# Extravehicular Mobility Unit System-Level Model (SINDA EMU) Usage for Operational Mitigations in Support of US EVA 80

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**During United States Extravehicular Activity 80 (US EVA 80), water was observed in the helmet of an Extravehicular Mobility Unit (EMU) during cabin repressurization. Through a comparative analysis and Test, Teardown, and Evaluation (TT&E) of this EMU, the most likely cause of the US EVA 80 water failure was determined to be sublimator carryover caused by a comparatively high latent load (water vapor production by the crewmember). High latent load can be reduced by the crewmember adjusting the thermal control valve (TCV) setting on the EMU to prevent the onset of significant sweating. To reduce the risk of high latent load leading to water in the helmet, a potential warning system was developed using the Systems Improved Numerical Differencing Analyzer EMU model (SINDA EMU). The goal of this warning system is to alert the crewmember when they are producing a high latent load and recommend adjustment of the TCV to increase cooling. This warning system was designed to ensure high risk conditions are avoided while simultaneously preventing a system that warns the crewmember too frequently. Theoretical tests of the warning system through modeling calculated that if the warning system were used during US EVA 80, the total latent load could have been reduced by up to 33% which would have significantly reduced the risk of water in the helmet. This analysis also investigated the effectiveness of the warning system on EVAs that occurred after US EVA 80.**

## Nomenclature

| | | |
|---|---|---|
| *CCEM* | = | Crew Communication Electronics Module |
| *$CO_2$* | = | Carbon Dioxide |
| *DCM* | = | Display and Control Module |
| *EMU* | = | Extravehicular Mobility Unit |
| *EVA* | = | Extravehicular Activity |
| *HITL* | = | Human-in-the-Loop |
| *ISS* | = | International Space Station |
| *JSC* | = | Johnson Space Center |
| *LCVG* | = | Liquid Cooling and Ventilation Garment |
| *Metrate* | = | Metabolic Rate |
| *NASA* | = | National Aeronautics and Space Administration |
| *PLSS* | = | Portable Life Support System |
| *SINDA EMU* | = | Systems Improved Numerical Differencing Analyzer Extravehicular Mobility Unit |
| *STS* | = | Space Transportation System |
| *TCV* | = | Thermal Control Valve |
| *TT&E* | = | Test, Teardown, and Evaluation |
| *US* | = | United States |

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## I. Introduction & Background

DURING the repressurization phase at the end of United States Extravehicular Activity 80 (US EVA 80) on 23 March 2022, liquid water entered the helmet of the Extravehicular Mobility Unit (EMU) of Extravehicular Crew 2 (EV2). The volume of liquid water was estimated to be between 30-50 $cm^3$. This volume of water covered the front of the helmet visor, potentially disrupting the crewmember's ability to see clearly. Had this volume of water entered the helmet while outside of the crewlock, it would cause significant risk to the mission and crewmember. For this reason, an investigation into the cause of water in the helmet during US EVA 80 was conducted. This investigation also investigated potential risk mitigation methods that could be implemented.

The investigation determined that the most likely cause of water in the helmet during US EVA 80 was integrated performance induced sublimator carryover caused by a comparatively high latent load. Figure I-1 shows a simplified schematic of the ventilation loop to help explain sublimator carryover. During an EVA, the crewmember adds water vapor to the ventilation loop through respiration, diffusion through the skin, and sweat evaporation. The latent heat added to the ventilation loop through the evaporation of water is also called the latent load. The humidity added to the gas by the crewmember leaves the suit and enters the Portable Life Support System (PLSS). In the PLSS, the gas passes through a sublimator which cools the gas, causing liquid water to condense out. The sublimator contains small holes called slurper holes, which were designed to remove the liquid water from the sublimator. However, if the slurper holes aren't able to remove all of the liquid water, some water may move downstream of the sublimator towards the helmet. This liquid water is called sublimator carryover.

The amount of sublimator carryover depends on the latent load and the efficiency of the sublimator's ability to remove liquid water. Through a comparative assessment of historical EVAs, it was determined that US EVA 80 had a high latent load compared to previous EVAs which did not present water in the helmet[1]. The comparative assessment also found that other historical EVAs with high latent loads often presented some form of sublimator carryover. For this reason, it was determined that the water in the helmet during US EVA 80 was most likely due to sublimator carryover caused by an elevated latent load. Further evidence from the Test, Teardown, & Evaluation (TT&E) of the EMU confirmed that there were no individual components performing below specification, which implies that the water was caused by the integrated performance of the EMU rather than an individual component failure. Latent load is an important factor when it comes to the risk of water in the helmet since a high latent load results in an increased likelihood of sublimator carryover that may eventually enter the helmet.

