Jacksonville University

Cryogenic Fuel and Transfer: The Human Interface – Monitoring and Mitigating Risks

NASA Human Lander Challenge (HuLC) 2025

The Dolphin Cryogenic Group - Team Members
George J. Bowdouris (Junior Finance; Aviation Mgt & Flight Operations)
Dylan A. Brand (Junior, Aviation Mgt & Flight Operations)
Casada B. Homan (Junior, Aviation Mgt & Flight Operations)
Donald G. McDermid (Senior, Aviation Mgt & Flight Operations)
Isabella K. Sargent (Sophomore, Aviation Mgt & Flight Operations)

Faculty Advisors: Dr. Gayl Angela Masson, Dr. Brian Kopp, Dr. James Simak, Dr. Reza Sarraf

Jacksonville University

Cryogenic Fuel and Transfer: The Human Interface – Monitoring and Mitigating Risks

Major Objectives & Technical Approach

- Develop a new low cost and innovative design to safely identify leaks from cryogenic tanks
- Proactively conceal hazardous leaks within minutes by having a pinpoint location of where the leak is coming from
- Limit crew endangerment by implementing a self-sealing system
- Transmit leak detection data to the ICAS (Integrated Crew Alerting System) display
- Integrate a robotic arm that can autonomously receive signals from the detection strips and initiate the sealing process

Graphics:

Key Design Details & Innovations of the Concept

- The strip uses pyroelectric sensors and thermochromic materials to identify the cryogenic leak
- Use of existing AI software for sending information to ICAS
- Use of real-time leak detection with adaptive sensitivity
- The ICAS system will provide visual feedback on leak location, status, and robotic arm progress
- A new smaller design of a robotic arm is required for more precise functions

Summary of Schedule

- Design begins 2025
- Advance testing 6-9 months
- System Integration 3-6 months
- Manufacturing and Deployment 6-12 months
- **Total estimated time frame:** 3-4 years

Costs Summary

- Total cost: $1,179,625.00

Table of Contents

1. Executive Summary/Problem Statement

NASA's Artemis program is paving the way for future human missions to Mars through a series of lunar expeditions. A key component is the Human Landing System (HLS1), designed to transport astronauts to the Moon's surface. This paper introduces the Cryogenic Complex within HLS, which includes a Fuel Depot in cislunar orbit, a Fuel Farm for cryogenic storage and transfer on the Moon, and a shuttlecraft—such as the Starship V3—to ferry Universal Cryogenic Storage Tanks (UCSTs) between the Moon, Fuel Depot, and Gateway Space Station. The Cryogenic Complex integrates human and automatically monitored elements to enhance safety and efficiency, including electrical detection of hazardous leaks during refueling, real-time system monitoring, and an AI-driven robotic arm for leak mitigation. We propose our solutions in "Cryogenic Fuel Storage and Transfer: The Human Interface – Monitoring and Mitigating Risks" based on these elements.

2. Project Description - Design and Use

2A. Electrically Identifying Hazardous Leaks – The Cryogenic Detection Strip

Cryogenic Propellants, such as liquid hydrogen and liquid oxygen, are essential components of modern space travel. However, these substances are stored at extremely low temperatures, and any leakage poses a significant risk to both the spacecraft and crew. A cryogenic leak can lead to hazardous conditions, including loss of fuel, structural damage due to thermal contraction, and even potential fire or explosion hazards.

Currently, NASA uses temperature and pressure sensors that are not on specific parts of the cryogenic tanks, and if a preventative step is needed to stop the leak, the crew would have to physically find the leak and seal it. Cryogenic leak detection strips with pyroelectric sensors would narrow down the exact location of the leak. The strip would detect the leak and create a charge of electricity to be sent to the Cryogenic Indicating system, allowing the robotic arm to counteract the leak immediately. Recreating a smaller and more precise robotic arm to aid in sealing leaks would decrease crew workload and ensure a consistent temperature within the tanks, allowing for the life duration of the tanks to increase.

