04ICES-388

Freeze Tolerant Radiator for Advanced EMU

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ABSTRACT

The current Extravehicular Mobility Unit (EMU) system provides thermal control using a sublimator to reject both the heat produced by the astronaut's metabolic activity as well as the heat produced by the Portable Life Support Unit (PLSS). This sublimator vents up to eight pounds of water each Extravehicular Activity (EVA). If this load could be radiated to space, the amount of water that would need to be sublimated could be greatly reduced. There is enough surface area on the EMU that almost all of the heat can be rejected by radiation. Radiators, however, reject heat at a relatively constant rate, while the astronaut generates heat at a variable rate. To accommodate this variable heat load, NASA is developing a new freeze tolerant radiator where the tubes can selectively freeze to "turn down" the radiator and adjust to the heat rejection requirement. This radiator design significantly reduces the amount of expendable water needed for the sublimator. This paper describes the development of this freeze tolerant radiator.

INTRODUCTION

During an ExtraVehicular Activity (EVA) the astronaut's metabolic heat, as well as the heat produced by the Portable Life Support Unit (PLSS), must be rejected. A sublimator currently rejects this heat load, venting up to eight pounds of water each EVA. If this load could be radiated to space, the amount of water that would need to be sublimated could be greatly reduced. The PLSS has enough surface area to radiate almost all of the heat. Unfortunately, a radiator rejects heat at a relatively constant rate, but the astronauts generate a variable heat load depending on how hard they are working. Without a way to vary the heat removal rate, the astronaut would experience cold discomfort or even frostbite.

It has long been known that a radiator can be "turned-down" by sequentially allowing tubes that carry the liquid to the radiator to freeze. The problem with the freezable radiators developed to date is that they are far to heavy for use on a PLSS, because they use heavy construction to prevent the tubes from bursting as they freeze and thaw. This creates the need for a large radiator to reject most of the heat but with a lightweight tube that doesn't burst as it freezes and thaws.

The new freezable radiator for the EMU has features to accommodate the expansion of the water when it freezes, and still have the high tube to fin conductance needed to minimize the number and weight of the tubes. This design maintains all materials within their elastic limits so that large volume changes can be achieved without breaking the tube. This concept couples this elastic expansion with an extremely lightweight, extremely high conductivity carbon fiber fin that can carry the heat needed to thaw a frozen tube. By using almost the entire surface area of the PLSS as a radiator, the system can reject about 50% of the average heat load, and reduce amount of water required for the sublimator by half.

DESCRIPTION OF FREEZE-TOLERANT RADIATOR BENEFITS IN AN ADVANCED EMU

Figure 1 presents a simplified schematic of an advanced Portable Life Support System (PLSS). In this system CO_2, water vapor, and trace contaminants are absorbed from the ventilation gas by a metal oxide sorbent. The heat of absorption, as well as the heat directly removed from the astronaut's Liquid Cooling Garment (LCG), is carried away by a water loop to the heat rejection system. The metabolic heat load, as well as the heat generated by the PLSS is rejected to space by a sublimator, which evaporates water. Weighing in at 3.48 pounds, the sublimator itself is light, but the water tank weighs an additional 4.4 pounds, and the water weighs 8 pounds, for a total of 15.9 pounds [1]. With this system, at roughly

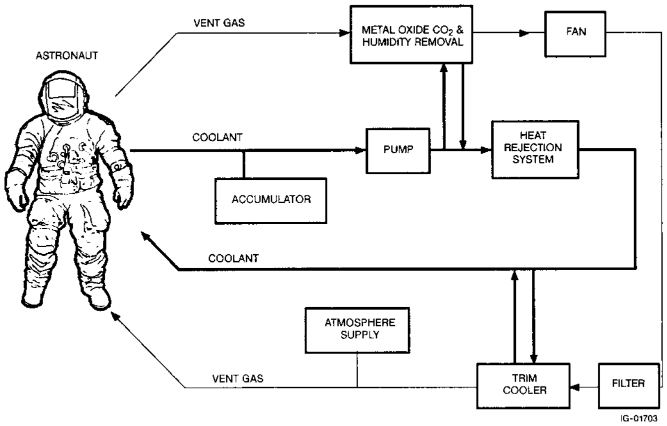

Figure 1

1000 Btu/lb, 6 to 8 lbs of water are sublimated (evaporated and lost) during each EVA. On extended missions this is an unacceptably large loss. It is reported that the sublimator water loss is the single largest expendable in the current EMU [2].

