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System Overview and Operations of the MX-2 Neutral Buoyancy Space Suit Analogue

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ABSTRACT

A fully operational space suit analogue for use in a neutral buoyancy environment has been developed and tested by the University of Maryland's Space Systems Laboratory. Repeated manned operations in the Neutral Buoyancy Research Facility have shown the MX-2 suit analogue to be a realistic simulation of operational EVA pressure suits. The suit is routinely used for EVA simulation, providing reasonable joint restrictions, work envelopes, and visual and audio environments comparable to those of current EVA suits. Improved gloves and boots, communications carrier assembly, in-suit drink bag and harness system have furthered the semblance to EVA. Advanced resizing and ballasting systems have enabled subjects ranging in height from 5’8” to 6’3” and within a range of 120 lbs to obtain experience in the suit. Furthermore, integral suit instrumentation facilitates monitoring and collection of critical data on both the suit and the subject. Records of the LCG inlet and outlet temperatures, heart rate, air temperature and humidity provide quantitative performance metrics for comparison between tasks or between subjects. These quantitative measurements enable studies of metabolic workload, as well as alert test conductors to declines in performance, system failures or health emergencies.

There are numerous ongoing and near-term applications of the MX-2 to EVA research. These include human-robotic interactions at a variety of levels, from dexterous manipulator support of EVA operations to the direct integration of robotic arms onto the suit system. The MX-2 is also designed to facilitate bidirectional high-bandwidth communications for experimental assessment of advanced controls and displays to provide real-time training and support to the suited subject.

The MX-2 has proven itself as an extremely valuable tool, providing researchers with a low-cost analogue to obtain experience in simulated EVA. It is also a useful platform for investigating future EVA technologies.

INTRODUCTION

Neutral buoyancy is the most valuable and realistic tool available to simulate the micro-gravity environment of space for extended operations. This is especially true in the field of Extra Vehicular Activity (EVA). Astronauts spend hundreds of hours in the Neutral Buoyancy Laboratory (NBL) at Johnson Space Center in preparation for their EVA, as this is an invaluable analogue to the real environment. The experience of working within a pressurized suit in a weightless environment cannot be explained or taught, but must be experienced and practiced. The only way to obtain this experience, other than neutral buoyancy or in space, is aboard parabolic flights. The benefits of parabolic flights for EVA research are limited though, due to their short duration. Thus, advanced suit technologies and metabolic studies in the very foreign EVA-environment cannot be examined accurately on Earth without the use of neutral buoyancy.

Unfortunately, few opportunities exist for researchers to experiment with pressurized suits in the neutral buoyancy environment. Typically experienced subjects perform the tasks at facilities such as the NBL, and compare their results to prior experiences. High fidelity suits such as near flight-rated Extravehicular Mobility Units (EMU) are used.

This type of research has two main drawbacks; the results are usually qualitative, and the costs are prohibitively high for external research groups. Space-rated designs and materials, as well as the required testing and documentation that accompanies flight-level safety requirements, can drive the costs to the order of $5000/hour. As a result, many EVA-related research fields have been insufficiently explored.

While there is no doubt that astronauts in training should use the highest fidelity suits available, EVA and advanced suit research can be done with lower fidelity suits and methodologies. Further development of testing methodologies will allow quantitative measurement of human performance during EVA, as well as evaluation of advanced pressure suit design [1]. For example, Ranniger et al. [2] used fiber optics to obtain joint angles, and electromyography (EMG) to measure intensity and quantity of muscle contractions during various activities. This research provided great insight into biomechanics and muscle endurance during EVA and could certainly be furthered. Application of this type of bioinstrumentation during manned tests on Earth prior to space flight would be very beneficial.

In response to these issues, the University of Maryland Space Systems Laboratory (SSL) has developed a space suit analogue for use in the Neutral Buoyancy Research Facility (NBRF). As the second pressure suit developed under the Maryland Advanced Research/Simulation (MARS) Suit program, the MX-2 provides the SSL research team with a realistic space suit analogue and a test bed for neutral buoyancy EVA research. The suit replicates important aspects of higher fidelity suits without the associated costs, enabling research in many areas that would otherwise remain elusive.

The complete design of the MX-2 has been described in detail [3-6] and is outlined here only as a brief synopsis in Section 1. Section 2 presents an overview of the design upgrades, including new glove and boot designs, resizing capabilities, and the greatest advance towards quantitative EVA research; the integrated instrumentation and processing onboard the MX-2. Section 3 describes ongoing manned operations of the MX-2 in the NBRF, outlining procedures and results obtained thus far. Section 4 summarizes current research now possible with the fully operational MX-2. Finally, future design upgrades and research possibilities are proposed in Section 5.