Identifying these leaks before launch and during space missions is crucial to ensuring the safety and integrity of space missions. To address this challenge, we propose the development and implementation of a Cryogenic Detection Strip—a visual and electronic monitoring system to identify and signal leaks in preflight conditions and during long-duration missions. The Cryogenic Detection Strip is a specialized tape-like sensor designed to be placed around areas susceptible to leaks, such as sharp corners, cryogenic tanks, and transfer tubes. The strip serves a dual function:

1. Visual Leak Detection – The strip changes color from red to blue upon exposure to cryogenic fluids. The color change feature of the strip is based on thermochromic materials, specifically a combination of Leuco dyes and liquid crystals. These materials undergo a molecular structure change at specific temperatures, causing a shift in their light absorption properties. Leuco dyes remain red at ambient temperatures but become colorless at cryogenic temperatures, revealing the blue layer beneath. Liquid crystals are used to ensure an immediate

and visible transformation when a leak occurs. The rapid and clear color change provides an easy-to-see warning for ground crews during preflight inspections and can also serve as an additional indicator in space missions where real-time visual inspections may be limited.

2. Electronic Leak Detection – The strip utilizes pyroelectric sensors to detect rapid temperature drops and send an alert signal to mission control and onboard monitoring systems. The strip also incorporates pyroelectric sensors, which generate an electrical charge in response to rapid temperature fluctuations. Pyroelectric sensors work by detecting a change in polarization with temperature. When exposed to infrared radiation, the material absorbs energy and heats up, causing a change in its polarization. The change in polarization is what creates a current and charge that can be sent to the mission control and onboard monitoring system. When cryogenic fluid escapes, it immediately evaporates into an extremely cold gas, causing a sharp drop in temperature. This rapid cooling is detected by the pyroelectric material, generating a voltage that is processed through a small electronic circuit embedded within the strip.

