Abstracts book

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[1] *Development of a Microlith® Catalytic Oxidizer for Exploration Trace Contaminant Control*

Matthew Kayatin (NASA MSFC), Jay Perry (NASA MSFC), Saurabh Vilekar (Precision Combustion, Inc.) and Curtis Morgan (Precision Combustion, Inc.).

The state-of-the-art in long mission duration spacecraft trace contaminant control processes rely on high-temperature catalytic oxidation for light contaminant removal. Target compounds for oxidation include metabolic methane, carbon monoxide, and low molecular weight volatile organics such as formaldehyde and methanol. Precision Combustion, Inc. and NASA Marshall Space Flight Center have been developing and testing prototype high temperature catalytic oxidizers based on PCI's patented Microlith® technology to meet the requirements of future spaceflight exploration missions. To this end, our latest generation Microlith oxidizer, featuring an integrated heat recuperator, was subjected to endurance testing to simulate catalyst ageing over a Mars transit mission duration. Periodic reactor health testing indicates our approach results in a robust contaminant control solution for exploration missions beyond low earth orbit. Based on the demonstrated performance of this unit, a next-generation prototype was designed to meet exploration contaminant load control demands while upgrading the prototype form and fit to match flight-compatible interfaces. Prototype design considerations intended to reduce power consumption, impacting process thermal and hydraulic performance, are discussed herein.

[2] *History of NASA's Odor Assessment (Test 6)*

Benjamin Greene (Sierra Lobo, Inc.), Vanessa Buchanan (Sierra Lobo, Inc.) and Susana Tapia Harper (NASA).

NASA's Odor Assessment (Test 6) for nonmetallic materials and assembled articles for spacecraft has evolved since the Apollo program in 1966 to meet various habitable spacecraft nonmetallic programmatic requirements. The purpose of Test 6 is to determine if the odor from a material or assembled article is objectionable or revolting on an odor-characteristic scale of 0 to 4. Samples of the toxicity-screened test atmosphere from a conditioned specimen container are administered to an Odor Panel of qualified human research subject volunteers using a syringe and mask, and are assigned a scored odor characteristic of undetectable (0), barely detectable (1), easily detectable (2), objectionable (3), or revolting (4). The odor from a material or assembled article is objectionable or revolting if an average rating of 2.5 or higher is assigned by an Odor Panel. This manuscript presents the history of Test 6, beginning with the Apollo spacecraft nonmetallic materials selection guidelines and test requirements from 1966, in which tests were performed in oxygen atmospheres, and follows the odor test through Skylab, Space Shuttle, International Space Station, and Orion nonmetals testing, and acceptance requirements.

[3] *JUICE (JUpiter ICy moons Explorer) Thermal Vacuum Test*

Romain Peyrou-Lauga (ESA) and Séverine Deschamps (Airbus Defence and Space).

JUICE - JUpiter ICy moons Explorer - is the first large-class mission in ESA's Cosmic Vision 2015-2025 programme. Planned for launch in 2022 and arrival at Jupiter in 2031, it will spend at least three years making detailed observations of the giant gaseous planet Jupiter and three of its largest moons, Ganymede, Callisto and Europa. The JUICE spacecraft will carry the most powerful remote sensing, geophysical, and in situ payload complement ever flown to the outer Solar System. The payload consists of 10 state-of-the-art instruments. JUICE spacecraft thermal control has to cope with a large variation of external environment during the mission (Sun flux from 3323 W/m² in the inner Solar System down to 46 W/m² in Jovian environment) and long eclipses of up to 4.8 hours. The JUICE thermal control is designed with the objective to minimize the impact of the external environment on the spacecraft through high efficiency Multi-Layer Insulation. Minimizing heating power demand especially during science and communication phases and minimizing hardware mass is a constant concern and solutions are found to build to a maximum extent a robust and passive thermal design supplemented by heaters. This paper will focus on the thermal verification of the Spacecraft and particularly on the first and long thermal test. This test included several phases of thermal balance, with or without Sun simulator, and the functional verification in cold and hot environment.

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[4] *Flame Retardant Polyamide Fibers for Space Crew Clothing*

Krishnaswamy Rangan (Materials Modification Inc) and Tirumalai Sudarshan (Materials Modification Inc).

NASA's vision is to eventually establish human outpost stations on the Moon and explore Mars and other destinations further out of the Lower Earth Orbit (LEO). New fabrics for astronauts are needed for a sustainable human presence beyond LEO. During these space missions, astronauts need to be protected inside space vehicles and space habitats with oxygen-rich atmospheres. State of the art in flame-retardant fabrics are based on Nomex, FR rayon, FR cotton, and FR wool. These materials are suitable under terrestrial conditions, with 21% oxygen in the air. However, these fabrics may not protect crew members at higher oxygen concentrations found in space applications (36% oxygen). Therefore, an intrinsically flame-retardant (FR) and inherently strong, nontoxic, and comfortable fiber to use for next-to-the-skin clothing has been developed and the details will be presented at this conference. The novel FR polyamide polymer produced was extruded into multifilament fibers. Thermal and flame retardant properties of the novel polyamide fibers will be presented.

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[5] *Suborbital Testing of the OSCAR Trash-to-Gas System*

Ray Pitts (NASA Kennedy Space Center), Anne Meier (NASA Kennedy Space Center), Joel Olson (NASA Kennedy Space Center), Malay Shah (NASA Kennedy Space Center), David Rinderknecht (NASA Kennedy Space Center) and Jaime Toro Medina (NASA Kennedy Space Center).

With the sustained human exploration of nearby celestial bodies on the horizon, a renewed outlook on waste management must be realized. Current waste management strategies aboard the International Space Station become impractical as we venture further away from low Earth orbit and the resources that can be extracted from waste streams are substantial. One method of combatting this issue is by thermally degrading solid and liquid crew waste items into a chemically inert, ventable gas stream, a process known as Trash-to-Gas. The Orbital Syngas/Commodity Augmentation Reactor (OSCAR) is the state-of-the-art Trash-to-Gas system which has been designed to explore microgravity Trash-to-Gas concepts for improved mass/volume reduction and resource recovery from waste. OSCAR is a subscale testbed design that supports the NASA Logistics Reduction (LR) project under the Advanced Exploration System (AES) Program and Space Technology Mission Directorate (STMD) Flight Opportunities Program to determine the feasibility of Trash-to-Gas technology for use on future long duration space missions. OSCAR has flown on two suborbital flight demonstrations aboard Blue Origin’s New Shepard launch vehicle. This paper presents an overarching comparative analysis of these microgravity test campaigns with 1g laboratory experimentation. Percent gasification, product gas composition, soot and water production, reactor temperature and pressure, trash injection methodology, and system automation are compared to highlight the operational discrepancies within the microgravity environment for future optimization. The OSCAR system design progression and up-to-date lessons learned are also discussed for consideration into follow-on human spaceflight mission architectures.

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[6] *Review of Targeted Lighting Approaches for Controlled Environment Agriculture in Space Habitats*

James Hardy (University of Colorado Boulder), Gioia Massa (NASA Kennedy Space Center), James Nabity (University of Colorado Boulder) and Patrick Kociolek (University of Colorado Boulder).

Providing light to plants is expected to dominate the operational costs of agriculture in space habitats. Not only is lighting power intensive, but power introduced into a crop chamber must also be removed to maintain thermal equilibrium. To decrease the power and subsequent cooling demands, advancements in lighting methods must be implemented. Lighting efficiency improvements are limited as LEDs are converging to their maximum theoretical efficacies, which also reduces the effect of optimizing the spectrum to boost efficiencies. Instead, one could consider the effectiveness of light delivery to the canopy by each diode. Plant chambers like the Veggie and the Advanced Plant Habitat on the International Space Station provide power uniformly across the light fixture, often lighting walls and empty spaces, especially when the plants are small. To help ensure that light introduced to the growth area is useful, light fixtures may employ a targeted approach, where emitters are controlled such that those pointed directly towards foliage are activated while others are not. This paper reviews previous targeted lighting approaches and identifies a candidate method that could be applied in future controlled environments, especially those aboard space habitats.

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[7] *Mitigation of Silver Ion Loss from Solution by Polymer Coating of Metal Surfaces, Part IV*

John Vance (NASA AMES RESEARCH CENTER / KBRwyle) and Lance Delzeit (NASA).

Ionic silver (Ag+) biocide is a leading candidate to provide residual microbial control in spacecraft potable water systems, but suffers from rapid concentration loss due to interactions with the metallic containers and tubing. One approach to mitigate this is the coating of metal surfaces with an inert barrier film. In previous reports, we have described our investigations addressing Ag+ loss mitigation and adhesion performance of parylene barrier coatings on coupons of several metal alloys and 316L tubing under static immersion. In such conditions, parylene-C and -AF4 coatings have shown excellent Ag+ loss mitigation and mixed long-term adhesion performance, depending on parylene species and substrate surface chemistry/structure. In Part IV of this series, we report on our work to investigate the performance of parylene-C barrier coatings, under more challenging and realistic conditions, in order to evaluate potential suitability for use. The resilience and associated Ag+ loss with Parylene-C coating on 316L tubing and fittings under medium-term immersion and repeated fitting dis/reassembly were investigated. Potential mechanical challenges to barrier coatings in spacecraft potable water systems were investigated, with two main focuses being identified: liquid flow/pressure cycling in tubing and cyclic operation of bellows in positive-expulsion storage tanks. Two corresponding testbeds for experimental characterization of coating performance were developed. In the Flow/Pressure Testbed System, Ag+ solution will be pumped through coated 316L tubing, with optional pressure cycling. In the Bellows Tank Testbed System, an internally coated edge-welded 316L bellows containing Ag+ solution will be cyclically extended and compressed, analogous to the operation of bellows tanks used for potable water storage and delivery on the International Space Station. The design and operation of these testbeds are described. Finally, the Ag+ adsorption and saturation behaviors of Kalrez and Viton, for potential use as seal materials in fittings and other connections, were characterized in limited experiments.

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[8] *Considerations on Electrolytic Conductivity Measurement for Monitoring of Ionic Silver Biocide Dosing*

John Vance (NASA AMES RESEARCH CENTER / KBRwyle), Lance Delzeit (NASA) and John Abdou (NASA AMES RESEARCH CENTER / KBRWyle).

NASA interest in ionic silver (Ag+) as a biocide for spacecraft potable water systems motivates the development of Ag+ concentration sensors to ensure nominal dosing. The electrolytic conductivity change of highly-purified potable water is linearly related to the concentration of chemically-dosed Ag+ and could serve as a useful proxy measurement, while the conductivity change during electrolytic dosing may be less so, depending on the influent water chemistry and electrolytic efficiency. Understanding and mitigating the potentially deleterious effects of Ag+ interaction with conductivity measurement systems requires investigation. Issues associated with traditional conductivity cells, which rely on wetted (typically metal or graphite) electrodes, and capacitively-coupled contactless conductivity detection (C4D) for this application are considered. Traditional conductivity cells may potentially be subject to significant excitation-induced or auto-galvanic reduction of Ag+. These may result in Ag+ depletion or electrode fouling and associated measurement error. Proper selection of electrode material, excitation parameters, and cell geometry may limit such effects. C4D uses electrodes placed outside an inert, insulating material, with dielectric polarization enabling the production of an electric field and resultant current across the analyte solution. This approach could potentially mitigate problems with Ag+ depletion and fouling by eliminating the possibility of auto-galvanic deposition and reducing the Faradaic current density. However, it is necessary to confirm C4D performance at very low conductivity levels and to determine if long-term operation produces conductive deposits, which could result in measurement error. A commercial C4D system employing 1/16" (1.59 mm) outer diameter flow tubing and claimed performance in the conductivity range appropriate for this application was identified, and its sensitivity in the middle and upper parts of this range was confirmed in preliminary experiments. A concept for a C4D detector that could potentially allow for full rate flow-through using planar electrodes and thin-film dielectric layers is discussed.

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[9] *DirectINJECT: Dosing Systems for Concentrated Liquid Biocides*

John Vance (NASA AMES RESEARCH CENTER / KBRwyle) and Lance Delzeit (NASA).

Reliable and mass-efficient techniques for biocide dosing are necessary to enable residual microbial control in spacecraft potable water systems. DirectINJECT is an approach to provide ultra-low flow rate injection of stable aqueous biocide concentrate solution (e.g., highly soluble silver salt). This method has the benefit of low consumable mass and is insensitive to the chemistry of the target water. With a 40 g Ag+/liter solution, required dosing rates would be ~1 µl/minute during water processing (for a system similar to the ISS WPA), requiring only approximately 20 ml/crew-year of concentrate. The performance of three dosing systems were identified and characterized: pressure-driven flow through a robust micro-capillary tube with a solenoid valve shut-off, a miniature peristaltic pump, and a multi-piston pump with integrated valving. Several potential system performance and reliability concerns are addressed including prevention or segregation of gas bubbles in the concentrate reservoirs as well as long-term materials compatibility, leak minimization at valves and seals, and mechanical life.

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[10] *Engineering Polymers as Structural Materials in Spacecraft Water Systems*

John Vance (NASA AMES RESEARCH CENTER / KBRwyle), Alexander Shaw (NASA AMES RESEARCH CENTER / UNIVERSITIES SPACE RESEARCH ASSOCIATION) and Lance Delzeit (NASA).

High-performance engineering polymers, such as PEEK, PEI, and PVDF, have found increasing use as structural materials in a broad array of demanding applications, including in the aerospace, medical implant, and chemical processing fields. In many cases, they have replaced passive metals, due to cost or mass savings, improved chemical resistance and inertness, and/or ease of fabrication. As of yet, there has been little concerted investigation considering the replacement of metals in spacecraft water systems to take advantage of these developments. The decision to baseline ionic silver as the biocide of choice for future exploration-class systems motivates considering this change, as rapid Ag+ depletion to metal surfaces can result in loss of microbial control. The development of inert barrier coatings may enable the continued use of metal alloys in many applications, but introduces additional failure modes and suitable robustness has yet to be adequately demonstrated. In this early work, we began to address the myriad issues of concern associated with materials selection for performance-critical life support hardware. These include mechanical properties, failure mechanisms, design requirements, leaching into potable water, chemical resistance, radiation tolerance, outgassing, flammability, and others. We selected several engineering polymers for initial consideration and conducted Ag+ compatibility tests on a limited selection of these, including materials with reinforcing fibers or lubricant fillers. We identified useful literature regarding rational materials selection, design, and mechanical behavior of engineering polymers. We found that there is significant potential for use of engineering polymers in spacecraft water systems but note that much work remains to assemble a knowledge and experience base regarding long-term mechanical reliability of pressurized thermoplastic components and to develop relevant design/test qualification practices and standards. Finally, we suggest some directions for future research.

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[11] *Plant Water Management in Microgravity*

Tyler Hatch (NASA Glenn Research Center), Marc Wasserman (Portland State University), John McQuillen (NASA Glenn Research Center) and Mark Weislogel (IRPI LLC).

The NASA Plant Water Management (PWM) experiments conducted aboard the ISS are a set of technology development demonstrations that apply recent advances in microgravity capillary fluidics research towards the mundane yet problematic challenges of simply watering plants in space. Plant growth in a low-g environment is often hampered by inadequate aeration and over-saturation of the root zone. The PWM effort aims to exploit the passive capillary forces of poorly wetting liquids (i.e., contaminated water) within unique system geometries that effectively replace the role of gravity in providing sufficient aeration and hydration for simulated plants. Fourteen ISS operations supported by nine crew members were completed on-orbit in 2021, including approximately six days of soil-based and eight days of hydroponic models in single and parallel channel networks. Supportive terrestrial and low-g drop tower tests were conducted to aid in experiment design via small scale- and full-scale demonstrations. To date, the experiments demonstrate proofs-of-concept, limits of operation, system stability, and more. Applications are discussed in relation to plant growth facilities for both near-term microgravity plant science research and long duration human exploration missions.

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[12] *Plant Water Management Experiments: Hydroponics 3 & 4*

Marc Wasserman (Portland State University), Mark Weislogel (IRPI LLC), Logan Torres (IRPI LLC), Tyler Hatch (NASA Glenn Research Center) and John McQuillen (NASA Glenn Research Center).

As humans consider longer-duration missions in space, NASA has identified production of fresh vegetables aboard spacecraft as beneficial for crew nutrition, mental wellbeing, and enabling bioregenerative life support (i.e., air, water,

and waste processing). Current low-g plant growth techniques have successfully grown a variety of leafy and flowering plants. However, unique microgravity fluidics challenges to maintain plant moisture levels persist which hamper overall system reliability. The Plant Water Management (PWM) experiments seek to demonstrate low-cost, low-mass, reusable plant growth systems that leverage recent advances in low-g capillary fluidics phenomena to provide routine, largely passive, water delivery to plants. This paper presents findings from a series of PWM Hydroponics experiments, which were collected during four different ISS flight operations that occurred in February, March, May, and July of 2021. Open hydroponic capillary channel flows with synthetic evapo-transpiring plant models were used. Tests demonstrated flow stability for single, parallel, and serial channel flow configurations across a range of flowrates, plant types, and plant arrangements. Technology demonstrations of both passive aeration and bubble phase separation are also reported. We provide details of the data reduction and archive. Insights from the successful flight demonstrations provide a foundation from which follow-on PWM Hydroponics experiments on ISS, potentially incorporate living plants, are being considered.

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[13] *The Plant Water Management Experiments on ISS: Soil*

Marc Wasserman (Portland State University), Mark Weislogel (IRPI LLC), Rihana Mungin (Portland State University), Tyler Hatch (NASA Glenn Research Center) and John McQuillen (NASA Glenn Research Center).

A simple means of watering plants in the low-g environment aboard orbiting spacecraft is not obvious. Since the beginning of spaceflight, numerous approaches have been pursued to water plants that seek to maximize plant viability and system reliability, while minimizing crew time and system complexity. We are not there yet. The Plant Water Management (PWM) Soil experiments seek to apply recent advances in low-g capillary fluidics phenomena to the challenges faced by plant growth operations aboard spacecraft. The primary challenge is to establish earth-like flows minimizing low-g specific adaptations required of the plants. This is difficult due to the ever-present fluid physics challenges associated with poorly-wetting multiphase inertial-visco-capillary flows in geometrically complex conduits and containers—which change dramatically as the plants grow. In this paper, we present recent flight results for the simple visual PWM-Soil experiments where arcillite 'soil reservoirs' are arranged in a non-wetting host soil that serves as an O2-breathing wetting barrier. In this way, a largely terrestrial water-soil environment might be mimicked where, as liquid is evapotranspired through the growing plant foliage, the effective water table passively 'falls' reducing viscous lengths and increasing oxygenated water uptake for the plant. We present data from 6 days of 24-7 experiments on the ISS testing 3 different plant root models geometries. Not everything goes as planned as the 'widely' varying plant models eventually perform similarly regarding total transport rate. We explain why via reference to a capillary flow model developed to capture the primary features of the flow. We summarize that successful passive capillary soil delivery systems can be designed at will, but the time/growth-dependent water requirements for plants in low-g environments may prove an elusive requirement.

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[14] *Evaluation of monoethanolamine and ammonia adsorbents for atmosphere control*

Charles Cummings (QinetiQ) and Edward Harris (QinetiQ).

Royal Navy (RN) submarines use monoethanolamine (MEA) absorbent in carbon dioxide (CO_2) removal plants to maintain acceptable CO_2 levels on-board. Cool MEA reacts with CO_2 to produce an MEA-carbamate, which when heated in the boiler-stripper reverts back to MEA and releases CO_2. This process can introduce hazardous MEA and ammonia (NH_3) into the enclosed atmosphere. Adsorbent filters within the ventilation system and the CO_2 removal plant are used to capture these compounds. This paper details the evaluation of functionalised and un functionalised charcoals, weak acid cation (WAC) resins and strong acid cation (SAC) resins for their MEA and NH_3 removal performance. Unlike NH_3, it is difficult to produce challenge gases with stable MEA concentrations. Work presented here details a bespoke experimental procedure using a direct liquid injector – vapour generator (DLI-VG) to reproducibly generate stable levels of MEA vapour in air. Results show that functionalised charcoals had a higher adsorption capacity for MEA than the resins evaluated. In contrast, resins had greater adsorption capacity for NH_3 than the functionalised charcoals. Based on the data collected, calculations of the adsorption performance at different breakthroughs will be discussed.

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[15] *Spacecraft Scale Magnetospheric Protection from Galactic Cosmic Radiation*

John Slough (MSNW LLC).

n optimal magnetic shielding configuration for significantly reducing astronaut exposure to Galactic Cosmic Radiation (GCR) on long interplanetary missions has been realized, and is referred to as the Magnetospheric Dipolar Toroidal Magnetosphere (DTM). This configuration was shown to have the singular ability to deflect the vast majority of the GCR including High Z Energetic (HZE) ions. This external (to the spacecraft) dipolar field is created by an array of unidirectional toroidal High Temperature Superconductor (HTSC) windings mounted externally on the surface of the toroidally-shaped spacecraft habitat. In this way the spacecraft directly supports the magnetic hoop forces generated by the toroidal

currents and thereby significantly reduces the structural mass requirements for the shield. The magnitude of the toroidal currents are arranged poloidally to flow so as to maintain the spacecraft shell as a constant flux boundary where the poloidal flux ⍰ = 0 inside the spacecraft keeping the habitat field-free. As the dipole magnetic field is perpendicular to the spacecraft habitat in all directions, the DTM provides a deflecting shield to all the incoming GCR which is nearly isotropic. In addition, the DTM shields the HTSC magnets as well thus eliminating the secondary particle irradiation hazard, which can dominate over the primary GCR for shields with closed magnetic topologies. With DTM shielding it was found that both the structural and magnet mass as well as power requirements were significantly reduced. A 3-D relativistic particle cod was used to evaluate shielding effectiveness for the GCR spectrum encountered in space. Four topics that will be covered involve a direct comparison of the three principal efforts developed to date for shielding; They are: (1) Effectiveness of the magnetic shielding (2) Issues with secondaries; (3) Launch and space assembly (4) Advantages and other uses.

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[17] *Astro Garden® "Salad Diet" Scale Ground Prototype Assembly and Plant Growth Testing*

Samuel Moffatt (Sierra Nevada Corporation), Robert Morrow (Sierra Nevada Corporation), John Wetzel (Sierra Nevada Corporation) and Joseph Klopotic (Sierra Nevada Corporation).

The Astro Garden aeroponic plant-growth system ground prototype was developed as a spacecraft analog to produce sufficient planting capability in support of the requirements for a "salad diet" as outlined by the Baseline Values and Assumptions Document (BVAD). The Astro Garden prototype was designed to operate with mostly gravity-independent systems, and an overall planting volume sufficient to meet the salad-diet production requirements. Astro Garden provides unique plant-growth capabilities in comparison to current spaceflight systems. Through aeroponic nutrient delivery, Astro Garden is capable of producing: potatoes, carrots, radishes, and other root vegetables. Initial testing in Astro Garden was performed with heritage spaceflight plants to provide a basis for the system performance in comparison to systems like Veggie. This paper documents the initial Astro Garden system build and a sample of plant-growth test results.

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[18] *Ultra-Pure, High Endurance Liquid Bladder with Volume Sensor for Space Applications*

Marc Ramsey (RAPA Technologies), Cinda Chullen (NASA JSC) and Raymundo Moreno (Jacobs).

The NASA Portable Life Support System (PLSS) for the Exploration Extravehicular Mobility Unit (xEMU) incorporates a Feedwater Supply Assembly (FSA) to store consumable cooling water. The FSA accepts pure water prior to each Extra-Vehicular Activity (EVA), then supplies this water to a membrane evaporator at ambient suit pressure during the eight hour EVA. The FSA must function reliably for hundreds of EVAs over 15 years of service without introducing contamination that may accumulate and foul the membrane. We present a unique design that combines the benefits of a flexible fluoropolymer bladder with the strength and convenience of a rigid tank, providing an ultra-pure, ambient-pressure reservoir with fill-drain cycle life exceeding 3000, internal pressure tolerance exceeding 100 psi, high volumetric efficiency, near-zero dead volume, optical transparency for visual inspection, simplified mounting, and very low mass. We also incorporate a novel volume sensor suitable for both microgravity and arbitrarily accelerated environments and capable of real-time monitoring with accuracy on the order of 2.5% full scale. Analytical predictions are supported by experimental test data from a mature subscale prototype.

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[19] *Impact of Solar Cycle Duration on Astronaut Radiation Exposure during a Human Mars Mission*

Ronald Turner (Analytic Services Incorporated).

The mitigation of health risks from GCR presents a significant challenge for human missions to Mars. Mission dose varies significantly with solar cycle. The flux of galactic cosmic rays varies over an approximate 11-year cycle with an intensity that is inversely correlated with solar activity. During higher solar activity, the GCR intensity is at a minimum, whereas at solar minimum, the GCR intensity is maximal. At solar maximum exposure estimates behind typical spacecraft shielding are reduced by roughly a factor of two. Significant shielding would be required to provide an equivalent reduction in dose. Major SPEs during solar active periods could reduce the variability by increasing mission dose during solar active periods, but since SPE exposure is significantly reduced by nominal spacecraft shielding, and further reduced by internal storm shelters, the largest exposure would still likely occur on missions occurring over Solar Minimum. Efforts to improve the ability to forecast solar cycle length would be beneficial to long range Mars Mission planning. Under conditions modeled here, it was found that reducing the uncertainty in solar cycle duration by half (from 2.8 years to 1.4 years) increases the length of the launch window to meet a 600 mSv exposure limit, from six months to two years. However, the dates of favorable launch depend on the average forecast duration. Research is focused on predicting solar cycle intensity: peak at Solar Maximum and depth at Solar Minimum. However, solar cycle duration is going to have a

significant impact on forecasts of solar activity if the projection is for twenty years out: Two short cycles (9.6 years) will be at solar minimum in 2039; two nominal solar cycles (11 years) will be at solar minimum in 2042; two long cycles (12.4 years) will be at minimum in 2045.

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[20] *Feasibility Testing of Silver Electrolysis for Disinfection of Spacecraft Potable Water Systems*

Phillip Hicks (Jacobs Technology) and Niklas Adam (NASA).

Anodic dissolution of silver electrodes, or “silver electrolysis,” is being investigated as a means of introducing biocidal silver into potable water on exploration spacecraft. A proof-of-concept prototype of a silver electrolysis reactor was developed, and feasibility was demonstrated for imparting a target silver concentration into a spacecraft water system. Prototype testing showed that the primary initial concerns related to the technology - inefficiencies of electrolysis in low conductivity water, the potential formation of resistive oxides on the electrode surfaces, and the potential for release of electrolytically-generated silver particles to the effluent water - were not problematic over the duration of the feasibility testing. The testing also demonstrated advantages of the technology, including the ability to consistently deliver silver at targeted concentrations and the ability to directly correlate the silver concentration to measurements of water conductivity. On the other hand, the reliability of the system has not yet been demonstrated. During prototype testing, intermittent periods of poor reactor performance manifested as a decrease in voltage accompanied by a decrease in silver output. It was determined that the cause of this behavior was silver-based deposits on inter-electrode wetted surfaces forming a conductive “bridge” between electrodes. Ongoing testing and refinement of the prototype reactor design seek to elucidate the root cause of the bridging phenomenon and identify associated mitigation strategies. Once resolved, long-term performance testing is planned as part of continued development of the electrolytic silver dosing system.

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[21] *Development of a Gravity-Insensitive Liquid-Vapor Phase Separator for Extreme Environments*

Thomas Conboy (Creare, LLC), Gregory Daines (Creare, LLC) and Lucas O'Neill (Creare, LLC).

Future space exploration missions require advanced thermal control systems (TCS) to dissipate heat from spacecraft, rovers, or habitats to external environments. These systems must be lightweight, reliable, and able to effectively control cabin and equipment temperatures under widely varying heat loads and ambient temperatures. In contrast to single phase pumped coolant loops, two phase pumped loops are very attractive for this application because of the uniform cooling temperature provided by the boiling coolant, low required pumping power, high heat transfer coefficients, and high thermal conductance. However, introduction of two phase flow can pose design challenges associated with flow management and dynamic stability. Phase separators can play a role in stabilizing flows in spaceborne two-phase pumped loops by segregating liquid and vapor into separate streams. The current development is a gravity-insensitive capillary-based phase separator fabricated using advanced powder metallurgy methods to create a novel microporous metallic tube forms. The paper describes fabrication and testing of the initial prototype of this device.

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[22] *Habitability and the Golden Rule of Space Architecture*

Sheryl Bishop (University of Texas Medical Branch), Sandra Haeuplik-Meusburger (TU Wien space-craft Architektur) and James A. Wise (Neutra Institute for Survival Through Design).

The social, psychological and also spatial significance of living in an extraterrestrial environment place demands not only on the type of persons who would be ‘best fit’ to inhabit such environments but also on the living spaces that must be crafted to support human habitation in such environments. One of the critical characteristics for living and working in those environments – and thus mission success – is the dependency on the habitat, its technological capability as well as the capacity to counteract the stresses of a closed loop, extreme environment. Historically, such habitats have lacked all but the merest attention to such details with a focus primarily on surviving rather than thriving. This is changing and the built environment is slowly becoming an accepted important factor to ensure both physical and psychological wellbeing. The challenge for the design of off-Earth facilities is a permanent trade-off between the needs of resources and our technological capability. Designing for that kind of environments basically means making use of every possible item that you bring and bringing only what is absolutely necessary. Making Use of what you have or making do without is what we call ‘The Golden Rule of Space Architecture’. This paper highlights relevant concepts of the term Habitability for isolated, confined and extreme (ICE) environments from the user perspective of available resources. Examples of enhancing social cohesion and reduction of stress literally ‘by design and built architecture’ are discussed.

[24] *Status of Development of a Thermal Probe for Icy Planet Exploration - II*

Calin Tarau (Advanced Cooling Technologies, Inc.), Kuan-Lin Lee (Advanced Cooling Technologies, Inc.), Brett Leitherer (Advanced Cooling Technologies,Inc.), Krishna Chetty (Advanced Cooling Technologies, Inc.), Andy Lutz (Advanced Cooling Technologies,Inc.) and Srujan Rokkam (Advanced Cooling Technologies, Inc.).

To support NASA's future Ocean Worlds Exploration missions, Advanced Cooling Technologies, Inc. (ACT) is developing a thermal management concept for a radioisotope-powered ice melting probe. The concept consists of a series of integrated thermal features for efficient and reliable ice penetration, designed to deliver maximum power fraction for forward ice melting and to mitigate challenges encountered by a melting probe in icy environments. The main thermal features of the ice melting probe are: 1. Pumped two-phase (P2P) loop to collect waste heat from the cold end of the thermoelectric convertors and to deliver the waste heat to the front vapor chamber with minimal thermal resistance. 2. Front vapor chamber to collect the waste heat from the P2P condenser and distribute the heat uniformly to the inner wall of melting front of the probe. The same vapor chamber will deliver heat to the variable conductance sidewall as needed. 3. Liquid displacement system to displace water from the sides of the probe to generate thrust for maneuverability and steering. Under NASA SBIR funding, ACT is designing, fabricating and testing a lab-scale ice melting probe prototype consisting of the aforementioned thermal features. This paper presents the development status of the P2P loop that includes bench testing results as well as the lab-scale prototype final design and manufacturing strategy before 3D printing. Since the probe could not be assembled by the time when this paper was written, the only experimental results that were included are for the P2P loop lab testing.

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[26] *Thermal Performance of Parker Solar Probe through Orbit Eleven*

Carl Ercol (JHUAPL), Elizabeth Congdon (JHUAPL), Krithika Balakrishnan (JHUAPL) and G. Allan Holtzman (JHUAPL).

The Parker Solar Probe (PSP) spacecraft has successfully completed eleven of 24 solar orbits that have explored the inner region of the heliosphere through in-situ and remote sensing observations of the Sun's magnetic and electrical fields, plasma, and accelerated particles. During the first four years of the 7-year primary mission that launched on 12 August 2018, the spacecraft has experienced a wide range of hot and cold thermal environments. So far, PSP has performed nominally during the eleven perihelion encounters and the five Venus fly-bys that have included two 11-minute eclipses. The extreme solar constant experienced during the mission minimum perihelion required the development of two revolutionary technologies: (1) to actively cool photovoltaic solar arrays and (2) to passively protect the spacecraft from the intense solar heating without changing shape or insulating performance when the sun-side temperature reaches nearly 1000 °C. The maximum heating from the Sun's corona region, when the spacecraft reaches the minimum perihelion distance of 9.86 solar radii (RS / ~475 suns), will occur during the final three orbits. Key to spacecraft electric power generation and overall mission success are the actively cooled photovoltaic solar arrays that use thermally conditioned water provided by the state-of-the-art Solar Array Cooling System (SACS) and state-of-the-art construction of the Thermal Protection System (TPS) that utilizes C-C foam sandwiched between C-C face sheets to create the very large structurally ridged and thermally insulating packaging umbra for the rest of the spacecraft below. This paper will discuss the thermal performance of the SACS and the passively cooled spacecraft during Orbit 11, when the spacecraft reached a minimum solar distance of 13.28 RS (~262 suns), and compare this performance to that previously measured during the first ten orbits.

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[27] *A Rao-Blackwellized Particle Filter for Modeling Neurovestibular Adaptation to Altered Gravity*

Victoria Kravets (University of Colorado, Boulder), Nisar Ahmed (University of Colorado, Boulder) and Torin Clark (University of Colorado, Boulder).

During spaceflight, astronauts experience acute sensorimotor impairment when exposed to gravity level transitions. This impairment poses severe operational and health risks, including spacecraft accidents due to incorrect manual control maneuvers, or injury during emergency egress or EVAs. The Central Nervous System (CNS) adapts over time, but scientists only have a conceptual understanding of the adaptation process. A deeper understanding of this process would allow development of mitigation strategies and countermeasures. Here, we discuss a computational model capable of simulating neurovestibular response and adaptation to altered gravity, offering insight into the neural computations involved in this process. We build upon our previous work which used 20, parallel versions of the "observer model" (a model of healthy, human spatial orientation in 1g environments). Each of the "observers" assesses a different hypothesis of the magnitude of gravity in the set of 0.1, 0.2…2.0g. Using these gravity hypotheses, each observer generates a "sensory conflict" signal by comparing experienced sensory afference to that expected. The model then utilizes Bayesian inference to identify gravity hypotheses that minimize the sensory conflict level. The aforementioned approach assumes

a static set of 20 discrete gravity hypotheses and does not allow for adaptation to gravity levels outside of this set. Additionally, it is unlikely that the CNS always considers the entire 0.1-2g range. We implement and simulate an alternative algorithm utilizing a Rao-Blackwellized particle filter which generates and updates a dynamic list of gravity hypotheses at each time step. Unlike the previous approach, this allows the model to accurately adapt to any continuous range of gravity levels, while predicting the tilt and translation misperceptions during the adaptation period. This model could be used to inform future experimental work, counter-measure design, and operational risk mitigation strategies.

