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NASA Advanced Space Suit xEMU Development Report – Wired Heart Rate Monitor

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For the past several years, the Exploration Extra-Vehicular Mobility Unit (xEMU) team at NASA's Johnson Space Center (JSC) has focused on development and testing of the xEMU to support missions to the International Space Station (ISS) and a moon landing in 2024. In that context, this paper examines the development and detailed design of the xEMU Wired Heart Rate Monitor (WHRM). This paper outlines the challenging technical requirements, significant architectural trades, technical solutions required to overcome these challenges, and a status of the detailed design. The preliminary results of Design Verification Testing (DVT) as it relates to WHRM are also provided, along with a forward strategy for final maturation into a flight-ready design.

Nomenclature

ASIC	=	application-specific integrated circuit
bpm	=	beats per minute
COTS	=	Commercial-off-the-shelf
DVT	=	Design Verification Testing
ECG	=	electrocardiogram
EMC	=	electromagnetic compatibility
EMI	=	electromagnetic interface
EMU	=	Extra-vehicular Mobility Unit
HITL	=	Human-in-the-loop
HUT	=	Hard Upper Torso
ISS	=	International Space Station
JSC	=	Johnson Space Center
LET	=	linear energy transfer
NASA	=	National Aeronautics and Space Administration
NVR	=	non-volatile residue
PLSS	=	Portable Life Support System
PCB	=	Printed circuit board
PTRS	=	Project Technical Requirements Specification
SEE	=	Single event effects
SMAC	=	spacecraft maximum allowable concentrations
μA	=	micro-ampere
xEMU	=	Exploration Extra-vehicular Mobility Unit
xPGS	=	Exploration Pressure Garment Sub-system

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I. Introduction

THE Extra-Vehicular Mobility Unit, or EMU, was first flown by NASA in 1983 on STS-6. Over the subsequent four decades, the EMU has been enhanced and modified to fit the changing missions that it supports. However, limited spares of critical EMU components, such as the HUT (Hard Upper Torso) and PLSS (Portable Life Support System) motivated the ISS Program to develop a replacement for the EMU capable of supporting ISS operations through the end of its life, expected to be 2028 or later. In addition, in 2019 NASA was challenged by the presidential administration to accomplish the goal of landing astronauts on the surface of the Moon by 2024. This challenge was followed by funding from Congress to develop the necessary infrastructure to accomplish this goal, including but not limited to the launch vehicle, lander, suits, and other surface assets.

It is in this context that the xEMU, or Exploration Extra-vehicular Mobility Unit, came to be the NASA advanced suit program of record. While the xEMU has heritage in the EMU and previous advanced suit prototypes (Z-2.5, Z-2, Z-1, and Mark III), it is a new suit design whose architecture represents the best combination of architectural elements from previous suit prototypes, while at the same time addressing the various shortcomings of these prototypes identified through years of development and testing. This paper documents one of these elements, the xEMU Wired Heart Monitor (WHRM).

The technology associated with monitoring a crewmember's heart inside a space suit has seen very little modification and development over the past 30 years of EMU operation. The current EMU design monitors the crewmember's heart rhythm, and it was originally developed by the University of Denver in the 1970s. New heart monitoring requirements for the xEMU program, namely the option to measure heart rate instead of rhythm, enabled the design of a simpler in-suit system. After conducting a trade study, NASA settled on a chest-strap based design for the xEMU WHRM.

II. Driving Requirements

The significant driving requirements for the xEMU WHRM are enumerated below in Table 1.

Table 1. Significant xEMU WHRM Driving Requirements.

Requirement	Specification Summary
Biomedical Data Acquisition	System shall acquire the heart rate of suited crew members
Accuracy	Measure heart rate over range of 30 to 200 bpm with accuracy of +/-10%
Data Transmission Method	WHRM is required to transmit data over hardline connection
RS-485 Interface	WHRM is required to output data in RS-485 format
Anthropometric Range	Chest circumference of 5% percentile to 95% percentile
Ionizing Radiation	No destructive failures when exposed to exploration-level radiation levels
Auto-scaling	Automatically adjust to varying peak-to-peak heart voltage differentials
Consumables	No consumables are permitted
Batteries	System is required to operate without batteries
Electric Shock Protection	WHRM is required to be two-fault tolerant against electric shock