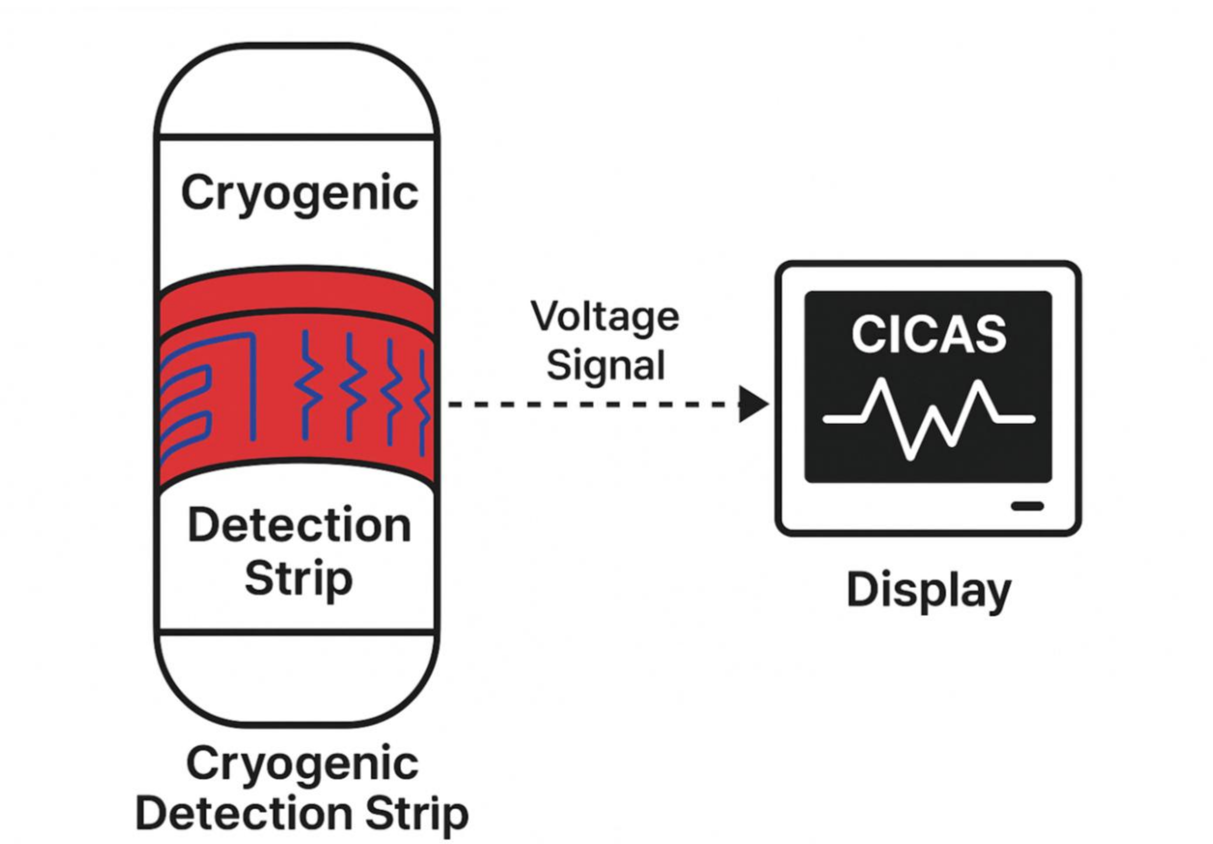

Figure 1 Cryogenic Detection Strip to CICAS

To maximize effectiveness, the Cryogenic Detection Strips will be applied to key structural areas prone to leaks, cryogenic storage tanks, transfer tubes, and sharp corners. These are areas where thermal stress is most concentrated, areas of elevated risk for cracks and joint failure, and points where mechanical stress can cause microfractures and potential leak sites. Each strip will be designed to withstand the harsh conditions of a spacecraft environment, including extreme temperature fluctuations to function for months in space aligning with NASA’s long-duration mission requirements.

The Cryogenic Detection Strip represents a simple yet highly effective solution to the problem of cryogenic leaks in spacecraft. By combining visual leak detection with an electronic alert system using pyroelectric sensors, this innovation enhances both preflight safety inspections and onboard monitoring for long-duration missions. Its implementation will significantly reduce the risks associated with cryogenic leaks, ensuring the safety of astronauts and the successful execution of space missions. With further research and testing, this technology could become a standard safety feature for future space exploration endeavors, including NASA's Human Landing system missions and beyond. This innovation aligns with the goals of the 2025 Human Lander Challenge by offering a lightweight, durable, and cost-effective solution for long-duration cryogenic storage and transfer systems in cislunar space and beyond.

2B. Cryogenic Fuel Transfer and Storage – Automated Monitoring

The first part of the monitoring system is creating a display function that can pinpoint leak locations and notify the crew monitoring systems. We researched an effective way to use the flight control systems on a CRJ-700 (Bombardier regional aircraft) to relate to a theoretical orbiting space hydrogen refueling station. Our research found that we can contribute a revision of the CRJ-700's Engine Indication and Crew Alerting System (EICAS) display. This project addresses the NASA issue of storing cryogenics for longer durations for space missions. We were able to generate a model of the EICAS system to be used specifically for the Cryogenic strips, renamed as the Cryogenic Indicating and Crew Alerting System (CICAS). The CICAS system will be created with the Department of Defense Design criteria standards so that the lighting and indications in the space control room will not interfere with the pilots' ability to control the aircraft. This CICAS system operates in collaboration with the electrical sensor system to create a Cryogenic Indicating system where the pilot and/or fueling personnel can observe the productivity of the tanks to keep the hydrogen at a specific temperature.

A typical Engine Indication and Crew Alerting System (EICAS) used on transport vehicles, such as the CRJ-700, provides an example of a monitoring system that is being developed. The EICAS display on the CRJ-700 is part of a 115v AC and 28v DC system (Aerosim Technologies, Inc., 2015). The main sources of AC electrical power consist of the two-engine driven integrated drive generators, APU driven generators, emergency and air driven generators, and external ground power units. The main sources of DC power are the transformer rectifier units and batteries. This electrical system for the CRJ-700 has a lot of moving parts and a variety of different purposes. Currently, electrical power for space missions is provided through Photovoltaics (PV) power or Radioisotope Power Systems (RPS) (Clark, Hill, & Day, 1998). Photovoltaics is the most common for generating DC power to be stored in batteries or capacitors (Clark, Hill, & Day). The CRJ-700 EICAS system has a battery which consists of a 24v DC 17amp/hr. Nichel-Cadmium battery (Aerosim Technologies Inc., 2015). This is constantly charged in case of electrical failure within the aircraft. These are the same batteries used for different space missions, charged by the PV system. Our proposal is that the battery will stand as a backup to a Super Magnetic Energy Storage (SMES) system located within the storage area (Rogers, 1981).