SECTION 1: MX-2 OVERVIEW

The MX-2 is a rear-entry pressure suit with a fiberglass Hard Upper Torso (HUT) and an integrated hemispherical helmet. Three layer soft goods (pressure bladder, restraint layer and Integral Ballast Garment (IBG)) are used for the arms and Lower Torso Assembly (LTA). A Liquid Cooling Garment (LCG), Communications Carrier Assembly (CCA) and harness system are worn within the suit. Air is supplied from the surface at a rate of 6 Cubic Feet per Minute, maintaining the pressure in the suit at 3 psi above ambient. Double redundant back-up systems provide onboard air to the subject in the event of an umbilical failure. While the MX-2 is not of the fidelity of the EMU, experiments [4-6] have shown that joint torques, external envelope and field of view are comparable, thus providing a simple and realistic simulation of EVA pressure suits. Figures 1-3 show some of the results from these previous works, demonstrating the baseline characteristics of the MX-2.

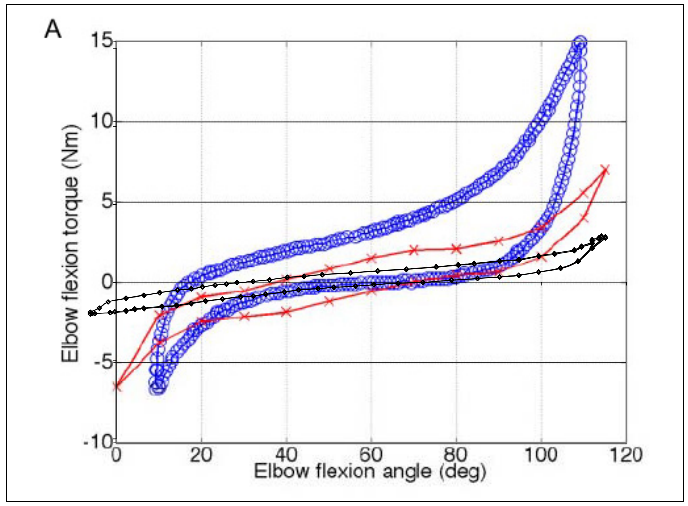


Figure 1: Elbow torque plotted vs. bend angle. Circles indicate EMU data from Ref [7], X's indicate EMU data from Ref [8], and black points indicate MX-2 data[5]

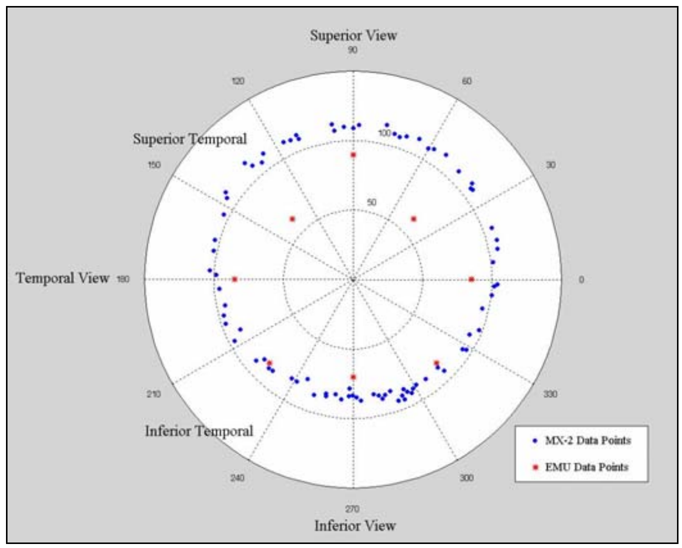
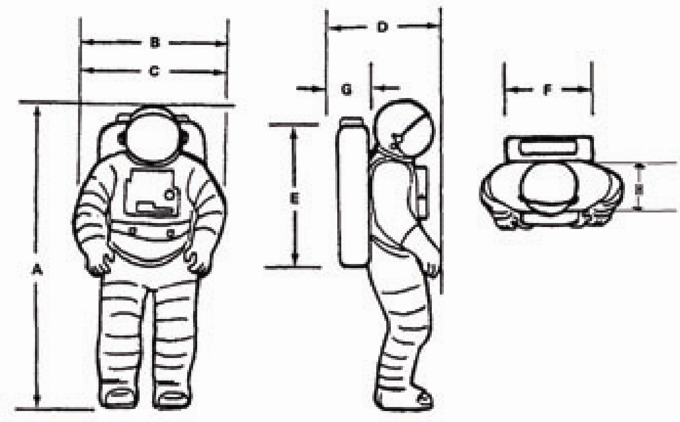


Figure 2: Field of view comparison between the MX-2 and the NASA STD-3000 [5]



Size Range Comparison			
	STD-3000 EMU	MARS Suit MX-2	I.S.S. * EMU
A - Height	75.5"	74.5"	75.52"
B- Maximum breadth at elbows (arms relaxed)	33.4"	40"	41"
C - Maximum breadth at elbows (arms at side)	26.0"	36"	N/A
D - Maximum depth with PLSS/SOP	27.0"	26.3"	22" **
E - PLSS height	32.0"	38.5"	43.7" ***
F - PLSS breadth	23.0"	24.5"	N/A
G - PLSS depth	7.0"	7.5"	N/A
H - PLSS to DCM distance (maximum)	20.77"	19.5"	N/A
* = Updated data provided by ILC Dover.			
** = This dimension becomes 29.69" when including the MMWS.			
*** = Includes SAFER.			