A. Biomedical Data Acquisition

While the EMU was required to monitor the crewmember's heart rhythm, the xEMU suit is only required to monitor heart rate. In 2008, as a part of the Constellation program, NASA flight surgeons conducted an extensive survey to determine whether electrocardiogram (ECG) rhythm monitoring is required for lunar surface operations.[1] A panel of experts from inside and outside of NASA was convened, and the panel included outside cardiovascular medicine experts, NASA flight surgeons, and representatives from NASA Engineering and NASA Space and Life Sciences. The panel concluded that only heart rate monitoring is required to monitor the health of the suited crewmember. An excerpt from this report is shown below. The JSC medical community conducted an additional review of this recommendation in 2018, and they reaffirmed that heart rhythm monitoring was not required for xEMU.[2]

> "Heart rate monitoring alone allows the effective monitoring of astronaut health and function, as well as the identification of sudden changes that might require more detailed queries or evaluation. Further ECG monitoring in this otherwise healthy population would add little value in revealing a clinical circumstance that would be managed differently from returning the astronaut to the vehicle for more detailed evaluation and management,

> though it was acknowledged that in some circumstances, diagnosis of a transiently symptomatic arrhythmia would not be possible after the symptoms had resolved.
>
> It was emphasized that there are negative aspects to rhythm monitoring as well. These include cost and complexity; distraction of crew and engineers away from the truly life-threatening aspects of exposure to the vacuum of space; and the high likelihood that in this highly screened, healthy population with a low pre-test probability of disease that the majority of abnormalities identified would be artifact or clinically insignificant."

A heart rate sensor is simpler than a heart rhythm sensor because the latter system typically requires at least three electrodes, while heart rate can be determined with two electrodes (in the case of a chest strap-based system). Therefore, xEMU focused on the development of a heart rate sensor system for WHRM.

B. Anthropometric Range

The WHRM is required to accommodate test subjects with a chest circumference range from 5% percentile female to 95% percentile male (29.8in to 46.7in). The WHRM accommodates this range with two chest strap sizes. The goal of WHRM was to use commercial-off-the-shelf (COTS) products where possible, and two commercial chest strap sizes from Cardiosport accommodate the required size range.

C. Data Transmission Method

The WHRM is required to transmit data over a hardline connection to the PLSS. There are several reasons for this requirement: a wireless connection requires a battery to amplify/condition/calculate the heart rate and/or wirelessly transmit the data; a wired connection is inherently more reliable than a wireless connection; a wireless system requires more power to operate than a wired system (power draw into the suit's enriched oxygen environment should be minimized); the PLSS radio is only designed to wirelessly transmit data to/from a vehicle (e.g., ISS) and the PLSS does not have a system to wirelessly communicate with other parts of the suit. This requirement reduced the possibility of using an unmodified COTS heart rate monitor because most COTS heart rate monitors employ a wireless technology.

D. RS-485 Interface

The WHRM is required to communicate via RS-485 because this is the PLSS's communication protocol with other sensors/systems in the PLSS. Along with the hardline data transmission requirement, this requirement reduced the possibility of using an unmodified COTS heart rate monitor.

E. Ionizing Radiation

xEMU will operate in an elevated radiation environment because the suit will operate for extended durations on the moon and Mars, which are outside of the Earth's protective magnetosphere. The radiation requirements are summarized in Table 2. The WHRM cannot have any destructive (non-recoverable) failures for the levels described in the table. Non-destructive failures are permitted at the prescribed rate, and these failures include soft errors like bit flips that can be cleared with a power reset.

The radiation requirements were developed based in part by the WHRM's criticality, which is a measure of a failure's effect. NASA determined the WHRM's criticality to be 2N. With this rating, a failed WHRM would not endanger the life of the crew member and it may not necessarily affect the mission. The decision on how to proceed in the event of a failed WHRM would likely reside with the NASA flight surgeon. This failure effect is similar to the EMU's heart monitoring system. Because a failed WHRM would not endanger the life of the crew member and it may not affect the mission, NASA relaxed some of the radiation requirements, as described below.

The linear energy transfer (LET) is the energy that an ionizing particle transfers to a material, per unit distance. Heavy-ion radiation is required to test hardware at exploration-levels of LET (>60 MeV-cm^2/mg), and NASA judged this to be too expensive when compared to the criticality of the WHRM system. Thus, NASA levied a lower LET level that was affordably achievable at a local radiation test facility.

