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First-order feasibility analysis of a space suit radiator concept based on estimation of water mass sublimation using Apollo mission data

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Abstract

Thermal control of a space suit during extravehicular activity (EVA) is typically accomplished by sublimating water to provide system cooling. Spacecraft, on the other hand, primarily rely on radiators to dissipate heat. Integrating a radiator into a space suit has been proposed as an alternative design that does not require mass consumption for heat transfer. While providing cooling without water loss offers potential benefits for EVA application, it is not currently practical to rely on a directional, fixed-emissivity radiator to maintain thermal equilibrium of a spacesuit where the radiator orientation, environmental temperature, and crew member metabolic heat load fluctuate unpredictably. One approach that might make this feasible, however, is the use of electrochromic devices that are capable of infrared emissivity modulation and can be actively controlled across the entire suit surface to regulate net heat flux for the system. Integrating these devices onto the irregular, compliant space suit material requires that they be fabricated on a flexible substrate, such as Kapton film. An initial assessment of whether or not this candidate technology presents a feasible design option was conducted by first characterizing the mass of water loss from sublimation that could theoretically be saved if an electrochromic suit radiator was employed for thermal control. This is particularly important for lunar surface exploration, where the expense of transporting water from Earth is excessive, but the technology is potentially beneficial for other space missions as well. In order to define a baseline for this analysis by comparison to actual data, historical documents from the Apollo missions were mined for comprehensive, detailed metabolic data from each lunar surface outing, and related data from NASA's more recent "Advanced Lunar Walkback" tests were also analyzed. This metabolic database was then used to validate estimates for sublimator water consumption during surface EVAs, and solar elevation angles were added to predict the performance of an electrochromic space suit radiator under Apollo conditions. Then, using these actual data sets, the hypothetical water mass savings that would be expected had this technology been employed were calculated. The results indicate that electrochromic suit radiators would have reduced sublimator water consumption by 69.0% across the entire Apollo program, for a total mass savings of 68.5 kg to the lunar surface. Further analysis is needed to determine the net impact as a function of the complete system, taking into account both suit components and consumable mass, but the water mass reduction found in this study suggests a favorable system trade is likely.

Keywords: Apollo; Lunar; Extravehicular activity; Space suit; Sublimator; Radiator

1. Introduction

During extravehicular activity (EVA), space suits must collect and remove metabolic heat generated from within the suit by the crew member, waste heat from the suit's electronics, and absorbed heat from the environment. Since the net sum of these heat sources can vary considerably, the space suit thermal control subsystem must be capable of maintaining a reasonably narrow band of internal temperature over a wide range of heat inputs and outputs in order to provide thermal equilibrium for the crew member. Both the US and Russian space suits currently employ a water sublimation process to provide cooling when operating without umbilical attachment to the supporting vehicle.

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This solution involves exposing consumable (feed) water through a porous metal surface to the cold vacuum of space, where it freezes into a thin layer over the sublimator plate (Tongue and Dingell, 1999). As heat rejection is needed, waste heat is transferred to the sublimator through a heat exchanger, causing the ice to sublimate directly to water vapor and vent away from the suit, transporting the waste energy as latent heat of vaporization. Therefore, the sublimator is an “open-loop” technology, meaning that it expends mass that is not recovered.

Both manned and unmanned spacecraft, on the other hand, typically use radiators for heat rejection. Radiators emit waste heat to the environment via electromagnetic radiation by transferring heat to an exposed surface with high infrared emissivity and, therefore, are considered “closed-loop” with respect to mass. Radiators typically provide a steady level of cooling performance, as the amount of heat rejected depends primarily on the environment (sink) temperature, which is predictable in orbit or transit (Gilmore, 2002). For space suit applications, however, the heat load and radiation view factor change almost continuously, making adequate control of radiator cooling a challenging prospect. Common methods of turning down or turning off radiator cooling, including actuated surface orientation, mechanical louvers, and freezable fluid lines, would be less effective and/or likely excessively cumbersome for space suit applications. Also, there is limited surface area for mounting a flat, metallic radiator array on a suit, and previous studies that have focused on the Portable Life Support System (PLSS) backpack as a structural basis for a radiator have found it to offer inadequate surface area for effective cooling (Sompayrac et al., 2009).

Electrochromic materials have properties that can potentially solve both the turn-down and surface area problems that have so far prevented successful application of space suit radiators. By definition, electrochromic materials provide variable optical properties that can be controlled electrically (Granqvist, 1995). In recent years, this technology has also come to include thin-film devices with variable infrared emissivity that can be built onto flexible substrates, such as Kapton film (Bessiere et al., 2002; Kislov et al., 2003). The thinness and flexibility of electrochromics means that they can potentially be integrated with space suit fabric, covering nearly the entire suit, not just the flat PLSS backpack surface. Their variable emissivity control enables electrochromic devices to be used like solid-state thermal flux modulators, with heat emission controlled electronically as a function of the emissivity setting, which is itself a function of the applied voltage (Hodgson et al., 2004).

Due to the expense of delivering mass to the lunar surface, as well as achieving programmatic goals of increasing EVA duration and frequency upon returning to the moon, a reduction or elimination of water consumption for space suit cooling is particularly desirable for lunar missions (Jones, 2009; Nabity et al., 2008). The primary goal of this study was to conduct a first-order analysis of whether electrochromic space suit radiators offer a feasible alternative and/or supplement to water sublimation. As the basic purpose of using such radiators is to reduce water consumption for heat rejection, our initial assessment of the radiators' feasibility was to analyze potential consumable mass savings if they were incorporated into the suit. This was done by using the best available actual surface EVA operational data, namely that of the Apollo lunar missions.

2. Background

The concept of using electrochromics for thermal control was introduced as part of a futuristic design called the Chameleon Suit (Hodgson, 2001; Hodgson et al., 2004). These studies, however, did not isolate the thermal performance of electrochromic technology from the various other technologies employed in the integrated Chameleon Suit concept, nor did they quantify the expected water consumable mass savings for detailed EVA scenarios in specific environments. From this starting point, therefore, we began a series of research tasks aimed at more thoroughly examining the feasibility of this proposed novel application.

Initial approaches for physically integrating electrochromic radiators into existing and future space suits have already been conceptually outlined, with preliminary thermal analysis conducted and emissivity control functions defined (Metts and Klaus, 2009). Theoretical assessment of this concept using assumed environmental boundary conditions and manufacturer product specifications suggested that electrochromic technology would be capable of meeting the heat rejection requirements for lunar missions, pending demonstration of the required electrochromic material performance (Metts et al., 2010). Testing of electrochromic materials for space applications is an ongoing effort, with empirical results and methodologies published for both steady-state, thermal vacuum testing (Bannon et al., 2010) and transient, bench-top testing (Metts and Klaus, 2010). The next step was to examine more practical considerations for assessing the electrochromic technology application for space suits, including potential sublimator water use reduction during operational environmental interactions.

To perform a more detailed thermal analysis of electrochromic radiator performance, realistic metabolic heat load data and lunar surface environmental parameters were needed, ideally coming from the Apollo missions. NASA documents define “average” EVA metabolic rates for mission planning, classified as minimum/nominal/maximum values (Hanford, 2004). These values, however, were not of sufficient resolution to accurately determine the dynamic heat rejection needs over the course of a real EVA. Fortunately, additional unpublished Apollo medical data, recorded by James M. Waligora at the NASA Johnson Space Center between 1972 and 1975, had been compiled and correlated to specific EVA operations by Carr and Newman (2007). This historical dataset includes