Figure 3: External envelope comparison [5]

Figure 4: SSL gloves, Mark 1 and Mark 2

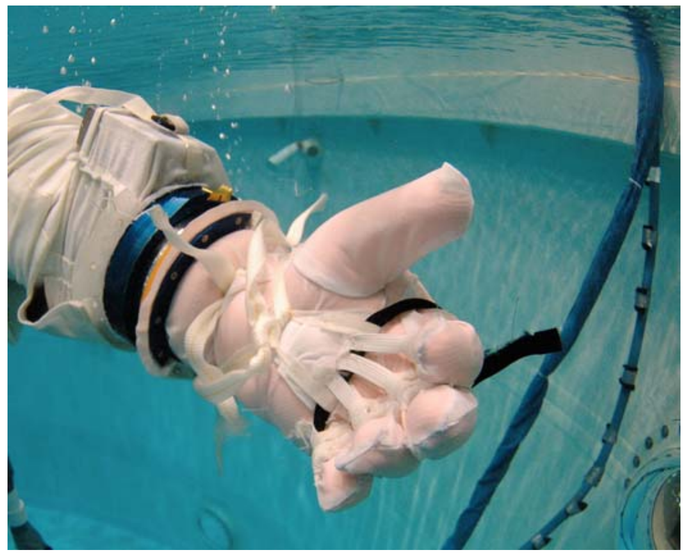


Figure 5: Mark 3 glove

SECTION 2: DESIGN UPDGRADES

GLOVES

Creating a pressure suit glove that provides comfort and dexterity is an extremely difficult task. The gloves must be easy to don and doff, fit the subject's hands very well, and allow the subject to perform fine motor tasks without fatiguing. A review of many glove designs (10-14) was combined with the SSL's experience in advanced EVA glove technologies [15, 16], to design and integrate new low-cost, resizable gloves. Mark 1 of these gloves provided limited mobility, but could be sized for large hands and sufficiently held pressure. Mark 2 incorporated thermo-plastic restraint systems around the palm and back of the hand, significantly increasing mobility of the metacarpophalangeal (MCP) joint, and increasing glove comfort. The latest series of gloves, the Mark 3, incorporate advanced systems of restraint lines and adjustable palm bars, integrated into a handmade restraint layer. An elastic restraint system for the fingers has been designed, improving distal and proximal interphalangeal mobility. These gloves are not of the fidelity of EMU gloves or previously used Orlan gloves; however they do provide an acceptable level of mobility and comfort, can be developed quickly and easily for any size hand, and are incredibly low cost relative to flight-rated gloves.

BOOTS

One of the most important pressure suit design challenges is to design a suit that closely fits the subject's dimensions while remaining easy to ingress/egress. Boots can be especially hindering and much work has been done in the area of boot design [11, 12, 17]. Previous generations of MX-2 boots caused significant delays in ingress time and therefore were redesigned to incorporate an easily adjustable system with a quick connect interface. Ski boots with adjustable buckles were modified to interface with the LTA, and their base was redesigned to lock into standard NASA foot restraints. The new boots have increased comfort, allow for easy resizing, and have significantly lowered ingress times.

Figure 6: MX-2 resizable boots

RESIZING

One of the purposes of the MX-2 is to provide a platform for many different people to experience EVA simulation. To that end, it is a design requirement that the suit be resizable and adjustable to accommodate test subjects of all sizes. The dimensions of the HUT cannot be altered, but the soft goods incorporate resizing elements; restraint layer cuffs paired with restraint lines of different lengths can be inserted or removed to accommodate different lengths of arms and legs. The harness system within the suit is also adjustable so that the subject is centered within the suit, regardless of subject height, and three different sizes of LCG have been made. As the suit is used in the neutral buoyancy environment, an adaptable ballast system is necessary to accommodate a wide range of masses. The Integral Ballast Garment (IBG) contains pockets of different sizes dispersed around the entire exterior of the suit. The ballast can thus be added or removed, and arranged in the configuration necessary so as to collocate the suit's center of gravity with its center of buoyancy. These resizing systems have enabled subjects varying in height from 5'8" to 6'3", and a weight range of over 120 lbs, to experience simulated EVA in the MX-2.

ELECTRONICS

The integrated electronics box onboard the MX-2 is the greatest advance in quantitative EVA research capabilities at the SSL. A Macintosh mini is mounted inside the electronics box, integral to the MX-2 backpack. This enables real-time monitoring of suit pressures and temperatures, humidity, LCG inlet and outlet temperatures, and heart rate. Onboard software samples and logs data from the sensors arranged throughout the MX-2. The data is then sent to the surface via Ethernet where it is displayed and monitored at the deck control station. Figure 7 shows the onboard processor within the electronics box.