The total ionizing dose (TID) is the cumulative radiation load that a material absorbs, per unit mass. From a testing perspective, a higher TID equates to an increased duration of radiation exposure. This did not appreciably drive the cost of TID testing, so NASA was comfortable with levying the xEMU exploration-level TID requirement on the WHRM.

Table 2. WHRM Ionizing Radiation Requirement

Non-Destructive SEE Rate	Linear Energy Transfer (MeV-cm²/mg)	Total Ionizing Dose (Rad)
≤ 0.01 failures per 2000 hours	14	13325

F. Auto-Scaling
The peak-to-peak voltage differential across the human heart varies from person-to-person.[3] The EMU heart rhythm monitoring system, which is discussed later in this paper, needs to be tuned with a gain adjustment for each sternal harness and crewmember combination. This adjustment is required so that the amplified output of the EMU system is within specification of the PLSS's allowable voltage input. To eliminate this logistical overhead, the WHRM was required to incorporate an auto-scaling feature to automatically adjust its output, regardless of the crewmember's peak-to-peak heart voltage.

G. Consumables
The xEMU is expected to perform EVAs at remote locations with limited resupply opportunities. As such, the WHRM was required operate without consumables. Examples of consumables required by the EMU's heart rhythm monitoring system include electrode gel to improve electrical conductivity, tape to secure electrodes to chest, and a shaving kit to remove chest hair from electrode area. These are not required to operate the WHRM.

H. Batteries
The WHRM is required to operate without batteries because batteries are ultimately a consumable. Batteries are also a measurable fire risk inside a spacesuit's enriched oxygen environment, and significant controls are required to ensure that the battery is safe. To manage this risk, the EMU heart rhythm sensor's module, which uses a battery, is sealed and the battery is not replaced or re-charged during flight; rather, the entire module is replaced when the battery is discharged.

I. Electric Shock Protection
Because the WHRM is attached to the body and it is powered, it is essential to protect the crewmember from accidental electrical shock from a fault within the WHRM. SSP 51721 dictates the maximum safe shock current level for sources applied externally to the body, and these levels are summarized in Table 3.[4] No power is nominally applied to the chest strap's electrodes, but the WHRM incorporates electronics to limit the current and voltage to each electrode. For each electrode signal path, the WHRM has a resistor to limit the current to 48.5µA (at 3.3V) and a signal switching diode to limit voltage to 3.3V. With a resistor on each electrode channel, the WHRM limits the current to 48.5µA for up to 2 faults.

Table 3. Maximum Permissible Fault Currents for WHRM

Number of Faults	Maximum Permissible Current, µA
0	100
1	500
2	500

III. Heritage EMU Design

The EMU Operational Bioinstrumentation System (OBS) measures/amplifies/transmits the crewmember's heart rhythm to the EMU PLSS radio. The radio then transmits the data to Mission Control Center, where the signal is analyzed by medical staff. The OBS was originally designed by the University of Denver in 1979, and it was redesigned by Hamilton Sundstrand in 2011 to replace obsolete components and improve safety and reliability. The OBS uses three electrodes to measure the Lead II voltage across the heart, as shown by Figure 1. The OBS is comprised of a signal conditioner assembly, output cable, 3-electrode sternal harness, and an electrode attachment kit. The OBS signal conditioner is powered by a non-rechargeable/non-replaceable battery. The electrodes require the following consumables: electrode gel to improve electrical conductivity, tape to secure electrodes to chest, and a shaving kit to remove chest hair from electrode area.

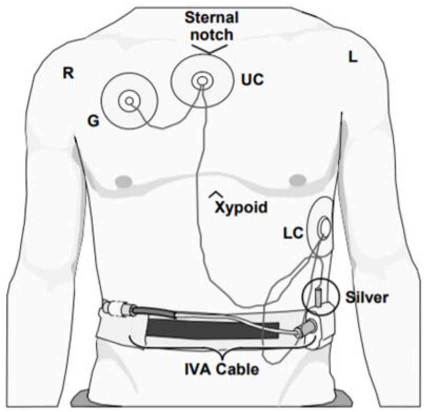

Figure 1. Heritage EMU OBS Layout on Person

IV. Market Survey

A market survey was conducted at the beginning of WHRM development in 2018 to understand what COTS solutions were available (including different detection methods, vendors, electrodes, soft-goods, donning methods, heart-rate monitor systems, and semiconductors), whether any of those solutions could meet the requirements for the WHRM (either directly, or with modifications), and whether those vendors were able and willing to participate in any necessary modifications.[5] Below is a summary of this market survey.