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[28] *Progress of Four Bed Carbon Dioxide Scrubber*

Gregory Cmarik (Jacobs Space Exploration Group, NASA/MSFC/ES62), James Knox (Dynetics Technical Solutions) and John Garr (NASA Johnson Space Center).

The Four Bed Carbon Dioxide Scrubber flight demonstration is presently operating onboard the International Space Station. After being launched in August of 2021 and installed in October, the system has been removing metabolic CO2 from the cabin as a supplement and replacement for other CO2 systems, specifically the two Carbon Dioxide Removal Assemblies. This work describes the conclusion of the ground integration and testing campaign and the start of on orbit operations. Additionally, performance, reliability, and forward works will be summarized. Interactions of the software with off-nominal events will be discussed and how the system will be reconfigured to sustain operations.

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[29] *Photogrammetry for Deformation Mapping: 3D Strain Measurement for the Design of Mechanical Counterpressure Spacesuits*

Theodore Macklin (Imperial College London).

With pressure being provided by tensioned materials in contact with the skin, mechanical counterpressure spacesuits must be designed around the unique shape and motion of a user's body. This design process requires the extraction of the flexure-induced strain field on a wearer's body as well as an accurate 3D representation of the joint in each position. Previous works have successfully demonstrated the use of stereoscopic digital image correlation to collect such data but required custom rigs and were sensitive to the accuracy of the set-up. This work presents the results of the development of a new technique based upon the use of photogrammetry. This technique does not require specialist equipment and returns a dataset in full 3D space. The application of coloured dots onto the skin allowed for mesh-aware feature-extraction algorithms to be employed on the generated texture-maps. Point clouds representations of tracking features in a normal and deformed state were correlated to identify the motion of the skin. This automatically filtered out bulk movements (e.g. joint rotation) which would typically cause significant errors in such methods. The strain field isolated from a test subjects is shown to demonstrate the viability and limitations of the technique. Potential improvements to the computational and mathematical methods are discussed and the course of future development on this technique is outlined.

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[31] *Computational Engineering Models for the Design of Mechanical Counterpressure Spacesuits*

Theodore Macklin (Imperial College London).

Superficially, mechanical counterpressure (MCP) spacesuits appear much simpler in design and operation than a gas-filled spacesuit (e.g. the use of taut fabric wrapped around the body removes the challenges of retaining a seal through bearings and reduces that of defending the suit against puncture). However, the unique strains on the surface of an individual's skin during joint flexure, changes in the local radius of the body, and formation of concavities (where no pressure can be applied) cause MCP suits to be extremely strenuous to design. This paper describes work performed to employ computation engineering principles to the design of MCP suits. Models to compensate for the deformation of the body under MCP were developed. The use of the slip-layer (a comfort layer to be worn beneath the MCP layer) to improve pressure-uniformity was investigated. This considered the use of tuned friction between the layers to allow a controlled reduction in tension and so to apply less pressure around smaller radii without the inclusion of additional tensioning elements. Detailed models for the behaviour of suit elements were developed and a methodology was outlined for the automation of design processes. Overall, this work demonstrates a new methodology for investigating MCP suit concepts that enables research to focus on the design of individual elements, allowing overall suit design to be automated.

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[32] *Thermal System Design of the Mars Ascent Vehicle for the Mars Sample Return Mission Surface Phase*

Stefano Morellina (Jet Propulsion Laboratory), Pradeep Bhandari (JPL), Ruwan Somawardhana (JPL), Carl Guernsey (JPL), Ashley Karp (JPL), Felix Lopez (NASA Marshall Spaceflight Center) and Patrick Junen (NASA MSFC).

The Mars Ascent Vehicle (MAV) is the rocket designed to bring samples from the surface of Mars back to Earth for scientific investigation as part of the Mars Sample Return (MSR) mission. This endeavor would be the first attempt in human history to return a spacecraft with collected material from another planet. Although samples from smaller bodies and interstellar particles have been successfully returned to Earth, return missions from planets present additional challenges to overcome, including the larger gravitational field to access. In this manuscript, we present the baseline architecture and design of the MAV thermal control system necessary to maintain its hardware, including the solid rocket motors, its control and guidance system, and associated avionics within temperature requirements during all flight phases starting from launch until landing and mission completion after successful transfer of the samples to the Earth Return Orbiter. Design challenges are imposed by the cold-biased, large temperature oscillation environment on Mars (in excess of a 100 °C swing during a diurnal cycle), and the limited thermal power generated by the solar panels. The overall thermal design of the MAV includes both passive and active control to survive the harsh conditions on Mars. CO2 gas gap insulation and conductive and radiative heat loss management are the hallmarks of the MAV-to-Lander thermal interface design described in this paper.

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[33] *Overall Thermal Architecture & Design of the Mars Sample Return Lander Mission*

Pradeep Bhandari (JPL), Razmig Kandilian (Jet Propulsion Laboratory), Keith Novak (Jet Propulsion Laboratory), Jennifer Miller (NASA), Stefano Morellina (Jet Propulsion Laboratory), Jacqueline Lyra (Jet Propulsion Laboratory/), Ruwan Somawardhana (JPL) and Kaustabh Singh (JPL).

NASA and the European Space Agency are currently planning a Mars Sample Return campaign that would bring Martian regolith and rock samples collected and cached in tubes by the Perseverance rover (Mars 2020) back to Earth for scientific investigation. The Mars 2020 rover landed on Mars, in Jezero Crater, on February 18, 2021. The Mars Sample Retrieval Lander (SRL) would land the Mars Ascent Vehicle (MAV) on the surface of Mars. A Sample Fetch Rover (SFR), in a separate mission, would collect the sample tubes deposited by the Perseverance Rover and insert them in the MAV, followed by the MAV launching them into Mars orbit within an Orbiting Sample (OS) container. The Earth Return Orbiter would rendezvous with the OS, and capture and seal it inside a primary and secondary containment vessel, followed by the OS landing on Earth in the Earth Entry System. The SRL is being designed to maintain the thermal integrity of all thermally controlled components residing in it, including the MAV, lander avionics, the propulsion system, etc. during all flight phases starting from launch until landing and the completion of its mission on the surface of Mars. During cruise, the primary thermal control is achieved by a mechanically pumped fluid loop heat rejection system. On the surface of Mars its environment varies significantly (in excess of a 100°C swing) during a diurnal cycle. There is significant shortage of solar thermal power to maintain the proper temperature range of the SRL, hence its thermal design is very challenging. This paper discusses the thermal design of the SRL during all flight phases by the innovative use of thermal control methods. This minimizes volumetric, mass and power resources to maintain its components and systems within their allowable temperature limits, while surviving the severe environment of cruise & on Mars.

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[34] *Vapor-Venting Thermal Management System for Sample Return Missions*

Jeff Diebold (Advanced Cooling Technologies) and Calin Tarau (Advanced Cooling Technologies).

Sample return missions represent some of the most challenging but scientifically promising missions under consideration. Returning samples to Earth allows for in-depth scientific studies that are not possible in-situ. The scientific community is interested in studying samples from a variety of bodies including, Mars, the Lunar surface and comets. In order to maximize the scientific value of any returned sample, it is critical that the sample not be mechanically or thermally altered. For samples originating from extreme cold environments, such as comets and permanently shadowed regions on the Lunar surface, this may require maintaining the temperature of the sample at or below temperatures ranging from -60°C to -150°C depending on the particular sample. The temperature of the sample must be maintained throughout all phases of the mission including transit, reentry and recovery on the ground. This requires a reliable thermal management system (TMS) that is mass and volume efficient.

Advanced Cooling Technologies, Inc. has developed a novel, consumable-based TMS for sample return missions that utilizes the latent heat of vaporization of a working fluid to absorb heat leaks from the environment. The system stores the working fluid within a positive-expulsion bladder that passively distributes liquid to a vapor chamber shielding the sample capsule. The saturated working fluid within the vapor chamber absorbs heat leaks through latent heat of vaporization. By periodically opening a valve, heat is released from the system by venting vapor into the external environment. The TMS is lightweight, scalable, requires minimal energy input and is applicable to a range of mission requirements. This paper will discuss the design, fabrication and testing of a vapor-venting TMS prototype for sample return missions.

[35] *Non-Integrated Hot Reservoir Variable Conductance Heat Pipes*

Jeff Diebold (Advanced Cooling Technologies), Calin Tarau (Advanced Cooling Technologies), Joshua Smay (Advanced Cooling Technologies, Inc.), Timothy Hahn (Advanced Cooling Technologies, Inc.) and Ryan Spangler (Advanced Cooling Technologies, Inc.).

As NASA prepares to further expand human and robotic presence in space, it is well known that spacecraft architectures will be impacted by unprecedented power requirements and extreme thermal environments. Thermal management systems need to reject large heat loads into hot environments and have high heat rejection turn-down ratios in order to minimize vehicle power needs during periods of darkness, such as the 14-day lunar night. Variable conductance heat pipes (VCHP) are capable of passively transporting large quantities of heat and provide high thermal turn-down ratios ideal for surviving extreme cold environments.

In this paper, Advanced Cooling Technologies, Inc. (ACT) will discuss the design and testing of two unique non-integrated warm reservoir VCHPs. The first VCHP is flight hardware designed to fly onboard Astrobotic Technology's lunar lander Peregrine. The Astrobotic VCHP is designed to operate during transit and on the lunar surface and utilizes a hybrid wick design. The evaporator wick was 3D printed while the adiabatic and condenser sections utilized grooved wicks with high permeability optimum for operation in a microgravity environment. The second VCHP was designed for NASA's lunar rover VIPER. A unique feature of the VIPER VCHP was the flexible adiabatic section. In order to accommodate relative motion between the heat spreader panel and the radiator panel, due to launch induced vibrations, nested flexible lines for the VCHP envelope and internal non-condensable gas tube were used in the adiabatic section. Both VCHPs utilized a non-integrated warm reservoir of non-condensable gas. The non-integrated reservoirs provided high thermal turn-down ratios and the ability to independently heat the reservoir in order to purge working fluid increasing the reliability of the device.

[36] *Design of a Life support architecture for a reusable lunar habitat*

Juliette Mollard (Centre National d'Etudes Spatiales (CNES)), Marie-Christine Desjean (Centre National d'Etudes Spatiales (CNES)), Alexis Paillet (Centre National d'Etudes Spatiales (CNES)) and Gregory Navarro (Centre National d'Etudes Spatiales (CNES)).

The lunar reconquest ambitions of NASA's Artemis program spell out multiple crewed missions to the Moon and later to Mars. A compact shelter for the typical duration of the missions, which can be deployed autonomously and reused during the same mission but also from one mission to the next, would greatly ease this exploration and expand the area of exploration. The aim of Spaceship FR team at CNES (Centre National d'Etudes Spatiales) is to determine the most efficient LSS (Life Support System) equipment for this lunar habitat and whether the concept of operation of a reusable shelter justifies the level of recycling equipment for water and atmosphere. A comparative analysis of life support equipment is performed by computing the Equivalent System Masses (ESMs) of the main high TRL life support equipment and by developing an equivalent continuous mission duration for the discrete mission durations. This equivalent mission duration takes into account the occupied time but also the uninhabited periods of the habitat by weighting and summing these parameters. ESMs are then compared to determine for each major subsystem such as carbon dioxide removal or water management, whether open-loop, partially closed-loop or closed-loop solutions are more optimal. The computed ESMs facilitate to identify the most efficient equipment for a dedicated mission duration and enable to propose an architecture solution. These results are to be interpreted with the Life Cycle Costs (LCC) but also with the mass requirements of the chosen lunar lander.

[37] *Fabrication and Experimental Testing of Variable-View Factor Two-Phase Radiators*

Jeff Diebold (Advanced Cooling Technologies), Calin Tarau (Advanced Cooling Technologies), Andrew Lutz (Advanced Cooling Technologies, Inc.), Srujan Rokkam (Advanced Cooling Technologies, Inc.), Michael Eff (EWI) and Lindsey Lindamood (EWI).

Radiators for manned spacecraft, satellites, planetary rovers and unmanned spacecraft are sized for the highest power at the hottest sink conditions, so they are oversized and prone to freezing at low sink temperatures. In order to address the need for light-weight, deployable and efficient radiators capable of passive thermal control and a significant heat rejection turndown ratio, Advanced Cooling Technologies, Inc. (ACT) has developed a novel vapor-pressure-driven variable-view-factor and deployable radiator that passively operates with variable geometry (i.e., view factor). The device utilizes two-phase heat transfer and novel geometric features that passively (and reversibly) adjust the view factor in response to the internal vapor pressure in the radiator. The variable-view-factor two-phase radiator (VVFTPR) consists of hollow curved and straight panels, filled with a two-phase fluid. An increase in internal vapor-pressure, due to an increase in fluid temperature, results in elastic bending of the curved panel and an increase in view-factor. In addition, since the radiator is a two-phase device, its efficiency will approach unity.

ACT and the Edison Welding Institute (EWI) have successfully manufactured and tested VVFTPR panel prototypes from aluminum 7075 via ultrasonic welding. Two radiator prototypes will be presented. The first prototype was made of several separate channels containing a two-phase working fluid. The second prototype utilized a continuous channel design that allowed the working fluid to flow continuously through the prototype and could function as a radiator for loop heat pipes. This paper discusses the manufacturing process and experimental testing of the prototypes.

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[38] *Lunar Surface Cargo Offloading Concepts*

Tracy Gill (NASA), Jaime De Jesus Gomez Jr. (NASA), Don Pittman (NASA), Mark Lewis (NASA), Kara Beaton (The Aerospace Corporation), Steven Chappell (The Aerospace Corporation) and Paul Kessler (NASA).

A sustainable presence on the lunar surface will serve as a vital training ground and technology demonstration test site in preparation for future human missions to Mars. Robotic lunar surface campaigns will focus on the exploration of resources providing information on the availability and extraction of usable resources, such as oxygen and water, and prepare the surface for a sustained human presence. Landers, outfitted with sensor packages, will be used to conduct risk-reduction activities and aid in the development of technologies prior to the crewed lunar missions that drive the need to for a logistics supply chain that requires offloading.

A series of landers will be required on other planetary surfaces to build up the capabilities, capitalizing on those resources, required for sustained human presence. In each of those landers will be cargo including ascent vehicles, habitats, supplies, science packages, spare parts, fluids commodities for fuel and life support, and others varying in volume and ranging from mass in hundreds of kilograms to an estimated 6-14 metric tons to support Human Landing Systems and surface logistics requirements. This paper will examine the challenge of offloading examples of these cargo elements from different categories of landers on the lunar surface using a variety of methodologies. Challenges on the lunar surface arise with the conditions present (thermal, lighting, communications, regolith consistency), the desire to minimize mass of all landed systems, the desire to perform much of the activities with limited to minimal human interaction, and the overall configuration of the landers that are responsible for landing the cargo.

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[39] *U.S. Spacesuit Knowledge Capture – Creation, Curation, and Dissemination*

Cinda Chullen (S&K Global Solutions), Vladenka Oliva (Jacobs), Gordon Andrews (Jacobs), Sarah Hargrove (Jacobs) and Diana Rodgers (S&K Global Solutions).

The U.S. spacesuit is a special system that has intrigued and fascinated the world since Neil Armstrong set foot on the Moon in 1969. With over 50 years since that momentous achievement, NASA is planning to land the first woman and next man on the Moon in the near future. This goal begets the need to build a new spacesuit, a spacesuit created from the legacy knowledge of the Extravehicular Mobility Unit (EMU), combined with knowledge gained from technology development over the decades. As NASA transitions to its new horizon, the U.S. Spacesuit Knowledge Capture (SKC) Program is poised to help. The SKC Program's primary function has been to capture, curate, and disseminate spacesuit-related knowledge among scientists, engineers, and technicians. The SKC Program was created in 2007 to capture knowledge primarily from spacesuit subject-matter experts (SMEs) who were retiring from NASA. These SMEs had 30 to 50 years of spacesuit knowledge. Over the years, the SKC Program has evolved and expanded its scope with a current focus on complementing the buildup of the Exploration EMU (xEMU) at the Johnson Space Center. As part of this focus, the SKC Program recently teamed with the xEMU Community of Practice (CoP) for knowledge sharing. The xEMU CoP provides a forum where early career engineers, professionals new to human spaceflight, and the xEMU community can come together regularly to seek guidance, share knowledge, meet their peers, discover resources, and ask questions. The CoP created an environment where the knowledge can be easily and routinely captured and recorded. The recorded events are archived and curated in an SKC Program library and disseminated as appropriate. This paper details the roles that the SKC Program and CoP play in the xEMU buildup, along with the navigation of the creation, curation, and dissemination processes.

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[41] *Modal Optimized Vibration dust Eliminator (MOVE): An Active/Passive Dust Mitigation Technology for Spaceflight Exploration*

Connor Joyce (Paragon Space Development Corporation) and Ryan Kobrick (Paragon Space Development Corporation).

Exploring the Moon in a sustainable manner requires contending with the adverse effects caused by lunar regolith, in particular the fine dust. Lunar dust is abrasive and electrostatically charged, resulting in a problematic tendency to disrupt the function of hardware situated on the lunar surface. Dust buildup on thermal regulators can greatly decrease thermal performance by increasing solar absorptivity (through darkening the surface) and decreasing effective rejection temperature (by adding a low-conduction layer on top of the surface). Over the course of three EVAs on Apollo 17, dust

covering the Lunar Roving Vehicle radiator system continuously decreased radiator effectiveness, resulting in the battery exceeding its maximum rated survival temperature. The Modal Optimized Vibration dust Eliminator (MOVE) concept is an active dust mitigation system for lunar thermal radiators that uses vibrational excitation at targeted modal frequencies to mitigate dust adhesion with the assistance of passive dust mitigation coatings. During testing under a NASA Small Business Innovation Research Phase I contract with NASA Johnson Space Center, MOVE used standard and custom lunar highland dust simulants to verify and validate models, as well as to aid with scaling the methodology to several radiator solutions raising the Technology Readiness Level from 2 to 4. Additional test variables included radiator fixation points, orientations with respect to gravity, with passive coatings and uncoated surfaces, and atmosphere versus rough vacuum conditions. Proof-of-concept testing demonstrated >90% removal of dust from the test panels. The low power and low mass solution has the advantage of easy integration into new or retrofitted radiators. Select results are highlighted within this paper as Paragon is working to commercialize the technology as humanity continues to push to explore the cosmos.

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[42] *Supported Ionic Liquid Membranes for Carbon Dioxide Capture in Spacecraft Cabin Atmospheres*

Bharath Tata (University of Colorado Boulder), Pawel Sawicki (University of Colorado Boulder) and James Nabity (University of Colorado Boulder).

Long-duration human space exploration demands a robust Environmental Control and Life Support System (ECLSS) to keep the crew alive, healthy and productive. An ECLSS provides a breathable atmosphere via trace contaminant and particulate removal, temperature and humidity control, oxygen provision, and carbon dioxide removal. The loss of any of these functions could result in mission abort or loss of crew. Since the first human spaceflights more than half a century ago, numerous CO2 capture technologies for ECLSS have been implemented. These flight-proven technologies, specifically the use of solid sorbent canisters, superoxides, amines, and zeolites, are assessed and compared to emerging technologies. The development progress of advanced CO2 capture technologies, namely ionic liquids, membrane contactors, deposition by freezing, and metal organic frameworks are examined in detail. In particular, we compare CO2 permeance and selectivity through a novel supported ionic liquid membrane to the mass transport achieved with more traditional membrane contactors. The merits, capabilities, and pitfalls of flight-proven and emerging technologies are summarized with recommendations for future work to enable their use beyond low Earth orbit.

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[43] *Surface Systems and Interface Standardization*

Jaime Gomez (NASA KSC), Don Pittman (NASA KSC), Gabor Tamasy (NASA KSC), Chad Caron (NASA KSC), Michael Dupuis (NASA KSC) and Mark Lewis (NASA KSC).

Space exploration on planetary surfaces will require the use of various surface systems which will likely need to interface with one another. These systems must communicate and share data, as well as distribute power and transfer fluids for sustainable surface operations. Such systems can range from landers, surface habitats, mobility systems, cargo, and In-Situ Resource Utilizations (ISRUs). Previous and current programs have developed space interoperability standards that help aid in reducing potential risks of interface integration. One example of this is the International Deep Space Interoperability Standards (IDSIS) which focuses on deep space exploration. A goal of the Artemis program is to develop a sustained human presence on the lunar surface that would be a training ground for future Mars exploration. Therefore, it will be beneficial to identify interface standards between the surface assets which will help mitigate risk and reduce complexity in the harsh environments of space exploration.

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[45] *Evaluation of Heritage Hardware for Use in Cabin Environments with Reduced Pressure and Increased Oxygen Concentration*

Morgan Abney (NASA), Robert Bagdigian (ESSCA), Chase Hopkins (NASA Intern), Michael Pedley (NASA), Ariel Macatangay (NASA), Holly Cagle (NASA) and James Knox (ESSCA).

On the International Space Station (ISS), the crew perform pre-breathe procedures prior to Extravehicular Activity (EVA) to prevent decompression sickness as their bodies transition from the ISS ambient environment of ~14.7 psia and ~21% oxygen (O2), to the ~4.3 psia and 100% oxygen environment of the suits. To reduce or eliminate the time required for this transition, exploration missions with high-frequency EVA, such as Lunar surface or Martian surface missions, are considering cabin environments of 10.2 psia and 26.5% O2 and 8.3 psia and 34% O2. Although beneficial to EVA operations, these new environments will have consequences on cabin hardware including the environmental control and life support systems (ECLSS), the crew health care system (CHeCS), and crew habitation systems. Given the agency focus on crewed exploration missions within the next decade and incentives to utilize flight-proven cabin hardware, a comprehensive assessment of hardware suitability is needed to begin retrofit and development of exploration cabin hardware. Here we report the results of a study to evaluate the effects of reduced pressure and increased cabin oxygen

concentration on the operational performance, the thermal performance, and the material flammability of ISS heritage systems. A discussion of possible mitigations for negative effects and their relative impact on mission planning is provided.

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[48] *Microalgae for Oxygen and food production on the Lunar or Martian surface – Impact of In-Situ Resources Utilization*

Gisela Detrell (Institute of Space Systems - University of Stuttgart) and Johannes Martin (Institut of Space Systems, University of Stuttgart).

Human spaceflight independence from Earth resources can only be achieved producing food in-situ, for which bioregenerative Life Support System (LSS) technologies will be required. Besides higher plants, microalgae are a potential candidate for future space missions. Microalgae, like higher plants carry out photosynthesis, producing oxygen and biomass, while consuming carbon dioxide, water, nutrients and light. At the Institute of Space Systems of the University of Stuttgart, Germany, research on microalgae for space applications has been carried out for over a decade. The feasibility of a microalgae photobioreactor has been demonstrated and but first estimations suggest that a photobioreactor of a considerable size would be required, ranging from 100 Litres per person with high volumetric efficiency systems to over 10.000 with more simple structures. The use of simpler structures reduces manufacturing and maintenance efforts, making them more interesting. However, the high mass required, if needed to be brought from Earth, makes them uncompetitive with other food supply alternatives. Missions on the Lunar or Martian surface open a new range of opportunities, since those offer a high variety of resources, which potentially include water, construction materials and nutrient sources. This paper analyses the current status of PBR technologies, the potential of In-Situ Resources Utilization (ISRU) and the impact that ISRU would have in the feasibility of a microalgae-based bioregenerative LSS technology on the surface of the Moon or Mars.

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[50] *Final Thermal Design of the Mars 2020 Sample Tube*

Keith Novak (JPL/Caltech), Takuro Daimaru (JPL/Caltech) and Pradeep Bhandari (JPL/Caltech).

The Mars 2020 Rover landed on Mars, in Jezero Crater, on February 18, 2021. One of the primary mission objectives for the Mars 2020 Rover is to collect and cache a set of Martian regolith samples for potential future return to Earth. Regolith and rock samples will be collected and placed into sample tubes using a coring drill located at the end of a large Robotic Arm. Filled sample tubes will be transferred from the outside of the Rover into the Adaptive Caching Assembly (ACA), located inside the Rover chassis, via the Bit Carousel. Once a filled sample tube is brought into the ACA, the Sample Handling Arm (SHA) will transfer it to all of the internal processing stations of the ACA for volume assessment, sealing and finally drop-off on the Martian surface. The sample tubes could remain on the Mars surface for as long as 10 years. In order to preserve the sample's scientific integrity, the sample tube temperature may not exceed 60°C. This paper documents the bounding flight temperature predictions for the final Mars 2020 Sample Tube design, lying on the Mars surface, in the Jezero Crater landing site. This paper discusses the thermal design of the sample tube that uses passive thermal control coatings to keep the sample below its maximum allowable temperature limit during exposure to the Mars surface environment.

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[52] *Build to Print Cruise Phase Thermal Design and Performance of the Mars 2020 Spacecraft*

Jennifer Miller (NASA), Keith Novak (Jet Propulsion Laboratory), Jacqueline Lyra (Jet Propulsion Laboratory), Kaustabh Singh (Jet Propulsion Laboratory) and Kurt Gonter (Jet Propulsion Laboratory).

The Mars 2020 spacecraft, launched July 30, 2020, heavily leveraged hardware and design from the MSL mission. Unlike the MER missions, designed and built in parallel, the separation of nine years between MSL and Mars 2020 provided time and data to better understand performance, address deficiencies, and clarify documentation. As an example, early MSL unknowns such as thermal test requirements became early Mars 2020 knowns and allowed teams to adapt and improve on model correlation and implementation. Meanwhile, the duplication emphasized the need to understand capabilities, margins, and workmanship differences to effectively judge mission variances. The following takes a look at some of the Mars 2020 thermal lifecycle differences and similariaties with its predecessor as well as its performance during the cruise phase of the mission.

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[53] *Mars 2020 System Thermal Vacuum (STV) Test Implementation and Results*

Jennifer Miller (NASA), Kaustabh Singh (Jet Propulsion Laboratory), Sean Reilly (none), Keith Novak (Jet Propulsion Laboratory) and Jacqueline Lyra (Jet Propulsion Laboratory/).

The Mars 2020 Spacecraft, launched July 30, 2020, successfully completed its system-level thermal test in May 2019. The test leveraged support hardware from its predecessor, MSL, while taking a new approach with a surrogate rover due to flight rover unavailability. The surrogate rover had to meet both structural and thermal requirements in order to accommodate the test configuration and perform in both acoustic and thermal environmental tests. While the absence of unavailable subsystem-level flight hardware components is not uncommon, the rover contains the flight computer, completes the flight cruise heat rejection system, and generates 2000 W from the MMRTG (Multi-Mission Radioisotope Thermoelectric Generator) of heat inside the aeroshell. The test identified unique spacecraft idiosyncrasies while providing the data to empirically and analytically validate the design and verify the implementation. Although overall a build-to-print design, the team observed small performance differences from MSL due to workmanship, differences in implantation, and design changes. The subsequent Rover system thermal test included a vacuum portion to confirm its performance for the duration of the cruise to Mars. The following takes a look at some of these results while focusing on the advantages and disadvantages of a surrogate rover in test.

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[54] *"Getter" Development for International Space Station Sabatier Assembly*

Ping Yu (Collins Aerospace), Julius Woods (Collins Aerospace), Matthew Corcoran (Collins Aerospace), Oscar Monje (NASA Kennedy Space Center), Riley Finn (NASA Kennedy Space Center), Jay Perry (NASA Marshall Space Flight Center), Matthew Kayatin (NASA Marshall Space Flight Center), Lynda Gavin (NASA Johnson Space Center), John Garr (NASA Johnson Space Center) and Stephanie Walker (NASA Johnson Space Center).

The Sabatier Assembly (SA) P/N SV1015510-1 was designed by Collins Aerospace to partially close the life support loop on ISS by reacting two waste gases (carbon dioxide and hydrogen) to form water (and waste methane). Waste CO2 is recovered by the Carbon Dioxide Recovery Assembly (CDRA) and waste H2 comes from the Oxygen Generation System (OGS). By recycling these waste gases, the SA reduces the need to launch excess water from earth ground.

The SA was successfully launched in 2010 and remained in operation until October 2017. it had produced approximately 1081 liters of water. During the last year of operation, the Sabatier on-orbit unit began to show significant signs of degradation in the reactor which required increasingly involved procedures to restart the reaction after a shutdown. Eventually the SA was deactivated and returned to Collins for Test, Teardown and Evaluation (TT&E).

In 2018, Collins performed a TT&E on the SA. TT&E results indicated that the primary source of degradation in the Sabatier system was due to contamination. In specific, the Reactor had become significantly poisoned with sulfur, silicon, fluorine, and chlorine which caused the active sites within the reactor to become inactive. Upon completion of the TT&E, a list of upgrades were recommend for a Sabatier 2.0 design. An upgraded Sabatier 2.0 system would be used to support Exploration demonstration hardware on ISS and beyond. One of the primary recommendations was to incorporate a “getter” sorbent bed. Collins has since worked with KSC, MSFC and JSC to develop the “getter” sorbent bed component for loading upstream of Sabatier reactor with a goal to provide a protection to the reactor from contamination and to extend its service life. This paper describes the joint efforts in developing a suitable Sabatier “getter”.

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[57] *Effects of Ambient Alcohol Levels on the Real-time Monitoring of the Atmosphere of the International Space Station*

William Wallace (KBR), Thomas Limero (KBR), Kenneth Clark (JES Tech), Daniel Gazda (NASA) and Edgar Hudson (JES Tech).

Monitoring of the spacecraft environment is required to ensure the health of the crew and the vehicle systems. For the ISS atmosphere, routine volatile organic compound (VOC) monitoring has been performed for almost a decade by Air Quality Monitors (AQMs). The target compounds measured by the AQMs include three types of chemicals: 1) those compounds that would be harmful to crew, 2) those compounds that have been detected regularly in archival samples, and 3) compounds that, while not necessarily harmful to crew health, could present problems for Environmental Control and Life Support Systems (ECLSS). Following the docking of SpaceX-Demo1 (SpX-DM1), the AQMs began to report high levels of isopropanol (IPA). While elevated IPA is routinely observed with visiting vehicles, the level measured by the AQM, and its continued presence following multiple days of scrubbing, caused concerns regarding the U.S. Water Recovery System. Following the departure of SpX-DM1, the IPA levels decreased to nominal levels, allowing the team to investigate the cause of the elevated measurements. Based on the changes in the shape of the gas chromatograph (GC) traces in the IPA region during docked operations, it appeared that an unknown coeluting species was causing problems with quantification. However, with the docking of Northrup-Grumman-11 (NG-11), the elevated IPA returned, as well as the changes in GC traces. In contrast to the SpX-DM1 results, the AQM IPA results did not return to nominal levels following the departure of NG-11, suggesting that the changes could not be tied directly to the visiting vehicle. In this paper, we will discuss a number of potential causes for both the genuine (measured in archival samples) increases in IPA as well as the much higher levels measured by the AQM. Additionally, we will discuss methods being explored to decrease the potential for a reoccurrence in the future.

[58] *Quantitation of Trace Water in ISS Atmosphere Samples Recovered from CO2-Removal Systems*

Steven Beck (KBR), William King (KBR), Cristina Muko (KBR) and Daniel Gazda (NASA).

As crewed spaceflight continues to push the limits of exploration, instruments and hardware used to maintain and monitor crew and vehicle health must become more integrated, reliable, and efficient. By combining a carbon dioxide (CO_2) removal system with a resource recovery system like a Sabatier or Bosch reactor, the waste gas from the removal system can be converted into valuable resources that help reduce reliance on ground resupply. Due to the high-pressure nature of the Sabatier and Bosch reactions, the vent gas from most CO_2 removal systems will need to be compressed before it can be processed. In order to prevent condensation in the compressor of the recovery system, it is critical to ensure that the vent stream from the CO_2 removal system does not contain an excess of water. There are currently three different CO_2 removal systems that are being developed as candidates for exploration missions. Each of these systems will be evaluated as a technology demonstration on ISS, and vent gas samples will be collected in Summa sampling canisters fitted with Entech valves. Due to the need to measure low levels of water in these samples, it was not possible to use the current ISS miniature grab sample containers (GSCs) to collect these samples. The Summa containers, which were used to collect archive samples during Shuttle missions, have a different surface treatment that makes it possible to measure the low levels of water in samples collected in these containers.

This paper will provide some background on the CO_2 removal systems being evaluated for exploration missions as well as results from ground-based testing of the current miniature GSCs and Summa canisters. Details on the development of the analytical method and the plan for preparing the canisters that will be used for in-flight sampling are also discussed.

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[59] *Influence of ECLSS Performance on Spacecraft Habitability*

James Nabity (University of Colorado Boulder), Kathleen Laughton (University of Colorado Boulder) and Christine Escobar (Space Lab Technologies).

Space habitats for human missions shall keep the crew alive, healthy, happy and productive. Together, these attributes inform habitability, “How well does the space habitat meet crew physiological, psychological, and resource needs throughout the mission?” First and foremost, the Environmental Control and Life Support System (ECLSS) must provide for crew metabolic inputs and manage their outputs. Sustenance of human life, i.e. ‘keep the crew alive’, demands that these be met. ECLSS performance and efficacy also influence crew physical and behavioral health which in turn may affect productivity. For these reasons, habitability management requires active real-time assessment of ECLSS performance. In this paper, we define habitability parameters and organize them according to their categorical influence on “alive, healthy, happy and productive.” Paramount among these are ECLSS design and operational parameters, factors affecting crew safety, and space habitat facilities and features that accommodate the crew. We discuss, assess and rank each for inclusion in a habitability index that will characterize the overall health of the space habitat. We then recommend a subset of habitability parameters to quantify ECLSS robustness.

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[60] *Optimization of a Deionization Bed for an Oxygen Generator Assembly for Exploration Missions*

Katherine Westhoff Larner (MEI Technologies Inc), Christopher McPhail (KBR Inc) and Cody Romero (KBR Inc).

Chemical and particulate filtration is a critical feature of water quality maintenance for closed-loop spacecraft water systems to prevent damage due to corrosion, blockage, and other adverse events that can impair the function of water systems. The Oxygen Generator Assembly (OGA) on the International Space Station (ISS) includes a deionization bed in the water recirculation loop to protect the electrolysis cell stack. Upgrades are being considered for the OGA in support of future exploration missions, one of which is to optimize the deionization bed in the recirculation loop to increase performance and operational life while minimizing mass, volume, and maintenance. The design team is investigating the most effective methods of redesigning the bed design to meet the needs of the system and the mission architecture, which will be validated on ISS OGA before deployment in advanced exploration vehicles.