Figure 7: MX-2 Onboard processing and instrumentation

Several other minor improvements have been made to the MX-2. An in-suit drink bag is incorporated into the suit, providing ice-cold water to the thirsty suit subject. Headgear originally designed for wrestlers was modified to make a new Communications Carrier Assembly (CCA) that can be securely fastened to the subject's head. This innovative method of imitating the EMU "snoopy cap" serves to replicate the auditory environment of an EVA and enables the suited subject to communicate with both the surface crew and the safety divers. The harness system is also improved to distribute the subject's weight within the suit.

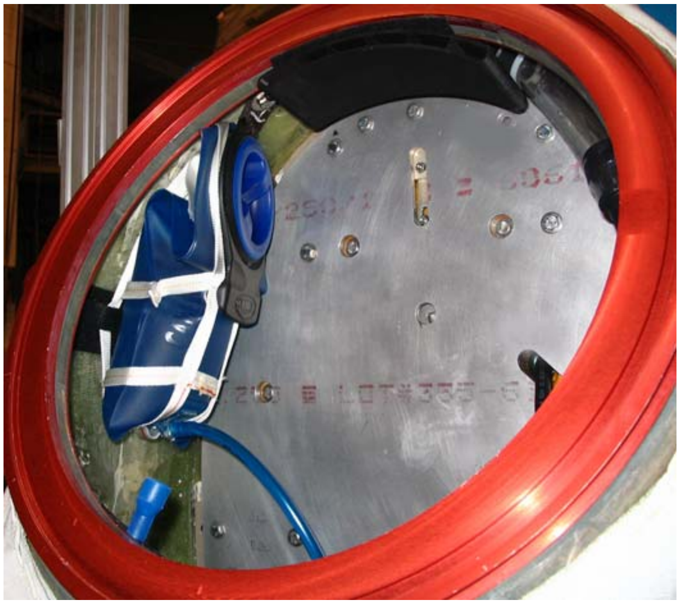


Figure 8: MX-2 In-Suit Drink Bag

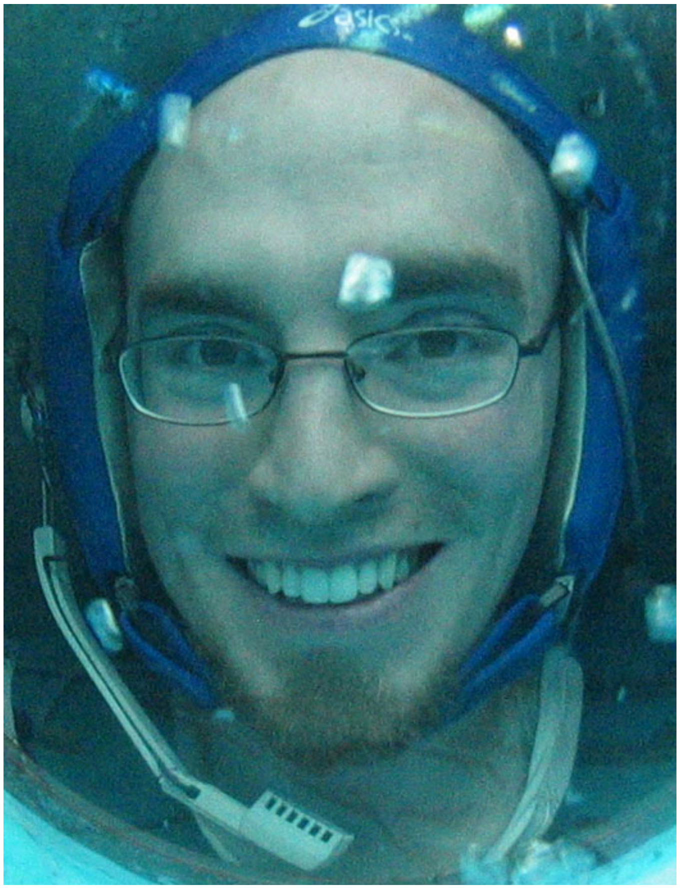


Figure 9: MX-2 Communications Carrier Assembly

SECTION 3: MANNED OPERATIONS

Complete with all of the design upgrades, the MX-2 is now fully operational and currently in use at the SSL. To date, three different test subjects, all volunteers and members of the SSL, have donned the MX-2 and experienced simulated EVA in the neutral buoyancy environment. A variety of tasks have been performed, including hand traversing an International Space Station (ISS) truss mockup, opening and closing doors of a Hubble Space Telescope (HST) mockup, using an underwater version of a Mini Power Tool, locking into standard EVA foot restraints, and demonstration of EVA-Robotic cooperative satellite servicing.