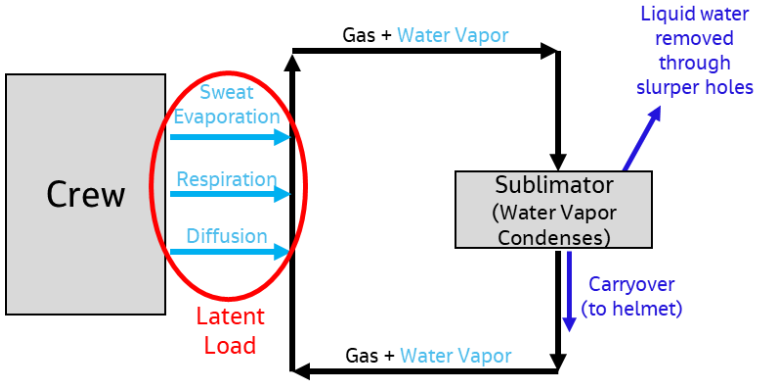



**Figure I-1: Simplified Diagram of Interactions Between Crew and Ventilation Loop**

The simplest way to reduce the latent load experienced during an EVA is to reduce the sweat produced by the crewmember. When the temperature of the body increases, it produces sweat to remove the excess heat that is stored by the crewmember. Increased sweating results in increased evaporation into the gas and a higher latent load. Figure I-2 shows the results of a parametric analytical study on the impact of crewmember heat storage (measurement of deviations in body temperature from thermal neutrality) on total latent load generated during a 7-hour EVA[1]. At negative and neutral heat storage levels, the latent load does not depend significantly on heat storage. This is because at negative heat storage levels, the body is not producing significant amounts of sweat. Once the crewmember heats up into the positive heat storage range, the latent load begins to increase rapidly due to the initiation of sweating.

The thermal comfort of the crewmember is maintained by the transport loop of the PLSS which flows cooling water through the Liquid Cooling and Ventilation Garment (LCVG) of the crewmember. The crewmember adjusts

the temperature and flowrate of this liquid water by adjusting the Thermal Control Valve (TCV), a manual valve located on the Display and Control Module (DCM) of the suit. The TCV settings are H,0,1,2,…,9,10,C with lower settings indicating less cooling being provided to the crewmember. The status of the TCV setting is not monitored and is only available when the crewmember calls down adjustments during an EVA or as they recall settings after the EVA is completed. The EMU contains enough cooling capacity to maintain a crewmember at a thermally neutral condition, however maintaining neutral heat storage requires manual adjustments by the EVA crewmember, which requires predictive action and focus on thermal comfort while performing complex activities. It may also be difficult to adjust the TCV when performing particular tasks. Since a crewmember will never be able to perfectly maintain a perfect thermal neutrality, a warning system that would alert the crewmember when they reach elevated heat storage (and subsequently latent load) could be a critical tool in reducing the risk of sublimator carryover.

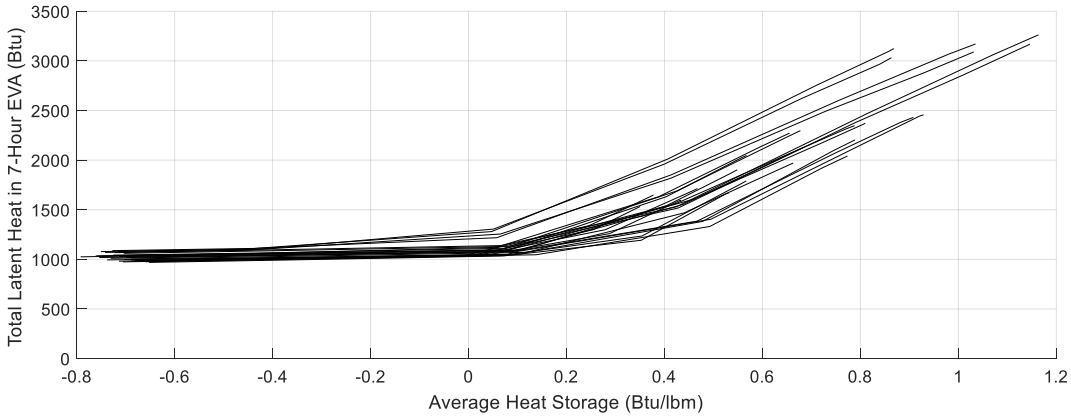



**Figure I-2: Total latent load that would occur in a 7-Hour EVA based on crew heat storage. Each line represents a specific EVA that was modeled assuming different crew heat storage.[1] Crew mass was another unknown in this assessment, so each EVA consists of two lines which represent runs with different mass.**

The goal of this analysis was to use the lessons learned from the comparative assessment of EVAs to develop an operational tool that could be used to assess the latent load of a crewmember during an EVA. This tool could then allow for the crewmember to be alerted if the latent load is calculated to be high enough to cause significant risk of water in the helmet. This analysis will be primarily based on determining appropriate limits to quantitatively assess the risk of water in the helmet and determine if mitigations taken by the crewmember in response to a high latent load are effective. This analysis will also assess the performance of the warning system on EVAs conducted since US EVA 80.