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[61] *An enhanced Earth InfraRed flux and Albedo model based on real data*

Romain Peyrou-Lauga (ESA).

Within the last years, a larger number of spacecrafts have been launched in Low Earth Orbit (LEO). The current trends show that it is continuously increasing, with a growing part for light CubeSats. Most of the LEO spacecrafts are dedicated to Earth observation, and they can feature relatively large instrument openings and/or low thermal inertia, especially for the CubeSats. This usually makes the payloads or the entire spacecraft thermal behavior particularly sensitive to the Earth

environment, for both the albedo and the Earth emitted infrared fluxes. In parallel, the development of numerous Earth climate monitoring missions has provided more accurate and detailed data about the Earth albedo and infrared flux in the last 2 decades. It appeared recently that this data can be used to feed statistical survey of the real thermal environment as viewed from spacecrafts in low orbit depending on their orbital parameters. For this purpose, ESA have developed an internal tool that, for a given orbital position, generates incident infrared and albedo flux values based on real measurements available daily, generating a sizeable number of parametric environmental flux results. A systematic series of simulations have been run with these real data to cover circular orbits ranging from 100 to 800 km altitude and with various inclinations. The emphasis was particularly put on the Sun Synchronous Orbits (SSO) and how their Local Time at Ascendant Node (LTAN) has an impact on the perceived Earth environment. The paper will explain briefly the method of calculation and will present how the worst cold and hot Earth environments were identified for different types of orbits. It will eventually present some ranges of perceived albedo and perceived Earth temperature for the short and long term as a function of the altitude, the inclination and the LTAN for the SSO.

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[64] *Double ChemFET for the In-Line Monitoring of Silver Dosing in Potable Water Systems*

John Abdou (KBR), Lance Delzeit (NASA), Jing Li (NASA) and Ami Hannon (KBR).

With NASA Advanced Exploration Systems (AES) Life Support Systems (LSS) baselining ionic silver (Ag+) as the biocide of choice, development in silver monitoring technologies becomes necessary to monitor and control Ag+ release. Ion-selctive field effect transistors (ISFETs) and chemically-sensitive field effect transistors (ChemFETs) are capable of selective detection of Ag+ with reversible and low detection limit responses. However, one major hurdle to ChemFET technologies is the requirement of a reference electrode, which can leak its fill solution into the potable water system and is prone to drift requiring frequent calibration. To circumvent this issue, a double chemically-sensitive field effect transistor (dChemFET) was proposed. The dChemFET uses a second ChemFET to selectively monitor the counter ion and serves in place of the reference electrode. This work reports on the development of the dChemFET, starting with the development of the Ag+ and NO3- ion selective memberanes (ISMs) to be used in the ChemFETs. The Ag+ ISM has a detection range of 50-100000 ppb. The counter ion ISM, NO3- ISM, has shown a detection range of 50-500 ppb. However, both ISMs face significant challenges in terms of drift that obstruct its application for long-term monitoring, but it can serve as a starting point for demonstrating the dChemFET proof of concept.

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[65] *Evaluation of Candidate Crop Plant Lactuca Sativa in Biologically Enhanced Martian Regolith*

Jennifer Russell (Department of Space Studies, University of North Dakota), Gary W. Stutte (SyNRGE LLC) and Pablo De Leon (Department of Space Studies, University of North Dakota).

Under a recent NASA EPSCoR grant, the Department of Space Studies at the University of North Dakota, in collaboration with SyNRGE LLC developed a project to demonstrate the feasibility of biologically processing Martian regolith and inedible biomass through vermicomposting to reduce waste volume, enhance quality of regolith and recycle and replenish nutrients. Eisenia fetida (Red Worms) were fed inedible biomass, consisting of spent growing media, inedible biomass (root balls, leaves, and stems) shredded paper, and other compostable materials, that are produced during simulated planetary missions in the Inflatable Lunar/Mars Habitat (ILMH) analog facility at the University of North Dakota. In situ Martian regolith was simulated by adding Martian Global Simulant (MGS-1) into the E. fetida feedstock where it was consumed and assimilated by the worms. The biocompatibility of bioprocessed Martian simulant on growth of L. sativa were then evaluated using a seedling bioassay system. Lettuce seeds planted on MGS-1 alone germinated but failed to grow. Seeds planted in processed biomass contained from 10 to 25% vermicomposted MGS-1 germinated and grew with no discernable nutritional deficiencies. Fresh weight of the lettuce grown on vermicultured regolith ranged from 70 to 76% of a commercial potting mix containing controlled release fertilizer. These results suggest that vermicomposting of inedible biomass with E. fetida in Martian regolith is a viable technology for use in a closed ecological life support system (CELSS). Eisenia fetida can be maintained in dormant condition, consume a wide range of organic material, and require limited volume to be effective. The optimal environmental setpoints are like that of the crop growth requirements and establishing a self-replenishing population eliminates resupply cost. Although these results are very promising, several factors were identified that need to be understood before vermiculture can be recommended as technique for in situ processing of regolith.

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[66] *Development and Test of a Spacesuit Informatics System for Moon, Mars, and Further Deep-Space Exploration*

Jake Rohrig (Collins Aerospace), Ashley Himmelmann (Collins Aerospace), Monica Torralba (Collins Aerospace), Gregory Quinn (Collins Aerospace), Pascal Lee (Mars Institute), Sawan Dalal (Baylor College of Medicine), Magnus Arveng (Ntention), Moina Tamuly (Ntention) and Jostein Lysberg (Ntention).

Today, crewmembers use paper cuff checklists, a 12-digit LED display, and oversight from Mission Control to attain mission situational awareness. As humans explore deeper into space and expand our presence outside of low Earth orbit, the demand for on-location situational awareness independent of Earth operations grows substantially. In the case of Mars exploration, real-time oversight and communication from Mission Control are not possible. These future crews will need to have cognizance of suit and consumable status; location, terrain, and heading for navigation; personal and team biometric information; access to procedures, checklists, and data; and the ability to review and record field notes, among other capabilities. Collins Aerospace is developing an Information Technologies and Informatics Subsystem (IT IS) that includes these features to provide intuitive, Earth-independent situational awareness to astronauts. The IT IS uses an in-helmet head-up display (HUD) and a natural language interface (NLI) for instinctive, convenient interaction between the crewmember and the spacesuit. Human-robotic collaboration capabilities were also added to aid in exploration and sample collection. By combining Ntention's Interaction Framework and associated Astronaut Smart Glove (ASG) with the Collins' IT IS, a new multi-modal Astronaut Interaction System (AIS) was generated that allows crewmembers to use robotic assets through verbal commands and physical gestures. During the 2021 Haughton Mars Project (HMP) field campaign, these systems were integrated into an analog spacesuit and tested in a relevant environment. This paper reports on the need for an informatics suite and interaction system, providing a brief review of informatics testing at HMP that preceded the 2021 field tests, a statement of the 2021 HMP test objectives, a description of the technologies enabling the fielded solution, and the results of the field tests.

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[68] *Development of an automated photobioreactor test system*

Johannes Martin (Institut of Space Systems, University of Stuttgart) and Gisela Detrell (Institute of Space Systems - University of Stuttgart).

Microalgae-based biological components are being investigated at the University of Stuttgart as a potential part of a Life Support System capable of producing food in situ thus reducing the required resupply mass for exploration missions. By photosynthesis, microalgae use CO2, nutrients, water, and light to produce oxygen and biomass. Therefore, many interfaces with other LSS-components such as air and water treatment are feasible. One topic of research is the automation and long-term stability of such systems. During the technology transfer project "PBR@Earth" an automated teststand for the treatment of groundwater based on the ability of microalgae to absorb nitrate was developed. The Development included a photobioreactor, an illumination system, a sensor unit, and a harvesting/feed unit as well as automated cleaning strategies. The teststand was developed in a modular manner, so that different harvesting technologies, sensors, and photobioreactors can be attached, thus enabling a future use of the developed teststand to investigate the influence of different configurations and components on the automated long-term cultivation. This paper presents the final configuration of the teststand and the results of the automated long-term cultivation and discusses its application as platform in the test of different components relevant to the automated cultivation.

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[70] *Spacecraft Harness Evaluator (SHARE) a New Software Tool for Thermal Analysis of Spacecraft Harnesses*

Edwin Bloem (Royal Netherlands Aerospace Centre NLR), Roel van Benthem (Royal Netherlands Aerospace Centre NLR), Johannes van Es (Royal Netherlands Aerospace Centre NLR) and Robert Kroll (European Space Agency).

Harness sizing for space applications is driven by derating rules. The respective derating standards are known to be rather conservative, resulting in significant design margins and thus unnecessarily increasing harness mass. A recent ESA study, conducted by the Royal Netherlands Aerospace Centre (NLR) and Airbus DS (France), aimed at reassessing existing derating rules, supported by extensive testing and analysis, and ultimately led to an update of the ECSS-Q-ST-30-11C standard to Rev2, relevant for a wide range of European space projects. The update resulted in a significant reduction of the uncertainty margins and encourages the use of validated thermal simulation tools to further optimize harness designs. As of today, no such simulation tool, specifically validated for harnesses in space applications is commercially available to the European space industry. This paper describes the validation of the Spacecraft HARness Evaluator (SHARE), a new tool that performs thermal analysis and enables mass optimization of spacecraft harnesses. The validation of SHARE and its underlying thermal model is performed via correlation and verification using an extensive set of measurement data, consisting of 417 single wire and 117 cable bundle test cases, collected during thermal-vacuum testing in the frame of the before mentioned ESA study. The correlation is performed by means of Black-Box optimization to determine "optimal values", for the emissivity, the bundle-to-enclosure radiative scaling factor and the wire-to-wire contact conductance. It is concluded, that SHARE is able to predict the maximum temperature in a given wire bundle in the defined validation range with an accuracy of -9.5°C / +9.8°C in 95% of all cases. It is foreseen to further improve

SHARE by enhancing the accuracy and the validation range through model extensions and additional thermal test campaigns. Future updates of SHARE may include shielding, solar flux consideration and convective analysis in various atmospheres, covering planetary exploration.

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[71] *A Guide for Evaluating Spacecraft Environmental Control & Life Support Systems (ECLSS) Technology Developments*

Darnell Cowan (NASA), Morgan Abney (NASA), James Broyan (NASA), Jay Perry (National Aeronautics and Space Administration), Lance Delzeit (NASA), Marit Meyer (NASA), Orlando Melendez (NASA) and David Williams (NASA).

Environmental Control and Life Support Systems (ECLSS) are the core of any human spacecraft or habitat and are key to the astronaut's survival during missions. NASA continues to invest in the development of ECLSS technology that more efficiently recycle air, water, and waste. These advancements are needed to enable longer duration Artemis missions to the Moon or Mars and reduce dependency on Earth. Objectively evaluating the content of a technical portfolio is critical to identifying and advancing the most technically relevant and/or promising technology solutions, particularly in limited resource scenarios. Here we define four types of technical portfolio evaluations: 1) Technology Down-Selects where one or more technologies are selected over others within the same trade space (for development or flight), 2) Technology Continuation Reviews where a technology's relevance and development progress is weighed against stand-alone metrics and the risks of continued development, 3) Technology Flight Necessity Assessments to determine whether a flight demonstration is required to meet critical performance goals, and 4) Flight Demonstration Readiness Assessments to determine whether the technology is technically ready to be considered for flight demonstration. Historically, the processes used to evaluate technologies within the ECLSS portfolio have varied from project to project. Therefore, an assessment was performed to improve consistency and transparency of ECLSS technology evaluation processes within NASA. This involved evaluating the processes employed on historical NASA projects, and those used in industry and other government agencies to identify the most relevant and useful aspects of each. The product is a guide to quantitatively and objectively evaluate ECLSS technology developments, and case studies were performed using the new guide on previously completed technology development projects. The outcomes were compared, and findings are reported in this paper along with a discussion of how this new guide will be applied for future NASA ECLSS technology projects.

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[73] *NASA Universal Waste Management System and Toilet Integration Hardware Operations on ISS – Issues, Modifications and Accomplishments*

Melissa McKinley (NASA-JSC), Melissa Borrego (NASA) and James Broyan Jr. (NASA-JSC).

The Universal Waste Management System (UWMS), which has the ISS operational nomenclature "Toilet", was initially installed on the International Space Station (ISS) in 2020 with final installation completed in 2021. Although technical issues were encountered that delayed installation and operations, progress was made towards the objectives of the project. Technical issue work arounds resulted in operation of the Toilet with use by male and female crew members in a controlled extended checkout and a longer nominal use. This paper will summarize operations of the Toilet and Toilet Integration Hardware in both of those configurations, problems encountered during installation and checkout, the modifications made to allow further usage on ISS, and the future modifications planned for nominal use. It will also describe the portions of the technology demonstration that were completed and the benefits from that work and how that knowledge informs the Orion-installed UWMS unit and future manifesting of consumables for both Orion and ISS.

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[75] *Gas Trap Plug Design, Function and Performance*

Grant Bue (NASA), James Phillion (NASA) and Amanda Rivas (The Boeing Company).

The cooling loops of the Internal Active Thermal Control System (IATCS) on the Node 3, Node 2 and US Laboratory (USL) Modules of the International Space Station (ISS) have been serviced by Gas Traps (GTs) since the onset of operations. These traps serve to protect the pumping function of the cooling loops by eliminating free gas that would otherwise impact the impellers and cause a loop shutdown. Gas Trap Plug Assemblies (GTPAs) have been designed, manufactured and tested, to permit function of the IATCS in the event of a loss of cabin atmosphere and long term decrew event. The GTPA also serve to give the crew additional time to evacuate the United States Operating Segment (USOS) in the unlikely event of an Ammonia breach of an Interface Heat Exchanger (IFHX). These GTPAs have been installed on the ISS IATCS since May 2019. This paper will address purpose, design and testing of the GTPA. The paper will also provide analyses showing residual trapping capability and free gas elimination of the GTs even while tightly plugged, for both the GTs and the Alternate Gas Trap Assemblies (AGTAs) ground spares.

[76] *Supercritical Startup Experiment of Cryogenic Loop Heat Pipe for Deep Space Mission.*

Takeshi Yokouchi (Institute of Fluid Science,Tohoku University), Xinyu Chang (Institute of Fluid Science), Kimihide Odagiri (Japan Aerospace Exploration Agency), Hosei Nagano (Department of Mechanical System Engineering, Nagoya University), Hiroyuki Ogawa (Japan Aerospace Exploration Agency) and Hiroki Nagai (Institute of Fluid Science).

A cryogenic loop heat pipe (CLHP) is a two-phase heat transfer device for cooling devices in the cryogenic operating temperature range, such as infrared detectors. CLHPs have a longer heat transport capacity than other heat transfer devices, allowing for greater flexibility in the cryogenic detector and cryocooler layout. Furthermore, the heat source and the cryocooler can be decoupled, reducing the effects of vibrations from the compressor of the cryocooler. It is expected to lead to more accurate observations of optical instruments. The final goal of the research is to develop CLHP for deep space applications. For this purpose, it is necessary to properly understand the startup characteristics of CLHPs, whose initial state is supercritical. In this study, the CLHP was arranged in a gravity-assisted attitude to realize the startup from the supercritical state. (i.e., the condenser is arranged at a higher position than the evaporator.) Nitrogen was used as the working fluid, and a CLHP that can transfer more than 10 W for 2 m was designed. A 300 ml gas reservoir was installed in the CLHP, and the charge amount of nitrogen was 11.5 g. The charging pressure was 3.26 MPa at 300 K. The operating performance, such as the startup characteristics, stability of steady-state operation, and maximum heat transport capacity, was investigated in the tests.

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[78] *Performance of the Four Bed Carbon Dioxide Scrubber ISS Technology Demonstration*

James Knox (Dynetics Technical Solutions), Gregory Cmarik (Jacobs Space Exploration Group, NASA/MSFC/ES62) and John Garr (NASA Johnson Space Center).

The Four Bed Carbon Dioxide Scrubber technology demonstration is presently operating onboard the International Space Station after being launched in August of 2021 and activated in October. This work describes the ground and flight performance of the 4BCO2 and the methods used to determine performance on the ISS where limited sensor data is available.

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[79] *A Cloud Computing Infrastructure to Support xEMUs and Future EVAs*

John Manlucu (University of Baltimore), Najya Ahsan (University of Baltimore), Ruth Robinson (University of Baltimore), Michael Vandi (University of Baltimore), Kaitlyn Baker (University of Baltimore) and Giovanni Vincenti (University of Baltimore).

EVAs are arguably one of the most dangerous parts of a mission. With the advent of xEMUs, the safety and toolkit of an astronaut is greatly augmented; however, there are still significant limitations imposed by the environment. This paper explores how we can utilize cloud-like technologies and infrastructures to assist an astronaut's activities, augment the xEMU's capabilities, and ultimately create a safer operational environment. OCTaVIA, or Operations Control, Translation, and Visual Interface Assistance, is a modular and robust system that incorporates industry standard technologies used in cloud architectures. The main architecture is inspired by a RAID-1 data storage and transfer system with a communications infrastructure, designed for disaster recovery and computational load balancing. OCTaVIA also serves localization purposes, utilizing multiple methods to pinpoint an astronaut's position. We utilize a testbed composed of several Raspberry Pi and Jetson Nano devices which operate as nodes in a Kubernetes infrastructure, a system that automatically deploys, manages, and scales applications. Each of the nodes will be placed in the EVA workspace. The system offers distributed processing and communications through the Raspberry Pi devices, as well as GPU-intensive computing devices with Jetson Nanos. The system also integrates LiDAR technology to support remote as well as automated monitoring of EVA worksites. This manuscript describes OCTaVIA in detail focusing on its underlying IT architectures, and reports initial performance results of its location and distributed processing systems. We also report proof-of-concept data about our LiDAR-based systems aimed at terrain sensing and astronaut passive activity monitoring. The results support its viability as an infrastructure for an autonomous and resilient support system for astronauts during EVAs. OCTaVIA is part of ARGOS, a larger solution presented at ICES 2021 aimed at creating an information and communications management system that utilizes augmented reality to let astronauts interact with mission personnel and assets.

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[80] *CREW HaT: A Magnetic Shielding System for Space Habitats*

Paolo Desiati (University of Wisconsin - Madison) and Elena D'Onghia (University of Wisconsin - Madison).

At the dawn of a new space exploration age, aiming to send humans back to the Moon and for the first time to Mars, it is necessary to devise a solution to mitigate the impact that space radiation has on spacecraft and astronauts. Although

technically challenging, active magnetic shielding is generally considered a promising solution. We propose a lightweight deployable system producing an open magnetic field around a space habitat. Our Cosmic Radiation Extended Warding (CREW) system consists of a cylindrical Halbach array coil arrangement, or Halbach Torus (HaT). This configuration generates an enhanced external magnetic field while suppressing it in the habitat volume. The CREW HaT takes advantage of recent innovations in high-temperature superconductors (e.g., ReBCO) that enables the needed high currents. We present a preliminary feasibility design of the magnetic shielding system and its collapsible mechanical structure to sustain the internal magnetic forces while protecting astronauts. We also lay down the next steps towards a more evolved and comprehensive design of the device.

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[81] *Feasibility of MCP and Hybrid GP/MCP Architectures for Martian EVA: A Trade Study Perspective*

Abby Rudakov (RMIT University), Jonathan Clarke (Mars Society Australia), Braid MacRae (RMIT University), James Waldie (Human Aerospace) and Rajiv Padhye (RMIT University).

To meet the intensive extravehicular activity (EVA) schedules proposed for Martian surface exploration, EVA suits will need to be lighter, safer, and more mobile. Current gas pressure (GP) space suits are excessively heavy, lack mobility and dexterity, subject astronauts to a high rate of injury due to stiffness and fit, and possess inadequate durability. These limitations necessitate the investigation of solutions to enable future astronauts to explore the Martian environment safely and effectively. Several suit architectures have been proposed utilising (at least in part) mechanical counter pressure (MCP). This is the application of pressure directly to the body, typically using a skin-tight, elastic garment. Considerable research effort has been put into the concept of a full MCP suit and numerous proposals for hybrid suits have been made. These hybrid suits incorporate a combination of GP and MCP in different configurations (layered and segmented). In this perspective piece we explored both MCP (full and augmented) and GP-MCP hybrid architectures as alternatives to full GP suits to determine the most promising pressure garment architecture that best serves Martian EVA requirements. The MCP and GP-MCP hybrid architectures were assessed by trade study for their suitability to meet Martian EVA requirements (custom capability scale) and to evaluate their maturity using NASA's TRL system. Overall feasibility was defined as the product of normalized capability and maturity scores. Architectures that failed to meet minimum requirements were ruled out. Results indicated GP suits are the most mature technology (TRL), while augmented MCP and 60% segmented hybrid architectures are best suited to meet Martian EVA capabilities (capability assessment). Overall, we suggest the augmented MCP and 60% segmented hybrids are the most feasible architectures for effective Martian EVA. The findings of the study aim to highlight key areas of future research which may help orientate development and funding.

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[82] *Development of a Mechanical-Loading Countermeasure Skinsuit to Mitigate Post-Spaceflight Sensorimotor Dysfunction*

Braid MacRae (RMIT University), Ruth Bunford (RMIT University), James Waldie (Human Aerospace), Gordon Cable (Human Aerospace), Rajiv Padhye (RMIT University) and Abby Rudakov (RMIT University).

Exposure to altered gravity is an ongoing challenge for sensorimotor function and, accordingly, countermeasures are required to preserve a range of functional outcomes. Here, we describe the sensorimotor countermeasure skinsuit (SMCS) concept and preliminary characterization of the baseline suit component. The SMCS is proposed for sessional intravehicular use while in microgravity and comprises a full-body garment providing mild axial loading from the shoulders to the feet and mild resting compression over the torso, arms, and legs. Mechanical properties of the suit fabric and integrated loading elements are to provide tailored limb and torso 'weighting' via resistance to certain movements and static and dynamic cutaneous pressure stimuli. In a first step of development, the baseline suit component was custom-made for one participant and preliminary characterization performed. The baseline suit was able to meet or exceed the 0.1 g axial loading (AL) targets at the shoulders (~0.2 g AL) and feet (~0.15 g AL). Range of motion (ROM) of the arms was promising despite inclusion of arm coverage, with shoulder flexion and abduction limited by <20% (versus without the suit). The dominant influence of the suit on restricting ROM was for hip flexion (limited by ~35%) and integrated hip and back flexion (poor reach during the sit-and-reach test). A range of improvements to the baseline suit are planned and integration of the additional loading elements for targeted weighting of limb movement are next steps.

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[83] *Development of Thermal Control Systems for Low Power Hall Effect Propulsion System (HEPS-350) dedicated to Small Satellite Applications*

Jin-Soo Chang (SATREC INITIATIVE (SI)), Youn-Ho Kim (SATREC INITIATIVE (SI)), Yong-Sang Jung (SATREC INITIATIVE (SI)) and Eun-Deok Bae (SATREC INITIATIVE (SI)).

Satrec Initiative has developed the Hall Effect Propulsion System (HEPS) with a nominal anode power consumption of 350 W, HEPS-350, for a 400 kg-class sub-meter EO satellite platform.

HEPS-350 has been developed to provide better performance than the previous based on technical heritages such as development and on-orbit operating experiences from the previous model, HEPS-200. To realize it, the thermal control design for each component has been optimized based on the thermal analysis result that had been conducted to each unlike the previous.

Also, we have conducted a thermal vacuum test to evaluate thermal performance and integrity. We didn't find any issue related to the thermal control systems but we faced an unexpected issue related to the degree of vacuum during the test. So, we conducted the test once again after resolving it, and the thermal vacuum test was completed without any issue.

Currently, HEPS-350 is waiting for launch and flight.

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[85] *Development of CO2 hydrogenation-water electrolysis tandem reactor*

Asuka Shima (JAXA), Yoshitsugu Sone (JAXA), Masato Sakurai (JAXA), Hironori Nakajima (Kyushu Univ.), Mitsuhiro Inoue (Univ. of Toyama) and Takayuki Abe (Univ. of Toyama).

As a new ECLSS technology for future manned space missions, the authors have developed a tandem water electrolysis and CO2 hydrogenation reactor to generate methane and water. The reactor concept is based on a water electrolyzer thermally coupled to a CO2 hydrogenation reactor which directly transfers thermal energy generated by the catalytic CO2 methanation (as known as the Sabatier reaction) to the water electrolyzer. In this paper, we report that 1 L/min-scale hydrogen production with corresponding CO2 methanation was achieved by further developing a scale-model tandem reactor.

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[86] *Development and qualification of ECLAIRs Instrument Thermal Control System using Variable Conductance Heat Pipes*

Yann Cervantes (CNES), François Gonzalez (CNES), Philippe Guillemot (CNES), Helene Pasquier (CNES), Victor Cleren (ESA), Adrien Frezouls (EPSILON), Adrien Jeanmougin (EPSILON), Mikael Mohaupt (EHP), Alexandre Van Haute (EHP) and Alexandre Guevezov (Airbus Defence and Space).

SVOM (Space-based multi-band astronomical Variable Objects Monitor) mission objective is a thorough monitoring of Gamma Ray Burst (GRB) phenomena.

Based on a collaboration between France (CNES: French Space Agency) and China (CNSA: China National Space Administration and CAS: Chinese Academy of Science), the SVOM payload includes four scientific instruments (ECLAIRs and MXT provided by CNES, GRM and VT provided by CNSA/CAS) installed on SVOM spacecraft. On Earth, several telescopes and a data center contribute to GRBs observations in addition to SVOM payload.

This paper covers the ECLAIRs instrument, designed to detect GRBs autonomously in near real time in the X-Gamma ray energy range, and then to quickly transmit to the ground telescopes their direction in the universe. After a GRB detection, a change of the spacecraft orientation points the other instruments in the GRB direction. Therefore, the ECLAIRs TCS (Thermal Control System) main constraint is to allow ECLAIRs instrument to detect GRBs whatever the attitude and the position of the spacecraft on its orbit. Indeed, the ECLAIRs TCS copes with a large variation of external environment during the mission with low heating power allocations. Thus, the ECLAIRs detection plane thermal bus uses Variable Conductance Heat Pipes (VCHP) with a regulation loop, in order to minimize heating power consumptions and to allow temperature control on the detectors.

The presentation of the ECLAIRs instrument TCS highlights its development, validation and verification with TCS full qualification before instrument delivery to the SVOM spacecraft.

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[87] *Energy and Power Demand of Food Production in Space based on Results of the EDEN ISS Antarctic Greenhouse*

Paul Zabel (German Aerospace Center (DLR)), Vincent Vrakking (German Aerospace Center), Conrad Zeidler (DLR) and Daniel Schubert (DLR).

The EDEN ISS greenhouse is a space-analogue test facility near the German Neumayer III station in Antarctica. The facility is part of the project of the same name and was designed and built since 2015 and eventually deployed in Antarctica in January 2018. The first operational phase of the greenhouse started on February the 7th and continued until the 20th of November 2018. The purpose of the facility is to enable multidisciplinary research on topics related to future plant cultivation on human space exploration missions. Research on food quality and safety, plant health monitoring,

microbiology, system validation, human factors, horticultural sciences and resource demand were conducted. Part of the latter were measurements of the electrical energy and power demand. Those measurements were conducted on the facility and subsystem level, which were complemented by determining the demand of single components like LED lamps at different illumination settings. This paper describes the electrical energy and power demand during the experiment season between February and November 2018. Furthermore, the impact of these results on designing and planning future plant cultivation system in space are evaluated.

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[88] *PFPU – Microgravity Precursor Food Production Unit development status*

Giorgio Boscheri (Thales Alenia Space Italia), Giovanni Marchitelli (Thales Alenia Space Italia), Christel Paille (European Space Agency) and Thomas Fili (Thales Alenia Space Italia).

So far, several technical issues related to the development, implementation and operations of food production system for space applications were identified. They include food quality prediction, food safety, integration strategy as well as microbial contamination, humidity and nutrient delivery management. Thus, considering the amount of issues and their respective criticalities, the cost-conscious development of a food complement production unit for space application requires a step-by step approach based on a modular technological demonstrator. PFPU is a study of a modular food complement production unit demonstrator, aiming at a statistically representative production of edible tuberous plants in micro-gravity. The study is performed within the MELiSSA framework under contract with the European Space Agency. It is carried on by an Italian and Finnish consortium led by Thales Alenia Space Italia. Breadboards of the PFPU key subsystems have been designed, built and tested. The remaining subsystems breadboards have been designed and are now under manufacturing, in preparation for integrated system testing. This paper describes the PFPU development status and the associated roadmap.

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[89] *Deployable Passive Radiator Development*

Fabian Preller (INVENT GmbH), Reinhard Schlitt (Engineering Services), Frank Bodendieck (OHB System AG), Ondrej Krepl (OHB Czechspace s.r.o.) and Felix Beck (ESA).

Due to the use of high-power payload electronics, today's spacecraft of all classes require generally larger payload radiators as the spacecraft body can provide. The use of deployable radiator seems to be the next logical step to achieve the required enlargement of the radiative area. Large deployable radiators based on two-phase heat transportation systems are today available, but these systems are technically complex and therefore not suited for smaller spacecraft, especially in future spacecraft constellations. We started therefore the development of an innovative deployable passive radiator, incorporating a high thermal conductivity panel. In our design the heat conduction will be maximized by introducing layers of high conductive graphite foils, which exhibit an 8 times larger in-plane conductivity compared to aluminum alloys of the same thickness. Graphite foils have a maximum thickness of only about 40 micro-meter and need therefore to be stacked to obtain the necessary radiator panel thickness. To increase structural strength and to compensate the low CTE of graphite, we propose an innovative solution with the graphite stack covered by thin aluminum sheets on both sides, which have integrated hooks penetrating into the graphite plate, thus increasing mechanical strength as well as out-of-plane thermal conductivity. Depending of mechanical requirements, the panel can be further strengthened with a thin honeycomb sandwich. The graphite foils extend over the panel area to form a flexible section, which is necessary to follow the deployment movement of the radiator. The flexible part is again fixed on the spacecraft side with the mentioned hooked aluminum sheets to represent a heat exchanger for collecting waste heat of the spacecraft. The paper will present the performed verification campaign, which includes mechanical / thermal analysis and sample testing, as well as mechanical / thermal test at breadboard level.

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[90] *Integrated Logistics and Supportability Challenges of Sustained Human Lunar Exploration*

Andrew Owens (NASA), William Cirillo (NASA), Chel Stromgren (Binera, Inc.), Jason Cho (Binera Inc.), Chase Lynch (Binera, Inc.) and Jon Vega (Binera, Inc.).

NASA's Artemis program plans to establish a sustained human presence on the lunar surface. The International Space Station and other space station programs have demonstrated long-duration human spaceflight operations that reuse infrastructure in Low Earth Orbit, sometimes including long uncrewed "dormant" periods. In contrast, all human exploration beyond Low Earth Orbit to date has consisted solely of relatively short sortie missions, rather than a sustained presence. A sustained human outpost on the Moon that can support month-long crewed exploration missions and be reused by multiple crews will be more challenging than past operations, particularly from the perspective of logistics, supportability, and risk. This paper examines the integrated logistics and supportability challenges of sustained human lunar exploration and provides a review of historical spaceflight experience in terms of crewed mission endurance, uncrewed duration, transportation overhead, and access to abort. Planned Artemis Base Camp crewed

mission endurance is approximately 2.5 times longer than past lunar surface crewed mission endurance, but similar to the average time between resupply for the International Space Station. Sustained human spacecraft have only twice experienced uncrewed durations longer than the planned interval between Artemis Base Camp missions, and Artemis surface assets will face long uncrewed periods more regularly than any past sustained human spacecraft. Transportation of crew and cargo to and from the Moon will be more difficult and time-consuming than transportation to and from Low Earth Orbit, and crew access to abort will be more limited. The implications of Artemis lunar operations for crewed Mars mission planning are also discussed. Historical approaches to risk management—including logistics, supportability, and abort strategies—should be reexamined and re-optimized for this new mission context. Sustained lunar operations will provide a valuable proving ground for testing new approaches to crewed space exploration.

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[91] *Overview of Potential Candidates for Partial Gravity Water Recovery Systems*

Ingrid Pinel (Lenntech), Niels van Linden (Lenntech) and David van Lennep (Lenntech).

Partial gravity habitats built on the moon or Mars can take advantage of a larger range of terrestrial technologies to improve their water recovery. The objective of this review was to compare efficiency, mass and energy consumption of treatment systems with potential application to urine, humidity condensate and hygiene wastewater. In-house knowledge from Lenntech B.V., combined to literature from earlier NASA research and the general academic field allowed to narrow down the selection of technology candidates. Most promising treatment architectures were suggested and benefits of mixed or segregated streams were assessed in each case. Some research gaps were defined that would allow for more accurate comparison. Distillation/pervaporation, electrooxidation and SCWO showed a higher potential for the treatment of urine, compared to pressure-driven membrane and electrically driven membrane processes when aiming at high water recovery. From gathered data, mixing urine and humidity condensate is advised for the oxidation processes to facilitate the removal of readily bioavailable VOCs and prevent downstream biological growth. The efficiency of total organic removal and increased requirement in specific energy should still be assessed for the mixed streams. This study identified several advantages of the development of a partially segregated greywater treatment assembly for reuse as hygiene water. These include lower requirements in terms of water quality and more flexibility in operation. This approach would allow substantial reduction in the flowrate of wastewater towards the water processor assembly. Train architectures were proposed and Lenntech B.V. is investigating suggested treatments and configurations on representative streams in its facilities.

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[92] *Direct printing of heating elements for thermal control systems of spacecraft*

Michael Aldorf (Airbus Defence and Space GmbH, Airbus-Allee 1, 28199 Bremen, GERMANY), Moritz Greifzu (Fraunhofer-Institut für Werkstoff- und Strahltechnik IWS, Winterbergstraße 28, 01277 Dresden, GERMANY), Marten Berlin (Technische Universität Braunschweig, Universitätspl. 2, 38106 Braunschweig, GERMANY), Jaschar Salmanow (Technische Universität Dresden, Institute of Materials Science, Berndt-Bau, Helmholtzstr. 7, 01069 Dresden, GER-MANY), Jonas Vom Weg (Fraunhofer-Institut für Werkstoff- und Strahltechnik IWS, Winterbergstraße 28, 01277 Dresden, GERMANY), André Holz (Airbus Defence and Space GmbH, Airbus-Allee 1, 28199 Bremen, GERMANY) and Lukas Stepien (Fraunhofer-Institut für Werkstoff- und Strahltechnik IWS, Winterbergstraße 28, 01277 Dresden, GERMANY).