Figure 2 CRJ-700 EICAS Display (Aerosim Technologies Inc. , 2015)

A High Temperature Superconductor will be placed near the cryogenic environment so that it can store electricity. This system works by receiving DC current from the photovoltaic solar system and directing that current into a coil within the SMES that stores it as a magnetic field (Rogers, 1981). A Power Conditioning System will regulate electrical flow into the CICAS system and serve as a voltage regulator directing a sufficient flow of current to supply the monitoring system. The Power Conditioning System will also be able to switch over to the backup battery for system redundancy, in case of a system failure. The SMES has not been used frequently in space missions due to the need for cryogenic cooling to store the system, which can be exceptionally expensive and heavy (Rogers, 1981). Cryogenic storage allows for the introduction of this system to be cost efficient and built on an already existing system. Additionally, this system will be stored at temperatures that allow for a long life. Typically, the EICAS system has a variety of different purposes including engine parameters, pneumatic information, flaps, gear settings, and more. If this system were specifically designed for the Leak Detection Strips, it would take a significantly lower amount of power from the SMES to run the system.

Figure 3 CICAS Display

Onboard the CRJ jet there is an anti-ice system that monitors pneumatic systems for bleed air leakages using sensors across the pneumatic ducting (Aerosim Technologies Inc., 2015). Although the leak detection will be different, our system will have a system consisting of a Data Concentration Unit that will receive system leak information and input a visual message displaying the severity of the leak. The CICAS will have a Control panel that allows the person monitoring to view the amount of leak and specific points where the system is having a leak. These systems incorporate a color-coded warning based on the severity of the failure and the crew's action required. A red-coded message includes a critical warning message to the crew and flight mission. An amber-coded message would display a caution message about the system that requires crew attention but may not always need a correction. The third type of message that could alert the crew is an advisory message to the crew about the system's performance (Mumaw, et al., 2018). Within each of the EICAS displays, there is a status page that displays specific information about certain systems.

Our proposal for automated monitoring and maintenance is to include a central monitoring system where leaks can be identified. This system would be linked to the cryogenic sensors to display a graphic of the storage area and indicate leak locations. With this Cryogenic Monitoring system, the sensors would be able to detect leakage and indicate a color-coded message to the crew. The system would be able to indicate the severity of the leak and provide information if additional steps are required. Our system will be based on a standard Aviation Flight Management System (FMS), allowing a crew to monitor the leakage within the cryogenic tanks to increase the duration that the tanks can last.

2C. Cryogenic Fuel Transfer and Storage – Automated Maintenance

The last part of our system is to use an automation-controlled robot arm to perform maintenance tasks. Our goal is to minimize physical human factors when it comes to repairing equipment. If we can limit the workload of pilots and re-fueling personnel by creating a system that is self-healing, we feel that everything will be more efficient, and the chances of human error will drop significantly.

Currently, NASA uses exceptionally large robotic arms with basic functionality. For our device to be successful, we would need to create a smaller, and more precise robotic arm to place the material and counteract the cryogenic leaks. This part of our proposal describes a CICAS that uses artificial intelligence to autonomously fix errors, particularly while keeping cryogenics at certain temperatures. Our system will have indicators throughout the cryogenic storage units, and together with the electrical system, the autonomous robot arm will be able to seal leaks detected within the tank and, for example, place down Kapton tape, which can withstand extremely low temperatures, and medical-grade tape with epoxy resin on top, or make other significant mechanical fixes remotely. Using Artificial Intelligence software, the robotic arm will take the data from the indications from the pyroelectric strips and maintain the safety and performance of the cryogenic storage units.