## II. Model Description

The Systems Improved Numerical Differencing Analyzer EMU (SINDA EMU) model was used to calculate the latent load for numerous EVAs. SINDA EMU models the crewmember and PLSS, connecting the two subsystems through flow of gas and cooling water in and out of the suit. SINDA EMU models all flow paths through the PLSS, which allows it to accurately calculate the temperature of the water, temperature of the gas, and dew point of the gas. The PLSS model accurately captures the impact of the crewmember adjusting the TCV by modeling the various flow paths through the PLSS. The crewmember side of the model accounts for the metabolism of the crew, sweat generation, and heat transfer to the LCVG and through the suit walls. This model allows for the conditions of US EVA 80 (and any other EVA) to be modeled. Additionally, it allows for theoretical changes to EVAs, such as adjusting the TCV, to be modeled. SINDA EMU was initially developed in the 1970s[2,3], and has since been improved and re-correlated through improvement of the crewmember modeling[4], re-correlation to EMU

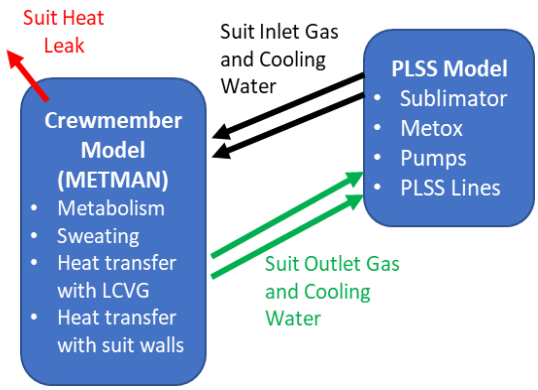



**Figure II-1: SINDA EMU Model**

performance verification tests[5], upgrades in language from FORTRAN 77 to FORTRAN 90[6], adjustment of $CO_2$ removal technology based on verification test data[7], and re-correlation to Exploration EMU (xEMU) PLSS 2.0 Human-in-the-Loop (HITL) test series[1,8,9].

### A. Model Inputs and Assumptions

SINDA EMU uses inputs from flight data, console logs, and thermal modeling to accurately model an EVA. The flight data is used to determine the metabolic rate, suit and environment pressure, and temperature of water exiting the sublimator. The metabolic rate (metrate) is determined by calculating the rate of decrease in the pressure of the oxygen supply tank and then calculating the metrate based on the rate of oxygen consumption[4]. The console logs are used to determine the TCV setting for the duration of the EVA. TCV setting affects the flowrate of water to the sublimator which impacts the amount of cooling received by the crewmember. The flow split caused by TCV setting varies by specific TCV, so the fleetwide average flowrate was used. Thermal modeling is used to determine the environmental sink temperature which impacts the heat leak through the EMU. Environment thermal modeling identifies the sink temperature for eight different orbit positions, with the model choosing the orbit position that best aligns with the actual timeline of the EVA. Finally, the model assumes the skin area and sweat rates based on average body size and sweat generation rates[4]. The mass of the crewmember is input into the model, and the average skin area for a crewmember of that mass is used.

## III. Proposed Warning System

For the causal investigation into the US EVA 80 water in the helmet event, SINDA EMU was used to calculate the latent load for numerous historical EVAs and tests in Chamber B at Johnson Space Center (JSC)[1]. This analysis indicated that EVAs with high latent loads are more likely to present some amount of sublimator carryover (either water in the helmet or a $CO_2$ sensor latching, which indicates water downstream of the sublimator). Examining the latent load for all modeled EVAs showed a clear split between EVAs with and without sublimator carryover. Every EVA that had a calculated total latent load over 1800 Btu (1899 kJ) had some amount of detectable water downstream of the helmet, while most EVAs below this limit did not. Using these results, a two-part warning system was developed to flag EVAs that are at a high risk of presenting significant water in the helmet. The warning would be triggered if either of the following criteria are met:

1. Latent load of greater than 300 Btu/hr (87.9 W) maintained for over one hour.
2. Total latent load of 1800 Btu (1899 kJ) sustained during an EVA. Total latent load is calculated by integrating the latent load with respect to time. For all investigated EVAs, the first criteria was also met in all EVAs where the second criteria was met.

This warning system would be used to alert the crewmember during an EVA if they were producing a latent load that significantly increased the risk of water in the helmet. The warning system would not mandate the crewmember adjusts the TCV, but rather allow operations personnel to make suggestions to the crewmember to consider their thermal comfort and potentially adjust their TCV. The goal of this warning system is to flag EVAs where there is a significant risk of water in the helmet, while also avoiding false warnings. If the warning system calls out warnings too frequently, it may lead to reduced trust in the warning system by crewmembers and flight directors. Additionally, adjusting the TCV requires a manual adjustment, so issuing too many warnings could result in a reduction in productivity during an EVA as crewmembers stop their tasks to adjust their TCV setting.

This warning system was tested on the same set of 45 historical EVAs that were used to develop the warning system. Testing the warning system using the same data that was used to develop the warning system may lead to overestimation of the effectiveness, which will be addressed in Section V. These EVAs were modeled using SINDA EMU to calculate the latent load through the duration of the EVA. These consisted of EVAs conducted using the sublimators that were on ISS during the time of US EVA 80 as well as any EVAs that presented some form of water in the helmet.