Heaters are a central element of a spacecraft's thermal control system. The state of the art is represented by polyi-mide foil film heaters with a structured copper film. The films resistance defines the thermal power of the heater. But these heaters have inherent limitations. They are limited to a maximum power density of 0.54 W/cm² in still air [1] and 3 W/cm² [2] and have an upper limit temperature for the polyimide material of 260 °C.

Other techniques already used in commercial electronics have yet to be applied in space applications but could overcome the inherent limitations mentioned above. Here, an approach is presented which utilizes a process called dispenser printing. For that paste material is applied onto the surface of either of titanium or stainless steel flight propulsion tubing. The electrical insulation between substrate and heater is applied by thermal spraying of an aluminiumoxide layer. This heater printing method was able to produce resistances between 35-935 Ohm, resulting in power densities up to 40 W/cm² under vacuum conditions without active substrate cooling. The measured temperature at the mentioned 40 W/cm² was 330 °C.

Different geometries, representing different resistances, were printed onto the tubes for two different paste com-pounds to test the effect of resistivity on the application and contact areas were printed using a paste containing silver and platinum to enable connection to a power source. The heaters were then tested in several conditons. With these tests we were able to investigate achievable power densities and also application failure mechanisms. Potential is seen in this technology, since it promises automatized application of heaters and possibility to expand the limitations of heater applications in the space industry [1, 2].

[1] ESCC Detailed Specification No. 4009/002, Issue 10 [2] S-311-P-079E Procurement Specification for Thermofoil Heater, Rev E

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[93] *Reduced Geometric Model of Sentinel-3A for Radiative Thermal Simulation*

Vincent Vadez (Dorea) and François Brunetti (Dorea).

Radiative thermal simulation of spacecrafts is a time-consuming and difficult process, even more challenging with geometric models becoming more complex. Furthermore, a need for real-time simulation of unpredicted scenarios has been growing in the industry, notably for the development of digital twins. As part of the rationalization of thermal simulators for operations project, result of a partnership between Dorea/Thales Alenia Space and the European Space Agency/French National Centre for Space Studies, the development of a thermal digital twin of the Sentinel-3A satellite from the Copernicus Programme is investigated. To tackle this subject, reduced geometric models obtained through mesh simplification algorithms coupled with numerical simulations are explored and validated for multiple configurations. The simulations consider albedo and Earth fluxes for low Earth orbit (LEO), as well as specular and diffuse radiations. Parallelization of external fluxes is depicted and implemented. Computation times and accuracies for reduced models are compared with reference calculation cases, highlighting numerical speedups. Moreover, the possibility to obtain and use different reduced models depending on the simulation is discussed (for instance one for the solar fluxes and one for the albedo and Earth fluxes). This study highlights the technological bottlenecks and compares the results obtained with ESATAN software used as reference. Finally, conclusions are drawn, and future work are elaborated.

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[95] *Real-time Thermal Co-simulation With A Simplified Fluid Loop Modelling Algorithm*

Adrien Boudin (Dorea), François Brunetti (Dorea) and Patrick Connil (Thales Alenia Space).

Thales Alenia Space (TAS) has built a two-phase Mechanically Pumped Loop (2Φ-MPL) for the transport of large quantities of heat over very long distances through telecommunication satellites. End of 2021, this loop is operational on the SES17 satellite in launch and early orbit phase (LEOP). The need to model and simulate the behavior of 2Φ-MPL fluid loops required the use of tools such as LMS AMEsim in co-simulation with the TAS e-Therm thermal simulation tool for satellite design. However, thermo-fluidic calculations do not allow real-time resolution of the characteristics of the pump (temperatures, flow rates, vapor quality) which causes the loop to re-converge at each “meeting time”. A simulated day can reach several days of calculation making real time simulation impossible. DOREA and TAS have developed a simplified algorithm for the resolution of fluidic parameters as well as temperatures at evaporators and compact condensers. This modelling is based on the AMEsim results allowing the characterization of physical behavior (e.g., linear conductance as a function of the power density, or specific heat as a function of temperature), these in the form of tables accessible by the algorithm. This study will develop the technological obstacles encountered, notably the convergence of certain parameters as well as the numerical problems and the solutions adopted. A major step was the initialization of the loop to reach these convergences through non-physical points or even oscillatory phenomena.

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[97] *Silver Foam: A Novel Approach for Long-Term Passive Dosing of Biocide in Spacecraft Potable Water Systems – Update 2022*

Tesia Irwin (The Bionetics Corporation), Wenyan Li (Amentum), Angie Diaz (Amentum), Luz Calle (NASA) and Michael Callahan (NASA).

A spacecraft water disinfection system, suitable for extended length space exploration, should prevent or control the growth of microbes, prevent or limit biofilm formation, and prevent microbiologically influenced corrosion. In addition, the system should have minimal maintenance requirements, be chemically compatible with all materials in contact with the water, be safe for human consumption, and be suitable to be shared across international spacecraft platforms and mission architectures. Silver ions are a proven broad-spectrum potable water biocide under investigation for future exploration missions. The competing technology for dosing silver ions in future water systems is based on actively dosing the ions via electrolytic production. Several challenges with this approach have prompted additional investigations into alternative dosing techniques. Control-release technology is an attractive option for developing a high-reliability passive silver dosing device. This paper describes the continued development of a nanoparticle/polyurethane (NP/PU) composite foam for the controlled release of silver ions, and is intended to build upon the 2021 International Conference on Environmental Systems (ICES) paper number 116. This paper provides the technical background and performance results (wash testing and ongoing long-term silver ion release testing) from the silver chloride (AgCl) NP/PU composite foams. The ultimate goal of the project is to develop a stable and reliable passive dosing silver ion release device for use in future spacecraft potable water systems.

[98] *Status of ISS Water Management and Recovery*

Jill Williamson (NASA), Andrew Gleich (Boeing) and Jonathan Wilson (NASA).

Water management on ISS is responsible for the provision of water to the crew for drinking water, food preparation, and hygiene, to the Oxygen Generation System (OGS) for oxygen production via electrolysis, to the Waste & Hygiene Compartment (WHC) for flush water, and for experiments on ISS. This paper summarizes water management activities on the ISS US Segment as of March 2022 and provides a status of the performance and issues related to the operation of the Water Processor Assembly (WPA) and Urine Processor Assembly (UPA).

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[99] *Thermal Control System Design, Analysis and Testing for a Supercritical Xenon HET S/S for Micro and Mini satellite*

Marco Sanitate (Sitael SpA) and Andrea Lucchi (Sitael SpA).

uHETsat will be the second mission based on the use of SITAEL S-50/75 microsatellite platform for IOV/IOD purposes. In this case the subject (and payload) of the In Orbit Validation will be SITAEL HT100 Hall Effect Thruster (HET) -one of the smallest of its kind- that for the first time will be intergated and operated onboard a small platform. Starting from its predecessor ESEO, the spacecraft has undergone a series of updates and upgrades necessary to comply with the new set of mission requirements. Most of the effort in the adaptation of the platform Thermal Control System (TCS) were spent to handle the temperature constraint required by the high pressure Xenon section of the HET feeding system: propellant shall be maintained in super-critical condition which translates, under the foreseen storage conditions, to guarantee a Xenon temperature never dropping below 17°C. Lumped-parameter model has been developed to represent the satellite behavior and carry out thermal analyses. Thermal design solutions specifically adopted for Xenon thermal control consists in a mix of active (closed loop heaters control) and passive solution (MLI, surface treatments, thermal fillers and conductive path). Payload section of the TCS is verified in two different tests: the functional test of the HET feeding system and the firing test of the complete HET subsystem. Each test is followed by a correlation campaign, performed to validate numerical models and confirm the effectiveness of the designed solutions. HET subsystem and its thermal control, developed in uHET IOV/IOD mission, will be adapted and integrated as service subsystem in the SITAEL 200kg-class miniSAT platform PLATiNO.

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[100] *Limiting Oxygen Concentration of Burning PMMA Cylinders under External Radiant Heating and Subatmospheric Pressures*

Charles Scudiere (University of California - Berkeley), Christina Liveretou (University of California - Berkeley), Carlos Fernandez-Pello (University of California - Berkeley), Michael Gollner (University of California - Berkeley), Sandra Olson (NASA Glenn Research Center) and Paul Ferkul (NASA Glenn Research Center).

Understanding flame spread over combustible solids under different environmental conditions is important for fire safety in spacecraft applications due to the criticality associated with such events. Environmental variables such as oxygen concentration, ambient pressure, external radiant heating, or gravity may change the flammability and fire dynamics of materials. The overall objective of this work is to study the effect of an external radiant flux on the opposed flame spread rate and the limiting oxygen concentration (LOC) for flames spreading over the surface of cylindrical samples of polymethyl methacrylate (PMMA) in Space Exploration Atmospheres (SEA). In the work presented here, experiments under normal gravity and subatmospheric pressure are conducted using a variable heat flux with peak values ranging from 0 kW/m2 to 1.9 kW/m2. A forced flow of air with a velocity of 10 cm/s is used to mimic the air flow velocity generated by the HVAC system inside a spacecraft. Flame spread rates and limiting conditions for flame spread were measured from video processing of the experiments at different environmental conditions and external radiant heat flux. Results show that the limiting oxygen concentrations depend on the amount of radiant heating received by the PMMA sample, decreasing as the radiant flux is increased. The data presented in this work provides a baseline for comparison with future microgravity experiments to be performed by NASA as part of the SoFIE/MIST project aboard the International Space Station. It is expected that the results will provide insight for what is to be expected in different conditions relevant for fire safety in future space facilities.

The work presented here was supported by NASA Grants NNX10AE01G and NNX13AL10A.

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[103] *Rapid Development of Instrument Thermal Models: Perspectives and Guidelines from NASA Goddard's Instrument Design Laboratory*

Kan Yang (NASA), Hume Peabody (NASA) and Rachel Rivera (NASA).

The Instrument Design Laboratory (IDL), part of NASA Goddard Space Flight Center's Integrated Design Center (IDC), is a concurrent and collaborative environment which allows for rapid development of science instrumentation concepts within the span of less than two weeks. Science goals set by a Principal Investigator from government, industry or academia are translated into engineering requirements, from which a team of engineers spanning multiple disciplines use an established study process and a suite of analysis tools to work towards an instrument point design. As part of this process, a staff thermal engineer is tasked with designing a thermal control system which meets all incoming thermal requirements, while iterating real-time with other subsystems to ensure compatibility and functionality as a completed system. Thermal engineers on spaceflight projects typically have weeks or months to develop thermal models. However, the severe time limitation in this conceptual study setting makes thermal design particularly difficult, as rapid thermal modeling solely over the span of a few days is required to develop the instrument thermal design and understand the performance over its intended mission, especially if the instrument concept contains multiple thermal challenges such as dynamic environments or high heat dissipating components. In this paper, the authors provide a condensed guide for the most efficient ways to develop thermal models and conduct thermal analysis within the span of one-to-two weeks, as informed by decades of design experience and best practices in the IDL. The authors also focus on quick methods for determining worst-case thermal environments, deciding which modeling details are essential at this early phase, and quantifying the engineering resources necessary for thermal control. This paper concludes with specific thermal design tips for different instrument types across the electromagnetic spectrum.

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[104] *Trash Compaction and Processing System Development and Testing*

Joseph Klopotic (Sierra Space) and John Wetzel (Sierra Space).

The Trash Compaction and Processing System (TCPS) processes waste products in support of human operations in space. Functions include compressing the waste into a manageable tile, recovering and recycling water from the waste, sterilizing and stabilizing the residual tile, and the processing and cleaning of any gaseous byproducts. Sierra Space leveraged our previous developmental systems, built to demonstrate and evaluate waste compaction effectiveness and water recovery techniques, to develop an integrated TCPS. Following design, fabrication and assembly, testing was performed to evaluate trash processing, tile compaction, water recovery, power requirements, and gas sampling, all with and without bag enclosures. This paper will summarize the TCPS system and initial testing performed.

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[105] *Demonstration of Paragon's Water Purification Assembly for Lunar Water Processing*

Jordan Holquist (Paragon Space Development Corporation), Sean Gellenbeck (Paragon Space Development Corporation), Connor Joyce (Paragon Space Development Corporation), Robert Rivera (Paragon Space Development Corporation), Chad Bower (Paragon Space Development Corporation) and Philipp Tewes (Paragon Space Development Organization).

Since the observation of direct evidence of water-ice in the permanently shadowed regions (PSR) on the lunar surface, in-situ resource utilization (ISRU) has been proposed for processing the regolith-bound water-ice to provide fresh water, breathable oxygen, and rocket propellant for lunar exploration missions. However, the water-ice is found concurrently with other typically volatile species that would contaminate and degrade downstream processing systems. Paragon Space Development Corporation® is developing the ISRU-derived water purification and Hydrogen Oxygen Production (IHOP) subsystem to collect, purify, and process water-ice from PSRs on the lunar surface. The primary water purification component of the IHOP subsystem concept is Paragon's Ionomer-membrane Water Processor (IWP) technology that can selectively transport water vapor through the membrane while rejecting contaminant components.

This paper presents results, analysis, and discussion of an experimental investigation to demonstrate the performance of the first iteration of Paragon's Water, ISRU-derived, Purification Equipment (WIPE) assembly, one of the major assemblies of the IHOP subsystem. The WIPE assembly was tested for a cumulative duration of 4-weeks with a supply of water vapor and a mixture of expected lunar volatile contaminant components (H2, CO, H2S, SO2, C2H4, CH4, CO2, and CH3OH). Liquid water samples were intermittently collected at the output of the WIPE assembly's process chain and analyzed for their constituents. Water utilization efficiency was also tracked over the course of the test. The controlled test operating conditions and rates matched the expected operating conditions in the lunar operation. The presented results inform next steps in incremental design advancements and demonstrate viability of a core assembly of the IHOP subsystem for lunar ISRU propellant production.

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[107] *Two-Phase Thermal Control Hardware Verification and Validation for the Ka-band Radar Interferometer Instrument*

Ruwan Somawardhana (JPL), Eric Sunada (JPL), Louis Tse (Jet Propulsion Laboratory) and Eugene Ungar (NASA).

The thermal architecture of the Ka-band Radar Interferometer instrument (KaRIn), part of the Surface Water Ocean Topography (SWOT) mission, utilizes loop heat pipes (LHPs) and constant conductance heat pipes (CCHPs) to transport waste heat (1 kW) from the instrument electronics to the radiator. The main thermal design risk is the ability to maintain a temporal stability of <0.05°C/min in a low earth orbit environment. The stringent thermal requirements are part of the overall error budget needed to meet the primary mission science goals. This is a culmination of a summary of the design and testbed activities previously reported, the evolution and the ultimate verification and validation of the thermal design for the flight hardware delivery.

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[109] ***Computational Fluid Dynamics Airflow Modelling of the CASA – Crew Alternative Sleeping Area of the ISS***

Chang Son (The Boeing Company), Nikolay Ivanov (Peter the Great St. Petersburg Polytechnic University), Evgueni Smirnov (Peter the Great St.Petersburg Polytechnic University) and Denis Telnov (New Technologies and Services).

Computational Fluid Dynamics (CFD) modeling was used to analyze the airflow and carbon dioxide distribution in the International Space Station (ISS) Columbus cabin, and the Crew Alternative Sleeping Area (CASA). The study was focused on the various CASA ventilation scenarios with respect to the crewmember safety and comfort. The focus of the discussion is; first, on the ventilation performance of the Columbus cabin aisle way with respect to the ISS cabin air velocity requirements and, second, on velocity magnitude and carbon dioxide spatial/temporal variations in the CASA volume. The computational data obtained was able to verify that there should be no considerable risk of stagnant zones formation within the CASA volume at the given flow rates analyzed. The velocity distribution in Columbus satisfied the ISS velocity requirements. It was verified that the CASA's intake and exhaust design and the direction of the airflow angles selected were able to minimize the re-introduction of CO2 rich air within the CASA. These aspects were important with respect to temperature and carbon dioxide control. The paper illustrates various points of the modeling and the results for the ventilation safety, according to the requirements and operations.

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[110] ***Reduced-order modeling for spacecraft thermal-structural applications***

Derek Hengeveld (Redwire), Jacob Moulton (Redwire), David Tobin (Redwire), Ryan Vasas (Redwire), Emmett Nelson (Redwire), Alice Liu (NASA Goddard Space Flight Center) and Hume Peabody (NASA Goddard Space Flight Center).

Reduced-order modeling has been successfully implemented for a broad range of spacecraft thermal analysis applications. Leveraging the speed of reduced-order models (ROMs), thermal analysis teams have access to rapid optimization, sensitivity studies, and new approaches to model correlation, to name a few. These methods have been successfully applied for such applications as the Mars 2020 Helicopter and Dream Chaser programs. In addition to the speed of the ROMs, an advantage of the developed approach is its relative robustness. Since the method is merely based on sampling and data-fitting, it is not directly tied to a specific analysis tool and can be readily applied to others. With that in mind, the ROM approach was expanded to include structural models leading to combined thermal-structural analyses.

In this paper, we will outline the methods used to implement reduced-order modeling into a structural analysis workspace, specifically Nastran. We will highlight our approach for implementation and discuss how structural ROMs can be robustly built for various Nastran platforms (e.g., MSC Nastran, Autodesk® Nastran, and Simcenter Nastran). We will then provide several example cases showing the utility of ROMs for structural analysis. We continue the discussion by examining how structural ROMs can be combined with thermal ROMs for thermal-structural applications. Here we will pair Thermal Desktop® and Nastran models to create these multi-disciplinary ROMs. We will conclude the overview by providing several thermal-structural use cases.

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[111] ***Machine-learning Solution for Automatic Spacesuit Motion Recognition and Measurement from Conventional Video***

Linh Vu (Aegis Aerospace (NASA Anthropometry & Biomechanics Facility)), Han Kim (Leidos (NASA Anthropometry & Biomechanics Facility)), Alex Gordon (KBR (NASA Anthropometry & Biomechanics Facility)) and Sudhakar Rajulu (NASA).

Extravehicular Activity (EVA) spacesuits exhibit unique movement patterns due to their design characteristics. Mobility assessments using traditional motion capture systems are cost prohibitive and not feasible for some training conditions (e.g., simulated lunar outdoor terrain). This paper aims to present the ongoing development of machine learning solutions to quantify suit motions from conventional videos without special sensors or hardware.

Given the fast growth in deep/machine learning technologies, external expertise was sought from open-source communities. This was expected to accelerate development and provide more cost-effective, time-saving solutions. This work was selected for a NASA Crowdsourcing project through an agency-wide solicitation. Partnerships were formed with the NASA JSC Center of Excellence for Collaborative Innovation and an execution crowdsourcing platform partner to solicit framework developments from external contenders. NASA provided contenders with video clips of spacesuits and simultaneously measured motion capture data during EVA simulation tasks. The contenders used this data to train and develop generalized algorithms to predict motions.

At the end of the crowdsourcing event, five solutions were selected from 250 submissions. Each submission was tested and scored using video clips not previously disclosed to the contenders. The scoring metrics measured how well the algorithm detected the suit shape, the 2D suit joint detection accuracy, and 3D joint detection accuracy. The winning solution was able to achieve roughly 85% prediction accuracy (weighted combination of scoring metrics). Overall, the algorithms could efficiently detect various types of spacesuits and motions across different EVA simulation environments such as the Neutral Buoyancy Lab (NBL). However, 3D joint identification is less reliable when parts of the suit were obstructed in the image. After continued improvements and validation, the fully developed system will enable EVA stakeholders to quantify suit kinematic patterns, which can help optimize suit, hardware, and task designs.

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[112] ***Hybrid Life Support System Full Scale Testing: Integrated bioreactor-desalination for an early planetary base***

William Jackson (Texas Tech University), Ghaem Hooshyari (Texas Tech University), Evan Gray (Texas Tech University), Michael Callahan (Texas Tech University) and Maryam Salehi Pour Bavarsad (Texas Tech University).

Future life support architectures for habitats on the moon or Mars will require higher reliability and reduced consumables. These habitats will likely have a wider diversity of wastewaters including showers, other hygiene activities, and showers. These wastewaters similar to humidity condensate are relatively low strength compared to urine and flush water. As such it may be beneficial to separate the urine from other wastewaters and treat using technologies optimized for each waste. This research evaluated a hybrid wastewater processing system that included separate biological pretreatment of urine and the combined hygiene, laundry, and humidity condensate (grey water). Biologically pretreated grey water was processed using reverse osmosis (RO) at 90% recovery and the brine was combined with biologically pretreated urine and flush water and processed using a static distillation system. Details of the greywater pretreatment and RO system are presented in a companion paper. This paper focuses on the performance of urine pretreatment and distillation of the urine+ RO brine. We evaluated the impact of pH, volume processed, and other operational variables on distillate quality and recovery. We also evaluated the ability to store brine/ brine solids in the distiller over multiple processing events and subsequent impacts on recovery and brine quality. Distillation of RO brine and pretreated urine produces a distillate similar to that produced by chemical pretreatment. Using the static distillation vessel at least 15 continuous days (2 crew/d) of produced wastewater (>100 L) could be distilled without solids or brine removal leading to total water recoveries > 99%. Distillate water quality was dependent on the pH of the biological pretreated wastewater and RO brine. Our results support the ability to use biological pretreatment of urine to produce a stable effluent that when distilled produces a high quality distillate and low odor easily handled brine.

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[113] ***Culture-Independent Microbial Air Profiling using a Spaceflight-Compatible Nanopore Sequencing Method***

Brandon Dunbar (GeoControl Systems Inc.), Hang Nguyen (JES Tech), Sarah Stahl-Rommel (JES Tech), G. Marie Sharp (KBR), Christian Castro (JES Tech) and Sarah Castro-Wallace (NASA).

Microbial monitoring of spacecraft air is critical toward assessing the efficacy of microbial controls within the environmental control and life support systems to protect the crew and vehicle environment. Currently, onboard the International Space Station (ISS), the air is monitored on a quarterly basis using an impaction air sampler. With this method, microbial cells and spores are pulled onto plates containing growth medium. Following onboard incubation, the crew reports approximate microbial levels to the ground, but sample return is required for identification. Upon return of the plates, the isolates present are identified for crew health risk assessments. As NASA moves beyond low-Earth orbit, sample return will be impractical, and a near real-time monitoring capability is essential.

Significant strides have been made in recent years to utilize a molecular-based method for microbial profiling of ISS surfaces. The developed method is independent of microbial culture, thus removing the bias toward detecting only culturable organisms, eliminates the need for sample return, and reduces risk to crew health from exposure to high microbial levels. The work described here details the evaluation of three different air sampling platforms whose product is amenable to downstream molecular processing. The three samplers were compared in terms of mass and power requirements, ease-of-use, and the resulting data. For the two highest-ranking samplers, a basic concept of operations was developed to transfer the sample into the already established preparation and sequencing process. Using these

concepts of operations, an in-depth comparison of the molecular data generated was compared to the historical culture-based method. Data from both methods detailed similar microbial profiles, while the molecular method detailed microbial identifications that were lacking from the culture data. The developed method will enable the generation of near real-time microbial profiles of the spacecraft atmosphere.

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[116] *Thermal performance of Ingenuity the Mars Helicopter*

Stefano Cappucci (NASA Jet Propulsion Laboratory) and Michael Pauken (NASA Jet Propulsion Laboratory).

Ingenuity, the Mars Helicopter was launched with the rover Perseverance on July 30th 2020. Seven months later, on February 18th 2021, Ingenuity and Perseverance successfully touched down on the surface of Mars, in Jezero crater. On April 19th 2021 Ingenuity performed the first controller powered flight on another planet. As of the writing of this paper, Ingenuity has completed its primary mission to demonstrate feasibility of heavier than air flight on Mars and has already survived over 250 Sols on the surface of the Red Planet. This paper discusses the performance of Ingenuity's thermal control system and the Daily Rotorcraft Mission activities executed during surface operations with a focus on thermal analysis and energy budget. During the primary mission, daily commands uplink and telemetry downlink were required to operate the Helicopter. Deep Space Network and orbiter passes availability dictated the communication windows, forcing analysis and mission planning to be performed on a tight schedule with little margin for error. The thermal control system of Ingenuity was able to keep the hardware safe within allowable temperature limits while minimizing heater survival energy during the night. This allowed for batteries optimal state of charge to perform the flights. Precise modeling and accurate predictions resulted in operational flexibility and efficient mission planning and execution. Ingenuity's thermal model was capable of predicting components temperature with an error of +/- 3°C and energy consumption with an error of less than 5%. This paper also presents future steps and new milestones for the Mars Helicopter in addition to its primary mission. As it gets harder for Ingenuity to operate on Mars with the seasons changing, the mission continues to unveil the potential of Mars exploration through aerial vehicles.

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[117] *Use of diffusion bonded Cu strap and Integrated MLI for thermal control of 100K IR detector on L'Ralph instrument*

Juan Rodriguez (NASA) and Daniel Bae (NASA).

Passive cooling of cryogenic instruments is one of the most challenging aspects of spaceflight thermal control systems (TCS). They are highly sensitive to parasitic heat leaks from their warmer environment, especially the spacecraft components. The L'Ralph instrument on the Lucy mission is an example of such a system, with its LEISA detector requiring passive cooling to temperatures below 112 K. MLI performance can be measured in terms of estar, and analysts apply bias between a high and low estar value. This approach works well for conventional MLI at room temperature, however, it can be dangerous when a mission goes through a wide range of temperatures during its lifetime, with estar values increasing exponentially as temperatures get colder. Various estar correlations are presented as well as how L'Ralph is approaching the MLI problem with the use of IMLI. IMLI uses discrete spacers to isolate each layer, and doesn't require intermediate layers such as dacron netting. This results in estar performance that can be more precisely estimated, and yields values around 0.004 at the 112K operating temperature. L'Ralph is using IMLI on the backside of the radiator, which permits a more effective use of increased radiator area, by minimizing the area dependent heat leak impact from the instrument backloading. The detector is thermally coupled to the radiator via a diffusion bonded Cu strap. The diffusion bonding process chemically bonds the Cu foil ends in order to maximize heat transfer effectiveness across the multiple foils used. Employing a pressure compensation design via the use of Ti blocks and a clamp at the strap ends ensures that as temperatures go colder, pre-load is maintained in order to minimize resistance at the strap ends. The use of both of these technologies, and how they work together are crucial to the success of the L'Ralph TCS.

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[119] *Multi-Angle Imager for Aerosols Thermal Control System and Articulating Thermal Strap*

Douglas Bolton (Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California).

MAIA is a NASA funded instrument that will collect data to help characterize airborne particulate matter over a number of population centers across the globe using multi-angle spectropolarimetric imagery. Data collected by MAIA will facilitate assessments of the impacts of different types of particulate matter on adverse health outcomes. MAIA is a hosted payload meant to operate in a near-circular LEO sun-synchronous polar orbit, with a mean altitude between 600 km and 850 km. The nominal on-orbit mission design lifetime is three years.

Temperature control of the MAIA instrument will be accomplished with a combination of passive radiators and heaters. The focal plane module (FPM) will be cooled to ≤ 235K with a disc shaped radiator that faces the anti-sun side of MAIA's sun-synchronous orbit. Heat from the MAIA camera and associated electronics is rejected through a cylindrical shaped radiator that projects a near constant area in the nadir direction as MAIA's camera rotates.

A noteworthy feature of the MAIA thermal control system design is the novel, low cost, rotationally articulating thermal strap used to transfer heat from MAIA's FPM to its associated radiator. The strap spans an axis of rotation that sweeps out an arc of nearly 70° as the instrument operates. A prototype of the articulating thermal strap was life tested to 132,000 cycles with no signs of any significant degradation. A second thermal strap and associated thermal shield were subsequently flight qualified in a test that subjected them to 115,000 cycles over a temperature tange of 175K to 343K.

The paper will present an overview of the MAIA thermal control system baseline design, with a focus on its novel aspects, including life and qualification testing of the flight articulating thermal strap.

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[120] *Functionally Aligning Emergent Technologies for Self-Sufficient Deep Space Smart Habitats*

David Klaus (University of Colorado Boulder), Sophia Zaccarine (University of Colorado Boulder), Patrick Pischulti (University of Colorado Boulder) and Annika Rollock (University of Colorado Boulder).

As the Artemis Program works to establish the Gateway in lunar orbit and a Base Camp on the moon, advancing emergent technologies for use in deep space habitats represents a next step towards enabling sustainable future exploration missions. The same basic functionality needed to keep the crew alive, healthy, happy and productive applies to a habitat design regardless of the ultimate destination – LEO, deep space, or planetary surfaces. With increasing mission durations and distances from Earth, however, future space habitats will require unprecedented levels of self-sufficiency to sustain operations due to impacts to ground communication links and limitations on resupply opportunities. To meet this challenge, autonomous and other emergent technologies including machine learning/Artificial Intelligence (AI), human-autonomy teaming, robotics, additive manufacturing, etc. offer unique solutions for performing the necessary functions by increasing onboard capabilities and decreasing reliance on Earth support. In this context, we refer to these technologies as collectively comprising a 'Smart System' that combines elements of hardware, software, humans and/or processes as needed to meet the required onboard functions without external intervention. This paper defines a process that starts by identifying essential habitat functions from a generic deep space Concept of Operations (ConOps), then aligns each function with one or more optional means for accomplishing it. The solutions can range from ground-commanded actions to onboard manual or automated task allocation to incorporation of various autonomy-enabling emergent technologies. Criteria are then presented for characterizing the potential benefits of emergent technology design solutions to conduct Nominal Operations and Anomaly Responses as a decision-making strategy for comparing their performance to current state-of-the-art approaches. Finally, we summarize a select set of emergent technologies currently being evaluated for specific functions by our colleagues as part of the NASA 'SmartHab' Space Research Institute (STRI) Habitats Optimized for Missions of Exploration (HOME) Project.

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[122] *IVA Space Suit Flight Qualification*

Theodore Southern (Final Frontier Design) and Nikolay Moiseev (Final Frontier Design).

Final Frontier Design has continued development work of an advanced Intra-Vehicular Activity space suit in preparation for flight qualification. The Automatic Pressure Regulation System was tested and validated at NASA's Marshall Space Flight Center vacuum chambers for high fidelity functionality in a variety of flight depressurization scenarios. High pressure tests and additional restraints allow an increase to 5 psid operational pressure. Two rounds of offgas testing have been performed, with a conclusion that the suit requires a bakeout prior to human use to reduce overall T levels. Custom bearings have been added at the wrists to improve manual capabilities. Vent tree tubing and interfaces were optimized for flow, comfort, and flexibility. Requirement validations for a variety of missions are being satisfied.

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[128] *Competition Between Pyrolysis Kinetics and Surface Radiation in Opposed-Flow Flame Spread in a Microgravity Environment*

Subrata Bhattacharjee (San Diego State University) and Michael Delichatsios (Northeastern University, Boston, MA, 02115).

The well-known de Ris formula for the flame spread rate in the thermal regime of the opposed-flow flame over condensed fuels assumes the vaporization temperature to be a thermodynamic property and, hence, a known constant. Experimental evidence has long indicated that the vaporization temperature not only depends on environmental and fuel conditions, but also varies along the pyrolysis zone. A recent work, based on simplified analysis and a comprehensive numerical model, was able to explain these dependencies, resulting in a closed-form formula for the vaporization temperature for flame spread in the thermal regime. In this work a similar analysis is carried out for flame spread in the low-velocity regime of the microgravity environment, also known as the microgravity regime. Because of the longer

residence time, radiation can no longer be neglected giving rise to some interesting consequences. The comprehensive numerical model is used to contrast the vaporization characteristics between the microgravity and thermal regime. The vaporization temperature monotonically decreases along the pyrolysis zone instead of the slight increase seen in the thermal regime. Moreover, there is no fuel burnout at low flow velocities, that is, the fuel density does not go to zero reaching an asymptotic value. In the absence of a burnout, the flame assumes a tulip shape and the unburnt fuel acts like a cooling fin. Based on a local non-dimensional number that compares local radiation loss to the conduction flux from the flame, a criterion is developed to determine when the fuel starts working as a cooling fin. Using it as an artificial burnout condition, the flame shape can be altered from a tulip shape to a closed shape without affecting the flame spread rate. The flame shape observed in an experiment, therefore, can be used to infer the burnout status of the pyrolyzing fuel.

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[129] *Design of a Jettison System For Space Transit Vehicles*

Steve Sepka (NASA), Michael Ewert (NASA), Jeff Lee (NASA), Thomas Chen (NASA - Jacobs Technology, Inc.) and Chandrakanth Venigalla (University of Colorado).

Many options to re-use waste are currently being developed by NASA. These include combustion, compaction, torrefaction, and converting waste materials to an easily stored base polymer for future use. Human exploration missions require large amounts of supplies such as food, clothing and spare parts. A many-month journey to Mars will still result in the generation of a substantial amount of problematic waste products. It is thought that this waste must be discarded to enable a Mars transit mission. The most cost-effective, reliable, and safest method to address this problem may be to simply jettison these materials from the spacecraft. The ability to jettison requires a multi-component integrated system design. Major components include a launcher, airlocks, trash bags, and tracking system. Depending upon mission requirements, a jettison dedicated airlock may be necessary. In other cases, the crew airlock might be all that is needed. This paper will discuss these design issues and give guidance to a pathway forward.

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[130] *Waste Heat-Based Thermal Corer for Lunar Ice Extraction*

Kuan-Lin Lee (Advanced Cooling Technologies,Inc.), Quang Truong (Advanced Cooling Technologies,Inc.), Sai Kiran Hota (Advanced Cooling Technologies,Inc.), Srujan Rokkam (Advanced Cooling Technologies,Inc.) and Kris Zacny (Honeybee Robotics).

The water ice accumulated in the Permanently Shadow Regions (PSR) of the Moon is considered to be the most valuable resource on the moon since it can be processed to generate Oxygen for life-supporting and converted into LH2 and LO2 for satellite and spacecraft refueling. It has been demonstrated that water can be extracted from icy-soil through in-situ heating and then collected by re-freezing the sublimated vapor within a cold trap container. Under this research, a thermal management system (TMS) for Lunar Ice Miners was developed, which consists of a thermal corer that can strategically use the waste heat of on-board nuclear power sources for ice extraction, and a cold trap tank that can use the lunar cold environment as the heat sink for ice collection. In order to investigate heat exchange between the corer and icy-regolith during the thermal extraction process, a two-dimensional transient model was developed and built-in ANSYS FLUENT environment as user-defined functions (UDF). The UDF provides the user-defined material properties of the icy-regolith as a function of temperature and porosity, including specific heat, thermal conductivity, saturation pressure, and mass fraction of ice. The model was validated against experimental water extraction of Mars regolith and Lunar regolith. Both experiment and simulation demonstrated a complete sublimation of 10% wt of icy-soil within ~ 9 minutes, using a thermal corer with 6 inches in length, 0.6 inches in inside diameter, and wall temperature of 57 ℃. On-going work focuses on optimizing the dimension of the full-scale corer, using the developed model, to achieve the targeted water collection of 2.78 kg/hr.