A. Heart Rate Sensing Technologies

The team reviewed all available heart sensing technology work that had been conducted by NASA. The team also investigated the space of commercial heart rate sensing technologies. This research is documented in detail in the market survey report[5], and summaries of the evaluated technologies are provided below. The team ultimately settled on an ECG-based technology to determine heart rate.

- Electrocardiogram (ECG) Measurement – Measurement of the electrical potentials across the heart to generate an ECG signal waveform is the primary method for monitoring the heart in terrestrial applications, and there are extensive COTS solutions that utilize this method. It is relatively simple to calculate heart rate from the ECG signal: The signal is first amplified and quantized to obtain the R-to-R interval (where R is a particular signal measured within a typical heartbeat). This interval is then averaged and converted to heart rate in beats-per-minute (bpm).
- Photoplethysmography (optical reflection) – This method uses a light source and a photodiode to measure the volumetric changes of blood vessels as an analog for heart rate. This is an effective method for detecting heart rate when distance to blood vessels is close and motion is kept to a minimum. This is most often done in clinical environments (e.g., a doctor's office or a hospital), or even at home with a finger-clamp device. However, this method is susceptible to motion artifacts and requires proximity to blood vessels close to the skin. Additionally, the xEMU helmet does not have available real estate to mount an optical sensor, and during an EVA the crew arms and hands are the most active. Therefore, the best places to use this technology (finger, wrist, and ear) are unattractive from an xEMU integration perspective.

- Video Magnification – This technique calculates heart rate by visually detecting variations in skin color as the blood near the surface ebbs and flows. While it is an unobtrusive detection method, there are several drawbacks to this method, including processing power required for video capture and signal processing analysis that is significantly higher than that required for ECG detection. This technology is also not as fully developed as ECG detection, and it would have required development of custom signal processing algorithms. Furthermore, packaging and installation into the helmet area would impact the design of other systems.
- Accelerometer – Accelerometers have been used on Earth to detect heart rate by observing fluctuations of skin position where pulse is measured. Terrestrially, accelerometer applications typically depend on the Earth's gravity vector and magnetic field to establish a reference for analyzing changes in orientation. These factors are not uniformly present in space (microgravity and on other planetary bodies). Additionally, pulse is not the only reason for skin movement, so pulse would need to be extracted from among the other contributors.
- Pressure – Pressure transducers have been used to detect heart rate by measuring fluctuations of pressure against the skin where pulse is measured. However, the best places to measure pulse are unattractive from an xEMU integration perspective.
- Phonocardiography – This technique uses a microphone to obtain an acoustic signal can be used to detect heart rate. For application with a space suit, though, heartbeat sound needs to be filtered from among the other audible factors, especially voice communications and respiration, and this is technically challenging and may not be feasible.

B. Commercial Vendors

In addition to reviewing heart sensing technologies, NASA reached out to 15 vendors of heart monitoring technologies to see if any commercial solutions existed to work with xEMU. The market survey provides details of these vendor reviews. [5] NASA ultimately concluded that no unmodified COTS solution exists, but the WHRM design leverages several COTS technologies.

C. Biochip Analog Front End

The team evaluated several COTS biochips for application with the WHRM, including the Analog Devices AD8232, Texas Instruments ADS1298, CardioSport CBa8, and CardioSport CBa9. The team also considered designing an in-house application-specific integrated circuit (ASIC), but the team decided not to pursue this option due to the long lead and high cost associated with an in-house ASIC development. Various factors were considered when evaluating the COTS biochips, including size, power consumption, production volume, and radiation tolerance.

D. Chest Straps

As the team settled on chest strap-based methods to determine the heart rate, the team conducted a review of COTS chest straps. The primary metrics for evaluating chest straps were: electrode resistance; ability to clean the chest strap; compatibility with a heart rate sensing biochip, and sizing range. The team looked for chest straps whose electrodes had relatively low resistance to allow as high of a voltage transfer as possible from the body to the WHRM biochip. Regarding chest strap/biochip compatibility, there is inter-compatibility between different biochip and chest strap vendors, but biochip vendors conduct extensive testing in the lab and field with their own chest straps. So, there is value in matching a chest strap vendor with a biochip vendor.