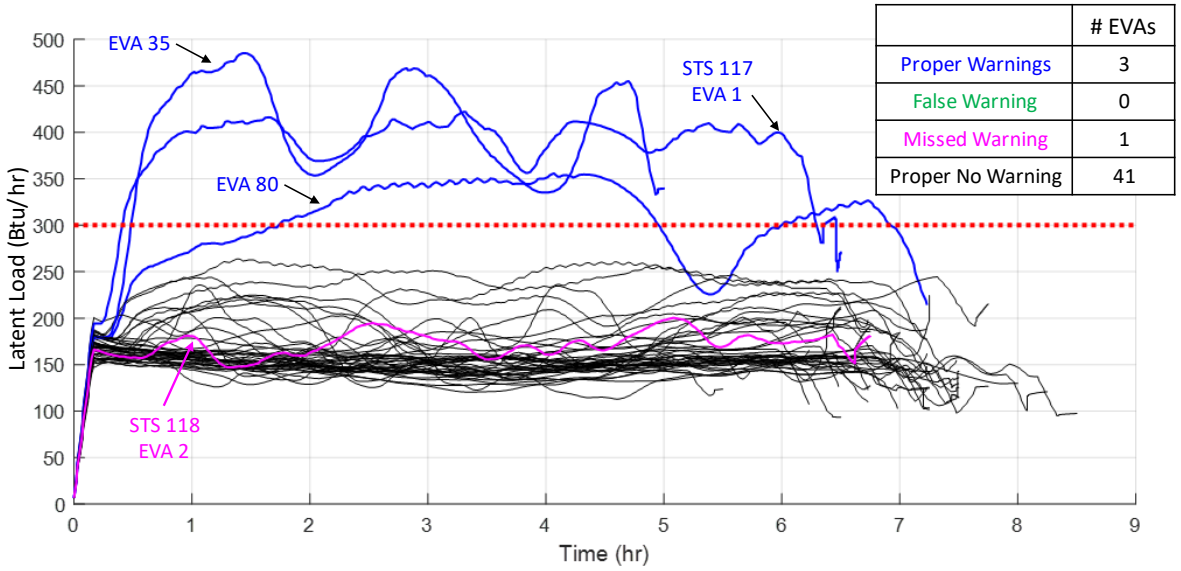



**Figure III-1: Latent Load for 45 Historical EVAs, Colored by Performance of Warning System**

On Space Transportation System 117 (STS-117) EVA 1, EV 2 had a latched $CO_2$ sensor which indicated potential water downstream of the sublimator. STS-118 EVA 2 (EV1), US EVA 35 (EV1), and US EVA 80 (EV2) all had water droplets in the helmet of the EMU. The remaining 41 EVAs did not have any water in the helmets or $CO_2$ sensor latching. The latent load limit of 300 Btu/hr (87.9 W) was exceeded for more than one hour on US EVA 35, US EVA 80, and STS-117 EVA 1. These cases are identified as proper warnings. This means that if the warning system had been implemented, a warning would have been called. This warning would have been justified since actual events showed significant water was downstream of the sublimator. There were no false warnings, indicating that there were no EVAs that would have experienced a warning but did not require a warning. STS-118 EVA 2 is categorized as a missed warning, since there would have been no warning called out, but water was present in the helmet. This is because STS-118 EVA 2 was an outlier when compared to other historical EVAs. STS-118 EVA 2 presented water in the helmet despite its comparable latent loads to historical EVAs that did not present any water in the helmet. This EVA may have presented water in the helmet due to sublimator degradation. The sublimator used during STS-118 EVA 2 was an older sublimator which may have resulted in significant carryover, even at low latent loads. The assumed thermal management of the crewmember during this EVA may also have not been properly determined (TCV and heat storage data is sparser on older EVAs) which could also explain this EVA as an outlier due to less accurate model inputs. Finally, there were 41 EVAs that are classified as proper no warning, since no warning would have been issued and no warning was required.

This warning system's ability to flag EVAs that are more likely to present water in the helmet was shown to effectively identify EVAs that will likely have significant sublimator carryover. This warning system was also shown to be effective at preventing warnings from occurring too frequently, particularly when warnings are not required. While this investigation shows that SINDA EMU is capable of identifying EVAs that are likely to present water in the helmet, additional work is needed to ensure that issuing a warning can provide a significant reduction in risk.

## IV. Effectiveness of Warning System to Reduce Latent Load and Risk of Water in the Helmet

### B. US EVA 80

To determine if adjusting the TCV after a warning reduces the latent load and risk of water in the helmet, theoretical TCV adjustments were investigated in US EVA 80 and US EVA 35. Figure IV-1 shows the latent load and TCV setting during US EVA 80 for the actual TCV settings and a parametric of theoretical TCV adjustments after a warning. In this figure, the blue lines indicate the latent load (top) and actual TCV settings (bottom) during US EVA 80. The green, red, and purple lines indicate the latent load and corresponding TCV settings for a parametric of theoretical TCV adjustments after a warning is issued. The color of the line in the latent load graph corresponds with the TCV setting plot of the same line color. Based on the warning criteria outlined in Section III, a warning would be issued shortly after 3 hours, after the latent load had been over the limit of 300 Btu/hr (87.9 W) for an hour. The parametric

cases indicate different rates of adjusting the TCV setting. The green line represents immediately increasing the TCV setting by two, the red line represents increasing the TCV setting by one every half hour, and the purple line represents increasing the setting by one every hour. This parametric was implemented to calculate the rate of increase in TCV required to significantly reduce the latent load, while preventing additional risks associated with rapid TCV changes from occurring. The TCV setting was increased until a setting of seven, which provides sufficient cooling to maintain a neutral heat storage for the duration of the EVA.