3. Verification & Validation of Solution

Superconductors are cooled to a specific temperature in order to conduct electricity with nearly zero loss. These conductors are cooled below Critical Temperature (T_C) in order to conduct this electricity with no resistance (DOE Explains...Superconductivity, ret. May, 2025). The Department of Defense explores an already completed study by the University of Illinois stating, “Negatively charged electrons, which normally repel each other, form into pairs below T_c. These paired electrons are held together by atomic-level vibrations known as phonons, and collectively the pairs can move through the material without resistance” (DOE Explains...Superconductivity, ret. May2025). Many scientists have explored a variety of materials and methods to allow these systems to work at warmer temperatures. Different materials such as copper-oxide can be used to conduct electricity at a warmer temperature. The two types of superconductors include low temperature and high temperature, the low temperature being created with materials such as Nb-Ti which can store at a T_C of 9K, and high temperature made of materials such as YBCO which can store at temperatures around 30-77K (Rogers, 1981). The high temperature conductors would be most efficient to be used due to the cryogenic storage and temperatures that the system is storing cryogenics. This research provides testing of these superconductors in an environment that is similar to the cryogenic storage that will already be in place on the Human Lander mission.

One challenge with designing this power system was calculating the specific amount of electrical power that is needed to power the CICAS monitoring system. On the CRJ-700 the EICAS is part of an electrical system that is powered by a 28v DC current system, but many other airplanes use around 24v (Aerosim Technologies Inc., 2015). Our system would only be monitoring the leakage from the tanks and would not need the additional information that the traditional EICAS system displays. Calculating the specific amount of power to continuously run the monitoring system and duration that the system could run needs further experimentation with the system. Using the specific microcontrollers that allow the system to run at low power for long periods of time. Another option would be a method where the system cycles on and off to decrease power consumption.

4. Realistic Technology Assumptions

The system, integrating cryogenic detection, thermal sensing, robotic response, and CICAS display, would need to undergo integrated testing in simulated space environments. This includes testing the system's overall reliability, signal transmission, and response to leaks under real-world space conditions, including vacuum and extreme temperature variations.

Pyroelectric sensors and thermal detection materials have already been demonstrated in laboratory conditions on Earth, but integrating them into a flexible, real-time system for space applications has not yet been fully validated in simulated space environments. The cryogenic detection strips need to undergo rigorous testing in vacuum chambers and cryogenic environments to prove their viability for space missions.

Thermal sensors, such as thermistors and thermocouples, have been widely used in various space applications. However, adapting them to detect cryogenic leaks in space-specific environments, such as the vacuum of space or the low-temperature extremes associated with cryogenic fluids, requires further validation. Thermal detection systems need to be rigorously tested for accuracy in space-like conditions.

The Integrated Crew Alerting System (ICAS) has been used in various forms for space missions, such as NASA's Space Shuttle and the ISS. The integration of leak detection data and robotic system control as a CICAS is a logical progression but would require validation in a space-relevant environment. Key areas for advancement include ensuring seamless real-time communication between the cryogenic detection system, robotic arms, and the CICAS.

Additionally, there is a need to develop intuitive user interfaces on the CICAS to enable astronauts to efficiently monitor and control the leak sealing process.

5. Size Estimation

Given that the cryogenic tanks are around 53,488 cubic feet in volume, we are focusing on wrapping the hazardous areas of the tanks that are most likely to leak, such as valves, seams, and joints, as well as sections of the tank under stress or near fittings and connections. Rather than covering the entire surface area of the tank, we will target these high-risk leak zones. We will assume that 20% of the lateral surface area is hazardous and needs to be wrapped.

Height: 46.9 meters
Diameter: 8.4 meters
Gross Mass: 760,000 kg
Lateral surface area of one tank: 13,343.5 sq. ft

We can calculate the dimensions using the formula for the volume of a cylinder:
HA (Hazardous area) = 0.20×13,343.5
HA = 2,668.7 sq. ft
Since there are often two tanks, the total hazardous area is:
HA×2 = 5,337.4 sq. ft

The Office of Science and Technical Support with the US Department of Energy explored the usage of these semiconductors that we propose stating the length and diameter of these superconductors to be around 900 mm x 900 mm with a weight being around 200 lbs. (Clark, Hill, & Day, 1998). This is a lightweight, cost-effective way to store electricity and power the cryogenic leak monitoring system. The CICAS system is typically 1kg depending on the display and a size of around 10x10 cm box with a depth of about 5 inches. The Power Conditioning unit would be around 90x90x18 mm with a weight of around 120 grams, based on the GomSpace Nano Power P60 system (NanoPower P60 System, ret. May2025).