RADIATORS TO REDUCE EXPENDABLES IN AN EMU - Using a radiator to reject the EVA heat load can greatly reduce the use of water in the sublimator. The radiator will also serve as the shell of the PLSS. Thus, the fins of the radiator will serve two functions: 1) thermal (to transfer heat) and 2) structural (to cover the components of the PLSS and protect them from damage by micrometeoroids or accidents, such as collisions with spacecraft or the item the astronaut is working on). This approach minimizes the weight penalty for the radiator and saves PLSS weight.

While the advantages of radiators have long been recognized (they can operate effectively in earth orbit, trans-lunar, trans-Martian, and in most lunar and Mars environments), they have a problem that has so far prevented their use: current simple designs reject heat at a relatively steady rate, but the rate of heat generation by the astronaut is highly variable. This is unacceptable, as it would literally result in the astronaut suffering both heat stroke and frostbite. Figure 2 shows a heat rejection profile for an EVA, which ranges from 350 Btu/h to 2000 Btu/h. In addition, thermal loads from the PLSS and heat gains and losses from the environment further extend the range, potentially decreasing the total thermal load by -100 Btu/h or increasing it by as much as 500 Btu/hr [3]. The total range is from 250 Btu/h to as much as 2500 Btu/h, a turndown ratio of 10:1. Given the relatively small temperature range in which the EMU operates (40°F to 75°), reducing the radiator temperature has little effect on heat rejection unless the radiator area is reduced (e.g., by freezing one or more tubes) or thermal resistance is increased. A previous approach to design a radiator with variable heat rejection, was to use a gas gap between the radiator plate and water loop [4]. The gas gap is normally filled with low pressure gas to facilitate heat transfer, however when the gas is evacuated the radiator heat rejection can be reduced. This radiator weighted 9.1 kg and rejects a maximum of 420 BTU/hr. It could be turned down to 310 BTU/hr. This design allowed some adjustment to the rejection rate, but the turn down ratio is not has high as desired. Another approach if to use only a small portion of the radiator area (3 ft^2) to reject about 250 BTU/hr [5]. A heater is used to moderate the temperature in the low load case. This radiator design reduces the amount of expendable sublimator water some, but does not take full advantage of the radiator area.

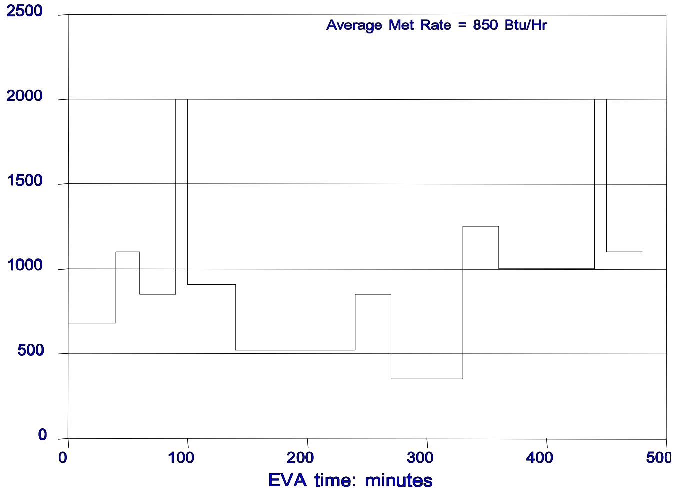

Figure 2. Nominal metabolic profile (BTU/h)

Because the area of the PLSS is limited, the maximum amount of heat that can be rejected by a radiator will probably be less than the highest heat generation rate, so a small sublimator will always be needed. However, just a small amount of heat is generated during these episodes, the sublimator weighs only a few pounds, and just a small amount of water is lost when it is used. Thus, the real question is how to "turn-down" the heat rejection rate of the radiator to keep from freezing the astronaut when he/she is resting and generating little heat. The heat rejection rate of a radiator can be controlled by selectively freezing some the tubes. If the tubes that supply heat to the radiator freeze, the section being supplied becomes inactive.