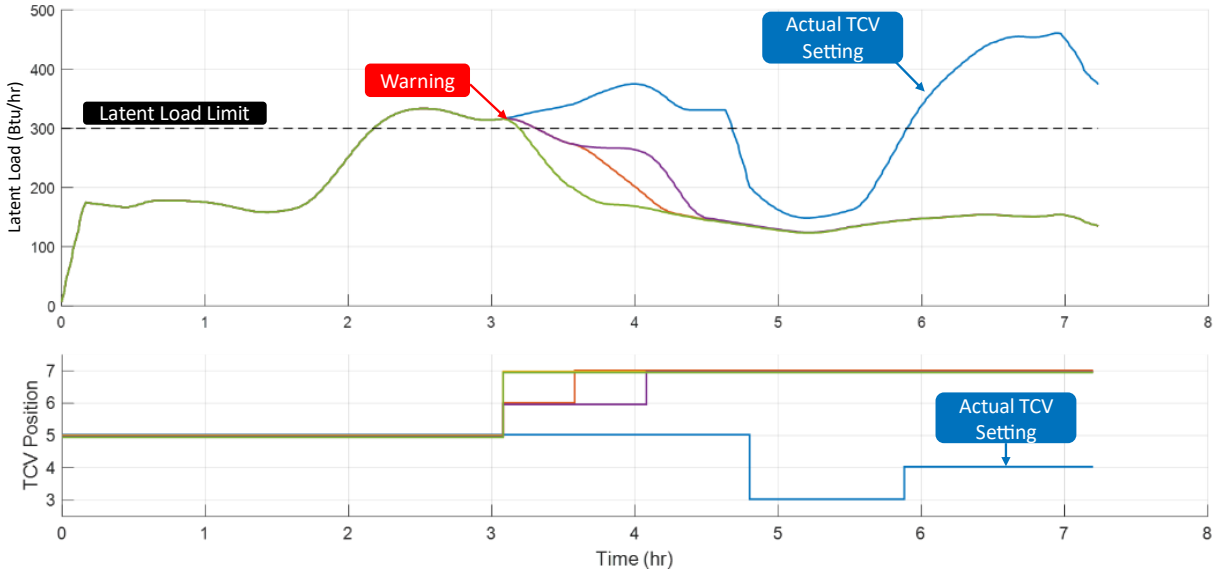



**Figure IV-1: Latent Load (Top) and TCV Settings (Bottom) for US EVA 80 with Parametric Adjustments of the TCV Setting**

For all theoretical TCV adjustments, the latent load decreases significantly after the warning is issued. The rate of increase of the TCV setting has a slight impact on the latent load, but all cases eventually reach the same line where the contribution of sweat evaporation to the latent load is zero. Table IV-1 tabulates the total latent load for each case and the percent decrease when compared to the latent load using the actual TCV settings from US EVA 80. This table shows that increasing the TCV setting at any rate after a warning is issued would result in a significant decrease in the total latent load experienced during the EVA. Increasing the TCV setting rapidly would result in a slightly larger reduction in latent load but does not cause a significant difference for US EVA 80 when compared to slower adjustments of the TCV. The theoretical TCV adjustments result in the latent load being below the limit of 1800 Btu/hr (1899 kJ) for US EVA 80 which would significantly reduce the risk of water in the helmet.

**Table IV-1: Theoretical Impact of Adjusting TCV Setting in Response to Warning on US EVA 80**

| Case | Total Latent Load | Percent Decrease |
|---|---|---|
| Actual TCV Settings for US EVA 80 | 2,013 Btu (2,124 kJ) | - |
| After Warning: Increase TCV by 1 Every 60 Minutes | 1,433 Btu (1,512 kJ) | 28.8 % |
| After Warning: Increase TCV by 1 Every 30 Minutes | 1,398 Btu (1,475 kJ) | 30.6 % |
| After Warning: Increase TCV by 2 | 1,347 Btu (1,421 kJ) | 33.1 % |

## C. US EVA 35

The TCV parametric investigation was also conducted for US EVA 35, which was another EVA that had significant water in the helmet, likely due to sublimator carryover. Figure IV-2 shows the calculated latent load and TCV setting for US EVA 35. The warning would occur around 1.6 hours, after the latent load exceeded the latent load limit for more than an hour. The blue line indicates the TCV settings and resultant latent load based on the actual TCV settings during US EVA 35. The remaining colors indicate parametric TCV adjustments up to a final setting of 6 which is sufficient to maintain adequate cooling to the crewmember. For all parametric TCV runs, there is a period of time where the latent load remains constant shortly after the warning. This is due to the evaporation of sweat runoff. During the first 1.5 hours of the EVA, the crewmember is at such a high latent load that significant amounts of the sweat production cannot be evaporated. This leftover sweat is absorbed by the LCVG and called sweat runoff. Sweat

runoff eventually evaporates into the gas once the latent load drops enough to allow more sweat to evaporate than is being produced. This model accounts for the evaporation of sweat runoff by assuming the sweat runoff evaporation will maintain a constant latent load. Once all of the sweat runoff is evaporated, the latent load drops off (e.g. green line shortly after 3.5 hours). The evaporation of sweat runoff did not occur during US EVA 80 because the latent load was not high enough to cause significant sweat runoff. By contrast, US EVA 35 had an extremely high latent load which resulted in significant levels of sweat runoff. This shows that if the latent load is extremely high and the LCVG gets soaked in sweat runoff, it will take longer to reduce the latent load due to the additional source of humidity on the LCVG, even if the TCV is rapidly adjusted to increase cooling.