6. Mission Timeline and Schedule

Engineering analysis and extensive testing will be conducted to ensure the reliability and effectiveness of the Cryogenic Detection Strip, including thermal response testing, material durability analysis, electrical signal processing, and modeling. These tests will verify the response time of the color change mechanism and pyroelectric sensor activation under controlled cryogenic conditions and evaluate the structural integrity and performance of the strip in vacuum, radiation, and temperature extremes. Testing can also assess the accuracy and efficiency of voltage generation and signal transmission to mission control. Computational fluid dynamics (CFD) and finite element analysis (FEA) can be utilized to predict leak patterns and optimize sensor placement.

The production of the Cryogenic Detection Strip will be streamlined for scalability and cost-effectiveness. The manufacturing process includes the fabrication of thermochromic layers through chemical deposition and polymer integration, incorporation of pyroelectric sensors using thin- film technology for minimal weight impact, and development of wireless transmission modules for integration with spacecraft monitoring systems. Deployment will follow a phased approach: 1. Prototype Development – Initial laboratory testing and material validation. 2. Subscale Testing – Application in simulated space conditions, including vacuum chambers. 3. Flight Demonstration – Deployment on small-scale missions for real-world validation. 4. Full-Scale Integration – Implementation into NASA's Human Landing System (HLS) and commercial lunar cryogenic vehicles.

Linking the Cryogenic Detection Strips to the CICAS system will be an initial step in the display process. This process will involve basing research on the system already in place and generating a revamped version. Testing the most efficient type of Data Concentration Unit for the Detection Strips and programing the DCU so that the monitoring display will output accurate information about the location of the leak. Generating a model based on the CRJ-700 system will include altering software specific to airplane system monitoring. Taking parts of the CICAS display, such as the FMS, will allow development of this monitoring to be done quickly. Basing this system on the system already in place will be more efficient than generating new software for leak detection.

Year	2025	2026	2027	2028	2029
Phase	Exploratory	Functional		Implementation & Operation	
Cryogenic Safe Planning	Engineering analysis of effectiveness of the Cryogenic Detection Strip and material validation. Testing of SMEC and CICAS Function with Detection Strips.	Manufacturing process and Flight Demonstration – Deployment on small-scale missions for real-world validation. Integrating CICAS sytem into the already functioning aircraft system.		Full-Scale Integration – Implementation into NASA's Human Landing System (HLS) and commercial lunar cryogenic vehicles	

Fig. 4 Mission Timeline

7. Budget Assessment

This budget assessment shows an up-to-date assumption of the total costs to bring our system to use for the mission. Most of the materials are cost effective and can be implemented quickly. Included is the current cost of the SMES unit, but upon further research it will be possible to create a needs-specific system. The quickest way to implement these functions would be to purchase an off-the-shelf SMES Unit. These prices were taken from real world vendors with accurate prices that display an estimate to bring our Cryogenic System to market.

Item	Quantity	Cost/Unit	Total Cost	Vendor
Polyimide Film	8,550 ft	$0.50/ft	$4,275	APICAL®
Polyvinylidene Fluoride	8,550 ft	$10.00/ft	$85,500	Arkema Global
Thin Film Thermocouples	8,550 ft	$2.00/ft	$17,100	Dwyer Instruments
Circuit Board	8,550 ft	$5.00/ft	$42,750	FlexPCB
EICAS Display	1	$15,000.00	$15,000.00	L3Harris
NanoPower P60 Power System	1	$15,000.00	$15,000.00	GomSpace
SMES Unit	1	$1,000,000.00	$1,000,000.00	American Superconductor
Total			**$1,179,625.00**	

Table 1: Cost Estimate

8. Conclusion

Our proposed system, "Cryogenic Fuel and Transfer: The Human Interface – Monitoring and Mitigating, Risks," represents advancement that is necessary for safety, efficiency, and the autonomy of cryogenic operations in space. By using cryogenic detection strips, advancements in monitoring with a CICAS system, and the use of an AI driven robotic arm for precise maintenance, we can address operational deficiencies that we may face in cryogenic fuel storage and transfer. Our proposed solution not only mitigates the risk of our crew but also decreases human workloads. With real-time diagnostic reports, crews will be able to have access to crucial information about the status of the cryogenic fuel systems, the spacecraft, and the completion of the mission. The integrated system is designed with existing NASA technology in mind, making it practical and realistic for use in the near future. With the use of our product, we can assure that any leakage detected will alert crews immediately and in turn enhance the longevity of these cryogenic systems, greatly increasing the sustainability of those elements critical to the HLS infostructure.