BASELINE ASSUMPTIONS - To be useful in advanced EVA, the radiator must be a part of the advanced EMU designs. Based on studies at NASA-JSC it was assumed that advanced PLSS has the dimensions shown in Figure 3. The available area is 9.2 ft^2 when all of the PLSS panels are used to reject heat. This area is sufficient to reject half of the average heat load in average conditions.

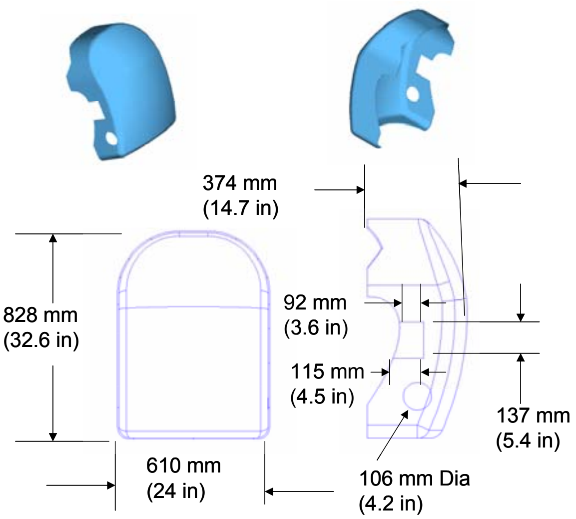

Figure 3. Radiator area layout in advanced PLSS design

To determine the nominal requirements for the radiator on the advanced PLSS, the following data were taken from the 1999 NASA Advanced Thermal Module Preliminary Design Review [5].

The radiator will be needed in many environments. However, because of the wide range of future missions and the many environments involved, the following three conditions we selected for analysis [5]:

1) Average = -20^{o}F
2) Minimum = -174^{o}F
3) Hottest > +110^{o}F (radiator isolated)

Table 1 shows the likely range for the Mars, ISS and shuttle environment temperatures.

Table 1. EVA Thermal Environment & Comparison to LEO.

	Hot	**Nominal Cold**	**Cold**
Mars Atmosphere	**65 to 80 F**	**-120 to –50 F**	**-180 to –155 F**
Mars Radiation*	**15 to 25 F (suit)** **-5 to 20 F (rad.)**	**-80 to –50 F (suit)** **-150 to –90 F (rad.)**	**-190 to –100 F (suit)** **-190 to –140 F (rad.)**
EMU ISS	**110 F**		**-169 F (night pass)**
EMU Shuttle PLB	**220 F (PLB-Sun)**	**-60 to 30 F (PLB-Earth)**	**-130 F (PLB-space)**
EMU Experience	**No hot cases**	**Typical**	**Several cold night passes**

The heat load of the PLSS depends on the environment and the metabolic load. The following important cases were identified:

1) Average heat load in the average environment, 600 Btu/h
2) Maximum heat load in the coldest environment, 2,500 Btu/h
3) Minimum heat load in the coldest environment, 192 Btu/h

The radiator must be able to handle this large variability in the PLSS heat loads. Either it must be a very small radiator, which only yields a small saving in expendables. Or it must be large radiator, which can save significantly on expendables, that can be turned down to prevent chilling the astronaut when the heat load is low. Additionally, the radiator must be isolated in hot environments. Otherwise it will experiences large heat gains that will have a high impact on expendables.

HEAT TRANSFER FLUID - Water is a safe and proven heat transfer fluid that can be used in the radiator. It has well-characterized, good thermal properties. However, water has a high freezing point at 32 °F (0 °C). The inlet temperature to the radiator is only ~70 °F, which is relatively close to the freezing point. Additionally, the environment can be as low as –174 °F. At these conditions, the radiator tubes can be difficult to thaw once frozen. Water also has large volume change on freezing. The density of water is 1.0 g/cc versus 0.917 g/cc for ice. Because water is an approved heat transfer fluid, it is being used as the baseline working fluid for the radiator analyses and tests.