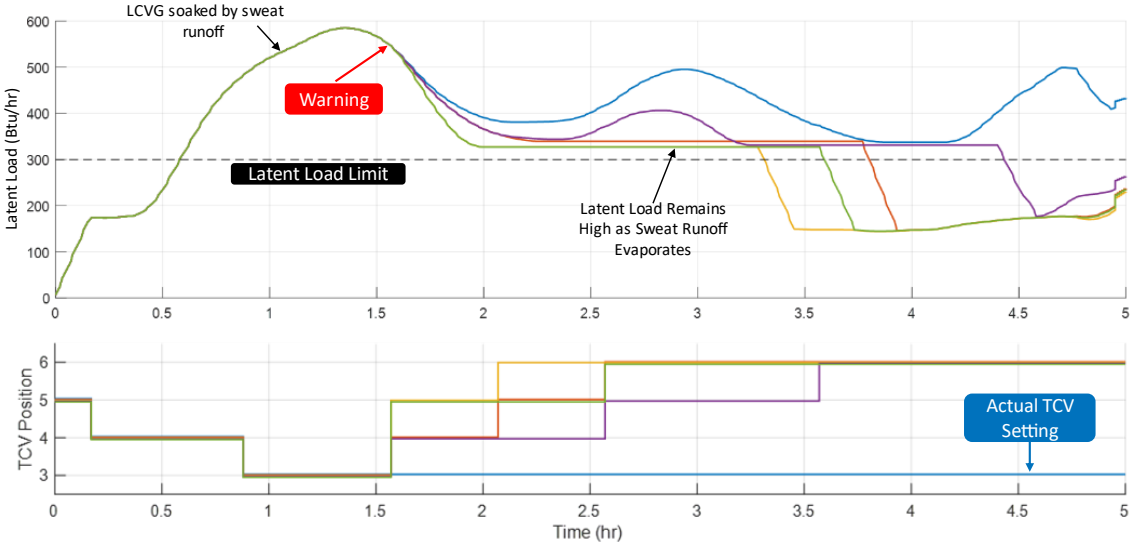



**Figure IV-2: Latent Load (Top) and TCV Settings (Bottom) for US EVA 35 with Parametric Adjustments of the TCV Setting**

Table IV-2 shows the calculated total latent load for the TCV parametric investigation and the percent decrease in latent load caused by adjusting the TCV after a warning is issued. When compared to US EVA 80, the reduction in latent load caused by increasing the TCV after a warning is less significant for US EVA 35. This is due to the evaporation of sweat runoff caused by the extremely high latent load at the start of US EVA 35. Increasing the TCV setting more rapidly has a more significant impact on reducing latent load when there is significant sweat runoff.

**Table IV-2: Theoretical Impact of Adjusting TCV Setting In Response to Warning on US EVA 35**

| Case | Total Latent Load | Percent Decrease |
|---|---|---|
| Actual TCV Settings for US EVA 80 | 2,029 Btu (2,141 kJ) | - |
| After Warning: Increase TCV by 1 Every 60 Minutes | 1,767 Btu (1,864 kJ) | 12.9 % |
| After Warning: Increase TCV by 1 Every 30 Minutes | 1,615 Btu (1,704 kJ) | 20.4 % |
| After Warning: Increase TCV by 2 Every 60 Minutes | 1,541 Btu (1,626 kJ) | 24.1 % |
| After Warning: Increase TCV by 2 Every 30 Minutes | 1,489 Btu (1,571 kJ) | 26.6 % |

For US EVA 80 and US EVA 35, adjusting the TCV setting to increase cooling after a warning is issued can significantly reduce the latent load. For both EVAs, the TCV adjustments dropped the total latent load below the total latent load limit of 1800 Btu (1899 kJ). This indicates that it is very likely that if a warning system were implemented on these EVAs, water in the helmet would have been avoided. The TCV setting should be increased as rapidly as possible to increase the reduction in latent load. This shows that a warning system which identifies when a crewmember is at a high latent load and recommends TCV setting adjustments is an effective way to reduce latent load and reduce the risk of sublimator carryover occurring during an EVA.