Each component of the system is built upon existing technologies such as thermochromic and pyroelectric sensors, CICAS systems, and AI enabled devices, adapted for space conditions. Transforming these items for space readiness would realistically take about 3-5 years through multiple testing phases. Long term the system will markedly decrease recurring operational costs, avoiding those damage and expenses caused by leaking cryogenics. Using thin film sensor manufacturing and existing cryogenic research methods ensures cost efficiency. The modular design can be integrated slowly and tested easily in lunar environments and architectures beginning with demonstrations slowly moving to full deployment of the design and can be confirmed through small flight trials and eventually moving to HLS missions. These systems reduce risks caused by human error, undetected leaks, and thermal stress failure. Built in redundancy via SMES backed power storage and color-coded alerting allows systems to recognize and promptly address the situation without mission interruption. Not only is this a technical advancement, but it also allows NASA to complete these long-term missions. Proven technologies and a clear path to flight readiness leave us with a durable foundation, with the belief that this can become a core piece of NASA's Human Lander System.

Appendix I

Motto and Labeling

References

[1] Aerosim Technologies Inc. (2015). Aerosim Ethos. Burnsville, Minnesota.

[2] Artemis Program https://www.nasa.gov/humans-in-space/artemis/ ret May2025

[3] Camara, J.A. (2021). *Spacecraft Electrical Power*. Pewaukee: PDH Academy.

[4] Canva. (2025 May 25). *CICAS Display*. Retrieved from Canva Digital Image: canva.com

[5] Clark, C. S., Hill, A. D., & Day, M., (1998). *Commercial Nickel Cadmium Batteries for Space Use: A Proven Alternative for LEO Satellite Power Storage*. Guildford: Centre for Satellite Engineering Research, University of Surrey.

[6] Cooper, D. W., & Kzchns, P. W. (1966). *Generator With A Superconducting Magnetic Field For Use In I-Megawatt Space Power Systems.* Cleveland: National Aeronautics And Space Administration.

[7] *DOE Explains...Superconductivity*. (n.d) Retrieved from U.S. Department of Energy: https://www.energy.gov/science/doe-explainssuperconductivity (ret. May,2025).

[8] Doody, D. (n.d.). Chapter 11: Onboard Systems. Retrieved from National Aeronautics and Space Administration: https://science.nasa.gov/learn/basics-of-space-flight/chapter11-3/ NASA Human Landing System https://www.nasa.gov/reference/human-landing-systems/ Ret May2025

[9] Gui, H., Chen, R., Niu, J., Zhang, Z., Tolbert, L. M., Wang, F., Choi, B. (2019). *Review of Power Electronics Components at Cryogenic Temperatures*. Cleveland: Institute of Electrical and Electronics Engineers.

[10] Johnson, W., Tomsik, T., & Moder, J. (2014). *Fundamentals of Cryogenics*. National Aeronautics and Space Administration.

[11] Mumaw, R. J., Feary, M., Fucke, L., Stewart, M., Ritprasert, R., Popovici, A., & Deshmukh, R. (2018). *Managing Complex Airplane System Failures through a Structured Assessment of Airplane Capabilities.* Ames Research Center Moffett Field, California: National Aeronautics and Space Administration.

[12] NanoPower P60 System. (n.d.) Retrieved from GOMSpace: https://gomspace.com/shop/subsystems/power/nanopower-p60.aspx ret May2025

[13] Rogers, J. D., *Superconducting Magnetic Energy Storage (SMES) Program.* Los Alamos: U.S. Department of Energy Office of Scientific and Technical Information, 1981.

[14] Scanlan, R. M., Malozemoff, A. P., & Larbalestier, D. C. *Superconducting Materials for Large Scale Applications.* Institute of Electrical and Electronics Engineers, 2004.