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[131] *Advanced Two-Phase Cooling System for Modular Power Electronics*

Kuan-Lin Lee (Advanced Cooling Technologies,Inc.), Sai Kiran Hota (Advanced Cooling Technologies,Inc.), Andrew Lutz (Advanced Cooling Technologies,Inc.) and Srujan Rokkam (Advanced Cooling Technologies,Inc.).

NASA envisions building future space power system architectures with many standardized, interchangeable, and reusable modular electronics to improve system adaptability and minimize the cost of development, operation, and maintenance. As the size of the electronics becomes smaller, future high-performance electronic modules will generate higher waste heat fluxes, which will be unmanageable by the current state-of-art cooling systems. More effective heat transfer devices and integrated cooling systems that can significantly reduce the overall thermal resistance from the semiconductors to the heat sink are highly desired. Under an SBIR program, Advanced Cooling Technologies, Inc. (ACT) developed a lightweight and effective cooling system for 3U modular electronics in a common enclosure. The system consists of multiple advanced thermal management components, including two-phase heat spreaders to move the heat from card center to edges and enhanced card locks to minimize card-to-chassis thermal resistance. Two types of two-phase

solutions were identified and investigated. The first one is heat pipe embedded card (i.e. Hi-KTM plate) and the second is pulsating heat pipe (PHP) plate. ACT designed, fabricated, and thermally tested on a lab-scale mock modular electronics system. A comprehensive trade study and the overall improvement in heat transfer by these two heat spreaders in comparison to an aluminum plate were discussed.

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[132] *Integrated Hot Reservoir Variable Conductance Heat Pipe with Improved Reliability*

Kuan-Lin Lee (Advanced Cooling Technologies,Inc.), Calin Tarau (Advanced Cooling Technologies,Inc.), William Anderson (Advanced Cooling Technologies,Inc.), Cho-Ning Huang (Case Western Reserve University), Chirag Kharangate (Case Western Reserve University) and Yasuhiro Kamotani (Case Western Reserve University).

A hot reservoir variable conductance heat pipe (VCHP) that can offer tight and passive thermal control is an ideal thermal link for future planetary landers and rovers. This is especially useful for the moon operation as surviving during the lunar night is energetically challenging. Under a Small Business Technology Transfer (STTR) program, Advanced Cooling Technologies (ACT) and Case Western Reserve University (CWRU) developed an advanced integrated hot reservoir VCHP with improved reliability. This novel design enables a momentum-induced flow to circulate through a non-condensable gas (NCG) loop, which can continuously and effectively remove the excessive working fluid vapor from the reservoir (i.e. purging) without using an electric heater. Based on the purging test results, the bulk induced flow velocity is in a cm per second range. Without the flow, purging is dominated by diffusion and it will take hours to complete. With momentum-induced flow, the purging rate is much faster and the heat pipe can get back to normal operation within 20 minutes. This paper summarizes prototype development and experimental study of hot reservoir VCHP loop, including a detailed analysis of the VCHP purging process, purging, and startup testing of VCHP loop. A compact hot reservoir VCHP loop prototype with both reservoir and NCG tube integrated was developed and tested.

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[133] *Human in the Loop Evaluations: Process and Mockup Fidelity*

Jackelynne Silva-Martinez (NASA), Gordon Vos (NASA), Jennifer Boyer (NASA), Robert Durkin (NASA), William Foley (NASA), Sarah Margerum (KBR), Kritina Holden (Leidos), Victoria Smith (KBR), Leah Beebe (KBR) and Christopher Van Velson (NASA).

Human-in-the-loop (HITL) evaluations are iterative events used during design and development to identify issues with the implementation of human systems integration. HITL evaluations involve human test subjects who are user-representative participants performing activities with representative hardware, software, and procedures. The paper will describe the process by which HITL evaluations can be implemented in a program or project. This will include definitions for developmental and verification HITL evaluations, levels of mockup fidelity, and certification of HITL articles. The proposed process can be tailored depending on the type of HITL evaluation being conducted. It is highly recommended that findings are timely reported and incorporated in the hardware and/or software design.

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[134] *Bubble Effects on Electrolysis for Water Purification in Microgravity*

Satoshi Matsumoto (Japan Aerospace Exploration Agency), Nasa Yoshioka (Japan Aerospace Exploration Agency), Hideki Saruwatari (Japan Aerospace Exploration Agency), Yukitaka Matsumoto (Kurita Water Industries Ltd.) and Kazuya Ishiwata (Kurita Water Industries Ltd.).

The electrolysis under high pressure and high temperature is one of promising water purification processes of urine for future human space exploration missions. Fine gas bubbles are generated around the electrodes by electrolysis. It is considered that the buoyancy acting on the bubbles promotes departure from the electrode and transportation in electrolyte solution. In microgravity where buoyancy disappears, the bubble motion might be different from nominal gravity conditions and affect efficiency of oxidization of organic carbon including urine. In this paper, the behavior of gas bubble is modeled and the effect of gravity on electrolysis process for water purification of urine is estimated. The electrolysis voltage and current experimentally processed in microgravity are compared with the experiment on the terrestrial conditions and the stability and efficiency of electrolysis are discussed.

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[135] *Optimization and Thermal Vacuum Testing of Variable Emissivity Coatings for Radiators*

Jean-Paul Dudon (Thales Alenia Space), Laurent Dubost (HEF-IREIS), Philipp Hager (European Space Agency), Stephanie Remaury (CNES), Frederic Vidal (Université de Cergy-Pontoise), Alice Ravaux (HEF-IREIS), Bérangère Doll (Thales Alenia Space), Bruno Bras (ESA-ESTEC) and Sophie Cantin (LPPI).

The objective for the development of variable emissivity coatings is to handle the variation of heat loads during the mission, by maximizing the heat rejection capacity and minimizing the heating power demand. The most promising of

these coatings are based on Thermochromic (TCH) and Electrochromic (ECH) materials. Thermochromic materials can be adjusted to behave as poor emitters at low temperature, and good emitters at high temperature without the need of any electronic feedback or electromechanical actuation, and therefore at zero power costs. The advantage of ECH for space application is achieved by adapting the infrared emissivity of a surface by application of a low power electrical potential. For the last 3 years an R&D activity co-funded by ESA, CNES and Thales Alenia Space, aimed at the development of thermochromic tiles based on VO2 thin film material and of ECH devices based on conducting polymers. A previous paper described the design, the manufacturing process and the tests of TCH and ECH materials. In this paper we present the continuation in the form of the thermal-vacuum testing of TCH and ECH radiator breadboard. Furthermore, the optimized performances of TCH tiles will be described in detail. We report as well on optical modeling showing the feasibility to lower the solar absorptivity for TCH tiles. The TCH and ECH breadboards were successfully assembled and tested in a vacuum chamber. Their emissivity contrast between cold and hot case was validated to be 0.3 with a hot case emissivity being 0.8. The further optimization of TCH full stack led to the reduction down to [10°C, 40°C] of the switching temperature range within which the emissivity change from low to high, due to the doping of the VO2 layer with tungsten. Concerning the optical modeling of the TCH, the main functions have all been successfully simulated.

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[137] *Study for a Rigid/Inflatable Greenhouse Module to Integrate Bio-regenerative Life Support Systems into Orbital Facilities and Deep Space Transfer Vehicles.*

Paolo Caratelli (Abu Dhabi University), Maria Alessandra Misuri (Abu Dhabi University) and Rowdha Begam Mohamed Hanifa (Abu Dhabi University).

A recurrent issue in concepts for future Deep Space Transfer Vehicles (DSTVs) and space habitats is the needing of a large provision of consumables necessary for crew's vital sustainment during prolonged missions without any external supply. The integration of ecological bio-regeneration into the environmental control and life support system (ECLSS) seems now an appropriate solution to reduce the amount of storage, favoring a circular economy of vital elements. The goal is a closed loop of oxygen, water, and food through recycling and regeneration of a given quantity, reducing the dead mass of consumables stored for backup and emergency supply only. The concept of Bio-regenerative Life Support System (BLSS) has been extensively tested by ESA, NASA and Roscosmos since the late 1980s. Projects like MELiSSA (Micro-Ecological Life Support System Alternative) financed by ESA has been tested both in ground facilities as fully closed biological lifecycle and in a series of orbital spaceflights, testing system's performance in conditions of microgravity. However, the reduction of consumables in term of dead mass, using a closed-loop paradigm, can come at a cost. Increased system complexity, greater energy usage, and more possible failure modes are all possible consequences of BLSSs. This paper explores the feasibility for a hybrid rigid/inflatable module based on the Cygnus cargo module by Northrop Grumman Space Systems, assumed as standard module for the Cislunar Gateway station. The expandable module would host an experimental greenhouse for plants, microalgae's photo-bioreactors, and necessary BLSS hardware, adding capability to the ECLSS of the station. Its scope is to test in extended conditions of microgravity the capability of food production, carbon sequestration, oxygen regeneration, humidity condensation, waste processing and wastewater recycling of the BLSS, increasing the habitable volume of the station and introducing an element of tangible natural bond with the home planet for crew's psychological support.

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[138] *Demonstration of 3D printed Phase Change Material Heat Capacitors for Space Application*

Lukas Schulz (Airbus Defence and Space), Ulrich Rauscher (Airbus Defence and Space), Martin Altenburg (Airbus Defence and Space), Florian Baumann (Airbus Defence and Space) and Erik Hailer (Airbus Defence and Space).

As peak dissipations in combination with thermal constraints become more and more a limiting factor in radar-satellite or planetary rover missions, it is becoming increasingly attractive to buffer the dissipated heat and release them over a greater period of time, e.g. one full orbit or one day/night cycle. An efficient way of storing large amounts of heat is the phase transition of pure substances, which occurs isothermal. To demonstrate this, two heat capacitors, each consisting of a 3D-printed housing, including an internal heat spreader, and Octadecane ($C_{18}H_{38}$) have been developed and built. Each prototype weights about 350g and has a capacity of 24.4kJ only in the alkanes phase transition, happening at 28°C. Those prototypes were then successfully subjected to a series of tests to verify thermal and mechanical models as well as the demonstration of its properties. The test sequence consists of determination of the thermal capacity, a thermal balance test in vacuum to determine the thermal conductivity, thermal vacuum tests for 8 thermal cycles from -50°C to 80°C and a theoretical use-case scenario, a CT-scan after the thermal tests and mechanical tests, including Eigen frequency searches and random vibration tests. This paper will discuss the design, modelling and testing of those prototypes to provide first lessons learned.

[139] *Feasibility Study on Thermal Design for Synthetic Aperture Telescope Using Formation Flying Micro-satellites*

Shinichi Yokobori (The University of Tokyo), Ryo Suzumoto (The University of Tokyo), Norihide Miyamura (Meisei University), Satoshi Ikari (The University of Tokyo) and Shinichi Nakasuka (The University of Tokyo).

Due to global warming, forest fires are becoming more frequent and serious. We study the development of a forest fire early detection system named Formation Flying Synthetic Aperture Telescope (FFSAT). Operating the synthetic aperture telescope constructed by multiple Formation Flying (FF) micro-satellites in geostationary orbit can provide both frequent and high-resolution monitoring of the target area. In addition, this system significantly reduces launch costs because the satellites are smaller and lighter than a single mirror telescope satellite with the same aperture size. The observation wavelength of the FFSAT is 4-um to detect the forest fire flames. Therefore, it requires the ultra-precise relative attitude and position control of about 1/10 of the wavelength, or less than 0.4-µm. Since thermal strains of the satellites are not negligible to this precise system, we constructed a thermal structure model of the FFSAT to evaluate and minimize the effect of thermal strains on the optical system. FFSAT consists of one imaging satellite and six mirror satellites that form one large mirror surface with a diameter of 5.82 meters. The primary mirror of each mirror satellite is supported by a piezo stage to control sub-µm displacements in six degrees of freedom, and the imaging satellite has a Deformable Mirror (DM) to correct the incidence light from the mirror satellites. As a result, the displacements of the optical planes by the thermal strains of the mirror satellites and the imaging satellite are less than several tens of µm. It is within the dynamic range of the piezo stage and the DM. We confirmed that the optical surface could be corrected on the sub-µm order.

[140] *ROXY - An economically viable process to produce oxygen and metals from regolith*

Achim Seidel (Airbus Defence and Space), Martin Altenburg (Airbus Defence and Space), Emanuele Monchieri (Airbus Defence and Space), Peter Quadbeck (Fraunhofer Institute for Manufacturing Technology and Advanced Materials IFAM), Christian Redlich (Fraunhofer Institute for Manufacturing Technology and Advanced Materials IFAM), Uday Pal (Boston University) and Florian Strigl (Airbus Defence and Space).

Future exploration missions to the Moon and beyond will be dependent on the use of local resources, provided that they can be produced very efficiently such that their mass exceeds the mass of any needed consumables or spares to sustain the process. Metals and oxygen are among the most important resources to be made available, in particular with the aim of supporting an incremental human presence on the Moon and beyond. A method to produce these resources from local feedstock via the use of a compact, light, and process efficient facility ensuring high yields and low requirements for resupply of material from Earth will therefore represent a strong enabler for several exploration scenarios. Among the many methods that have been studied so far, molten salt electrolysis with solid oxide membranes is very promising since it meets those basic criteria. A specific implementation of this method to lunar applications called ROXY (Regolith to Oxygen and Metals) has been developed and tested, and the design and operations of related demonstration and production facilities have been investigated. Performance figures of such facilities such as mass and power consumption in relation to the mass of produced materials are very attractive provided that the thermal design and operating parameters of the reactor are carefully matched to the process.

[141] *Linear Control Analysis & Review for Systema – Utilization of Complex Thermo-Elastic Transfer Functions*

Erik Hailer (Airbus Defence and Space), Johannes Burkhardt (Airbus Defence and Space) and Martin Altenburg (Airbus Defence and Space).

Due to the extremely demanding thermal stability environment of high precision optical instruments, thermal and thermo-elastic analyses are focusing on the effect of small disturbances on a nominal operational state. Performance requirements for some of these missions are formulated in the frequency domain and have to be evaluated within the frequency measurement bandwidth (MBW). In order to reduce computational effort and to improve numerical accuracy, the analysis is directly performed in the frequency domain which is preferable to the alternative of running multiple transient thermal analyses in the time domain and subsequent Fourier transformation. In previous papers (of the authors) such a methodology has been discussed in detail. It a) transfers the non-linear thermal network into a standard linear control system for one specific steady state point, b) subsequently transfers this system into the frequency domain via the Laplace transform, and c) calculates complex thermal transfer functions in the frequency domain. The associated S/W is Python based, and is part of the AIRBUS internal tool LCARS (Linear Control Analysis & Review for Systema).
Expanding the methodology, the paper will discuss the derivation of complex thermo-elastic transfer functions, based on previously derived complex thermal transfer functions (reference) and the standard thermo-elastic distortion (TED) macro-node approach (reference). Further inputs to evaluate the margins with respect to thermo-elastic performance requirements are thermal noise models established for S/C external and internal noise sources. This application of the

methodology is discussed exemplary for the ESA cornerstone mission LISA. The performance of a thermally compensated structure of the LISA instrument is analysed, detailing the influence of phase shifts and of amplitude attenuations in such a structure. Results of sensitivity analyses will be discussed, which allow to evaluate the capability of such a structural concept, to improve the TED performance.

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[144] *Performance of the Shortened Liquid Cooling Warming Garment During Simulated MicroG EVA*

Sophie Bielawski (University of North Dakota, Department of Space Studies), Pablo de Leon (University of North Dakota, Department of Space Studies) and Gloria R. Leon (University of Minnesota, Department of Psychology).

Surface temperatures during extravehicular activity (EVA) in low Earth orbit range from -157°C to 121° C. Although spacesuits shield astronauts from such inhospitable extremes, metabolic heat production due to physical exertion is trapped within the garment, leading to increased internal temperature. Cooling garments are utilized to maintain human thermal equilibrium.

NASA's Liquid Cooling and Ventilation Garment (LCVG) has been in use for decades. Koscheyev and colleagues developed a physiologically designed Shortened Liquid Cooling Warming Garment (SLCWG) at the University of Minnesota, focused on increasing the efficiency of the garment to support thermal balance. The performance capability of the SLCWG to remove excess metabolic heat during EVA was assessed by comparison with the LCVG and via metabolic heat development models. The SLCWG findings demonstrated similar thermal balance management and higher subjective comfort ratings compared to the LCVG.

However, the SLCWG has not been tested with subjects in a pressurized spacesuit. The current study assessed the thermoregulatory performance of the SLCWG within a pressurized spacesuit during a simulated microgravity EVA. Test subjects are suspended using the DL/H-1 spacesuit within a horizontal harness system while they perform a number of tasks comparable to the ones performed during microgravity EVAs. Performance of the SLCWG is then judged based on skin temperature measurements, calculated core body temperature, and subjective thermal comfort ratings. Based on data retrieved during the control phase, common metabolic heat development models are evaluated and a metabolic heat development model for the DL/H-1 spacesuit is created.

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[145] *Coolant Leak from ISS External Active Thermal Control System (EATCS) – An Examination of Most Probable*

Darnell Cowan (NASA) and Timothy Bond (NASA).

The Port (P1) and Starboard (S1) External Active Thermal Control Systems (EATCS) are single phase, mechanically pumped ammonia loops that operate independently to cool majority of the hardware and payloads onboard the International Space Station (ISS). A slow ammonia leak was detected using pressure and quantity telemetry five years after the P1 EATCS was activated. The leak gradually accelerated to a rate that locating and isolating the leak became imperative to maintain cooling capability. Partial pressure measurements from the Robotic External Leak Locator (RELL) scan surveys narrowed the search to the supply and return jumpers connecting one of three radiators to the system. Subsequently, the ISS crew performed high definition video surveys during an Extravehicular Activity (EVA), or spacewalk, and ammonia flakes were observed projecting from the jumpers. Thus, the ground teams were confident that the culprit of the ammonia leak were the jumpers. The ammonia leak stopped after ground teams remotely isolated and vented those jumpers and associated radiator. Both jumpers were removed and returned to the ground, and a root cause investigation was conducted. A calibrated leak test determined the bulk of the ammonia leaked through a pair of seals in a Quick Disconnect (QD), or connector, on one end of the return jumper. The return jumper QD was dissected, visually inspected, chemically tested and evaluated. The results indicated the most probable cause of the accelerating ammonia leak was due to defective seals, plating delamination underneath the seals, and on-orbit thermal cycles exacerbating the delamination. Both jumpers were refurbished, relaunched to the ISS, and scheduled to be reinstalled during an EVA in 2022. It appeared the issue was unique, but recently the S1 EATCS is showing signs of an accelerating ammonia leak, and RELL scans narrowed the source to a similar pair of radiator jumpers.

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[147] *SVOM MXT Instrument: Thermal Control System Design and Verification*

Narjiss Boufracha (CNES), Thierry Tourrette (CEA IRFU), Alexander Lodge (University Of Leicester), Adrien Jeanmougin (Epsilon Alcen), Alexandre Van Haute (Euro Heat Pipes), Alexandre Guevezov (Airbus Defense and space), Albert Gomes (CNES), Karine Mercier (CNES), François Gonzalez (CNES), James F. Pearson (University of Leicester), Diego GÖtz (CEA IRFU) and Aline Meuris (CEA IRFU).

SVOM (Space-based multi-band astronomical Variable Objects Monitor) is a mission developed within a Sino-French cooperation context and dedicated to the detection, localization and study of Gamma Ray Bursts (GRBs) and other high-energy transient phenomena.

Four scientific instruments (ECLAIRs and MXT provided by CNES: National French Space Agency, GRM and VT provided by CNSA: China National Space Administration), operating in different wavelengths, constitute the flight segment of the mission. A ground segment (several telescopes and a data center) contributes also to this GRB observations.

This paper addresses the MXT instrument, developed by CNES in collaboration with different scientific partnerships (CEA, MPE, IJCLab and the University of Leicester) and dedicated to the observation of GRB afterglows in the soft X-ray band.

SVOM is a Low Earth Orbit mission with a specific pointing law thanks to which the spacecraft can quickly change its orientation in order to observe GRB events as soon as they occur. This leads to a very variable and unfavorable external environment for low and stable temperatures. Indeed, the MXT detector (CCD) needs a temperature at -65 °C or lower. Passive cooling cannot achieve such a low temperature. As a consequence, Thermo-Electric Coolers (TEC) insure the additional active cooling. This leads to a significant heat dissipation to be evacuated. A thermal bus with propylene heat-pipes transports this amount of heat from its source to a radiator. Moreover, optical performances (alignment and focus), derived from scientific observations needs, require high performances in terms of temperature stability and uniformity.

The paper focuses on the Thermal Control System of the MXT instrument, and more specifically on its design, validation and verification.

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[148] *Preliminary Investigation of Microgravity Vortex Phase Separator for Liquid Amine CO2 Removal System*

Alexander Sarvadi (University of North Texas), Huseyin Bostanci (University of North Texas), Cable Kurwitz (Texas A&M University), Grace Belancik (NASA Ames Research Center) and Darrell Jan (NASA Ames Research Center).

Innovative, reliable, and cost-effective life support systems, such as CO_2 removal technologies, are key to support human exploration of deep space. ISS currently uses solid sorbent (granules of synthetic rock (zeolite)) to capture CO_2. NASA seeks to replace these solid sorbents as they have large volume, high desorption temperatures causing high power usage, and long-term reliability issues. Liquid sorbents may be used as an alternative to solid sorbents and are estimated to consume 65% less power. Liquid amines are currently being researched by NASA for CO_2 capture, however their implementation for space applications depends on an effective gas-liquid separation method under microgravity conditions. This study investigates the Vortex Phase Separator (VPS) technology as a new approach for a liquid amine CO_2 removal system. The microgravity VPS uses a nozzle attached to a right circular cylinder so that cabin air with high CO_2 levels enters tangentially along the separator wall. The injected stream breaks into very small bubbles and coalesces with a swirling liquid amine layer which is also tangentially injected by another nozzle on the opposite side of the separator. As the bubbles flow through and interact with the colder liquid amine layer, CO_2 is absorbed, and water vapor is condensed. Since the bubbles are subjected to a centrifugal acceleration field normal to the z-axis of the separator volume, gas (CO_2-lean air) moves to the gas column in the center of the separator and liquid (liquid amine with increasing CO_2 and water content) remains on the separator walls, effectively causing the liquid and gas phases to separate. A prototype VPS system is tested to demonstrate the separation of CO_2 from a warm, humid, CO_2-rich air stream and measure the system performance. Initial testing showed VPS capability for reducing water content in a humid air stream up to 49%.

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[150] *Design Strategies of Greenhouse and Food Production/ Preparation Module for Long-Duration Human Exploration Missions*

Mahsa Esfandabadi (University of Houston) and Olga Bannova (University of Houston).

Space horticulture has come a long way from germinating a single plant in orbit to producing vegetables for multiple meals. However, one of the main prerequisites of long-duration missions is producing and supporting nutritious food without resupply from the earth. A single small greenhouse chamber needs to transform into a larger module with both greenhouse and food production/preparation systems to reach this goal. This paper will describe current and novel macronutrient production technologies which transform a harvested plant into edible carbohydrates, protein, and lipids for consumption. Then, micronutrient and flavoring production methods will be considered to ensure the meal is both nutritious and tasty. 100% food support in zero gravity will not be possible without safe food preparation and storage systems. This review will show the timeline and pin the milestones needed to move one step closer to a long-duration mission.

[151] *Orthostatic Intolerance Garments for Spaceflight: Posture-Informed Design for Improving Garment Comfort*

Ruth Bunford (RMIT University), Braid MacRae (RMIT University), James Waldie (Human Aerospce), Rajiv Padhye (RMIT University) and Gordon Cable (Human Aerospace).

Astronauts are susceptible to dizziness and fainting when leaving microgravity as the cardiovascular system struggles to maintain cerebral blood flow during orthostatic challenge with the onset of gravity exposure. Orthostatic Intolerance Garments (OIG) are therefore worn to apply compression to the lower body to minimize blood pooling in the abdomen and lower extremities. The Artemis program intends to use OIG to reduce the risk of losing cognitive ability when transitioning to a higher-gravity environment when spacecraft control or physical capability (e.g., emergency egress) may be compromised. NASA's OIG for spaceflight is an abdomen-to-foot garment where the desired compression regime is graduated from 55mmHg at the lower leg to 15mmHg at the abdomen. Currently astronauts are measured for tailor-made compression garments which are donned for Earth re-entry. Challenges for improved OIG design include the preservation of wearer comfort under target compression regimes, especially around the knee in a seated position. Further, even if using a compression garment tailored to the astronaut, the stretch and pressure of the garment after microgravity exposure will be unknown due to anthropometric variance from height changes, muscle atrophy and fluid redistribution compared to pre-flight measurements. The intention of this study is to contribute new ideas towards the development of a new OIG design which allows for comfortable application of ankle-to-abdomen compression, allowing for flexion of the joints while preserving ambulatory capability. This is being achieved by extending anthropometric-centered-design and giving particular importance to the body posture while seated in the spacecraft re-entry chair.

[152] *Variable Stiffness Soft Knee Exoskeleton for Advanced Space Suits and Planetary Exploration: Energetics Evaluation*

Allison Porter (Massachusetts Institute of Technology), Katya Arquilla (Massachusetts Institute of Technology), Nicole McGaa (Massachusetts Institute of Technology), Alvin Harvey (Massachusetts Institute of Technology), Rachel Bellisle (Massachusetts Institute of Technology), Dava Newman (Massachusetts Institute of Technology) and Aleksandra Stankovic (Harvard Medical School/Massachusetts General Hospital).

Stiff joints in gas-pressurized space suits have restricted mobility and increase the risk of injury in astronauts during extravehicular activity (EVA). Prior work by Carr and Newman in the Massachusetts Institute of Technology Human Systems Laboratory has established that some level of knee joint stiffness may be beneficial in storing elastic energy, decreasing the metabolic expenditure during ambulation on planetary surfaces. Recently, an airbag-actuated soft knee exoskeleton (SKE) was developed to provide adjustable knee stiffness in parallel with the knee joint using airbag actuators. The SKE was designed to be integrated into the BioSuitTM, an advanced mechanical counterpressure space suit concept, to exert low levels of tunable stiffness to the knee joint to maximize energetics efficiency in suited EVAs during reduced gravity locomotion. In this proof-of-concept pilot study, the SKE is evaluated in a human participant study during hopping. Its impacts on metabolic energetics were assessed via VO2 and heart rate response. Participants completed a single-leg hopping protocol while wearing the inflated/stiff SKE which was compared to a non-exoskeleton/control condition. Metabolic expenditure during the trials was measured using a COSMED K5 metabolic cart system and Garmin chest-mounted heart rate sensor. The SKE V3 was demonstrated as a robust and durable proof-of-concept knee-stiffness exoskeleton during single-leg hopping. The results of this prototype indicate the promising operational feasibility of the SKE hardware. The pilot study investigating metabolic impacts showed that in some individuals the SKE V3 may beneficially impact metabolic expenditure indicators such as VO2 and HR, but the effects of trial order and fatigue should be further investigated to better understand the difference in outcomes between left and right leg hopping. Recommendations for future work include studies involving more participants, increased exercise duration, and other movement tasks motions to fully evaluate the metabolic expenditure impacts of the SKE V3.

[153] *Detection of task type through unobtrusive physiological monitoring*

Katya Arquilla (Massachusetts Institute of Technology), Michael Zero (University of Colorado Boulder), Kaitlyn Hauber (University of Colorado Boulder), Mark Shelhamer (Johns Hopkins University), David Klaus (University of Colorado Boulder) and Christine Fanchiang (The Space Research Company, LLC).

As deep space missions become more autonomous and self-reliant, the need to execute tasks collaboratively between humans and robots increases. As such, it also becomes important to monitor crew workloads in real time in order to adjust task allocation or advise countermeasures. In this work, we demonstrate the utility of monitoring psychophysiological signals – electrocardiogram (ECG), electrodermal activity (EDA), etc. – as an unobtrusive method for detecting the type of task being performed and level of effort expended by the subject. We conducted testing with 13 participants over periods of 8-10 days. The participants completed the same daily protocol with two different kinds of

rest activities and two different task types. The initial rest phase consisted of viewing meditative videos while slowly riding a stationary bike, with the next two phases viewing the videos only; the tasks consisted of a computer-based math test coupled with either slow biking or fast biking. Assessments of performance were measured during each task, and survey measures were collected between tasks. These observational and subjective measures are analyzed to identify and characterize trends shown in the psychophysiological signals. Results show that heart rate variability (HRV) decreases and mean EDA levels increase with increasing cognitive load, which coincides with other published findings. Additionally, individual participant analyses revealed that strong cognitive exertion prior to the experimental protocol resulted in no change in physiological signals throughout the testing, suggesting that this may be an indication of cognitive over-exertion. Such an indicator could be used for corrective action during real-time operations and provide an important capability in the development of collaborative human-robot teams.

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[154] ***New-generation spacecraft water monitoring with flight-ready solid state nanopore***

Zehui Xia (Goeppert LLC) and Brian DiPaolo (Goeppert LLC).

To provide a fast, simple and reliable way of identifying inorganics and organics present in the water systems aboard the international space station (ISS) and potentially other spacecraft (e.g., NASA's Artemis Gateway Outpost), we aim to develop a robust, portable and easy-to-use sensor system based on solid-state nanopore technology. The current water monitoring capability in the ISS is only limited to electrical conductivity, total organic carbon and selected ions of iodine and silver. Any other analyte must be brought back to Earth. The maintenance of safe living conditions in ISS is important in order to support the scientific activities of the crew, and to ensure their unharmed return to Earth upon mission completion. The solid-state nanopore system presents an inherently single-molecule sensor system that works on the principle of pore occlusion by the molecule which then can be registered as a change of the electrical current. Each analyte establishes its unique electrical signal upon passing through the nanopore of tailored characteristics. We use a low-noise and low-capacitance glass chip with an ultrathin (20 nm-thick) silicon nitride (SiN) membrane material which has flight heritage, together with a compact (centimeter-scale) nanopore reader to sense and identify analytes of interest to NASA. Enabled by special short DNA molecules ("aptamers") as probes, we demonstrate the detection of mercury and lead using 2-5 nm- diameter nanopores at concentrations down to 0.5 nM and 5 nM, respectively, which are below EPA and SWEGs levels. We observed distinct electrical translocation characteristics between these two metal ions, paving a path towards selective nanopore sensors by identifying their "electrical fingerprints". Our single-molecule nanopore instrument allows the detection of low-concentration analytes in water and is thus a promising tool for a miniaturized analytical laboratory for future NASA missions, together with other analytical tools available.

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[155] ***Water-resistant CO2-selective Absorbents***

Fuyuhiko Inagaki (Kobe Gakuin University), Ryo Murakami (Kobe Gakuin University), Hikari Kawamitsu (Kobe Gakuin University) and Hiroto Tanishima (Kobe Gakuin University).

CO2 Absorbents/Releasing Agents are effective technologies for reducing CO2 gas in various environments such as global environments and manned space station. Generally, amine absorbents are known to absorb water vapor simultaneously with absorption of CO2. Herein we found that alkylamine with the hydrophobic phenyl group such as meta-xylylenediamines (MXDA) absorbed CO2 selectively in air without any hydration. The MXDA-CO2 complex could release dry CO2 at 103–120 ºC easily, and dry high purity CO2 could be applied to the chemical reactions. In addition, removing co-absorption of water has reduced energy consumption of absorbent regeneration applications.

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[156] ***Roadmap of a Lunar Base Using the Lunar Lava Tubes and Their Vertical Skylights***

Masato Sakurai (JAXA), Asuka Shima (JAXA), Isao Kawano (JAXA), Yasufumi Wakabayashi (JAXA), Junichi Haruyama (JAXA), Takuya Goto (Doshisya University), Mitsuhiko Ohta (Nippon Steel), Ken Shoji (Taisei Advanced Center of Technology) and Hiroyuki Miyajima (International University of Health and Welfare).

With the participation of experts for the purpose of formulating a more concrete technology roadmap for the construction of a manned Lunar base in Lava Tubes and Their Vertical Skylights, which is essential for supporting long-term stays on the moon, resource utilization, and industrial activities, investigated. This paper, we proceeded with Robots, Architecture, Energy and in-situ resource utilization (ISRU) as an item to be examined. These are important not only for supporting human survival on the moon from the early stages of base construction, but also because they are deeply involved in transportation and energy problems.

[159] *Integrating Mushrooms into an Agent-based Model of a Physico-chemical and Bioregenerative ECLSS*

Sean Gellenbeck (University of Arizona), Joel Cuello (University of Arizona), Kai Staats (Over the Sun, LLC), Ezio Melotti (Over the Sun, LLC) and Grant Hawkins (Over the Sun, LLC).

The Scalable, Interactive Model of an Off-World Community (SIMOC) is an agent-based model, a simulation through which semi-autonomous agents interact and whose behavior, when allowed to unfold over a specified time, may exhibit non-linear, dynamic, and probabilistic behavior. Data were derived from plant physiology studies [Wheeler, NASA 2008], the Baseline Values and Assumptions Document [NASA BVAD 2018], and ECLSS modeling validated by Paragon Space Development Corporation. SIMOC approximates photosynthetic activated radiation (PAR), H2O, O2, and CO2 parameters with non-linear plant growth functions derived from a barley fodder experiment conducted at the University of Arizona's Biosphere 2 [Staats, ICES 2019]. To design a stable and integrated bioregenerative life support system for long-duration, off-world missions, several biological subsystems will need to be included in the initial trade study and modeling effort. One such proposed subsystem is mushrooms. The inclusion of mushrooms in the physical system provides the capability to begin the breakdown of the inedible biomass produced by plant-centric subsystems and provides a protein-rich food source for the crew. There are multiple advantages to mushrooms over other decomposers such as mealworms and insects, not the least of which is palatability across a broad set of cultures. Including mushrooms as the first step in the decomposition process opens the possibility to other uses for the inedible biomass like construction materials. To further advance the utility of this model and to give foundation to the design of an integrated bioregenerative life support system, a mushroom agent was added into the SIMOC simulation engine for use in habitat simulations. The data used to program the mushroom agent were derived from several terrestrial studies [Citations] and multiple simulations including several different combinations of biological subsystems were run. Validation of the modeled data and systems is in progress and will be discussed in this publication.

[160] *Demonstration of the International Space Station Particle Database Website*

Nathalie Tuya (Columbia University), Wenyan Li (NASA Kennedy Space Center), Luz Calle (NASA Kennedy Space Center), Marit Meyer (NASA Glenn Research Center), Meytar Sorek-Hamer (NASA Ames Research Center) and Irina Hallinan (Universities Space Research Association).