## V. Post-EVA Analysis for US EVA 81-84

One of the biggest issues with the development of the warning system based on historical EVAs is that, thus far, the warning system could only be tested on the same set of data that was used to develop it. This may result in overconfidence in the capabilities of the warning system. Fortunately, EVAs that occur after US EVA 80 allow for

the warning system to be tested on data that was not used to develop the warning system. After the US EVA 80 investigation, the importance of TCV setting on controlling heat storage and latent load resulted in increased awareness and reporting of the TCV setting. For this reason, all EVAs after US EVA 80 have much more accurate TCV setting information than was available for prior EVAs. These TCV settings allow for SINDA EMU to be run with significantly greater accuracy than previous EVAs. SINDA EMU was run for both crewmembers on US EVAs 81-84 and the performance of the proposed warning system was tested. To account for uncertainty in mass of the crewmember (since crewmember mass impacts latent load calculation), the model was run three times for each EVA (+/- 20 lbm [9.07 kg]).

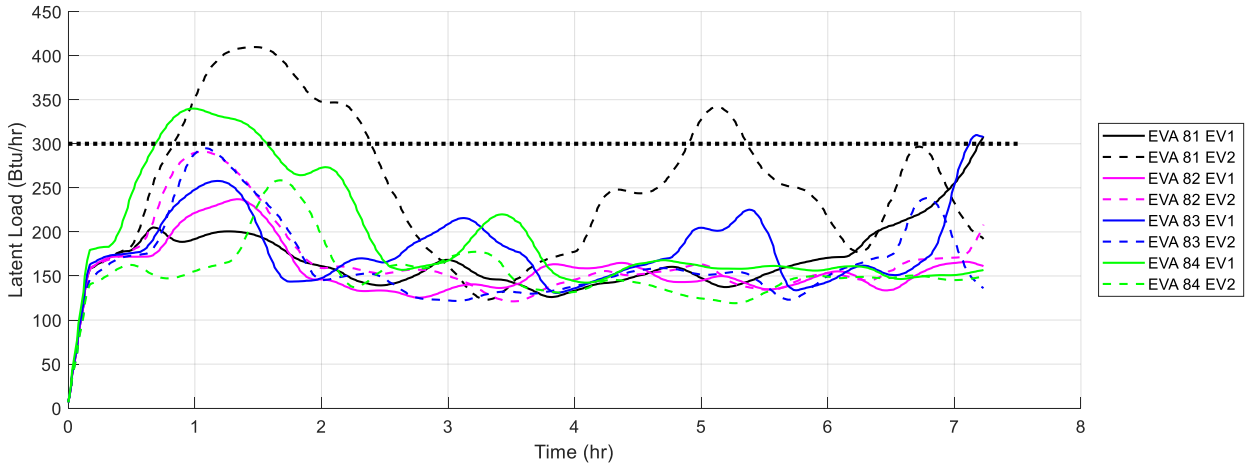



**Figure V-1: Latent Loads for US EVAs 81-84**

The latent load calculations for US EVAs 81-84 are plotted in Figure V-1 and compared to the proposed warning limit of 300 Btu/hr (87.9 W). This plot only shows one of the three parametric cases. This analysis showed that the impact of varying mass only affects the latent load by about 5%. For this discussion, the additional +/- masses will be neglected. Of the eight total model runs (2 crewmembers for each EVA), the latent load limit of 300 Btu/hr (87.9 W) was exceeded for a significant amount of time on two of the EVAs (US EVA 81 EV 2 and US EVA 84 EV 1).

On US EVA 81, EV 2 exceeded the limit for approximately 1.5 hours at the start of the EVA. Since the limit was exceeded for more than an hour, if the warning system were implemented, a warning would have been sent to the crewmember. Ultimately, there was no water in the helmet of EV 2 on US EVA 81 which would classify this EVA as a false warning. The reason this EVA likely did not produce water in the helmet is because the high latent loads were not sustained for the duration of the EVA. Shortly after a warning would have been issued, the latent load for EV 2 dropped below the limit, which is a similar response to what would be expected if a warning had been implemented.

During US EVA 84, EV 1 experienced a latent load over the limit for slightly less than one hour. Based on criteria for issuing a warning, this would not have been called up as a warning since the latent load was not maintained for more than one hour. Towards the end of EVA 84, communication with EV2 was lost in one ear, likely due to water in the ear cup of the Crew Communication Electronics Module (CCEM). This could have been due to either sublimator carryover or sweat from the ear. While communication lost occurred near the end of the EVA, it is possible that the high latent load at the start of the EVA contributed to the presence of water. Losing communications during an EVA is a common occurrence and for this reason, this will not be considered a water anomaly and this EVA was classified as an accurate no-warning.

The other six EVAs all remained below the limit for the duration of the EVA and did not report any water in the helmet so were flagged as accurate no-warnings.

### D. Additional Findings from Post-EVA Modeling

In addition to testing the warning system, the results from modeling these EVAs with SINDA EMU has led to a few additional findings. First, the highest latent load generally occurs at the beginning of the EVA. This could be due to the higher sink temperature in the crewlock, high metrates, or difficulties in predicting necessary cooling at the beginning of an EVA. When the crew begins an EVA, they are in a warm crewlock which reduces the heat leak from the suit and may increase the heat storage, causing sweating near the start of an EVA. Additionally, the high latent load could be caused by higher metrate at the start of the EVA. Finally, at the start of the EVA it may be difficult to

anticipate the workload which may result in incorrect TCV settings at the start of the EVA resulting in warmer crewmembers.