Because the EMU operates near the freezing point and water has such a large volume change on freezing, any design that will operate with water will also operate with a fluid with a lower freezing point.

Changing to a fluid with a lower freezing point than water would be advantageous in many ways, including:

1) Response times would be faster since fewer tubes would freeze to meet load changes,

2) Volume changes would probably be smaller,

3) Fewer tubes would be required because there would be a larger temperature difference available to transfer heat from a flowing tube to thaw an adjacent tube, and

4) Since tubes in the radiator must be relatively large to minimize pressure drop and pump power (i.e., only 2.5 Psia with a water flow of 200 lb/h is allowed), minimizing tubes will also minimize weight, since the tubes are the heaviest part of the radiator.

Propylene glycol (i.e., antifreeze similar to the ethylene glycol used in cars but much less toxic) is another possibility. DOWFROST* heat transfer fluid contains specially formulated packages of food grade industrial inhibitors that help prevent corrosion. Because propylene glycol fluids have low acute oral toxicity, DOWFROST propylene glycol-based fluid is often used in applications where contact with food or beverage products could occur. The recommended use temperature range is -50 °F (-45 °C) to 250 °F (120 °C).

NASA-JSC conducted a preliminary analysis of the toxicology for propylene glycol, with favorable results.

TDA measured the volume change on freezing for a 60% propylene glycol/ 40% water solution. They first rapidly froze the mixture and sub-cooled it to -200°F, then measured the volume change as it slowly increased in temperature. The volume change was also measured while cooling the mixture from room temperature. On cooling, the propylene glycol/water solution did not solidify until the temperature was minus 150°F or less; on heating, it did not thaw until it was at least -80°F. Two lines are shown in Figure 4. One line labeled “volume change of SS” is calculated based upon the known coefficient of thermal expansion for stainless steel. The second line demonstrates the measured volume change of the propylene glycol solution for the test, and excludes the effect of the volume change in the stainless steel. The volume change of the propylene glycol/water solution between 40°F to –100°F is 3.6 %. This is almost a third less than water which has a 9.05 % volume change in freezing.

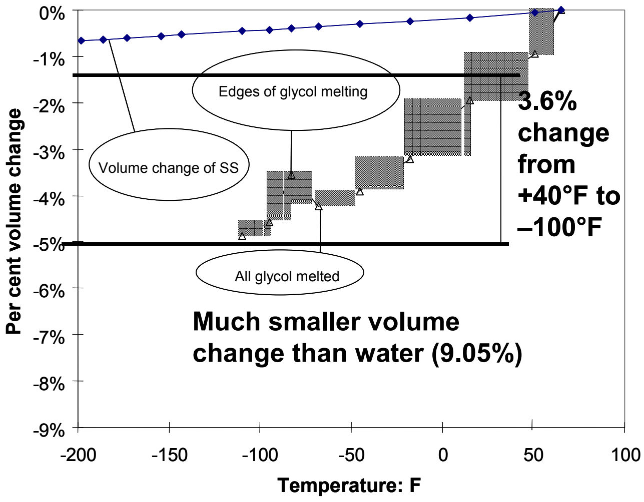

Figure 4. Volume contraction (expansion) upon freezing (thawing) of 60% propylene glycol / 40% water solution.

The propylene glycol solution has several advantages as a heat transfer fluid. It has a smaller volume changes, lower freezing point (~-60°F), is relatively non-toxic, and has good thermal properties. There are a number of issues to be addressed if a new heat transfer fluid is used. Its impact on the remainder of the PLSS system needs to be determined. TDA is continuing to explore issues with compatibility.

FREEZE TOLERANT RADIATOR - TDA has developed a SINDA/FLUINT model of the freeze tolerant radiator to calculate the radiator performance as a function of a wide range of system properties and designs. The model simulates the flow through the radiator tubes, the heat transfer from the fluid to the fin and the heat radiating out to space. An analysis was conducted of a radiator using the propylene glycol solution. A steady state simulation was performed for the three most interesting conditions:

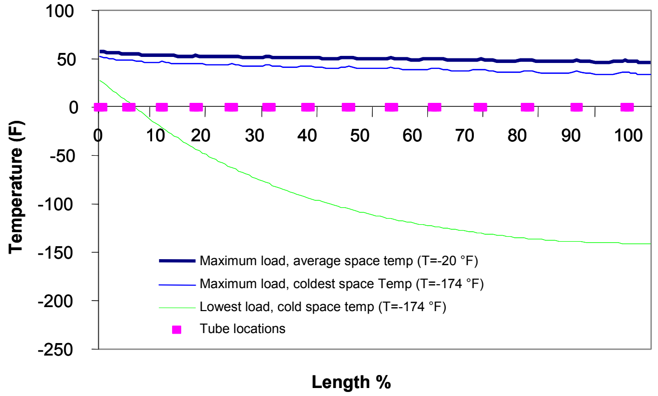

Figure 5. Steady state temperature profiles in the freeze tolerant round tube radiator with propylene glycol/water

1) Maximum heat load in the average environment, 65°F inlet, 247 lb/h
2) Maximum heat load in the coldest environment, 62°F inlet, 247 lb/h
3) Minimum heat load in the coldest environment, 75°F inlet, 32 lb/h

Figure 5 shows the temperature profiles in the radiator fin (back panel of PLSS) at the exit of the tubes. Under the two high load conditions, the temperatures at the exit decrease as one moves away from the non-freezing tube, illustrating the bias needed to selectively freeze. In the lowest load, coldest environment case, the non-freezing tube has a relatively low outlet (>25°F) and the second tube ~ 0°F is still flowing, but all others have very low flow or none at all.

The heat rejection was calculated for these three cases for 9.2 ft^2 radiator:

1) Maximum heat load in the average environment, 458 Btu/h,
2) Maximum heat load in the coldest environment, 804 Btu/h,
3) Minimum heat load in the coldest environment, 127 Btu/h

TDA is exploring using both propylene glycol and water in the freeze tolerant radiator. A summary of the radiator weights is given in Table 2. The water radiator is heavier due to the large volume changes on freezing (i.e. thicker pipe walls) and the large number of tubes to facilitate thawing.

The gross weight values include MMOD, impact protection, thermal insulation, and optical coating. Because of this, there are a number of items on the current shuttle EMU that would not be required with a radiator system. Since the radiator provides all of the MMOD, impact, and thermal protection for the PLSS the following 2.7 kg (6.0 lbs) of items could be removed:

1) Secondary oxygen package cover structure: 0.32 kg (0.72 lbs)
2) Tank cover structure: 0.60 kg (1.33 lbs)
3) Upper shield cover: 0.25 kg (0.55 lbs)
4) TMG (for 5 sides): 1.54 kg (3.4 lbs)

When the weight saving from removing these items is accounted for the net weights of the radiator system are quite reasonable. Table 2. also shows the net weight increase for the PPG and water freeze tolerant radiator designs.

Table 2. Estimated Gross and Net Weights of Freeze Tolerant Radiators

Freeze Tolerant Radiator	Gross Weigh, kg	Net Weight, kg
PPG radiator	4.8	2.1
Water radiator	12.5	9.8

The net radiator weight for the propylene glycol/water solution with freeze tolerant tubes is only 2.1 kg (4.5 lbs). These net weights are further offset by the decrease in the amount of water required for the sublimator. Based on the model, a freeze tolerant radiator can reject about 50% of the total heat rejection requirement in the average case and average environment. Rejection of this heat by radiation reduces the amount of sublimator water by about 1.6 kg (3.4 lb) of water per 8 hour EVA. When the un-needed water for the sublimator is accounted for, the PPG radiator is only 0.5 kg heavier than the current system. Likewise, the net weight of the freeze tolerant water radiator is about 9.8 kg (21.6 lb). This is about 8.2 kg more than the current system when the unnecessary sublimator water is subtracted.

CONCLUSION

The freeze tolerant radiator has potential for improvement in the EMU system. It is relatively lightweight and saves substantial expendables. The extra weight could be recovered in only two to four EVAs. Even lighter weight designs are being considered and the impacts on PLSS for using a propylene glycol heat solution transfer fluid are being evaluated.

ACKNOWLEDGMENTS

The authors wish to acknowledge the funding provided for the research by NASA Johnson Space Center (Contract No: NAS9-03052).

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