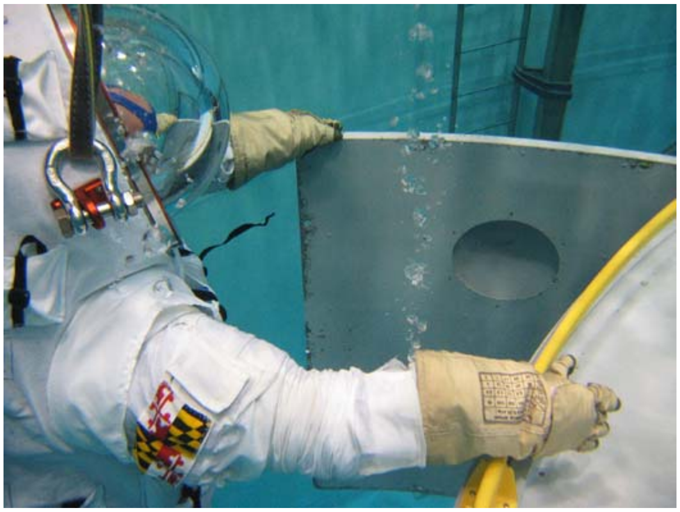


Figure 10: A subject in MX-2 opening door on HST mockup

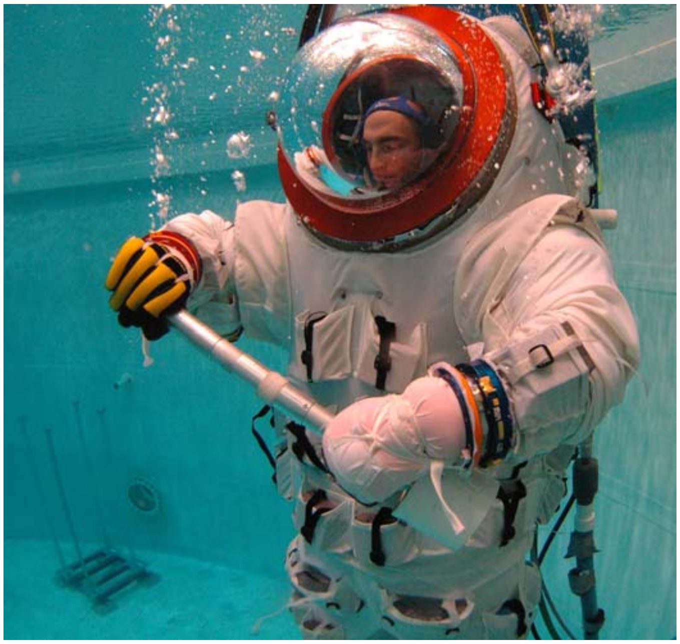


Figure 11: A subject in the MX-2 performing dexterous tasks

A team of safety divers as well as technicians on deck closely monitor each manned MX-2 operation. Suit and subject data are observed in real time for safety, and recorded and analyzed to demonstrate the feasibility of further research. Preliminary results of these operations are presented here.

PRESSURE

Pressures are monitored at all times by the suit technicians on the surface, to ensure that the suit is operating properly and near its nominal state of 3 psi above ambient. The electronics box is also pressurized to 3 psid, and the back hatch is sealed with a pneumatic seal that must maintain pressure at 60 psi. Should any of these pressures drop below their acceptable range, the suit technicians alert the divers and the suit is brought to the surface.

TEMPERATURE

Suit temperature and humidity are monitored to ensure the person within the MX-2 is not subjected to exceedingly harsh environments. The NBRF is maintained at 32 degrees Celsius to provide a comfortable thermal environment for shirt-sleeved SCUBA divers performing multiple hour dives. This makes the internal suit temperature excessively warm for the subject, as evidenced by the typical time history temperature graph in figure 12. Due to the MX-2's very low insulative properties, the suit temperature quickly rises to a steady state very near the water temperature. It is slightly lower as the fresh air blowing across the face is approximately 20 degrees Celsius. While this high suit temperature is not unbearable, it is certainly not ideal for subjects under high workloads. It is clear that the LCG is absolutely necessary, and further work must be done to better insulate the MX-2 to improve thermo-regulation.

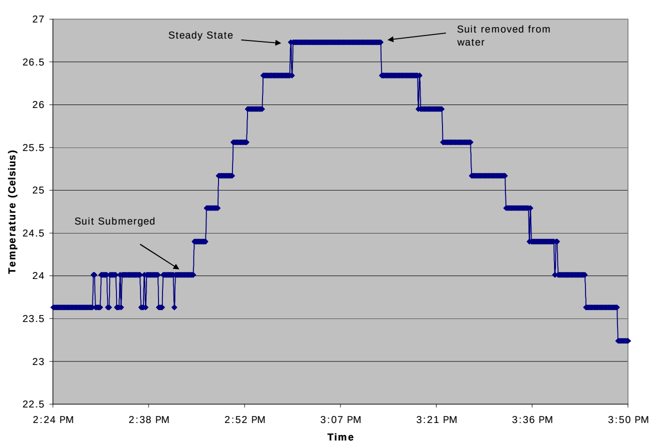


Figure 12: Typical graph of temperature vs. time

HUMIDITY

The air flowing into the suit is filtered according to the Compressed Gas Association grade E standard. This air is acceptable for breathing and designed for use in SCUBA tanks. It is very dry so as to prevent internal corrosion in the tanks; the water vapor is at or below 67 ppm. This is ideal for the suited subject because the completely contained environment of the suit does not allow any moisture to escape. The dry air mixes with moisture within the suit to maintain a relatively comfortable humidity level. Figure 13 shows a time history graph of relative humidity, displaying a constant 24% relative humidity within the suit at the beginning of the dive. The humidity outside the suit is significantly higher, typically 40-50% on deck. As the dive progresses, the humidity level begins to increase, although it remains within comfortable levels.

