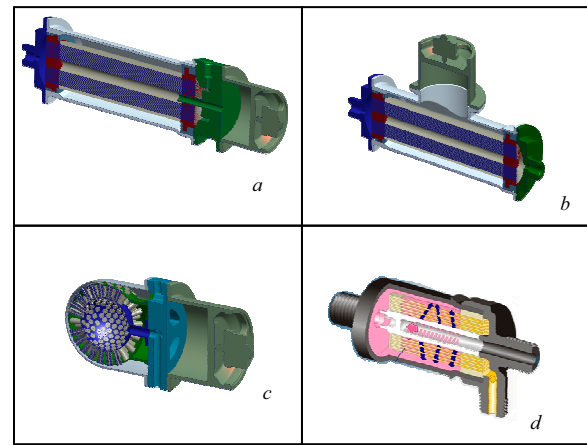


Figure 5. Major canister concepts.

Major fiber packaging concepts were

- Fanned – flat-stacked layers (see Figure 6e)
- Concentric – circular layers (see Figure 6f)
- Layered (S-shaped) (see Figure 6g)
- Radial fiber paths (see Figure 6h)
- Cigar (COTS axial style, spiral wound layers) (not shown in Figure 6)

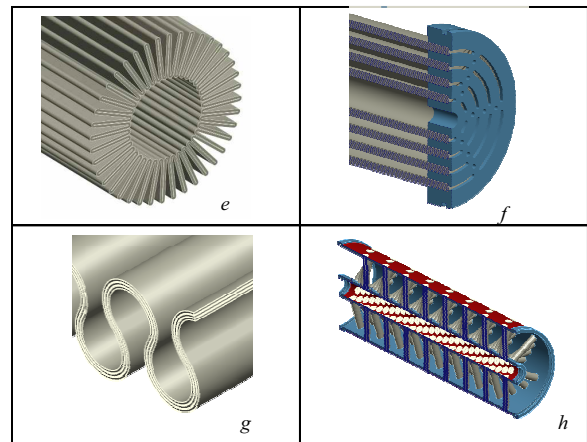


Figure 6. Major fiber packaging concepts.

Baseline Design

The selected SWME HoFi prototype design is an axial flow/axial vent arrangement that, as in Figure 5a, incorporates a stack of fiber layers in an arrangement that is similar to that in Figure 6e.

The benefits and advantages of the selected design include the following:

- The axial flow arrangement, which has a layout that is similar to the sheet membrane SWME design [5,6], is believed to have the fewest packaging impacts of the concepts that were studied.
- The selected design is more representative of the tested COTS product configuration than are

the other concepts, resulting in greater confidence for the TRL4 [Test Readiness Level 4] effort that will reflect successful test data of the Membrana COTS unit.

- The design housing components have a simple manufacturing complexity.
- The cartridge results in linear flow-through spaced elements.
- The design has the best packaging ratio of fiber quantity-to-fiber exposure-to-vacuum.
- The design is moderately simple to manufacture/pot “brick” elements.

Design Optimization from COTS Test Data

Given that the baseline design called for axial flow with stacks of fiber layers, the test data were analyzed to provide design optimization to determine the number of fiber layers per stack, the total number of fibers, and the fiber length that would be optimal in meeting design requirements. A preliminary thermal vacuum test that was conducted with a Membrana unit that had 7,400 HoFi tubes and a diameter of 4.2 cm had approximately the same heat-rejection performance as subsequent tests of the 2,300 HoFi tubes that had a diameter of 2.0 cm and 11.4 cm of length between epoxy headers. Both units consist of a tightly packed spiral bundle of fibers. Although they were rated for a vacuum, the units were not primarily designed for evaporation against a vacuum. The reason that the two units performed similarly may be that water vapor molecules emerging from the tubes that were near the center of the bundle were slow to migrate out of the spaces between the maze of tubes compared to those tubes that were in the outer layers. In the central region, the tubes may be less effective than the peripheral ones because water vapor pressure builds up in the center and reduces the pressure gradient for diffusion.

To find out whether the 2-cm bundle was also hindered by this bundle phenomenon, a test was performed comparing an unmodified unit (0% blocked) to two units with 50% and 90% of the central region blocked with epoxy [2]. The 0%, 50%, and 90% units were estimated to have about 2,300, 1,725, and 437 active fibers. An analysis of test data showed that with input parameters of mass flow equal to 4.813×10^{-6} kg/s per fiber, an inlet temperature equal to 296.10 K (22.95°C (73.32°F)), and an outlet temperature equal to 292.06 K (18.91°C (66.04°F)), the heat transfer per fiber at three different levels of blockage was

$$q_{00} = 0.057 \text{ W}$$

$$q_{50} = 0.067 \text{ W}$$

$$q_{90} = 0.081 \text{ W}$$

The 90% blocked unit, which had active fibers in the outer four layers of the bundle, performed 43% better on average than the average performance of the fibers that were in the unmodified bundle, which had 37 layers. A

design with the same heat transfer per fiber as the 90% blocked unit and 11.4 cm in length between the headers would have about 11,000 fibers to meet the 807-W performance with a 10% margin.

A stack of layers could match the 90% performance if it were composed of eight layers and if both sides of the stack were exposed to the vacuum environment. A sandwich arrangement with gaps between stacks of HoFi sheets that are eight layers thick or less may not perform as well as the 90% blocked unit, however, because the evaporation from one facing side of two successive layers may interfere with the evaporation of the other facing side. To provide a compact arrangement for the SWME, the gap distance would have to be small. It is reasonable to assume that sandwich stacks that consist of eight layers or less would perform better than a 70% blocked unit, which would be equivalent to stacks of 22 layers, provided that reasonable gaps were established between layers. The performance of a 70% blocked unit was, therefore, assumed for separated stacks of eight layers to conservatively determine the number of fibers that would be required to meet design specifications.

An analysis of test data for the 0%, 50%, and 90% blocked data shows that the temperature difference, as a function of the mass, fits well with the following equation:

$$\Delta T = 1.8110 \times 10^{22} \dot{m}^4 - 3.7767 \times 10^{17} \dot{m}^3 + 2.9543 \times 10^{12} \dot{m}^2 - 1.0979 \times 10^7 \dot{m} + 1.7875 f_b + 19.231$$

where f_b is the radial fraction of the blocked fibers. This equation was used to predict the inlet-to-outlet coolant temperature difference as a function of mass flow per fiber of a 70% blocked unit by setting f_b to 0.7, yielding a y-intercept at 20.482). The 70% curve represents the temperature difference across a COTS unit that has 70% of the central fibers blocked and a test inlet temperature of 296.15 K (23°C (73.4°F)). A different inlet temperature would be represented by a different curve because of the performance dependence of the saturation pressure at the membrane-water interface temperature.

The current design goal is a flight unit that has a specified flow rate of 90.72 kg/hr (200 pph) and an outlet temperature that is as cold as 283.15 K (10°C (50.00°F)). The COTS unit has about 0.114 m (4.50 in.) of exposed fibers between headers. It is desirable, as a design exercise, to consider other lengths that would each generate a separate curve for a given inlet water temperature and flow rate.

To add extra margin for the design, 10% is added to the anticipated maximum heat load of 807 W to derive the SWME module design target of 887.7. To balance the 887.7-W heat rate with the specified flow of 90.72 kg/hr, the number of fibers, N, was determined to match each specification. For the mass flow specification, N was determined by dividing 90.72 kg/hr by the mass flow rate per fiber. For the heat rate specification, N was determined by dividing the 887.7 W by the heat rate per fiber.