V. Overview of Design

The WHRM architecture is based on a measurement of the heart's ECG signal to calculate heart rate. The WHRM is comprised of two components to accomplish this: Chest strap and electronics module. A cable also connects the WHRM to the suit's electrical harness.

a) WHRM Assembly b) WHRM Assembly, as worn

Figure 2. WHRM Assembly

A. Chest Strap

The WHRM uses a COTS chest strap manufactured by CardioSport, part number FP3. This strap was selected because, of the straps that were tested, the FP3 had one of the lowest electrode resistances. Additionally, the team already selected a Cardiosport biochip, so there was an advantage of selecting a Cardiosport chest strap. The FP3 is also advertised as being machine washable up to 30 washes. While the WHRM would not be laundered in flight, this suggests a robustness to in-flight cleaning.

The FP3 chest strap is available in standard and XS lengths, and both sizes are used to span the required size range. The chest strap uses flexible fabric and two polymer electrode pads. The two electrodes measure the electric potential across the heart and pass this signal to the electronics module. There are two metal snaps on the strap to which the electronics module connects. In the commercial application, a CardioSport module connects to these snaps. This module has been replaced with a custom-developed electronics module.

B. Electronics Module

While the goal was to use a COTS heart rate sensing system, the team could not find a COTS system that completely met the WHRM requirements. Most COTS solutions are wireless, using a rechargeable battery for power and Bluetooth to transmit the heart rate signal to a watch/phone/other monitoring device. These are not compatible with the WHRM requirements. It was not feasible to modify any COTS solutions to be easily compatible with xEMU, but the team was able to leverage the elements of a COTS solution to develop an electronics module.

The WHRM electronics module consists of an Ultem enclosure and a printed circuit board (PCB). The PCB contains an analog front-end that detects and conditions the heart rate signal, and a digital back-end that calculates the heart rate and converts the signal into an RS-485 format for the PLSS. Figure 3 provides a functional overview of the WHRM electronics.

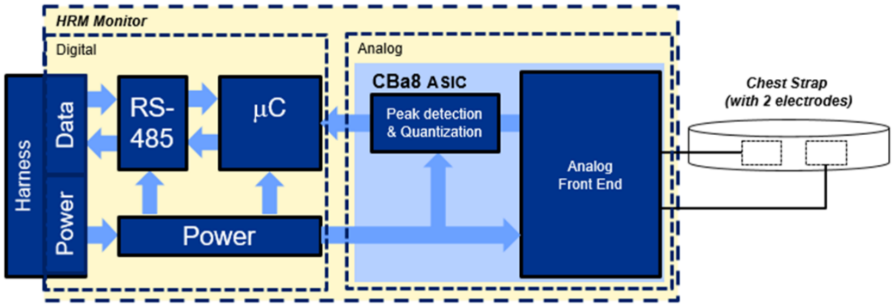

Figure 3. WHRM Electronics Overview

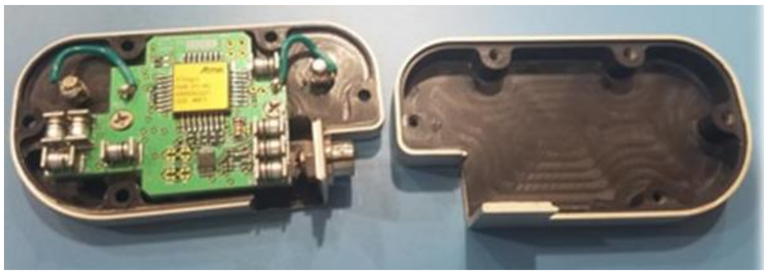

Figure 4. WHRM Electronics Module, internal

1. Housing

The WHRM electronics are housed in a two-piece Ultem 1000 housing. The outside of the enclosure has an electrolytic nickel coating to reduce susceptibility to electromagnetic interference (EMI). The design has a small push/pull LEMO electrical connector that provides electrical connectivity to the WHRM PCB. There are two metal studs on the housing that connect to the chest strap's female snaps; these studs provide electrical connectivity between the parts.