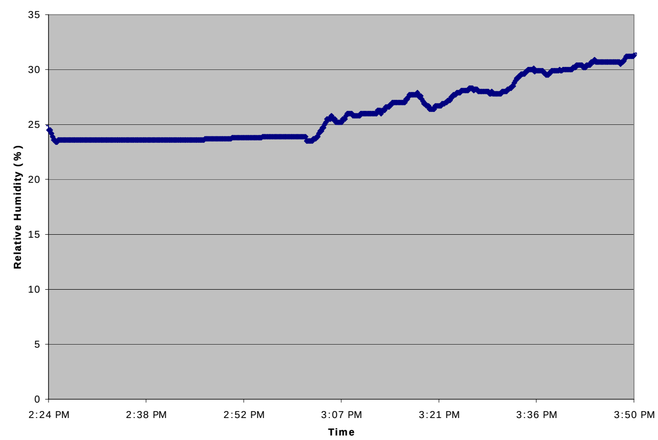


Figure 13: Typical graph of relative humidity vs. time

LCG INLET AND OUTLET TEMPERATURE

Thermocouples have been installed on the inlet and outlet of the LCG cooling water. A heat exchanger model can be applied to obtain a quantitative measure of the total heat loss to the cooling water, where rate of heat loss = mass flow rate · c_p · (T_{out}-T_{in}). The mass flow rate of the cooling water is approximately 0.025 kg/s, c_p for water is 4.2 kJ/kgK, and typical temperature differences in the range of 3-5 Kelvin have been observed. Thus the heat loss to the LCG is in the range of 300-500 Watts. The heat transfer from the surrounding air within the suit to the cooling water is assumed to be negligible, as the tubes are in direct contact with the subject's skin. As well, heat transfer is driven by temperature difference, and the subject's body temperature is much higher than the surrounding air. A typical healthy adult will exhibit an internal work rate of about 100 Watts at rest and at room temperature, while a very high work rate (such as running) would cause heat production of 1000 Watts or higher [18]. Such high internal work rates sustained for long periods of time, especially in warm environments, can lead to a dangerous rise in body temperature. Therefore, it is evident from manned operations that the removal of 300-500 Watts by the LCG is critical to the safety of the subject, especially at elevated work rates.

Other modes of thermoregulation include heat transfer from the subject to the surrounding air, and cooling due to evaporation. Further work will be done to model these heat transfer modes within the suit and quantify the subject's internal and external work rates.

HEART RATE

The subject's heart rate is monitored and recorded during each dive, providing a quick and effective estimate of the subject's work rate, complimenting the LCG temperature data. The instantaneous heart rate is displayed within the MX-2 helmet, allowing safety divers to monitor the subject and advise rest periods if the subject is working too hard. After the operation, using recorded video, events of high work activity during a dive can easily be correlated with elevated heart rate. Figure 14 shows an example of the measured heart rate and the correlation to specific events. Note that heart rate increases during ingress and egress, as the subjects must work hard to lift themselves into or out of the suit. Heart rate is also elevated when the subject is performing difficult tasks. The heart rate data has been filtered with a 5 Hz low-pass filter.

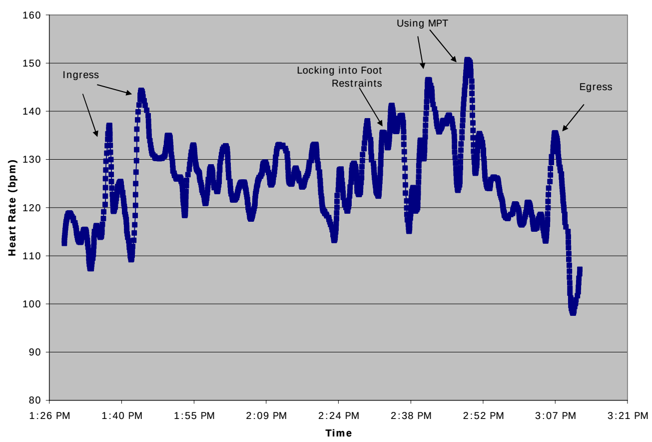


Figure 14: Sample Heart rate graph

SECTION 4: APPLICATIONS

The MX-2 provides an excellent test bed for a wide range of research currently underway at the SSL. Various research groups are using the MX-2 for biomedical instrumentation studies, human-robotic cooperation, and partial gravity simulations.