NASA has continuously emphasized the importance of allowing the public to interact and engage with its missions and initiatives by using open-source data. As a result of the large dataset gathered during the International Space Station (ISS) aerosol sampling missions, the ISS Aerosol Sampling Experiment Web Application was developed. This application allows users to easily plot and visualize data from the 2016 and 2018 aerosol experiments. This tool is an open-source and public-facing website, allowing anyone to easily plot the ISS aerosol data in order to develop their own research and conclusions. This platform allows for plotting and visualization of particle composition, geometry, morphology, sampling durations, and collection locations. The tool features an elemental composition pie chart, a plot tool, and an interactive plot tool. The work presented on this paper involves a demonstration of how this Web Application was used to show the morphology of aluminum-chlorine-zirconium particles as well as the presence of lead particles on Node 3 and Node 2 of the ISS.

[161] *Evaluation of temperature estimation accuracy using Physics-Informed Neural Network for small satellite model*

Hiroto Tanaka (Tohoku University), Koji Fujita (Tohoku University) and Hiroki Nagai (Tohoku University).

Thermal analysis of spacecraft is one of the most critical processes for the flight model, and the number of missions that need severe thermal requirements is increasing these days. However, the thermal mathematical model has many uncertain parameters, such as thermal contact conductance; hence, it is impossible to predict the true value of temperature distribution. On the other hand, the number of temperature sensors on the small satellites is limited, and it is difficult to predict the temperature distribution accurately. In this study, we propose a method to estimate the temperature distribution of the entire spacecraft system based on a small amount of temperature data. To realize the temperature estimation, we use the Physics-Informed Neural Network, which is a neural network that uses the physical conservation law and the observation error as evaluation functions. Specifically, the actual value of the temperature distribution is estimated using the conservation law of the thermal mathematical model, the difference between the operational temperature data and the estimated value, and the boundary conditions as the evaluation function of the neural network. As a result, the temperature distribution of the system can be reproduced from a small amount of temperature data. In this presentation, the temperature estimation accuracy of the proposed method will be shown by numerical experiments using a thermal mathematical model of a pseudo small satellite.

[164] *Thermal Design Approach for Efficient Development of CubeSats with a Common Bus System*

Toshihiro Shibukawa (The University of Tokyo), Shingo Nishimoto (The University of Tokyo), Shuhei Matsushita (The University of Tokyo), Shinichi Yokobori (The University of Tokyo), Kazuki Takashima (The University of Tokyo), Akihiro Ishikawa (The University of Tokyo), Ryu Funase (The University of Tokyo) and Shinichi Nakasuka (The University of Tokyo).

Recently, CubeSats have been widely used, from educational purposes to actual missions in both near-Earth and deep space environments. For example, the University of Tokyo and JAXA are co-developing a 6U deep space CubeSat probe named EQUULEUS targeting the cis-lunar region. For CubeSats with sophisticated missions such as EQUULEUS, both bus components and mission payloads have high power consumption despite their small mass, and therefore efficient power dissipation is demanded for mission success. Also, to demonstrate short development periods, which is one of the advantages of CubeSats, modularization of components and standardization of the bus system are matters that should be tackled. The University of Tokyo is now developing several CubeSats with different missions but having a common bus system. One of them is an Earth remote sensing CubeSat in collaboration with NSPO, called ONGLAISAT. Thermal design must be suitable for each of the CubeSats that have different payloads. To realize flexible optical property design with a uniform satellite panel design, we utilize thermal control tapes instead of Multi-Layer Insulations (MLIs) to implement the designed optical property values. Also, for efficient heat dissipation of power consuming components, structural interfaces are designed so that component surfaces and satellite panels have large direct contact surfaces to use gap fillers. For evaluation of thermal design, we have developed a common thermal mathematical model for the several different satellites in development. By this approach, thermal vacuum test data and on-orbit telemetry from different satellites can be used to evaluate and correlate the same model, leading to higher reliability of the model. By reusing this model to satellites developed in the future, we can realize fast model creation. In addition, we plan to introduce advanced uncertainty quantification and model correlation methods to speed up the thermal design and validation process in the near future.

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[165] *Holistic Resource Management for Sustainable Life Support beyond Low-Earth Orbit: Focus on Nitrogen*

Dries Demey (QinetiQ Space nv) and Marie Vandermies (QinetiQ Space nv).

A half century of manned space exploration engendered performant technology to support human life onboard the International Space Station (ISS). A protective and conditioned habitat with provision of water and oxygen are the crucial elements of the Environmental Control and Life Support System. Currently, onboard the ISS, resupply of water and food complement the resources obtained from partial recycling of metabolic waste products including urine, condensate and carbon dioxide. Clean water is produced from the liquid waste by a series of physicochemical processes. Carbon dioxide from the cabin air is concentrated on adsorbers and converted into water and methane by catalytic reduction using hydrogen. Oxygen is produced by the electrolysis of water. Long-term human space exploration on planetary surfaces like the Moon and Mars requires an even higher recycling rate of the other essential elements including carbon, nitrogen, phosphorus and minerals to produce food and other consumables. A combination of in situ-resource utilization (ISRU) and integral recycling of all waste products will determine the configuration of next-generation Life Support technology. Interactions between physical, chemical and (micro)biological processes require a holistic engineering approach to develop sustainable Life Support Systems (LSSs). Multiple disciplines among process and chemical engineering, bio-engineering, geo-engineering besides space engineering, having traditionally a dominant focus on mechanical or electrical aspects, will unite. Recycling technology will no longer be approached as an assembly of “sub-systems” but as interaction of “processes”. Waste recycling and ISRU rely on common fundamental processes including transformation by oxidation-reduction, separation and concentration. Whether the processes are physically, chemically or (micro)biologically driven, the thermodynamic laws and conservation of mass apply. Candidate technology will be evaluated by a design methodology evaluating yields and efficiencies normalized against required energy and system weight and volume. Reliability, safety and operational aspects complement the trade-off matrix for configuring (bio)regenerative LSSs.

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[167] *ECLSS Air Revitalization Technology Review 2022: Review of Current Published Units and their Fault Modes*

Daniela Ivey (Master's Student, Mechanical and Aerospace Engineering Department, University of California), Monica Torralba (Master's Student, Mechanical and Aerospace Engineering Department, University of California) and Stephen Robinson (Professor and Director – Center for Spaceflight Research, University of California Davis).

NASA, the commercial industry, and international partners are expanding humanity's reach into space, with milestones set for the Lunar Gateway, Artemis, and eventual crewed Mars missions. A key element of any long-term human spaceflight mission is the Environmental Control and Life Support System (ECLSS), composed of multiple subsystems, including an Air Revitalization subsystem that maintains a breathable atmosphere. To match programmatic milestones for deep-space exploration, there is a global push toward developing a next-generation ECLSS. As a result, there are many recent breakthroughs in the research and development of individual ECLSS units. This paper reviews both heritage and recent technologies in Air Revitalization, including US, Japanese, and European technologies for carbon dioxide (CO2) capture and oxygen (O2) generation in spacecraft habitats. Published fault modes are mentioned to facilitate discussions on the repairability and maintainability of potential future life support systems.

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[168] *ANITA2 – the advanced multicomponent air analyser for ISS – Pre-flight calibration and testing of gas measurement performance*

Atle Honne (SINTEF), Kristin Kaspersen (SINTEF), Kari Bakke (SINTEF), Anders Erik Liverud (SINTEF), Jens Thielemann (SINTEF), Brian Elvesæter (SINTEF), Michael Gisi (OHB System AG), Lukas Pfeiffer (OHB), Armin Stettner (OHB System AG), Roland Seurig (OHB System AG), Johannes Witt (ESA), Pierre Rebeyre (ESA), Scott Hovland (ESA) and Timo Stuffler (OHB).

The ANITA2 (Analysing Interferometer for Ambient Air) instrument is a trace gas analyser designed to operate onboard the ISS to monitor the cabin atmosphere. ANITA2 can detect more than 30 of the most important trace gases in parallel. The advantages of an ANITA-type instrument include high sensitivity, accuracy, precision, and time resolution of the measurement data, as well as no consumption except electrical power and no production of waste. This also makes ANITA a steppingstone into the future, as a precursor system for crewed stations, bases, and exploration missions, including the Lunar Gateway and to/on the Moon and Mars.

After a successful operation of ANITA1 for 11 months on-board the ISS in 2007 and 2008, the ANITA2 instrument was built in a contract between ESA, OHB and SINTEF and launched to the ISS in December 2021. ANITA2 operation started in March 2022 – after the deadline for this paper.

This paper covers the pre-flight gas analysis. It gives a brief overview of the method of calibration, and of the final gas scenarios for the calibration and the associated gas estimation models. The calibration for 37 gases is described, and the test results from the final testing on 30 multi-gas mixtures are presented. The key results are the detection limits for the 35 trace gases in the calibration.

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[169] *Development of a Low-cost Pyrolytic Graphite Sheet Thermal Strap for SpIRIT Nanosatellite*

Oliver Vogel-Reed (University of Melbourne), Simon Barraclough (University of Melbourne) and Robert Mearns (University of Melbourne).

The Melbourne Space Lab at the University of Melbourne is developing the SpIRIT nanosatellite with a consortium of Australian industry organisations. The nanosatellite contains thermal technologies to actively cool the HERMES payload supplied by the Italian Space Agency. As part of this effort, a number of Pyrolytic Graphite Sheet (PGS) thermal straps have been developed for the transport of waste heat to the spacecraft deployable radiators. PGS is a novel aerospace material for thermal applications and has been utilised to construct high performance thermal straps. While there is great potential of this material for thermal management strategies, it has required specialised and costly manufacturing processes. Here the potential for PGS straps using simplified manufacturing processes and using off-the-shelf PGS material is explored. A material study is performed with multi-layer PGS straps, using the PGS itself as an integral interface material. While the bulk thermal conductivity of the multi-layer PGS straps was found to reduce by half when layered 15 times, it still provides a ten times increase in thermal conductivity per unit mass over traditional copper straps. This paper presents the findings of the thermal performance characterisation testing of different configurations of PSG thermal straps. A flexible PGS thermal strap specifically designed for the SpIRIT nanosatellite is proposed, weighing only 10.98g with a thermal conduction of 0.2W/K, a weight saving of 90% over a traditional copper thermal strap, while retaining similar conductivity.

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[170] *A Cost Analysis of the use of In Situ Space Resources for Sustainable Habitation on the Moon and Mars*

Hiroyuki Miyajima (International University of Health and Welfare).

Commercial space launch companies have been drastically reducing their launch costs in recent years. This may change space logistics for future lunar and Mars missions. Staging points in the lunar orbit can be used to refuel propellants

produced from lunar in-situ resource utilization (ISRU). To further reduce mission costs, identifying where to optimally obtain propellant and to refuel spacecrafts is required. In this study, it was assumed that plenty of existing ice water can be found on Mars' surface and at the lunar south pole. Several cost analysis studies have been conducted on small-scale manned missions (4 to 6 crew members) utilizing lunar and/or Mars resources. Although most of the studies showed an economic advantage of using Mars resources, there are both positive and negative views on the economic advantages of using lunar resources. The author of this paper conducted a cost analysis on large-scale manned missions consisting of 100 people visiting the Moon and Mars every two years for 50 years to determine a range of viable parameters. The results show that as the number of flights and travelers increase, the cost per person for both Moon and Mars trips decreases; however, the decrease is small because the ISRU fixed cost and the transportation cost of moving propellants to the depo in a lunar orbit have a large impact on total costs.

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[171] *JAXA CO2 removal system ISS demonstration (DRCS) development status*

Kentaro Hirai (Japan Aerospace Exploration Agency (JAXA)), Yoko Sakai (Japan Aerospace Exploration Agency (JAXA)), Chiaki Yamazaki (Japan Aerospace Exploration Agency (JAXA)), Shotaro Futamura (Japan Aerospace Exploration Agency (JAXA)), Hironori Yada (Japan Aerospace Exploration Agency (JAXA)), Satoshi Matsumoto (Japan Aerospace Exploration Agency (JAXA)) and Hideki Saruwatari (Japan Aerospace Exploration Agency (JAXA)).

The Japan Aerospace Exploration Agency (JAXA) has been developing a highly reliable air revitalization system with less resupply for future manned space missions. This paper describes current and planned development status focusing on CO2 removal system for ISS demonstration.

JAXA considers to have ISS demonstration of CO2 removal system for 1-crew scale.

Ground tests and evaluation of new CO2 adsorbent canister, the lifetime and off-gas characteristics of the developed amine-based adsorbents, design overview of flight model are reported.

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[172] *Development of Portable Gas Chromatograph Using Ball Surface Acoustic Wave Sensor for Measurement of Crewed Space Environment*

Takamitsu Iwaya (Ball Wave Inc.), Shingo Akao (Ball Wave Inc.), Kazushi Yamanaka (Ball Wave Inc.), Tatsuhiro Okano (Ball Wave Inc.), Nobuo Takeda (Ball Wave Inc.), Yusuke Tsukahara (Ball Wave Inc.), Toru Oizumi (Ball Wave Inc.), Hideyuki Fukushi (Ball Wave Inc.), Maki Sugawara (Ball Wave Inc.), Toshihiro Tsuji (Ball Wave Inc.), Tomoki Tanaka (Ball Wave Inc.), Akinobu Takeda (Ball Wave Inc.), Asuka Shima (JAXA), Satoshi Matsumoto (JAXA), Haruna Sugahara (JAXA), Takeshi Hoshino (JAXA) and Tetsuya Sakashita (JAXA).

A gas chromatograph (GC) is effective as one of the methods for monitoring the atmosphere in a crewed space environment. However, the GC is generally large and difficult to carry. We have developed portable GC systems with a ball surface acoustic wave (SAW) sensor; ball SAW GC. The key features of the ball SAW GC are multiple roundtrips of SAW on a spherical element and a metal micro-electro-mechanical-systems (MEMS) column formed by etching and diffusion bonding of stainless-steel plates. In addition, using the feature of ball SAW sensor that can detect gases non-destructively, we have developed a forward flush method realizing fast analysis of multiple gases by combining two columns and two sensors. In this study, we developed a prototype ball SAW GC applied the forward flush method with the volume of 1 L and which has the same functions as a desktop GC such as a sampler, a preconcentrator, and a column heater. Using this GC, we succeeded in analyzing multiple hazardous gases assumed in the crewed space environment.

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[174] *Recent development status of Oxygen Generation System for future exploration missions*

Shotaro Futamura (Japan Aerospace Exploration Agency), Chiaki Yamazaki (Japan Aerospace Exploration Agency), Satoshi Matsumoto (Japan Aerospace Exploration Agency), Asuka Shima (Japan Aerospace Exploration Agency), Masato Sakurai (Japan Aerospace Exploration Agency) and Hideki Saruwatari (Japan Aerospace Exploration Agency).

Japan Aerospace Exploration Agency (JAXA) has been developing a highly reliable air revitalization system with a smaller supply for future manned space missions. In this paper, we report the results of long-term continuous operation of the Oxygen Generation System using a sub-scale water electrolysis cell with Nafion membranes or membranes being developed by JAXA. In this study, continuous operation up to 2000 hours was achieved and the characteristics of the two types of membranes were determined. In addition, data contributing to the lifetime of the water electrolysis cell, ion exchange resin, gas-liquid separator, and the hydrogen sensors in the oxygen line were obtained. This paper also presents the lessons learned for the entire system through long-term operation.

[176] *Dealing Order Determination for Various Simultaneous Device Failures for Material Circulation Control in ALSS by Hierarchical Approach.*

Masakatsu Nakane (Nihon University) and Hiroyuki Miyajima (International University of Health and Welfare).

An Advanced Life Support System (ALSS) achieves life support in the ultimate environment by regenerating materials in the system. Because of their complexity of material circulations in ALSS, it is difficult to control whole-system material circulations and to handle on abnormal situations. Because of this, we had proposed hierarchical and autonomous control method based on automatic scheduling and Multi-Agent Learning Control method, and had constructed automatic order determination system to deal with failure machines. We discovered the how much failure equipment can be handled by our procedure last year, but this was only Oxygen circulation system in the lower layer. In this year, we calculated material circulation with various failure situations using the O2 and CO2 gas circulation model in the lower layer to check how much broken equipment our mechanism could deal with it.

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[181] *Human outpost creation using multiple data sets and computational design*

Thomas Lagarde (Space Architecture Technical Committee) and Matko Brandic Lipinski (University of Zagreb/Sveuciliste u Zagrebu).

Designing human outposts in extreme environments is a particularly challenging process due to the multiplicity of factors involved. Resources utilization, protection from radiations, micrometeoroids impacts, atmosphere containment are just some of the co-dependencies that Space architects and mission designers have to consider in the preliminary design phase. To facilitate the process, we considered a new design path that has found application in both engineering and architectural design tools: the computational design approach. Thinking at the different factors and constraints as project parameters, we are designing a software tool based on co-dependent variables to enable scalability while significantly decreasing the process complexity. The parametric software tool or PST considers a large range of factors (weather, terrain conformation, in situ resources accessibility) and constraints (survivability requirements, safety requirements, and infrastructural requirements) to allow a data-based design process, reducing the chance for human errors and inconsistent design assumptions. This paper describes the tool functionalities and the rationale behind the constraint and factor definition. While the tool is still considered in an early-development stage now in which this research is presented, the paper outlines guidelines for future developments and plans for future work on the code. At the same time, new data sets about extreme environments coming from current and future missions are considered of primary importance for the development of reliable data models about the environmental constraint used by the tool.

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[182] *Development of a miniature heat exchanger for mechanically pumped loop systems for active thermal control of CubeSats*

Thomas Ganzeboom (Royal Netherlands Aerospace Centre (NLR)), Johannes van Es (NLR) and Ludovica Formisani (Delft University of Technology).

The relatively high power density of CubeSats results in large amounts of heat generated that needs to be dissipated to prevent overheating of a satellite's components. At present, passive thermal control means are used to resolve CubeSats thermal issues, however, as these satellites evolve, advanced active Thermal Control Systems (TCS) will be required. Especially the novel CubeSat propulsion systems require dedicated TCS for the propulsion unit and the corresponding electronics. A promising type of TCS for CubeSats was determined to be the Mini-Mechanically Pumped fluid Loop (Mini-MPL). One such system has been developed at the Royal Netherlands Aerospace Centre (NLR), which consists of a single phase fluid loop that is used for component cooling. One of the important components of this system is the I/F with the Payload. For this purpose a Miniature Payload Heat Exchanger (MPHX) is developed as commercially available heat exchangers are typically impractical for use in space environments. A custom design for the MPHX is presented in this paper. During the design phase, a tool which is able to evaluate the cooling performance of different MPHX models has been built. Using this tool, the three best designs in terms of cooling performance have been identified: the offset strip fin heat exchanger, and two straight channels configurations with respectively triangular and trapezoidal cross sections. The design thermal resistance of the MPHX is in the order of 0.45 K/W with a liquid pressure drop in the order of 1 mbar.

The heat exchangers are produced through additive manufacturing (using the Direct Metal Laser Melting method) which allows for greater flexibility and customization of the designs. The models are tested in a pumped fluid loop at the NLR's Thermal Management Facilities to confirm the results predicted in the design phase as well as feasibility of the DMLM fabrication method.

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[186] *Plasma Assisted Acid Leaching of Inedible Biomass for Nutrient Recovery*

Kenneth Engeling (NASA), Ryan Gott (Oak Ridge Associated Unniversities), Griffin Lunn (Amentum), Carolina Franco (Amentum), Misle Tessema (NASA) and Bruce Link (Southeastern Universities Research Associaton).

Sustaining a human presence on the moon, Mars or deep space will require closing loops on many life support systems. Some form of agriculture will be required because plants produce the vitamins, antioxidants, and essential oils in our diets that degrade over time in stored foods. In addition, they provide dietary fiber, restore air, and purify water. It is estimated that 93 Kg of plant nutrients are required to support one crew member per year. Growing plants will require recycling nutrients trapped in inedible vegetation. Researchers at Kennedy Space Center have investigated the use of a thermal plasma with various carrier gases to thermally degrade inedible plant biomass for nutrient recovery. Previous work demonstrated a thermally degrading environment such as a muffle furnace improved nutrient recovery from inedible biomass prior to an acid leaching process. However, a muffle furnace is an inefficient process. We have explored the use of a small scale, thermal plasma for degradation of pellets to enhance the breakdown of plant stems, leaves and debris to further close the nutrient loop. Plasma carrier gases such as carbon dioxide, nitrogen, and air were used to explore variations in recovery and potential chemical by-products. Plasma processed inedible biomass was added to varying concentrations of acid solution for leaching of nutrients (e.g. potassium, magnesium, calcium, and phosphorus) for reuse in the crop production cycle. We also examine total nitrogen recovery. Results are presented showing the impact of plasma processing prior to acid leaching on recovery of plant nutrients.

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[187] *Thermal Vacuum Testing of Advanced Thermal Control Devices for Flight Demonstration*

Satoshi Kajiyama (Nagoya Univ.), Takuji Mizutani (Nagoya Univ.), Takuya Ishizaki (Nagoya Univ.), Kota Tomioka (Nagoya Univ.), Hiroto Tanaka (Tohoku Univ.), Hiroki Nagai (Tohoku Univ.), Kan Matsumoto (WEL RESEARCH), Kenichiro Sawada (JAXA), Yoshihiro Machida (SHINKO ELECTRIC), Kazuaki Matsumoto (KANEKA) and Hosei Nagano (Nagoya Univ.).

In Japan, several unique thermal control technologies have been developed. However, there are no opportunity to demonstrate in orbit. Therefore, we have proposed to apply our thermal control devices named advanced thermal control devices (ATCD) to the Innovative Satellite Technology Demonstration Program conducted by JAXA, and accepted to apply to the Rapid Innovative payload demonstration SatellitE-2. In this paper, the test results of the thermal vacuum testing of ATCD are presented. ATCD consists of two types of flexible thermal straps: one is made of high-thermal-conductive material, and the other is made of a fluid-loop, and a re-deployable radiator. The conductive-type thermal-strap (CTS) is made of high-thermal-conductive graphite-sheets and aluminum blocks. The fluid-type thermal-strap (FTS) is made of a ultrathin loop-heat-pipe. The re-deployable radiator named reversible-thermal-panel (RTP) is made of high-thermal-conductive graphite-sheets as a flexible fin, and a shape-memory-alloy as a passive re-deployable actuator. As a result, it was confirmed that the thermal conductance between the two ends of CTS was 0.50-0.55 W/K. As for FTS, it was confirmed that it could operate even after recovering from the freezing condition of the working fluid, and that there was no leakage of the working fluid and no performance degradation under vacuum environment. As the heat load increased, the thermal conductance between the evaporator and condenser increased, and finally a thermal conductance value of 4.1 W/K (at 5 W heat load) was confirmed. For RTP, it was confirmed that the radiator fins were fully expanded to 130° when the SMA actuator reached 30 °C during heating. On the other hand, during cooling, the temperature of the SMA actuator dropped only to -15℃, and the fins retracted only to 40°. Furthermore, the temperature hysteresis of the SMA actuator was estimated to be about 40℃ based on the experimental results.

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[188] *DIANA - Dedicated Infrastructure and Architecture for Near-Earth Astronautics*

Denis Acker (University of Stuttgart), Elizabeth Gutierrez (University of Stuttgart), Adrian Pippert (University of Stuttgart), Nadine Barth (University of Stuttgart), Julienne Böttger (University of Stuttgart), Madison Diamond (University of North Dakota), Alma Kugic (Vienna University of Technology), Javier Palacios Calatayud (University of Cadiz), Prishit Modi (University of Stuttgart), Vincent Krein (University of Stuttgart), Sajeel Ahmad Khan (University of Stuttgart), Hubert Gross (Rzeszow University of Technology), Tim Lukas Kirsch (Technical University of Berlin), Olaf Drozdowski (Gdansk University of Technology), Filip Szyga (Warsaw University of Technology), Dominik Gentner (University of Stuttgart), Stefania-Denisa Bocu (University POLITECHNICA of Bucharest) and Elena Lopez-Contreras Gonzales (Massachussetts Eye and Ear, Harvard Medical School).

The Dedicated Infrastructure and Architecture for Near-Earth Astronautics (DIANA) is an autonomously deployable lunar base concept for a long-duration crewed mission on the Moon's surface. It will be robotically constructed in proximity to the De Gerlache crater ridge on the lunar South pole. The base, which accommodates four astronauts with a planned 2030 arrival, enables scientific operations and local sorties for human and robotic exploration. Furthermore, its self-sustainability will increase over its lifespan. The base will be transported in a compacted form and expanded to a habitable volume by autonomous deployment after reaching the lunar surface. The multilevel base encompasses all possible habitation needs including, but not limited to, dedicated private and communal spaces, technical support

systems and a greenhouse. To establish and operate the base, the following subsystem concepts are crucial. The electrical power system consists of solar panels and a regenerative proton exchange membrane fuel cell using water electrolysis for power storage. Thermal insulation and adequate temperatures are provided through a closed water loop system, radiators and the use of regolith, the latter further providing radiation shielding. The environmental control and life support system initially relies on a high technological readiness level physico-chemical approach. Over time, it will progress towards a biologically closed loop system through the implementation of a greenhouse for food production and in-situ resource utilisation (ISRU) for water and oxygen harvesting. ISRU is essential in supplying astronauts not only with life support, but also with a large variety of construction material leading to increasing self-sustainability and long-term cost effectiveness. The communication system uses a Low Lunar Orbit communication relay satellite constellation and the Lunar Gateway. DIANA also offers a phased antenna array for radio interferometry on the far side of the Moon to perform observations of the universe.

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[191] ***High Performance Mechanical Counter Pressure Spacesuit Glove for Martian Surface Exploration***

Gabriella Schauss (University of Colorado Boulder), Rachel Bellisle (Massachusetts Institute of Technology), Akshay Kothakonda (Massachusetts Institute of Technology), Dava Newman (Massachusetts Institute of Technology) and Allison Anderson (University of Colorado Boulder).

Future human exploration of Mars will rely on planetary surface extravehicular activity (EVA) for a majority of scientific tasks that enable the search for life. Mechanical counter pressure (MCP) offers solutions to current limitations of a traditional gas pressure suit including increasing mobility, decreasing metabolic work, increasing safety, while allowing for custom spacesuit fit to decrease injuries. In this paper, we design and develop a MCP glove using 3D knitting fabrication techniques to assess the feasibility of relying on MCP to apply uniform pressure on the hand. A glove is used as a proof of concept since hand anthropometry includes more degrees-of-freedom of movement than the entire rest of the body, and limited glove mobility was the most significant EVA challenge for lunar astronauts. From strain models and patterning methods, novel textile structure can be designed to allow for consistent pressure across the entire hand during both dynamic and static states. Seamless knitting allows for a customizable fit, complex patterning, and rapid prototyping that is imperative to continued advancement of the state of the art to enable the advantages of MCP to come to fruition. This work aims to develop and validate a MCP glove that applies 2 psi of uniform pressure on the hand using novel textile fabrication techniques to advance the development of a life support system and continuing to understand the boundaries of future spacesuit architecture for surface exploration.

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[192] ***Fire Characterization and Gas Analysis of Lithium-Ion Batteries During Thermal Runaway***

Byoungchul Kwon (Case Western Reserve University), Wohan Cui (Case Western Reserve University), Pushkal Kannan (Case Western Reserve University), Cole Compton (Case Western Reserve University), Ya-Ting Liao (Case Western Reserve University), Fumiaki Takahashi (Case Western Reserve University), Judy Jeevarajan (Underwriters Laboratories Inc.), Daniel Juarez-Robles (Underwriters Laboratories Inc.) and Mohammad Parhizi (Underwriters Laboratories Inc).

The objective of this work is to investigate the unique chemistry of fires associated with lithium-ion battery (LIB) thermal-runaway and its scalability. Experiments are conducted to collect data on the gas compositions and fire characteristics during and post-thermal runaway of LIB cells. Two different types of cell formats, 18650 cylindrical cell and pouch cell are considered. Prior to the experiments, cells are conditioned to different states-of-charge (SOC). The cells are then placed in an environmental chamber of volume ~ 600L and are forced into thermal runaway by an electrical heating tape at a heating rate of 10 ⍰C/minute. The chamber is connected to a FTIR gas analyzer for real-time concentration measurements and camcorders are used to record the cell venting and burning events. Thermocouples are placed on and near the cell samples to monitor the temperatures of the cell surface and the surrounding gas. In addition, the weight and voltage of the cell are also recorded. The experiments are conducted first at a single cell level and then at a module level. Results of different SOCs are compared. The fire scaling characteristics and flame spread between cells in the module configuration are also examined in detail. Data collected in this work will ultimately be used to develop a robust numerical model for the LIB fires.

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[194] ***Digitalization of Space Thermal Engineering***

Alexandre Darrau (ESA), James Etchells (ESA) and Matthew Vaughan (ESA).

Digitalization has been a hot topic across all industrial sectors for a number for years now. Within ESA there have been a number of R&D activities initiated on the topic together with industrial partners. The purpose of this paper is to present the digitalization topic to a wider audience, and with a specific focus on the thermal engineering and its related

interfaces. Generally digitalization refers to improving engineering activities by using digital technologies; for example to make processes more efficient, or to enable richer data sources to be exploited. Therefore a necessary precursor for digitalization is the “digitization” of engineering data into machine interpretable assets (e.g. transforming from a document centric to a model centric approach). This paper will present an analysis of the space thermal engineering process, identifying the input and output data of the different thermal engineering tasks. The way to capture and describe this data using formal ontologies as well as open standards will also be discussed. Some concrete examples of digitalization, including R&D activities ongoing at ESA, will be presented, specifically related to core thermal engineering tasks such as thermal testing and operations. The context for space thermal engineering software tools will also be discussed, for example, the needs for interfaces to author and consume metadata, such as design information, and test/flight data.

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[195] *Investigating Waste Preparation Methods for Trash-to-Gas Technologies*

Malay Shah (NASA Kennedy Space Center), Ray Pitts (NASA Kennedy Space Center), Morgan Benson (NASA Kennedy Space Center) and Jonathan Gleeson (The Bionetics Corporation).

Trash-to-gas technologies show promise in addressing the need for a sustainable waste management system onboard long-duration space habitats. However, a clear understanding on how the initial preparation and transport of waste into the reaction zone can affect the overall conversion efficiency must be realized. Factors such as the waste size, moisture content, and packing density can have significant impacts on the reactor performance. The goal of this study was to leverage current state-of-the-art preparation and delivery mechanisms to develop a concept for a full-scale, microgravity compatible system that can prepare and deliver waste that enhances the overall solid-to-gas conversion of existing trash-to-gas technologies. An extensive literature review was conducted to select potential candidates for such a system. High-performing candidates were tested in the laboratory environment using a mixed waste stream (organics and inorganics) to determine how these methods affect the total syngas production in a combustion reactor. This work will help lay the framework for implementation in a full-scale trash-to-gas system on exploration class space missions.

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[196] *Regenerative Life Support Systems for Exploration Habitats: Unique Capabilities and Challenges to Enable Long-Duration-Mission Habitats Beyond Low Earth Orbit*

David Howard (NASA), G. Richard Schunk (NASA), Christine Stanley (NASA), Paul Kessler (NASA) and Tiffany Nickens (NASA).

The Artemis I launch of NASA’s Space Launch System and Orion crew vehicle will mark a major milestone in the agency’s efforts to return humans to the Moon. Work is underway on the Human Landing System that will carry the next astronauts to the lunar surface, and the lunar orbiting Gateway that will host science and serve as a platform to support sustained human presence on the Moon and ultimately crewed missions to Mars. Two decades of continuous human presence on the International Space Station has provided a wealth of experience operating, upgrading, and demonstrating advanced Regenerative Environmental Control and Life Support Systems (Regen ECLSS). However, habitats that enable sustained lunar surface presence and transit to mars will encounter many unique conditions and challenges. System characteristics including reliability, maintainability, mass, and power become significantly more critical. Operating environments associated with lower total pressure, low gravity, contingency protocols, and extensive un-crewed and dormant periods impose additional functionality requirements and alter the performance of certain critical systems. Integration and combined operations with other elements such as orbiting outposts, logistics suppliers, and mobility platforms impact capability and interface requirements. Limits on allocated water and oxygen consumable mass influence the need for higher levels of water and oxygen recovery from waste products. Impacts and challenges these unique exploration circumstances impose on the suite of Regen ECLSS systems are explored and discussed herein.

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[197] *Sustainable Life Support enabled by microalgae: focus on biomass harvesting and culture medium recycling*

Marie Vandermies (QinetiQ), Dries Demey (QinetiQ), Estelle Couallier (University of Nantes) and Jordan Tallec (AlgoSolis).

Beyond ISS, actors of the space sector are now preparing for long-term manned space exploration and settlements. Life Support Systems will play an essential role in the success of these missions. With limited resupply possibilities, operation of LSS will rely on the rational (re)use of all available resources, including the valorisation of material flows traditionally seen as ‘waste’. Combining biotechnology with traditional physico-chemical processes will allow to perform high-yield molecular conversions in an energy-efficient way.

In this context, microalgae are regarded as a key component of a closed loop LSS. They provide oxygen and food to the astronauts by photosynthetic conversion of carbon dioxide. Among the challenges inherent to microalgae utilisation, biomass harvesting and culture medium recycling, including nutrient resupply, are the major challenges. In order to ensure biomass edibility and culture yield, it is paramount to maintain permanent axenic conditions to exclude competition from other microbial species, to protect cell integrity, and to prevent the release and accumulation of toxic compounds.

Recently, several studies investigated the development of a solid/liquid separation system allowing to harvest the model organism Limnospira indica and recycle culture medium in a way compliant with space design criteria (e.g., energy, mass, safety). The focus was given to technology selection, prototype design and process automation. Continuous experiments were carried to establish the mass balances and study the evolution of process performance over time. Lessons learnt encompass the essential role of filtration technology and associated membrane selection, technical challenges of automated process management, preferred sterilisation methods, and culture medium resupply with urine-derived nutrients. These will serve as an input for the design of a future flight hardware.

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[198] *Organic Carbon and Nitrogen Removal in a Two-Stage Nitrification- Anammox (MABR-PAX) System Treating High Strength Nitrogen Wastewater*

Behnaz Jalili Jalalieh (Texas Tech University), Maryam Salehi Pourbavarsad (Texas Tech University), Ophelie Messan (Texas Tech University), Andrew William Jackson (Texas Tech university) and Bill Cumbie (Pancopia Inc.).