Another trend is that the highest latent load cases were on EVAs where the crewmember was performing the first EVA of their career. Both US EVA 81 EV2 and US EVA 84 EV1 were the first EVAs for the respective crewmembers. The following EVAs for the crewmember on US EVA 81 had lower latent loads which may indicate that the crew is learning from experience and improving their ability at maintaining thermal neutrality. At the time of writing, the crewmember from US EVA 84 has not conducted another EVA to see if they are also able to reduce the latent load, but this will be investigated going forward.

## VI. Discussion and Future Work

Testing the warning system on EVAs 81-84 allowed for the warning system to be assessed. Overall, had the warning system been implemented, there would have been seven EVAs where no warning was issued or necessary, and one EVA where a warning was issued but not necessary. US EVA 81, EV 2 most likely did not present any form of water in the helmet because the crewmember was able to reduce the latent load relatively quickly after a warning would have been issued. This EVA shows the impact of reducing the latent load and preventing sustained high latent loads. Had they sustained the maximum latent load for the duration of the EVA, it is likely that significant sublimator carryover would have built up enough to enter the helmet.

One significant limitation of testing the warning system on additional EVAs is the lack of positive (i.e. water in the helmet) events that will occur after US EVA 80. Due to the US EVA 80 investigation, corrective actions were put in place to prevent crewmembers from sustaining a high latent load for a significant length of time. For this reason, the likelihood of a future EVA having significant water in the helmet is reduced. It will be difficult to test the warning system's ability to identify high risk EVAs since high risk EVAs will theoretically be less likely. For this reason it is necessary to rely on the historical dataset or expand knowledge on the integrated performance of the EMU to further quantify the divide between high risk and low risk latent loads.

The warning system outlined an effective method of screening for high risk EVAs, however there are still numerous steps that need to be taken to ensure that implementing this warning system is feasible and effective.

1. Capabilities for live modeling of SINDA EMU are recommended. Currently, SINDA EMU cannot be run in real time during an EVA. Properly implementing this warning system would rely on a version of the model which is able to receive live data and calculate the latent load in real time. The model is currently fast enough to run live, but the workflow is not simple enough to be reliably used. In the future, this model would most likely be run on the ground by an analyst and potential warnings would be reported to flight directors.

2. Further understanding of the EMU system is required to quantify the amount of sublimator carryover that will occur for a given latent loading of the sublimator. Through SINDA EMU modeling, it was shown that high latent loads are associated with more sublimator carryover. However, there is still a gap in understanding of how much carryover is expected for a given latent load and how much carryover is required to result in water reaching the helmet. With separately planned efforts that include testing and additional analysis and modeling, knowledge is expected to be gained concerning this gap. Once this is better understood, defining the high risk band of latent loads will become easier, improving the accuracy of the warning system.

3. Corrective actions and procedures in response to a warning are also recommended. This analysis has shown that adjusting the TCV to increase cooling after receiving a warning has the potential to drastically reduce the latent load in high risk EVAs. However, more work is necessary to determine how much the TCV should be should be adjusted and if this adjustment may cause other unintended consequences.

## VII. Conclusions

After the US EVA 80 water in the helmet failure, an investigation determined that the most likely cause was sublimator carryover caused by a comparatively high latent load. One of the most effective ways of reducing the risk of water in the helmet from this failure is to limit the latent load that is produced by the crewmember and sent to the sublimator. High latent load occurs when the crewmember is warmer than usual (high heat storage). This analysis outlined a potential warning system that could be used to alert the crewmember when they are experiencing a high latent load and at increased risk of water in the helmet. This would allow for the crewmember to adjust their TCV setting to increase cooling and reduce latent load. This warning system was based on thermal/fluid modeling of

numerous historical EVAs that included both EVAs with and without significant carryover. Using this data, a latent load limit was established. If this rate was exceeded for more than an hour, a warning would be issued and the crewmember would be alerted of the elevated latent load.

This warning system was tested on the historical EVAs prior to US EVA 80. This showed that if the warning system had been implemented, a warning would have been issued on three of the four EVAs that presented significant sublimator carryover. There would have been no false warnings issued on the 41 EVAs that did not present significant sublimator carryover. The analysis also showed that, had the warning system been implemented and resulted in a TCV adjustment on US EVA 80 and US EVA 35 (two EVAs with significant amounts of water in helmet), the total latent load would have reduced by up to 33.1% and 26.6%, respectively. The warning system was also tested on US EVAs 81-84, which occurred after US EVA 80. None of these EVAs presented water in the helmet, and the warning system would have issued one warning on US EVA 81, EV2. US EVA 81 most likely did not present water in the helmet because the latent load quickly lowered below the limit after a warning would have been issued. This warning system and operational controls will be further improved through future investigation into sublimator performance and modeling of future EVAs.

Ultimately, the warning system proposed in this analysis provides an effective way to monitor the latent load during EVAs and provides details on how to reduce the latent load using the TCV setting in high risk conditions. This system would provide an effective way to operationally reduce the risk of water entering the helmet again on future EVAs.

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