One of the historical limitations of EVA simulations has been the reliance on subjective evaluations to determine research outcomes. Whether developing operational procedures or evaluating suit improvements, frequently the decision is based on the opinions of a small number of test subjects evaluating the degree of improvement in completing the assigned tasks. A long-term goal of the MARS Suit program has been to develop quantitative metrics to allow objective evaluation of EVA operations. Prime among these has been the objective of metabolic workload measurement.

The improvements to the electronics onboard the MX-2 described above have made further instrumentation easy to incorporate. Gas analysis sensors are being installed within the MX-2 system to measure the subject's rate of oxygen consumption and carbon dioxide production. This will be combined with heart rate and LCG temperature data to quantitatively measure the subject's metabolic workload within the suit. This will allow the use of physiological workload as a key metric in identifying the impact of new procedures and technologies. For example, repeated performance of fiduciary tasks with and without a suit modification will provide a direct numerical comparison of the effects of the suit modification. The same approach can be used to evaluate different procedures, or the use of external aids such as robotic augmentation devices.

One of the primary ongoing uses of the MX-2 is in furtherance of the long-time SSL interest in EVA/robotic teams for space operations. The SSL's dexterous robotic servicing system, Ranger, is being used to investigate robotic manipulator support of EVA operations. Ranger's configuration provides both mobile foot restraints and assistive dexterous manipulators to work together with the suited subject, as shown in figure 15. To date, test tasks have focused on Hubble Space Telescope servicing operations, such as the change-out of an HST Electronic Control Unit. Previous analytical studies have predicted reductions in EVA times of 40% or more based on robotic support for EVA operations; this will be verified by direct experimental measurements of completion times in each mode, supplemented by measurements of other important criteria such as human physiological work loads. This research will be extended to also compare the benefits of direct integration of dexterous manipulators onto the suit system. Feasibility studies of a small, six-degree of freedom manipulator mounted to the backpack are underway. This arm could be used to significantly expand the work envelope of the MX-2, assist with tasks and hold objects and tools. Ultimately, high-level cooperation between EVA and robots will significantly shorten EVA times for complex assembly and servicing missions [19].

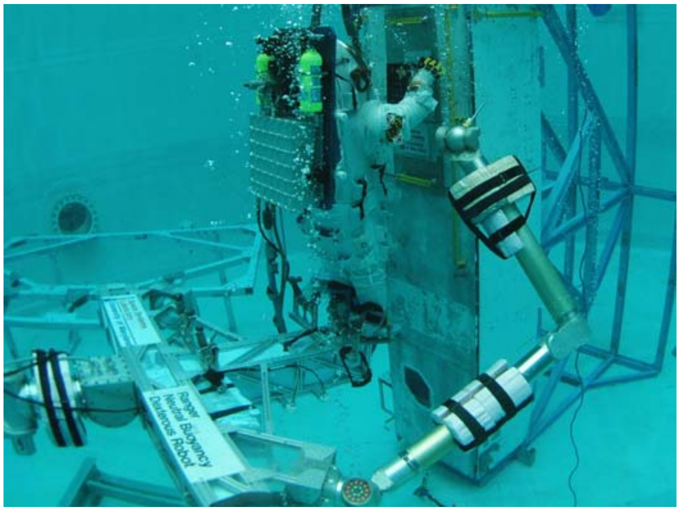


Figure 15: Demonstration of EVA-Robotic Cooperative Servicing: MX-2 Working with Ranger

As NASA sets its sights on the moon and Mars, one problem in abeyance since the 1960's comes back to the forefront: accurately simulating human operations under partial gravity conditions. While a number of counterweight mechanisms were developed at that time, most of the Apollo lunar surface operations training was performed at full Earth gravity conditions for simplicity.

A number of research activities have shown that ballasted underwater operations can accurately replicate many of the critical elements of partial gravity dynamics. The MX-2 is currently being fitted with a ballasting system that will allow simulation of lunar and Martian gravities in the NBRF. This will enable critical research as suit mobility and static stability, reach envelopes, tool design, rover and habitat interfaces including ladders, ramps, and door designs, suit constraints such as acceptable center of gravity locations, and operational procedures development. Even such simple tests as handling of tools and samples, which Apollo astronauts identified as critical tasks not well simulated prior to flight, are well represented by underwater partial gravity simulations.

SECTION 5: FUTURE WORK

In addition to the aforementioned ongoing applications of the MX-2, the existence of an affordable modular suit simulation system enables a wide range of possible research applications and extensions that will have significant impact on the Vision for Space Exploration and other NASA programs in coming years.