Water recovery from urine and flush water by using biological processes for potable applications is an alternative approach to reduce payload costs in space. Previous research on Membrane Aerated Biological Reactors (MABR) has demonstrated they can stabilize habitation wastewaters by oxidation of organic C (OC) and N to CO2 and NOX-, respectively. MABRs operated with reduced O2 concentrations are also capable of denitrification (N removal by reduction of NOx- to N2 gas). However, insufficient OC exists in habitation wastewaters to allow complete N removal, which is limited to < 50 %. The Anammox process is a new method that can anaerobically convert NH3 and NO2- to N2 gas. The main goal of this research was to demonstrate a two-stage nitritation-anammox biological system to remove N and organic C from urine + flush water. Urine contributes >90% of all N from habitation wastewaters and conversion of the N to N2 gas could provide a sustainable source of makeup gas for the cabin as well as increase desalination efficiency. Two first stage MABRs (48 L each) oxidized ~50% of the urine N to NO2- and removed > 90% of the organic C. Effluent from each MABR flowed to an anammox reactor (PAX) (50L) in which >89% of NH3 and 99% of NO2- were converted to N2. The MABR and PAX systems were continuously operated for 21 and 15 months. Maximum N removal rates were 6.7 g/crew-d which produced 5 L/crew-day of N2 gas. The combined system was able to stabilize the urine wastewater and produce N2 gas over long periods and could offer a sustainable alternative to wastewater pretreatment and long-term production of N2 gas.

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[199] *Status of the Advanced Oxygen Generation Assembly Design*

Kevin Takada (NASA), Alesha Ridley (NASA), Steven Van Keuren (S&K Global Solutions, Inc.), Phillip Baker (Collins Aerospace), Stephen McDougle (Aegis Aerospace, Inc.) and David Hornyak (NASA).

Future Exploration missions will require an Oxygen Generation Assembly (OGA) to electrolyze water to supply oxygen for crew metabolic consumption. The system design will be based on the International Space Station (ISS) OGA but with added improvements based on lessons learned during ISS operations and technological advances since the original OGA was designed and built. The goal of these improvements will be to reduce system weight, crew maintenance time and spares mass while increasing reliability. Over the past year, the team has performed additional design reviews, testing and analysis in an effort to optimize upgrade efforts and achieve the best value that meets Exploration mission requirements. Upgrades that will be incorporated include: redesign of the electrolysis cell stack, redesign of the hydrogen dome, replacement of the hydrogen sensors, redesign of the recirculation loop deionizing bed, and incorporation of recirculation loop nitrogen purging and water flushing. The ISS OGA will be upgraded to an Advanced OGA (AOGA) configuration and its operation demonstrated in a relevant flight environment.

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[201] *Lessons Learned from the Integration of Biological Systems in Series for Wastewater Treatment on Early Planetary Bases*

Jason Fischer (Amentum), Daniella Saetta (University of South Florida/NASA), Joshua Finn (The Bionetics Corporation), Talon Bullard (University of South Florida), Alexandra Smith (University of South Florida), Lawernce Koss (Amentum), Oscar Monje (Amentum), Daniel Yeh (University of South Florida) and Luke Roberson (NASA).

As humans begin to explore and build sustainable early planetary bases on the Moon and Mars, the crew will need environmental control and life support systems (ECLSS) that are capable of recovering key biogenic elemental resources from waste streams for reuse. Resupply from Earth during these long-duration deep space missions is not feasible; therefore, the requirement for advanced technologies is paramount to the success of these missions. Under NASA's Advanced Exploration Systems (AES) program the development of prototype bioreactors was established to help solve this resource recovery gap. The technology developed within the AES project utilizes 3 bioreactors to sustainably purify astronaut wastewater: An Organic Processor Assembly (OPA)/Anaerobic Membrane BioReactor and a Nutrient Processor Assembly (NPA) consisting of a PhotoMembrane BioReactor (PMBR) and a Suspended Aerobic Membrane BioReactor (SAMBR). In the early stages of the project, these subsystems were running independently for nominal and off-nominal testing and analysis. As the project progressed, the OPA and the PMBR were integrated as part of a bigger bioregenerative wastewater purification system. Integration of these two advanced biological systems required the merging of different electrical and operational control systems. This paper will describe the efforts required to link these systems as well as unforeseen issues that arose after integration. Lessons learned related to the integration of these two subsystems are presented and discussed.

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[202] *Design and operation of Photomembrane Bioreactor (PMBR) to balance nitrogen in high-ammonia wastewater treatment effluents*

Daniella Saetta (University of South Florida/NASA), Jason Fischer (Amentum), Joshua Finn (The Bionetics Corporation), Talon Bullard (University of South Florida), Alexandra Smith (University of South Florida), Lawrence Koss (Amentum), Daniel Yeh (University of South Florida), Oscar Monje (Amentum) and Luke Roberson (NASA).

A flat-plate photomembrane bioreactor (PMBR) has been designed and used as one component of a bioregenerative water system at NASA's Kennedy Space Center (KSC). PMBRs are systems that use a microalgae–bacteria consortium to treat high-nutrient water streams. The main goal of the PMBR at KSC is to balance the nitrogen cycle in the effluent of upstream anaerobic membrane bioreactor (AnMBR). The membrane component of the PMBR allows for biomass accumulation within the reactor to increase nutrient removal rates while producing a filtered permeate for downstream use. The upstream AnMBR releases bound nutrients in wastewater as it digests organic carbon without the presence of oxygen. The effluent is low in carbon and high in total nitrogen, mainly found in the ammonia-nitrogen form. The novelty of this system lies on its ability to nitrify ammonia to nitrate, creating a more suitable nitrogen fertilizer for downstream plant growth systems. This conference paper will present the PMBR design parameters, operation parameters, and lessons learned during its first 100 days. The PMBR has been able to convert a significant percentage of ammonia to nitrate, making it a suitable technology to create a sustainable nutrient source for plant growth systems. As the algal biomass grew via photosynthesis, carbon dioxide at concentrations equivalent to those found on the International Space Station (approximately 3000 ppm) was used to produce the oxygen needed for bacteria to nitrify the ammonia in the AnMBR effluent. Overall, this conference paper will detail how the PMBR technology designed in this project filled the gap between the AnMBR and downstream plant systems for lunar and planetary missions.

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[203] *Development of an Innovative Diaphragm Pump and Two-Phase Mechanically Pumped Loop for Active Antennas*

Charlton Castro (AVS), Christian Ortega (AVS), Kevin Picton (AVS), Monica Iriarte (AVS), Cristina Ortega (AVS), Henk Jan van Gerner (NLR), Ramon van den Berg (NLR) and Johannes van Es (NLR).

The development of Active Phased Array Antennas (APAAs) is a key enabler to effectively accommodate the growing demand of data transfer in commercial telecommunication satellites. A highly efficient and integrated thermal management system is required so as to reject the waste heat produced by the antenna's Solid State Power Amplifiers (SSPAs). The development of such a thermal control system presents a number of technical challenges, chief among them being the large number of heat sources involved (typically ranging from 100 to 1000, with varying duty cycles), the need for spatial and temporal isothermal conditions across the set of SSPAs, as well as a low thermal gradient between the SSPAs and the working fluid, high total heat dissipation (10+ kW), high heat flux (20+ W/cm^2 at the evaporator's interface) and large distances between the radiator and the payload, among others. An international consortium led by AVS is currently developing an ammonia two-phase pumped loop for APAAs within the frame of the IMPACTA project. MPLs (two-phase pumped loops in particular) are remarkably well suited for applications involving large heat loads, transfer of thermal energy over large distances (e.g. distributed payloads), high heat fluxes and payloads with tight temperature stability requirements.

In addition, a novel positive displacement pump for spacecraft thermal control is being developed by AVS. The pump features a diaphragm architecture, piezoelectric actuator and passive check valves. A series of performance characterization tests of the EM have been conducted using a two-phase mechanically pumped loop test system in laboratory conditions.

It is the purpose of the present paper to provide an overview of the IMPACTA project, current status and goals, as well as a description of the PDPump project, outlining the design and main requirements, as well as the development history and current status.

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[204] *Europa Clipper Magboom Deployment Thermal Design and Deployment Sequence*

Elham Maghsoudi (NASA Jet Propulsion Laboratory), Caroline Racho (NASA Jet Propulsion Laboratory), Jonathan Jones (NASA Jet Propulsion Laboratory) and Scotty Allen (Northrop Grumman Goleta).

Europa Clipper, a mission to Europa (the fourth largest moon of Jupiter), is equipped with selected scientific instruments, including Europa Clipper Magnetometer (ECM). The ECM subsystem consists of three fluxgate assemblies, designed and fabricated in collaboration between JPL and UCLA and a deployable Magboom, designed and supplied by Northrop Grumman (NG) Goleta. Each fluxgate assembly will be installed on the lower ring, mid-ring and the tip-plate, respectively. Prior to deployment, Magboom is in stowed configuration with the harness, mast and longerons stacked inside it. Deployment process is passive where kick-over springs will be used to push the harness and structure out of the canister at the time of the deployment. At the time of deployment (15 to 30 days after launch), the temperature of the Magboom harness needs to be raised to above its allowable flight temperature of -5ºC to reduce the Magboom harness stiffness. At this temperature value, Magboom Kickover springs are able to provide enough force (with above 100% margin of safety) to kick the Magboom harness.   There are 5 film heaters on the Magboom canister which will be used once only for deployment. There is a complicated thermal path including mast, a thermal sock and harness insulation, between the heaters and the harness. This paper describes a detailed design of the heaters for Magboom canister pre-heating prior to deployment and deployment sequence. While at the maximum bus voltage of 32.8V, maximum peak power is at 197W only for less than 30 minutes, the average heater power consumption remains at 111W when heaters start cycling. Resizing the heaters provided 56% duty cycle at the maximum voltage of 32.8V and 87% duty cycle at the minimum voltage of 27.8V. As a result, this robust design limits Magboom thermal verification and validation to “by analysis only”.

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[206] *Exploring the Benefits of Evolving ISS ECLSS Hardware to 3-D Printed Hardware for Lunar/Mars Surface Habitats: Trace Contaminant Control Subassembly Case Study*

Gregory Gentry (Self).

As humans return to the moon and venture on to Mars, subsystem hardware needs to be designed to be repairable, replaceable and duplicatable in-situ to the maximum extent possible. To ship all hardware and spares that would be needed for a lunar or Mars surface habitat, based on ISS designs, would debilitate any space program’s mass and volume numbers. Anticipating improvements in 3-D printing, surface habitat ECLSS hardware should be re-designed to utilize this new approach. Ultimately, every part that is possible to 3-D print (metal and plastic) should be made that way from the start and the files and printer capability included in the habitat to maximize the possibility of repairs, replacements or to make additional units as the facility grows. Similarly, a recycling capability for the broken/damaged/used parts (metal and plastic) should exist to avoid waste and minimize raw material resupply. As a case study for this effort, this paper will explore the potential benefits of evolving the ISS Trace Contaminant Control Subassembly to 3-D printed hardware. It will also propose incorporation of ISS lessons learned for sizing, maintenance and repair, and suggest changes to utilize surface gravity to reduce installed and spares hardware mass and volume.

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[207] *Overcoming Technical Challenges to Advance the MOXIE Solid Oxide Electrolysis Stack from TRL 3 to 9, Early Challenges to Successful ISRU Oxygen Production on Mars*

Jessica Elwell (OxEon Energy, LLC), Joseph Hartvigsen (OxEon Energy, LLC), S. Elango Elangovan (OxEon Energy, LLC), Dennis Larsen (OxEon Energy, LLC), Michele Hollist (OxEon Energy, LLC) and Tyler Hafen (OxEon Energy, LLC).

On February 18, 2021 the NASA Perseverance Rover Mission landed on Mars with a set of seven science instruments. One of these instruments, MOXIE, the Mars Oxygen ISRU (In-Situ Resource Utilization) Experiment, opened the era of ISRU on mission Sol 60 (April 20, 2021) with its first successful operation in producing oxygen by solid oxide electrolysis of the Mars atmosphere CO2. The development effort of the solid oxide electrolysis stack inside MOXE progressed from TRL3 to TRL6 in a period of 18 months, completing at TRL9 with the successful flight demonstration. OxEon Energy was at the core of the design, development, and production of the flight hardware in accordance with structural, mechanical, thermal, electrical, operational cycling, feed composition, outlet composition and mass requirements unlike any seen in previous applications of solid oxide fuel cells or electrolysis. This development effort focused heavily on analysis of design impacts on overall performance, as well as functional testing to validate those models.

The OxEon team built 21 consecutive stacks to aerospace quality standards with a maximum baseline performance of 1.6 ohm-cm2 dry CO2 and 99.9%+ oxygen purity. The stacks met cycling requirements, having demonstrated 61 operational

cycles while meeting target production rates and exceeding the program's end of life oxygen purity targets. The design underwent structural testing withstanding a load of 10kN with no effect to performance or seal integrity, as well as shock and vibrational testing with no significant performance changes. The stack, which met all interface requirements with the rover, also was able to withstand cryocycling to -40, -55 and -65 °C. This project resulted in a first of its kind success in ISRU applications for space exploration and has provided the basis for OxEon's subsequent scaling of the technology to capacities capable of supporting human exploration.

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[208] *In-Situ Electrochemical Generation and Utilization of Hydrogen Peroxide for Disinfection*

Santosh Vijapur (Faraday Technology, Inc.), Timothy Hall (Faraday Technology, Inc.), E. Jennings Taylor (Faraday Technology, Inc.), Santosh More (Faraday Technology, Inc.), Jeffrey Sweterlitsch (NASA Johnson Space Center), Michael Ewert (NASA Johnson Space Center), Sarah L. Castro-Wallace (NASA Johnson Space Center), Vicky Byrne (KBR), Brandon Dunbar (GeoControl Systems, Inc.), Hang Nguyen (JES Tech) and Melanie Smith (JES Tech).

Disinfection needs to meet personal hygiene requirements at the International Space Station (ISS) is currently accomplished through the use of pre-packaged, disposable, wetted wipes, which represent an appreciable carry-along mass and disposal burden. However, as human missions travel further into the solar system the availability of resources to resupply will be diminished. Therefore, next-generation system should use onboard utilities to create on demand disinfectants thereby reducing the dependence on earth-based supplies and further eliminating storage and disposal problems.

Accordingly, we are developing an in-situ approach to electrochemically generate hydrogen peroxide disinfecting solution utilizing onboard life support supplies (Air/Water) to neutralize surface microorganisms present in closed living systems. As discussed within our 2019 and 2021 ICES papers (ICES-2019-38; ICES-2021-273), we have continued to improve our TRL by scaling the electrochemical generation production process and validating the system in a zero-gravity parabolic loop flight test.

In this paper/presentation we will demonstrate a system that can achieve over 1 L of 2 w/w% peroxide per day with DI water and air reactor feeds. These electrolytes were then sent to NASA for microbial control property characterization.

Overall, the electrochemical peroxide generation system offers a more economical and practical alternative, with the disinfectant being generated on demand and in-situ (using available life support materials (Air/Water)); and applied to reusable cloths. The specific application of interest to this program is crew contact surfaces in space vehicles, but this approach could be utilized for waste water disinfection, heat exchanger biofouling remediation, and laundry applications. The peroxide generation system will also be able to address Earth-based needs in various settings such as field hospitals, restaurants, military, warehouses, movie theatres, among many others.

Acknowledgements: Financial support of NASA Contracts No. NNX16CA43P and NNX17CJ12C are acknowledged.

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[209] *Assessments of Physiology And Cognition in Hybrid-reality Environments (APACHE) – Physical Workload Approximation*

Alex Baughman (GeoControl Systems), Kyoung Jae Kim (KBR), Kadambari Suri (KBR) and Andrew Abercromby (NASA Johnson Space Center).

The Human Physiology, Performance, Protection & Operations Laboratory (H-3PO) at NASA Johnson Space Center (JSC) is developing a hybrid reality exploration surface analog, "Assessments of Physiology And Cognition in Hybrid-reality Environments" (APACHE). The goal of APACHE is to create a planetary extravehicular activity (EVA) simulation environment that provides a representative physical and cognitive workload approximation using a combination of virtual reality (VR), physical reality, and hybrid reality (HR) techniques. To develop and characterize the physical workload approximation within the APACHE environment, a two-part approach was implemented. In part 1, baseline physical workload during ambulation within APACHE was evaluated and compared with that in other planetary EVA analog environments and with existing data sets from Apollo planetary EVAs and reduced gravity testing of prototype planetary spacesuits. For this evaluation, 10 subjects were asked to ambulate in three surface analog environments: a passive treadmill in APACHE, natural terrain in an outdoor field environment, and a standard motorized treadmill. Subjects' heart rate and metabolic rate (VO_2/VCO_2) were measured and compared among the different test conditions and existing data sets. Gait parameters were also collected to compare with suited mechanics and to understand the role of gait kinematics in physical workload. In part 2, the aim is to evaluate the addition of a custom weighted body suit to the aforementioned surface analog environments and the ability to titrate the suit configuration to provide the best possible physical workload approximation for simulation of lunar and Martian EVAs.

[211] *Scale Up and Coupling of the MOXIE Solid Oxide Electrolyzer for Propellant Production on Mars*

Joseph Hartvigsen (OxEon Energy, LLC), S. Elango Elangovan (OxEon Energy, LLC), Jessica Elwell (OxEon Energy, LLC), Michele Hollist (OxEon Energy, LLC), Dennis Larsen (OxEon Energy, LLC), Tyler Hafen (OxEon Energy, LLC), Don Claus (OxEon Energy, LLC), Skyler Valdez (OxEon Energy, LLC), Abel Gomez (OxEon Energy, LLC), Piotr Czernichowski (OxEon Energy, LLC), Ainsley Yarosh (OxEon Energy, LLC), Jenna Pike (OxEon Energy, LLC) and Nathan Davis (OxEon Energy, LLC).

The successful operation of MOXIE on Perseverance mission Sol 60 (20 April 2021) has made Mars ISRU a reality. Since delivering the Solid OXide Electrolysis (SOXE) stacks for the Mars 2020 MOXIE project in 2017, the OxEon team, with the support of a NASA NextSTEP-2 ISRU award, has designed and fabricating SOXE stacks scaled 33 times the 0.5% scale of the device in MOXIE. A system containing six such SOXE stacks will have the oxygen production capacity to supply the propellant oxidant for a human mission Mars Ascent Vehicle (MAV). The full area SOXE design produced and tested in 2018 for commercial terrestrial energy storage applications has been joined in 2021 by an ISRU variant modified for oxygen collection.

While MOXIE has proven the case for atmospheric ISRU for oxygen production, use of the cathode byproduct CO was not demonstrated. OxEon has now demonstrated production of methane using solid oxide co-electrolysis of a CO2-steam mixture to produce syngas, a mixture of CO and H2 coupled with a subsequent methanation reactor converting the syngas to methane. Methanation of synthesis gas is related to the Sabatier reaction but has the advantage of producing half the water (due to starting with CO rather than CO2) which improves the thermodynamic equilibrium extent of reaction. Near quantitative conversion of syngas to methane has been demonstrated with the OxEon integrated breadboard system. This compact system has been operated in the same JPL Mars chamber used in MOXIE development. Extraction of Mars near-surface water, combined with the OxEon integrated SOXE co-electrolysis and methanation system will enable ISRU O2-CH4 propellant production on Mars.

The program objectives and results from full-scale area stacks operating in co-electrolysis mode coupled to a methanation reactor will be discussed.

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[212] *Advanced Nanocomposites for Exploration Extravehicular Mobility Unit (xEMU) Suits using STF-Armor™ for Lunar Regolith Dust Mitigation*

Richard Dombrowski (STF Technologies LLC), Erik Hobbs (STF Technologies LLC), Shane Jacobs (David Clark Company), Norman Wagner (University of Delaware), Maria Katzarova (University of Delaware) and Richard Rhodes (NASA Johnson Space Center).

Environmental protection garments (EPG) leveraging the benefits of shear thickening fluid (STF) enhanced textiles can directly address key space suit technology gaps and enable sustainable Lunar and Martian exploration missions. The addition of STF to conventional space suit textiles has been shown to provide mass-efficient enhancement of critical physical hazard protection properties, including dust mitigation, puncture, and MMOD/secondary ejecta (Cwalina et al., 2016; Dombrowski et al., 2018). Addition of approximately 9wt% of STF to conventional Orthofabric resulted in a nearly three-fold increase in puncture force. Here, we present ongoing testing and development of STF-enhanced EPG materials against low temperature and Lunar regolith simulant adhesion/penetration, culminating in the production of a demonstration prototype pair of EPG legs. A novel method was developed for evaluating interactions of Lunar highlands regolith simulants with STF-enhanced EPG shell fabrics. Quantitative estimates of dust penetration/total dust burden were obtained, as were qualitative results that demonstrated the effectiveness of the treatments for increasing dust rejection and facilitating cleaning. The dust test method is amenable to evaluating various factors of suit design vis-à-vis dust properties, including the effects of different seaming strategies and/or patterning on the potential for dust adhesion/penetration. STF treatment combined with a superhydrophobic “lotus leaf” coating facilitated removal of regolith simulant adhering to the surface of the shell fabric and significantly reduced the total dust burden (the sum of dust adhering to the fabric and dust able to penetrate through the fabric). Different seaming parameters did not have a strong effect on dust penetration, a result attributed to the fact that the face-to-back ties in the Orthofabric structure resulted in partial voids that were comparable in size to the holes created by the stitching needle. A prototype pair of leg EPGs was fabricated and delivered for NASA evaluation.

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[213] *Shear Thickening Fluid Treated Space Suit Layups: MISSE-13 Low-Earth Orbit Studies*

Erik Hobbs (STF Technologies LLC), Richard Dombrowski (STF Technologies LLC), Norman Wagner (University of Delaware, Department of Chemical Engineering), Maria Katzarova (University of Delaware, Department of Chemical Engineering) and Miria Finckenor (NASA Marshall Space Flight Center).

With upcoming lunar and Mars surface exploration a stronger, more resilient space suit is required to mitigate threats posed to astronauts. Vectran fabrics are of interest for this task due to the high strength of the fiber and its thermal stability. New fabric systems were developed using Vectran fabrics treated with shear thickening fluids (STF) known as STF-Armor™. STF incorporation has shown to provide enhancements of critical protection properties in conventional spacesuit materials. Here, results are presented from ISS experiments (MISSE-13) exploring the effects of low-earth orbit (LEO) on two Vectran based extra-vehicular activity (EVA) space suit layups that have been treated with a specially formulated, low-volatility, STF. One layup has an outer layer which is a modified version of the existing Orthofabric material which replaces the Nomex fibers with Vectran. Initial results showed this replacement led to a 50% increase in puncture while having a comparable aerial density. This fabric was also coated with a hydrophobic 'lotus leaf' material that has shown dust mitigation benefits. The other layup outer layer consists of a silicone coated Vectran fabric. A control layup and a shear thickening fluid treated layup for each were exposed to LEO for approximately one year in the RAM orbiting direction of the ISS. While in LEO the samples were exposed to atomic oxygen (AO), space radiation and large temperature variations. Post flight analysis after MISSE 13 includes puncture resistance, optical properties, dust mitigation and scanning electron microscope (SEM) images. Comparisons are made to related materials flown in MISSE 9 & 10.

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[214] *Electrostatic charging of the lunar surface*

James R. Phillips III (NASA Kennedy Space Center), Adrienne R. Dove (University of Central Florida), Charles R. Buhler (NASA Kennedy Space Center), Michael R. Johansen (NASA Kennedy Space Center) and Carlos I. Calle (NASA Kennedy Space Center).

Lunar regolith dust particles accumulate charge and interact electrostatically with rover wheels, astronaut boots, and equipment. We have developed instrumentation for in situ measurements of the electrostatic charge developed by the interactions of lunar regolith dust with the space-rated materials on these devices. This instrument is also capable of measuring the distribution of electric fields on or near the lunar surface and the ion currents present near the lunar surface. We also report on our efforts to characterize the charging behavior of lunar dust in low gravity environments. This behavior is nonintuitive due to complex interactions between individual dust grains. We are developing an experiment to study this interaction in a microgravity vacuum environment. Better understanding of this interaction will allow for improved dust mitigation on the lunar surface.

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[215] *Investigation into Simulated Microgravity Techniques Used to Study Biofilm Growth*

Angie Diaz (Amentum), Wenyan Li (Amentum), Tesia Irwin (The Bionetics Corporation), Aubrie O'Rourke (NASA), Luz Calle (NASA), Mary Hummerick (Amentum), Christina Khodadad (Amentum), Jonathan Gleeson (The Bionetics Corporation) and Michael Callahan (NASA).

Bacterial growth in liquid media in microgravity conditions is not well understood. Trends such as a shortened lag phase, longer log phase, slower growth rate, and a higher final population concentration have been noted but the underlying cause remains unclear. At the single cell level, it is predicted that bacteria are less gravity-sensitive than larger species. The effects on their immediate environment, including the lack of cell settlement and slower mass transfer of nutrients due to lack of density driven convection, could help explain the trends. Ground-based spaceflight analogs, or simulated microgravity devices, are often employed to achieve different attributes of weightlessness to study effects on bacterial growth. Though these technologies could isolate gravity's role in various biological processes, they cannot replicate all its effects and underlying mechanisms. Hence, interpretation of results could be misleading, even if similar to spaceflight. In this study two common simulated microgravity devices were investigated to determine whether they could simulate relevant microgravity conditions for bacterial growth. A bioreactor, the high aspect ratio vessel (HARV), was used with dyes of different density mounted on a random positioning machine (RP machine) or a rotating wall vessel (RWV). The RP machine displayed higher mixing rates than the RWV. The RWV was further tested at different rotations per minute (RPM). The range to minimize effects of density driven convection (low speeds) or centrifugal forces (high speeds) was between a range of 15-20 RPM. These results will help inform the selection of simulated microgravity device as well as interpretation of subsequent biofilm growth results.

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[216] *Shape Memory Alloys for Regulating TCS in Space (SMARTS): Validated Multiphysical Modeling and Design Optimization of Morphing Composite Radiators*

Sean Nevin (Texas A&M University), Joseph El-Ashkar (Texas A&M University), Collette Gillaspie (Texas A&M University) and Darren Hartl (Texas A&M University).

Future human spaceflight missions are expected to require increased turndowns in the amount of heat rejected by thermal control systems as they adjust to variations in heat loads and the surrounding thermal environment to maintain

crew cabin temperatures at a hospitable level. Current radiator systems can achieve a turndown ratio of 3:1; however, future missions are expected to demand ratios exceeding 6:1. Variable heat rejection space radiators are posed to provide this capability. The morphing radiator concept presented here accomplishes this via shape change, alternatively exposing low and high emissivity surfaces to the environment as passively thermally driven by shape memory alloys. Shape memory alloys are unique materials that use a thermally induced solid-solid phase transformation to generate strain and then fully recover it. This work covers the development and implementation of a modeling tool to simulate the morphing radiator behavior with ultimate application as a design tool. The model incorporates a multiphysics scheme to couple the thermal and geometric response of the radiator, which is required to capture radiation dependence on view factor. The fully developed model is then used to optimize radiator composite layup, SMA properties and number of wires to achieve full closure. The composite performance is further investigated to assess the optimal ply orientations through the use of black box surrogate modeling techniques such as efficient global optimization. This methodology efficiently searches through the design space for the computationally expensive finite element model. Full closure of the morphing radiator is essential to maximize turndown during cycling within operational temperatures of the thermal control system, and thus closed (cold state) aperture angle represents the primary objective of a design of experiments. Design study results shown provide a range of desirable shape memory alloy properties and wire quantity, which define the targets for upcoming prototyping and demonstration efforts.

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[218] *Optimization of Ultrasonic Drying Rate and Efficiency for Spacecraft Solid Waste Management*

Jonathan Bigelow (Ultrasonic Technology Solutions), Connor Shelander (Ultrasonic Technology Solutions), Tra-My Justine Richardson (Research Physical Scientist, Ames Research Center) and Ayyoub Momen (Ultrasonic Technology Solutions).

Our study aims to optimize the drying performance of the novel Direct Contact Ultrasonic Drying for bagged human solid waste relevant to the current waste management system at the International Space Station. Unlike the conventional thermal drying methods, direct contact ultrasonic drying does not entirely rely on heat or water evaporation. It, therefore, is not bound by the high energy input required for water vaporization. In a high moisture level content range, water is ejected from a wet object in the form of a cold mist (atomized water). This novel drying method removes water by shaking the object rapidly (on a micron scale) using piezoelectric transducers. By bypassing the evaporation process, the technology demonstrates a much higher efficiency and drying speed on a bagged human solid waste. In this paper, we will report the results of the design of experiment (DOE) testing for ultrasonic drying performance of different fecal bag thicknesses under different configurations. This study's outcome could help the design of a better solid waste management system for ISS.

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[219] *Opposed-flow spreading flames: Effect of sub-atmospheric pressure on spread and burning rates*

Luca Carmignani (UC Berkeley), Priya Garg (UC Berkeley), Maria Thomsen (Universidad Adolfo Ibanez), Michael Gollner (University of California, Berkeley), Carlos Fernandez-Pello (University of California, Berkeley), David Urban (NASA) and Gary Ruff (NASA).

Flame spread over solid fuels is a canonical problem in fire science, due to its direct implications on material flammability and importance in fire development. Flames in a microgravity environment can behave very differently than on Earth, posing additional risks for spaceflight life safety. Due to the difficulties associated with microgravity testing, sub-atmospheric pressures in ground-based experiments have been proposed to approximately replicate the burning behavior of solid fuels in reduced gravity conditions because of similar effects on heat and mass transfer mechanisms from the flame to the solid. However, the roles played by gravity and pressure vary with the flame spread configuration. In opposed flame spread, the solid fuel is heated by the flame ahead of its leading edge, and this process is strongly affected by the ambient conditions. In this work, we consider flames spreading over acrylic samples exposed to a forced flow of 20 cm/s, and pressures between 30 and 100 kPa. Flame characteristics such as spread rate, standoff distance, and length are obtained from the video analysis of the experiments and compared at different pressures. Mass burning rates are calculated from the samples weight measured before and after the experiments. Additionally, gas emissions measured during the experiments are used to estimate the heat release rate of the spreading flames. Results show a decreasing non-monotonic behavior of flame length, spread rate, and mass burning rate with reducing pressure. The comparison of the heat release rate obtained from the measured emissions and the estimated mass burning rate, suggests that chemical kinetics is not driving the decrease in flame spread rate observed at low pressures. These results could provide more information to guide future Earth-based flammability testing of materials for spacecraft applications.
This research was supported by NASA Grant NNX12AN67A.

[220] *Implementation of In-situ Resource Utilization for the Development of a Moon Village*

Marlies Arnhof (European Space Agency), Belinda Rich (European Space Agency), Hanna Lakk (European Space Agency), Advenit Makaya (European Space Agency), Aidan Cowley (European Space Agency), Georgi I. Petrov (Skimore, Owings & Merrill), Daniel Inocente (Skimore, Owings & Merrill) and Colin Koop (SOM).

In-situ resource utilization (ISRU) is considered to be an essential element to enable the sustainability of future long-term exploration missions. Sustainable construction, operation and maintenance of a permanent human settlement will require the use of local resources, to gradually reduce the dependence on shipments from Earth and the associated mission cost and complexity. Skidmore, Owings & Merrill LLP (SOM), in partnership with the European Space Agency (ESA) and faculty in the Department of Aeronautics and Astronautics at the Massachusetts Institute of Technology (MIT), are working on developing material and processes technologies that will be integrated into civil engineering and architectural applications for a permanent human settlement on the lunar surface. In this paper, we propose a gradual strategy for the development of the ISRU capabilities through the stages of the settlement's evolution and describe the infrastructure required to support the volume of activities corresponding to the various development phases. The spatial layout of the ISRU elements is developed in coordination with the Moon Village masterplan, which is documented in earlier publications. Aspects which can benefit from ISRU include oxygen and water production for propellant and life support, construction and hardware elements, energy generation and storage, as well as re-use and recycling of materials brought from Earth. This proposed strategy highlights areas where technology development goals are identified which maximize opportunities for the implementation of ISRU in the context of a lunar settlement.

[221] *Modeling and Simulation of Component Degradation and Faults in the Carbon Dioxide Removal Assembly*

Daniel Kaschubek (Technical University of Munich) and James Nabity (University of Colorado Boulder).

An Environmental Control and Life Support System (ECLSS) meets the environmental and metabolic needs of the crew. However, regenerable life support subsystems have required continuous monitoring and frequent maintenance and repair. For the International Space Station (ISS), ground control monitors these subsystems and directs maintenance and repair operations using replacement components and assemblies sent from Earth via resupply. While this has been sustainable for the ISS, space habitats beyond Earth orbit are expected to need autonomous systems to keep the crew alive when present and keep the habitat 'alive' when absent. Future ECLSS will need to be self-aware and self-sufficient to meet this need. For self-awareness, an autonomous ECLSS must be able to determine component and system health in real time. To do so, the possible failure modes of each ECLSS subsystem and their effects on operability and performance, habitability and crew health must be known. The Virtual Habitation modeling and simulation tool (V-HAB) has been under development at the Technical University of Munich since 2006 to dynamically simulate life support systems and their interactions with crew metabolism. In this work, the V-HAB submodel that simulates the Carbon Dioxide Removal Assembly (CDRA) was adapted to investigate the effects of screen blinding, heater failure, and vacuum pump degradation on the efficacy of CO2 removal.

[222] *Estimation of System States for Non-Measured Parameters and Integration with a Digital Twin framework to Boost Spacecraft Autonomy and Awareness*

Monica Torralba (Masters Student, Mechanical and Aerospace Engineering Department, University of California Davis, 95616), Cory George (Masters Student, Mechanical and Aerospace Engineering Department, University of California Davis, 95616), Stephen Robinson (Professor, Director, University of California Davis Center for Spaceflight Research, 95616), Samuel Eshima (PhD Student, Smead Aerospace Engineering Sciences, University of Colorado Boulder, 80303) and James Nabity (Associate Professor, Smead Aerospace Engineering Sciences, University of Colorado Boulder, 80303).

As technologies for human exploration develop to meet the challenges of Lunar and Mars transit and habitation, there is increasing need for technologies that boost vehicle autonomy and awareness with or without human presence. This need for autonomy is driven largely by distance, with two-way communications and resupply lead times exceeding practical limits for a more traditional ground-supported habitat such as the International Space Station. Vehicle autonomy depends on awareness, which relies on sufficient data to inform and predict the state of health of critical systems. This paper will describe a use case for the estimation of states of a carbon dioxide removal system which will mimic the operation of the Simulation Testbed for Exploration Vehicle ECLSS (STEVE), a physical testbed built and operated at the University of Colorado Boulder. Specifically, this paper uses state estimation and physics first principles to estimate the state of parameters inside the testbed's sorbent bed. Parameters within the bed must be estimated because sensors cannot be introduced internally to the sorbent bed without affecting performance. In addition to generating data about system state of health, vehicle awareness also relies on the availability of sensor data for use by autonomous agents or

intelligent modules aboard a spacecraft. This paper proposes a Digital Twin architecture that acts as the framework for storage, transport, and the exchange of data in an autonomous and self-aware vehicle.