2. ASIC Biochip - CBa8 ASIC

Heart rate detection is performed by the CBa8 ASIC. This biochip is manufactured by CardioSport and it is used extensively in CardioSport's commercial line of heart rate sensors. The chip receives the electrical waveform from the chest strap's electrodes. The chip has a peak detection algorithm and has several distinct advantages for the WHRM:

Figure 5. WHRM Housing (bottom view)

- Automatic gain control (auto-scaling) is built in. This reduces the amount of signal processing otherwise required in the microcontroller.
- The chip automatically senses if the chest strap is not attached to the chest.
- The chip is widely used in the commercial space, providing confidence in the robustness of the design

3. Microprocessor - Microchip ATmegaS64M1

The WHRM uses a Microchip ATmegaS64M1 microcontroller to compute the heart rate. This chip was primarily selected because it includes an analog-to-digital converter and because it is radiation tolerant. The chip is rated to have no destructive failures below an LET threshold of 60 MeV-cm^2/mg, which exceeds the WHRM requirement.

4. RS-485 Chip - Renesas ISL32450EIUZ-T7A

The WHRM uses a Renesas ISL32450EIUZ-T7A chip to convert the heart rate signal to the RS-485 protocol for communication with the PLSS. This chip was primarily selected because it survived component-level radiation testing without any failures that required reset.

5. Software

The WHRM computes the heart rate by performing a rolling average of the last 8 heart rates. This algorithm has been used by the exercise equipment software on the ISS. The software outputs faults to indicate if the heart rate is low/high, if the chest strap is off-chest, and if the CBa8 biochip has timed out.

While testing the WHRM, the team discovered that the CBa8 biochip automatically powers off if it does not detect a heart rate in approximately two minutes. This feature reduces battery consumption when the chip is used with battery-powered COTS heart rate sensors, when the sensor is not worn. For the WHRM's application, however, this function is not desired because there is no need to save power when the WHRM is connected to the PLSS (WHRM power draw is very low, 66mW). Additionally, this function adds overhead to the WHRM checkout process because the WHRM would need to be periodically reset by a crewmember. The CBa8 chip cannot be modified, so the team updated the WHRM design to automatically reset the CBa8 if the chip outputs an off-chest flag for more than two minutes.

6. Cable Harness

The electronics module connects to a detachable cable harness. A separate harness facilitates donning of the WHRM by allowing the crewmember to don the WHRM before donning the suit. The WHRM cable passes through the LCVG and connects to a suit electrical cable. The cable is removable so that only the cable needs to be replaced if the cable is damaged. The harness is shrouded in woven PTFE fabric to protect the wires from damage. Woven PTFE was specifically selected because various tests have shown that is difficult to combust this material in a space suit's enriched oxygen environment.[6] The materials selected also have heritage use with wiring harnesses in the EMU.

VI. Tests and Analyses

A. Unmanned Tests

1. Component-Level Radiation Testing

During the market survey phase, several prospective WHRM electrical components were subjected to proton radiation at Provision Cares Proton Therapy Center in Knoxville, TN. Components were tested at radiation levels of 14 MeV-cm^2/mg and a total dose of 13325 rad (WHRM requirements). The CBa8 biochip ASIC encountered some non-destructive latch-ups but it did not require any resets. The Renesas ISL32450EIUZ-T7A (RS-485 chip) had some minor bit errors, but it also survived without reset. The Microchip ATmegaS64M1 (microprocessor chip) was not tested because vendor-provided radiation data indicated that the chip would meet WHRM radiation requirements.

2. Functional Testing with Heart Simulator

As a part of acceptance testing, each WHRM unit was tested for basic functionality using an ECG simulator (e.g., Fluke PS410) across the required operating range. All WHRMs passed this basic functional test, meeting the accuracy requirement across the heart rate range of the WHRM.

3. Electromagnetic Compatibility (EMC) Tests

The WHRM assembly was tested for conducted/radiated emissions and conducted/radiated susceptibility, in accordance with GP 11461.[7] GP 11461 establishes the xEMU EMC requirements. These requirements exist to ensure that electrical equipment is not adversely affected by EMI that may be generated by other equipment, and that equipment does not create EMI that could interfere with other equipment. Below is a summary of the test results:

- The WHRM did not experience any catastrophic failures (permanent damage) during EMC testing.
- The WHRM passed conducted/radiated emissions tests.
- With respect to radiated susceptibility, the WHRM was tested across a range of 200 MHz to 18 GHz. The WHRM suffered some soft failures (erroneous heart rate data) in the radio frequency range 200 MHz to 2 GHz in both horizontal and vertical polarizations. No failures were observed in either polarization from 2 GHz to 18 GHz. To address this deficiency, an electrolytic nickel coating was added to the outside of the WHRM enclosure, increasing shielding effectiveness from 0 to approximately 40 dB. The WHRM has not been re-tested with this change, and this is forward work.
- The WHRM had several hard failures (power cycle required) and soft failures during conducted susceptibility tests (CS114, CS101, CS106 (28V Spike), CS118(ESD)). The coating that was added to the outside of the WHRM enclosure should also address these failures. The coating provides a conductive path that protects the unit against ESD and electrical contact events.