One of the primary research areas of interest is to better understand how the human body works in conjunction with (or in spite of) the pressure suit. In addition to the metabolic workload instrumentation described above, the SSL plans to pursue extensive biomedical instrumentation based on the MX-2. In past years the SSL developed a prototype instrumentation package used to measure muscular fatigue and joint motion histories inside pressure suits (2). Due to the limitations of working with NASA EMUs, this system was constrained to a stand-alone system worn inside the EMU hard upper torso, with data unavailable until after the completion of the simulation. With the computational power of the MX-2, a similar system can collect and display this data in real time. This will provide immediate feedback on musculoskeletal impacts of specific motions and techniques, and will provide an additional safety monitoring capability to ensure that test subjects do not injure themselves in repetitive stress situations.

The prototype joint angle measurement system only monitored hand and wrist motion; one long-term goal is to extend this to the entire body of the MX-2 wearer. This will facilitate a wide range of applications, from gestural control of robots and other external devices, to whole-body data collection and real-time range-of-motion studies. Understanding the ranges of joint motion for specific tasks will better define the design constraints for future space suit development, and will provide strong quantitative metrics for evaluating advanced suit joint technologies.

Further bioinstrumentation could be added to the MX-2 in support of specific advanced test objectives, including extensive electromyography (EMG), electrocardiography (EKG) or electroencephalography (EEG) measurement systems. Given the operational capabilities of the MX-2, one potential direction for future studies would be for advanced investigations of in-suit thermal control, which might require significant measurements of temperatures at various places in the liquid cooling garment, as well as body temperatures. One long-term debate that has raged in the EVA community centers on the potential benefits and limitations of restricting respiratory volumes through the use of oral-nasal masks interior to the suit helmet; the MX-2 would allow experimental investigation of this issue, through the incorporation of measurement systems such as non-invasive blood oxygen and in-helmet partial pressure gas species sensors.

The large volume within the MX-2 helmet was designed from the outset to accommodate the integration of advanced heads-up displays. Information that is currently monitored on deck could be overlaid on the subject's view, providing critical data to the subject at a glance. An alternative application would use the display to significantly improve neutral buoyancy simulation through immersive virtual reality. Computer-generated virtual environments could be used to compliment microgravity simulations, giving the subject the impression, both physically and visually, that they are actually working in space. Such a truly immersive system will require many of the augmentations discussed previously, such as the whole-body joint angle measurements, in addition to external measurements of suit position and attitude via instrumentation systems developed at the NBRF for autonomous free-flying robot control.

Given the highly modular nature of the MX-2, a number of advanced suit technologies become attractive for experimental investigation. Designs are currently underway for extremely lightweight bearings to increase arm and leg mobility. These designs also incorporate quick-change sizing elements to allow the accommodation of different test subjects by changing arm and leg segment lengths in seconds using a snap-twist locking resizing element. Replacement of individual suit joints, such as replacing the current rolling convolute shoulders with rigid four-bearing shoulders, will allow direct comparison and quantitative evaluations of alternative technologies in suit design.

One of the long-range visions of the SSL is to move beyond human/robot cooperation to a true state of human/robotic symbiosis: robotic capabilities fully incorporated into the suit system to provide augmentations to the wearer to make them more capable than a human in a shirt-sleeve environment. The highly capable computational architecture of the MX-2 will allow full voice recognition and voice synthesis, allowing direct voice interactions between the suit and the wearer. This will directly extend on-going NASA development activities in cooperative agents, and start the process of making the suit a full partner to the wearer in highly demanding EVA scenarios. Past SSL research into direct robotic augmentation of suit joints, which have included glove MCP and shoulder augmentations, will reduce wearer physiological workload and improve task performance. Longer-range visions of fully augmented suits will accommodate such “science-fiction” concepts as the self-rescuing suit, or in-suit haptic training prior to a particularly demanding EVA.

While this paper is focused on the MX-2 suit system, lessons learned from the development and testing to date are already being applied to future suit analogues. One of the most important coming areas of EVA research will be in planetary surface operations, particularly for EVA subjects in combination with advanced support robots for exploration and base construction. Preliminary design efforts are already underway for the MX-3: a light-weight soft suit designed specifically for field testing of planetary surface operations under Earth gravity. The MX-3 will accommodate a range of subject sizes, and will provide full pressure-suit constraints while allowing easy mobility in field conditions. Advanced technologies for composites rapid prototyping, developed elsewhere at the University of Maryland, are being evaluated for use in advanced hard suit technologies, ranging from rapid low-cost hard upper torso fabrication to full hard-suit concepts for future members of the MX family. Looking downstream, future MX units may not even resemble what is currently thought of as a “pressure suit”; concepts such as the UMd Space Construction and Orbital Utility Transport (SCOUT) system will incorporate many of the technologies and instrumentation of the MX series into advanced concepts such as atmospheric work suits for deep-space extravehicular operations. These revolutionary concepts will be testing at the NBRF in experimental systems in the MX lineage.

The MX-2 neutral buoyancy space suit analogue is truly a unique tool for EVA researchers and space suit design engineers. This low cost analogue is a first step into a family of valuable research systems, which will enable a wide range of experimental investigations that would otherwise be infeasible.

ACKNOWLEDGEMENTS

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The URL for the Space Systems Laboratory is http://www.ssl.umd.edu

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