4. *Vibration Testing*

Two identical WHRM units were tested for compatibility with workmanship vibration levels as well as the launch vibration environment.[8] During the test, the WHRM was supplied with a signal from an ECG simulator to verify the WHRM did not have intermittent failures during the test. The WHRM did not have any intermittent failures, and a post-test inspection of solder joints did not reveal any damage.

5. *WSTF Off-Gas Testing*

Before any material can be used inside a space suit (closed loop, sub-ambient pressure environment), it must be certain that the material does not offgas any toxic constituents. JSC-20584 identifies the spacecraft maximum allowable concentrations (SMAC) for several constituent.[9] A WHRM unit was offgas tested at the White Sands Test Facility, where it was baked inside a chamber at 100°F (38°C) for 24 hours, and the offgas constituents were sampled and measured. This test showed that the WHRM's off-gassed constituents are well below the SMAC limits.[10]

6. *Accuracy Testing*

NASA self-imposed an accuracy requirement of ±10 percent for the WHRM as compared to a 3-lead ECG system. Several test subjects simultaneously wore a WHRM and an ECG, and subjects performed a variety of tasks including walking, hand movements, and prone/recover. Results show that WHRM has an accuracy better than 5 percent.

B. Human-in-the-Loop (HITL) Tests

DVT units of the WHRM have been worn by suited subjects during various xEMU PGS tests. Thus far, test subjects have spanned the small-to-medium size range of the WHRM requirement. Once a large xPGS HUT is available for testing, larger subjects will evaluate the WHRM.

The WHRM has performed well in DVT tests: the WHRM has reliably reported heart rate data, and subjects have generally rated the WHRM as comfortable. Some female subjects have commented that the WHRM chest strap is too tight when worn under the sports bra, and these subjects have loosened the chest strap to alleviate this discomfort. While this has not adversely affected WHRM data, this feedback will continue to be monitored. If this is ultimately a systemic problem with a large fraction of female test subjects, then xEMU may consider purchasing new sports bras that have a lower band to accommodate the WHRM chest strap. This feedback is not unique to the WHRM; COTS vendors report that some initial discomfort is normal when wearing COTS chest straps under a sports bra.

As of this writing, only engineering subjects have evaluated the WHRM. However, several astronauts have worn a volumetric mockup of the WHRM during prototype space suit tests in the Neutral Buoyancy Laboratory (NBL). All the astronauts reported that the WHRM enclosure was comfortable.[11]

C. Thermal Analysis

A thermal analysis was conducted on the WHRM to verify that it would not overheat during use inside a space suit. The WHRM nominally draws very low power (66mW nominal), and the WHRM is limited to a maximum short-circuit power draw of 165mW. As expected, the temperature of the WHRM electronics does not rise more than approximately 5°F (3°C) above ambient conditions during nominal or short-circuit events.

VII. Forward Work

At the time of this publication, the WHRM is considered complete pending additional changes from DVT. Several tests remain to completed to fully buy down the risk of the design. These tests include: WHRM-level radiation testing; repeated component-level EMI/EMC testing; system-level EMI/EMC testing; and thermal cycling. There are also plans to evaluate the WHRM with larger subjects when the large HUT is ready for testing.

VIII. Conclusion

This paper describes the development and testing of the WHRM, a new heart rate monitoring sensor for the xEMU space suit. Compatibility with the PLSS radio architecture drove NASA to design a new heart rate sensor, but the design makes extensive use of COTS components, including a COTS chest strap and biochip. The xEMU WHRM is a considerable upgrade to the legacy EMU design in many ways. While the WHRM reports only heart rate and not heart rhythm, this architecture change eliminates all consumables that are present in the EMU design. As of this writing, the WHRM has been evaluated in component-level tests and HITL tests. The WHRM has reported accurate heart rate data for a range of test subject sizes, and test subjects have generally rated the WHRM as comfortable.

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