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[224] *A Numerical Study of Liquid Fuel Wick Flames in Artificial Partial Gravity in a Centrifuge Facility*

Arland Zatania Lojo (Case Western Reserve University), Ankit Sharma (Case Western Reserve University), Ya-Ting Liao (Case Western Reserve University), Michael Johnston (USRA/NASA GRC) and Paul Ferkul (USRA/NASA GRC).

Numerical simulations are performed to support a combustion and fire safety experiment campaign in partial (Lunar and Martian) gravity in a centrifuge designed for use in conjunction with the NASA Glenn Research Center's Zero Gravity Research Facility 5.2 second drop tower. The centrifuge is a circular dome chamber ~ 0.3 m3 with 81.3 cm diameter. The artificial gravitational field is controlled by the rotation rate of the chamber. This is complicated by gravitational gradients as a function of radius and Coriolis force as a function of flow velocity. The model is constructed with Ansys FLUENT utilizing a rotating non-inertial reference frame and simulates the entire chamber volume containing a heptane candle with a wick length of 10 mm x 3.18 mm diameter located at 32 cm from the centrifuge center. The candle is oriented in the radial direction (flame towards center). Simulation results locally near the candle are compared to a series of experiment images where the flame tip bends in the Coriolis force direction. The complex flow recirculation in the chamber under the influence of artificial gravity and Coriolis forces is discussed to help interpret the results and improve future test configurations.

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[229] *Controlled release silver coatings for antibacterial and anti-biofouling stainless steel surfaces*

Ali Ansari (Arizona State University), Rafiqul Islam (Cactus Materials), Francois Perreault (Arizona State University), Yuqiang Bi (Cactus Materials), Kiarash Ranjbari (Cactus Materials, Inc.), Afsana Munni (Arizona State University) and Fariya Sharif (Cactus Materials, Inc.).

Bacterial biofilm formation on different surfaces in International Space Station (ISS) especially on water treatment systems can be harmful for crew members and decrease hardware's reliability. Surface coating with silver nanoparticles (Ag NPs) have shown promise to provide a localized antibacterial property for biofouling control during space missions. However, since Ag NPs rapidly dissolve in water and release silver ions, the lifetime of the antimicrobial coating is short. In this study, partial passivation of Ag NPs using sulfidation was suggested to slow down the silver release and sustain antimicrobial performance. Stainless steel (SS) was chosen as the substrate of interest for coating with sulfidized Ag NPs, since it is being widely used in ISS water systems. SS coupon coating with silver sulfide NPs was done by using two different reducing agents: sodium borohydride and glucose (green chemistry). Passivation through sulfidation slowed down by 85% the silver release while maintaining a high bacterial inactivation. Sulfidized Ag NPs coating was also done with a flow through system on a surface with complex geometry (bellow). The coating was found to be homogenous along the bellow. The efficacy of the antimicrobial coating as well as changes in the water quality over time is now investigated during a long-term dormancy test using the 5 strains of bacteria that are the most common in ISS. This innovation will improve silver efficiency in water treatment systems of spacecraft, which will reduce the costs for water quality control and reduce potential health risks or system damage from biofouling.

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[230] *Preparations for 2nd US Navy Submarine Sea Trial Utilizing NASA and US Navy Analyzers*

Joshua Manney (Naval Surface Warfare Center Philadelphia Division), Jay Smith (Naval Surface Warfare Center Philadelphia Division), Paul Mudgett (NASA Johnson Space Flight Center), Jeffrey Pilgrim (Vista Photonics, Inc) and Joshua Bowman (Naval Sea Systems Command).

In 2017, a team consisting of representatives from the US Navy, NASA and industry conducted the testing of two NASA-developed analyzers onboard a submarine, fostering a mutually beneficial relationship and the successful transition of analyzing technologies between very similar closed-atmospheric environments. The first NASA-developed analyzer was the tunable diode laser spectroscopy (TDLS)-based Multi-Gas Monitor (MGM) mainly monitoring life gases, and the second was a gas chromatography/differential mobility spectrometer-based Air Quality Monitor (AQM) observing select volatile organic compounds. Both of these analyzers had previously been deployed on the International Space Station (ISS) with proven success of long-term operation in a closed atmosphere.

The Navy remains interested in performing recurring evaluations of alternative atmospheric monitoring equipment and technologies to maintain and improve onboard submarine atmospheric monitoring. Furthermore, the performance of this sea trail supports NASA's goal of studying submarines as closed environment analogs to spacecraft. Preparations for the second sea trial on a Navy submarine are ongoing and strongly leverage technologies in development under an

existing US Navy Small Business Innovation Research (SBIR) grant. The following technologies are presently under consideration: cavity ringdown spectroscopy, Raman spectroscopy, infrared spectroscopy, tunable laser absorption spectroscopy and photoacoustic spectroscopy. Additionally, discussions with NASA continue concerning incorporation of a successor to the MGM, and a modified AQM based on the findings of the initial sea trial.

During the sea trial, the selected analyzers will sample from the same locations as existing onboard atmospheric equipment for comparison purposes and will be operated continuously for a duration of months with little crew intervention beyond ensuring operation. This paper will provide an overview of the decision-making behind the technologies selected, the preparations for the sea trail and results, and comparisons of the data recovered from the analyzers, if full execution can occur prior to submittal of the paper.

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[231] *Investigation of the Anomalous Low Voltage Condition of the Oxygen Generation Assembly*

Phillip Baker (Collins Aerospace), Robert Roy (Collins Aerospace), Alesha Ridley (NASA) and Steve Van Keuren (S&K Global Solutions, Inc.).

Hydrogen orbital replacement unit serial number 00002 of the oxygen generation assembly was exhibiting an increasingly anomalous low voltage condition in cell #1 of electrolysis cell stack serial number 00005. The hydrogen orbital replacement unit was removed on November 16, 2016, and the on-board spare hydrogen orbital replacement unit serial number 00003 installed to continue oxygen generation system operation. The removed orbital replacement unit was returned from the International Space Station to Collins Aerospace for test, teardown, and evaluation, and failure analysis.

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[232] *Feasibility of using Low-Cost COTS Sensors for Particulate Monitoring in Space Missions*

Marit Meyer (NASA - Glenn Research Center), Nima Afshar-Mohajer (Gradient Co.), Eben Cross (QuantAQ Inc.) and Paul Mudgett (NASA - Johnson Space Center).

Real-time measurement of particles suspended in the spacecraft cabin is of great importance to verify that maximum allowable dust concentrations are not exceeded. This is primarily to protect astronaut health, but also has implications for dust-sensitive equipment. Recently, there is growing interest in low-cost commercial off-the-shelf (COTS) particle sensors by air quality researchers for their ability to map concentrations of airborne particulate matter in various terrestrial settings. In addition to low cost (< $2,000), the compact size and minimal weight of these sensors make them a potential choice for space missions. The detection mechanism for these aerosol sensors is typically measurement of light scattered by particles as they flow through a sensing volume. The amount of scattered light for detection depends on the particle size, shape, density, and refractive index of the particle material. Ideally, particle instruments should be calibrated with reference instruments for each different type of aerosol measurement. In this study we review multiple parameters that may impact the performance of state-of-the-art low-cost aerosol sensors. Environmental factors such as temperature, relative humidity, low ambient pressure, radiation and charge environment, partial-gravity and microgravity can affect the accuracy of particle measurements. Characteristics of the dust aerosols including particle size distribution, aerosol composition, refractive index, morphology and concentration levels also affect the measurement accuracy. Finally, we look at these parameters and issues with respect to an example COTS low-cost aerosol sensor. Instrument performance specifications are evaluated, and experiments are performed to measure real-time concentrations of Arizona Road Dust (a terrestrial reference test dust) and lunar dust simulant in a laboratory chamber. Overall, this study provides insight for evaluating spacecraft particulate monitoring technologies and raises questions to be answered before incorporating low-cost COTS sensors in future space missions to dusty destinations.

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[234] *Operation of an Eight-Loop Heat Pipe Architecture for High Dissipative Applications*

Paula Prado Montes (Airbus), Georges Lefort (Airbus), José Luis Pastor Fernández (IberEspacio), Felix Beck (ESA) and Sandra Macías Jiménez (Airbus DS).

Architectures with several Loop Heat Pipes (LHPs) connected to a network of Heat Pipes (HPs) can be considered as an attractive solution for space missions with highly dissipative equipment onboard. This kind of architecture allows transferring significant heat loads efficiently on long distances towards different cold thermal sinks, while ensuring stable and uniform temperature of the dissipating units. Operation of several LHPs in parallel has been historically considered unstable due to the intrinsic features of the LHP performance during transients and in particular for start-up. A system based on eight LHPs connected to a network of 12 HPs has been defined for the thermal control of all Dual State Solid Power Amplifiers (DSSPAs) in a highly dissipative Active Antenna. The system design has been challenged to cope with stringent operational requirements such as high heat transport capability in the range of 5kW and temperature homogeneity among the DSSPAs, with temperature gradients < 5K. To prove the concept, a dedicated Thermal Model

(TM) has been built and tested at different operational scenarios and boundary conditions. The TM consists of eight LHPs distributed on a network of 12 HPs in parallel, each LHP being mounted on six HPs, so that each HP remains in contact with at least three, and up to five, LHP evaporators. The TM has been tested both in vacuum and in climatic chamber. The test sequence included start-up in cold and hot environment and from different initial conditions including dry-out and preconditioning, shut-down tests and performance with several power and sink levels, with and without heat leaks to the reservoir. Start-up and shut down ability of the LHPs, plus reliability of the system operating during steady conditions and transients has been proven.

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[236] *Improved Shear Thickening Fluid Treated Space Suit Layups: Terrestrial and ISS MISSE-10 Low-Earth Orbit Studies*

Erin Hogan (Department of Chemical and Biomolecular Engineering, University of Delaware), Maria Katzarova (Department of Chemical and Biomolecular Engineering, University of Delaware), Elaine Stewart (Department of Chemical and Biomolecular Engineering, University of Delaware), Jacob Hewes (Department of Chemical and Biomolecular Engineering, University of Delaware), Norman Wagner (Department of Chemical and Biomolecular Engineering, University of Delaware), Richard Dombrowski (STF Technologies LLC), Erik Hobbs (STF Technologies LLC) and Miria Finckenor (Space Environmental Effects Team, Marshall Space Flight Center).

More resilient, flexible materials are required for human extraterrestrial exploration as damage from regolith and puncture threats threaten astronaut survival on the lunar and Martian surfaces. Prior work has shown that nanocomposites comprised of STF-Armor™ provide superior puncture and MMOD resistance (Composites Science and Technology, 131, 61-66 (2016)), as well as enhanced resistance to regolith interpenetration. Here, results are presented from ISS experiments (MISSE-10) exploring the effects of LEO conditions on TMG lay-ups of an EVA space suit with improved puncture resistance (STF-Armor) due to the incorporation of a low-volatility shear thickening fluid (STF) with variation in particle loading. Puncture resistance (ASTM F1342) was found to be optimal for an intermediate nanoparticle loading (72 wt%) with a 347% increase in resistance for the treated Orthofabric and 236% increase in resistance for a treated Spectra® layer, which are higher resistances than were observed relative to related formulations deployed on a prior ISS experiment (MISSE-9, ICES2021_278, https://hdl.handle.net/2346/87233). Six months of exposure in low earth orbit (LEO) on MISSE confirmed results of a prior MISSE-9 experiment showing extended LEO exposure increased the puncture resistance of the STF-treated Orthofabric outer layer (420% over near Orthofabric for ASTM F1342) and did not result in any mass loss, but increased absorptivity. STF-treated Spectra® absorber layers remained unaffected. Complementary terrestrial materials characterization by scanning electron microscopy show changes in the nanoscale structure of the exposed face of the Orthofabric suggesting a localized surface degradation of the MAC suspending oil used in the STF formulation. These results demonstrate a mass-efficient nanocomposite with significant increase in puncture protection for use in EVA suits for possible use in lunar and Martian exploration. Moreover, these flight results contribute to the TRL advancement of TMG space suit materials.

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[239] *Situational Cues for Continuous Trust Calibration in Automated Systems*

Alexandra Forsey-Smerek (Massachusetts Institute of Technology), Katya Arquilla (Massachusetts Institute of Technology) and Julie Shah (Massachusetts Institute of Technology).

Appropriate user trust calibration in automated systems is critical for optimizing system usage, improving task performance, and reducing user workload. While undertrust in a system may lead to system disuse and suboptimal performance, overtrust in a system can result in reduced user situation awareness and susceptibility to consequences of system failure. In dynamic domains, the reliability of an automated system may fluctuate based on environmental conditions and the type of task being performed. Fluctuation in system reliability demands that user trust in the system adapts to optimize system usage and task performance. Recent attention has been focused on the presentation of adaptive trust calibration cues based on quantified human operator trust to promote appropriate trust calibration. In dynamic domains such as future human and robotic space exploration missions, real-time quantification of operator trust in an automated system may not be possible. In this work, we expand the application space of trust calibration cues through the introduction of situational trust cues (STCs), presented independent of user real-time trust in the system. Situational trust calibration cues are presented if environmental conditions or task type is changed in a manner that significantly affects performance of the automated system. We present the design of an experiment investigating the application of STCs to a Lunar rover path planning automated decision support tool in a dynamic mission operations environment. The experiment is designed to assess the impact of STCs on user selection of the most appropriate level of automation to afford an automated decision support tool, where the most appropriate level of automation fluctuates between three automation levels based on the type of planning task being executed and the state of the simulated environment. We ultimately plan to investigate the utility of STCs in mitigating user overtrust and undertrust in automated systems.

[244] *The neutron component of the lunar radiation environment*

Lawrence Heilbronn (University of Tennessee).

The upcoming Atermis missions will return crew to the Moon later this decade. The risk to crew and electronics from exposure to the lunar radiation environment is one of several environmental risks that must be understood to ensure mission success. The lunar radiation environment is different in comparison to the free space and low-Earth orbit environments in that the primary galactic cosmic rays and solar energetic particles interact in both man-made structures and the lunar surface, creating a unique mix of both primary and secondary radiation. Neutrons are a significant component of the secondary radiation field and span energies up to several GeV. Measurements have been made of neutrons both in orbit around the Moon (for example, the Lunar Reconnaissance Orbiter) and on the surface (Chang'e 4), over a limited range in neutron energy. Several radiation transport model calculations have also been made to provide predictions of the neutron environment, as well. Measurement of neutron fluence and energy spectra are difficult, especially in a mixed radiation environment. Neutron dosimetry may be limited by the technological challenges that limit the dynamic range of neutron energies that can be measured. This paper will review measurements and calculations made to date, as well as provide additional calculations of the neutron albedo created under different conditions of lunar soil composition and topology, in order to investigate what may or may not be needed for neutron dosimetry on the Moon.

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[245] *Removal of Urea and Ammonia from Real Human Urine using Bio-electrochemical Reactor system for Closed Loop Environments.*

Wilfredo J Cardona Vélez (University of Puerto Rico), Carlos R. Cabrera Matinez (University of Texas El Paso), Gary A Toranzos (University of Puerto Rico), Santosh H Vijapur (Faraday Technology Inc), Tim Hall (Faraday Technology Inc.) and E. Jennings Taylor (Faraday Technology Inc.).

Water recycling system with improved efficiencies to satisfy the water demand in a closed loop environment is required by NASA's Environmental Control and Life Support Systems (ECLSS). Wastewater recycling system in the ECLSS has a water reclamation efficiency limitation of approximately 90%. Therefore, next-generation technologies are required to improve the ECLSS in spacecraft and future planetary space stations for the Moon or Mars. Accordingly, the University of Puerto Rico, in collaboration with Faraday Technology, are developing a sustainable continuous bio-electrochemical process for urea and ammonia removal from wastewater. that will aid the water reclamation process by limiting precipitation events that result from the presence of urea in the urine. This approach will convert the urea to ammonia in a continuous enzyme-based bioreactor, then the bioreactor effluent will travel through an electrochemical oxidation reactor where the ammonia would be oxidized to H2 and N2.

The bioreactor uses P. vulgaris microbial enzyme that consumes the urea, through urease catalyzed hydrolysis. Urease hydrolysis generates an ammonia rich bioreactor effluent that can be electrochemically treated . Our work has demonstrated that the resulting effluent from the bio-electrochemical system has significantly reduced ammonia and urea concentration, when testing synthetic urine feed streams. Furthermore, the semi-continuous operation of the bio-electrochemical system has been validated during a zero-gravity parabolic loop flight test flown in May 2021.

Recently, the bio-electrochemical system was evaluated with real human urine, and we intend to report those results at ICES. Overall, this project demonstrates the potential of a bio-electrochemical system that can improve the lifetime and durability of the water recovery system used in closed loop living environments.

Acknowledgements: This project is partially supported by the National Aeronautics and Space Administration (NASA) Training Grant No. NNX15AI11H. Also, NASA Contract NNX17CA30P, 80NSSC18C0222.

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[249] *Mechanical Counter-Pressure EVA Suits: NASA Outlook and Development Strategy in 2022*

Shane Mcfarland (NASA).

Mechanical counter-pressure has been investigated as a possible alternative architecture to traditional extra-vehicular activity suits for some time. MCP aims to provide physiological protection against the ambient vacuum environment by direct application of pressure to the skin by a fabric, as opposed to surrounding the occupant in pressurized gas as is the defining characteristic of a traditional gas-pressurized suit. In reviewing the concept of MCP, it offers distinct hypothetical advantages to traditional EVA suits: reduced mass, consumables, and complexity; increased mobility and comfort. In addition, as rudimentary feasibility of the concept was established in the 1960s with the testing of the Space Activity Suit, MCP seems poised to inevitably supplant traditional EVA architectures with a modest degree of concentrated development. However, a closer examination suggests something quite different. This paper serves as a comprehensive summary of the technical work that has been completed related to MCP from 1960 to 2022, the technical gaps that currently prohibit development of a flight-capable design, and outlines a development strategy that serves to address these gaps moving forward over the coming decades.

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[253] *NASA Advanced Space Suit Pressure Garment System Status and Development Priorities 2022*

Shane Mcfarland (NASA), Richard Rhodes (NASA) and Don Campbell (KBR/NASA-JSC).

This paper discusses the current focus of NASA's Advanced Space Suit Pressure Garment Technology Development team's efforts, the status of that work, and a summary of longer-term technology development priorities and activities. For the past two years, the team has focused on the development and detailed design of the Extra-vehicular Mobility Unit (xEMU) to support two parallel missions: A 2023 deadline for delivery of the xEMU International Space Station (ISS) Demonstration configuration, and a planetary walking suit configuration to support landing on the Moon in 2024. The baselined design of the xEMU will be reviewed. The results of Design Verification Testing (DVT) will be presented and its ability to provide confidence in the hardware's ability to meet flight requirements will be discussed. To the extent possible, an impact assessment of the Exploration Extravehicular Activity Services (xEVAS) Contract will be provided. Finally, a brief review of longer-term pressure garment challenges and technology gaps will be presented to provide an understanding of the advanced pressure garment team's technology investment priorities and needs for future exploration missions.

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[254] *HEPA Filter Performance for Lunar Dust Removal in Extreme Conditions*

Andrew Walcker (Paragon Space Development Corp), Ryan Kobrick (Paragon Space Development Corporation) and Juan Agui (NASA GRC).

Lunar surface missions are a critical part for NASA's future human spaceflight exploration programs, such as the Artemis Program. The lunar surface is a harsh environment that poses various environmental challenges to both astronauts and mechanical equipment. Lunar dust poses a substantial threat due to dielectric properties and lack of weathering effects that cause a sharp and abrasive surface structure that traditional Earth dust does not exhibit. Measures are required to prevent lunar dust from causing bodily harm or excessive damage for human-rated systems both on the surface (such as the Human Landing System) or in-orbit and transit assets (such as HALO/Gateway/Orion). One such dust mitigation method is to utilize High Efficiency Particulate Air (HEPA) filters in an air ventilation system. HEPA filters are a critical element in air-purifying systems, however, the performance of a HEPA filters can be greatly impacted by environmental contaminants like dust. Because lunar dust exhibits severe properties, testing is necessary to verify the performance of the HEPA filter assembly. Testing consists of subjecting the HEPA filter to as close to the given lunar environment (pressure, dust loading and humidity) as possible and measuring performance characteristics. Two separate HEPA medias were analyzed: a traditional fiberglass and an advanced option. Test results consist of comparing the pressure drop of the two media, the efficiency of each load case, and determining if any environmental factors contribute to the effectiveness and pressure drop. Test results will aid in the knowledge of selection of an optimal HEPA filter that will be robust to performance degradation in these extreme environments. Future work consists of testing a flight-configuration HEPA filters and qualifying it for spaceflight.

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[255] *Main focusses on the use of higher plant growth models for life support systems*

Joanna Kuźma (Université Clermont Auvergne, CNRS, SIGMA Clermont, Institut Pascal), Jean-Pierre Fontaine (Université Clermont Auvergne, CNRS, SIGMA Clermont, Institut Pascal), Lucie Poulet (Université Clermont Auvergne, CNRS, SIGMA Clermont, Institut Pascal) and Claude-Gilles Dussap (Université Clermont Auvergne, CNRS, SIGMA Clermont, Institut Pascal).

In long-term plans for space exploration investigated by major space agencies, the exploration of the Moon or Mars involves solving many technological problems. One of them is the development of an efficient and robust life-support system. One-way trip to Mars will take between 6 to 8 months with current technology. According to NASA's economic calculations, for each trip over 10 months, at least 15% of the food for astronauts should be produced onboard. To make this possible it is necessary to switch from physicochemical (PC) systems in charge of recycling water and oxygen and stabilization of waste - like the one on the International Space Station - to hybrid ones where part of the system can be based on PC technology and part of it on biological processes in order to produce edible biomass, e.g. to grow plants. As the growth and development of higher plants are strongly influenced by the environmental conditions, bio-regenerative life-support systems require a high level of control and management. In systems that include plants, it is possible to use transpiring water as a source of potable water, which in turn can reduce the need for physical purification systems. For this to be possible, it is necessary to understand in-depth how the various parameters affect the plant growth and transpiration process - especially in closed systems. Most of the existing plant growth models do not consider gravity,

radiation, or CO2 concentration as variable parameters. However, over the years, new models are being developed in controlled environments. This article presents an overview of the existing models with a focus on the ones that can be used to simulate systems in space. The article also highlights the work that still needs to be done to understand the impact of certain parameters on plant growth for a closed-systems application.

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[256] *Designing for Powered Flight on Titan: Preliminary Testing and Analysis of a Thermal Control Design for the Dragonfly Battery Module*

Krithika Balakrishnan (Johns Hopkins Applied Physics Laboratory), G. Allan Holtzman (Johns Hopkins Applied Physics Laboratory), James E. Parkus (Johns Hopkins Applied Physics Laboratory), Robert F. Coker (Johns Hopkins Applied Physics Laboratory), Daniel Y. Jeong (Johns Hopkins Applied Physics Laboratory) and Carl J. Ercol (Johns Hopkins Applied Physics Laboratory).

Dragonfly is a rotorcraft lander that will explore a variety of surface locations on Saturn's moon Titan. During powered flight, the Dragonfly lander will draw power from a 24-cell battery system. Due to the cryogenic atmosphere on Titan, the Dragonfly lander will be insulated with Rohacell around the exterior surfaces – however, this poses a unique design challenge for powered flight, as the battery and other components need to be kept cool while they dissipate significant heat during this phase. In order to assess a thermal control design to cool the battery system during powered flight within the insulated lander, a sub-scale 9-cell thermal module was tested at the Johns Hopkins Applied Physics Laboratory. The results demonstrate the importance of having both passive and active thermal controls.

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[257] *NASA Advanced Space Suit xEMU Development Report – Liquid Cooling and Ventilation Garment*

Shane Mcfarland (NASA) and David Cox (NASA JSC).

For the past several years, the Exploration Extra-Vehicular Mobility Unit (xEMU) team at NASA's Johnson Space Center has focused on the development and detailed design 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 baseline detailed design of the xEMU liquid cooling and ventilation garment (LCVG). This paper will outline the challenging technical requirements, significant architectural trades, technical solutions required to overcome these challenges, and a current status of the detailed design. The preliminary results of Design Verification Testing (DVT) as it relates specifically to this hardware will also be provided, along with a forward strategy for final maturation into a flight-ready design.

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[258] *NASA Advanced Space Suit xEMU Development Report – Hard Upper Torso Assembly*

Ian Meginnis (NASA), Richard Rhodes (NASA) and Daniel Kim (NASA).

For the past several years, the Exploration Extra-Vehicular Mobility Unit (xEMU) team at NASA's Johnson Space Center has focused on the development and detailed design 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 baseline detailed design of the xEMU Hard Upper Torso (HUT) Assembly. This paper will outline 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 the HUT will also be provided, along with a forward strategy for final maturation into a flight-ready design.

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[259] *Multifunctional Sorbent (MultiSORB) Devices for Contaminant Removal*

Tra-My Justine Richardson (National Aeronautics and Space Administration), Andrew Lesh (National Aeronautics and Space Administration), Keith Peterson (National Aeronautics and Space Administration), Tane Boghozian (Analytical Mechanics Associates, INC.), Gurpreet Klar (Analytical Mechanics Associates, INC.) and Sander Visser (Analytical Mechanics Associates, INC.).

Many state-of-the-art (SOTA) Environmental Closed-Loop Life Support System (ECLSS) technologies use liquid or solid adsorbents to remove contaminants from spacecraft cabin air and wastewater. The solid adsorbent systems use commercial off-the-shelf (COTS) adsorbent pellets with predetermined characteristics such as adsorption capacities, thermal conductivities, and pellet shapes and sizes. The Multifunctional Sorbent (MultiSORB) project aims to produce sorbent lattices with custom adsorbent paste formulations and lattice designs. Heaters and sensors are embedded into the lattice. This approach aims to lower system mass, volume, and power. The MultiSORB production process employs either additive manufacturing (AM) or slip/freeze casting with paste formulations to fabricate adsorbent beds with a

desired pressure drop and customized air flow channels. Advanced heaters or heat transport systems such as heat pipes and vapor chambers can improve temperature ramp rates and uniformity within adsorbent beds, leading to lower power consumption and an increased capability for rapid cycling resulting in reduced system volume. This paper will discuss preliminary MultiSORB paste formulations and lattice designs for use in spacecraft systems.

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[260] *NASA Advanced Space Suit xEMU Development Report – Helmet and Extra-Vehicular Visor Assembly (EVVA)*

Kristine Davis (NASA) and Tymon Kukla (NASA).

For the past several years, the Exploration Extra-Vehicular Mobility Unit (xEMU) team at NASA's Johnson Space Center has focused on the development and detailed design 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 baseline detailed design of the xEMU Helmet and Extra-Vehicular Visor Assembly (EVVA). This paper will outline the challenging technical requirements, significant architectural trades, technical solutions required to overcome these challenges, and a current status of the detailed design. The preliminary results of Design Verification Testing (DVT) as it relates specifically to this hardware will also be provided, along with a forward strategy for final maturation into a flight-ready design.

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[261] *NASA Advanced Space Suit xEMU Development Report – Ancillary Hardware*

Tymon Kukla (NASA).

For the past several years, the Exploration Extra-Vehicular Mobility Unit (xEMU) team at NASA's Johnson Space Center has focused on the development and detailed design 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 baseline detailed design of the xEMU Ancillary hardware. This paper will outline the challenging technical requirements, significant architectural trades, technical solutions required to overcome these challenges, and a current status of the detailed design. The preliminary results of Design Verification Testing (DVT) as it relates specifically to this hardware will also be provided, along with a forward strategy for final maturation into a flight-ready design.

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[262] *NASA Advanced Space Suit xEMU Development Report – Waist Brief Hip*

Kristine Davis (NASA), Jaren Grimes (NASA) and Chanel Stephens (NASA).

For the past several years, the Exploration Extra-Vehicular Mobility Unit (xEMU) team at NASA's Johnson Space Center has focused on the development and detailed design 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 baseline detailed design of the xEMU Waist Brief Hip (WBH). This paper will outline the challenging technical requirements, significant architectural trades, technical solutions required to overcome these challenges, and a current status of the detailed design. The preliminary results of Design Verification Testing (DVT) as it relates specifically to this hardware will also be provided, along with a forward strategy for final maturation into a flight-ready design.

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[263] *NASA Advanced Space Suit xEMU Development Report – Lunar Boots*

Shane Mcfarland (NASA) and Zachary Fester (NASA).

For the past several years, the Exploration Extra-Vehicular Mobility Unit (xEMU) team at NASA's Johnson Space Center has focused on the development and detailed design 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 baseline detailed design of the Lunar Boots. This paper will outline the challenging technical requirements, significant architectural trades, technical solutions required to overcome these challenges, and a current status of the detailed design. The preliminary results of Design Verification Testing (DVT) as it relates specifically to this hardware will also be provided, along with a forward strategy for final maturation into a flight-ready design.

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[264] *NASA Advanced Space Suit xEMU Development Report – Integrated Communication System*

Ian Meginnis (NASA) and William Foster (NASA/ERC Inc.).

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 Integrated Communication System (ICS). 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 the ICS are also provided, along with a forward strategy for final maturation into a flight-ready design.

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[265] *NASA Advanced Space Suit xEMU Development Report – Environmental Protection Garment*

Maria Flores-Daley (NASA) and Bobby Jones (NASA).

For the past several years, the Exploration Extra-Vehicular Mobility Unit (xEMU) team at NASA's Johnson Space Center has focused on the development and detailed design 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 baseline detailed design of the Environmental Protection Garment (EPG). This paper will outline the challenging technical requirements, significant architectural trades, technical solutions required to overcome these challenges, and a current status of the detailed design. The preliminary results of Design Verification Testing (DVT) as it relates specifically to this hardware will also be provided, along with a forward strategy for final maturation into a flight-ready design.

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[266] *Modeling of Fabrics and Pressurization for Actively Tensioned Mechanical Counter Pressure Spacesuit*

Akshay Kothakonda (Massachusetts Institute of Technology) and Dava Newman (Massachusetts Institute of Technology).

Extravehicular Activities (EVAs) will be vital to future human spaceflight missions to the moon and Mars. Not only are EVAs the most visible part of a human planetary mission, as seen during the Apollo missions, they are also pivotal in maximizing scientific output from these missions. Design of spacesuits that impose the least impediment to natural human movement and augment astronauts' capabilities during EVA remains an area of active research. A Mechanical Counter Pressure (MCP) spacesuit promises to significantly improve mobility and minimize metabolic workload over a traditional gas pressurized suit by replacing gas pressure with contact pressure of a tensioned fabric directly against the body. Several engineering challenges remain before such a suit can be used operationally. Specifically, this paper addresses providing uniform MCP of 29.6 kPa over the body, enabling easy don and doff, and minimizing mechanical work from the astronaut during suited movements. The bidirectional actuation of two-way Shape Memory Polymers (2W-SMPs) is proposed to provide controlled MCP while allowing for easy don/doff. Analysis is carried out to estimate the most optimum polymer, in terms of highest MCP produced for a given manual force input. Two common fabric types were analyzed- a woven fabric and a jersey knit fabric. Planar nonlinear finite element analysis (FEA) models to analyze the deformation of these fabrics were developed, and these will be implemented on the body surface and integrated with SMP thermomechanical model to simulate strains and pressure distributions under suited movements. FEA simulation results will inform the fabric pattern that transmits the required MCP tensioning force while minimizing mechanical work during movements.

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[267] *The Microbiology of Microgreens Grown in Controlled Environment Chambers under ISS Conditions*

Mary Hummerick (Amentum Services), Aaron Curry (Amentum Services), Jennifer Gooden (Amentum Services), Cory Spern (Amentum Services), Lashelle Spencer (Amentum Services), Matthew Romeyn (NASA) and Jason Fischer (Amentum).

Microgreens have been identified as a new type of pick-and-eat salad crop that can be utilized in space crop production systems. The majority of traditionally grown leafy green crops can be grown as microgreens, in addition to crops such as legumes, sunflower, buckwheat, most herbs, and corn, presenting hundreds of microgreen crop options. Notably, microgreens are nutrient dense, high in beneficial compounds like antioxidants, Vitamins C and K, and exhibit a variety of desirable flavors and textures. The short growth cycles (7-14 days), low water requirements and volume optimization potential make them a viable option for sustainable production of nutritious and flavorful crops in space. The crop production team at Kennedy Space Center is investigating the food safety aspects of microgreens grown under spaceflight relevant conditions for crew consumption. Microbiological analysis and screening for potential foodborne pathogens was performed on over 20 varieties of microgreens that have demonstrated positive horticultural attributes. Additionally, a comparison of microgreens grown hydroponically under ISS environmental conditions and similar varieties from local markets was completed to collect baseline data on the microbial load on microgreens. In an effort to improve

microgreen quality, strategies to reduce the microbial load were tested, including bulk seed sanitization, harvest age, exposure to high blue light, and post-harvest chemical disinfection. The efficacy of a citric acid-based produce wash currently used for ISS grown produce and 1% H_2O_2 were investigated at different exposure times for reduction in bacterial and fungal counts on a variety of microgreens. Limited log reduction was achieved depending on exposure time. Our testing also demonstrated that seed sanitization impacted microbial load on microgreens and systems.

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[268] *Validation of a Human Thermal Model for Assessing Crew-Induced Loads in Spacecraft*

Timofey Golubev (ThermoAnalytics, Inc.), Mark Hepokoski (ThermoAnalytics, Inc.), Mark Klein (ThermoAnalytics, Inc.), Allen Curran (ThermoAnalytics, Inc.) and Hee Jong Song (NASA Johnson Space Center).

Human space exploration missions that require exercise prescriptions at high metabolic rates for the crew can make sizing the Environmental Control and Life Support System (ECLSS) challenging. An accurate human model is needed to calculate O_2 consumption and the production of CO_2, water, and metabolic heat of astronauts during exercise. In typical human thermal models, clothing is often not rigorously considered, but treated simply as a boundary condition at the skin described by its thermal and evaporative resistances. While this approach may be sufficient for modeling humans operating at relatively low metabolic rates, a clothing thermal model that does not explicitly consider the transport of moisture and heat through individual clothing layers can yield incorrect results in scenarios involving high activity levels. Additionally, many human models do not track the amount of sweat that accumulates on the skin or within the clothing during exercise; this sweat may only evaporate after the exercise routine is finished. Tracking all moisture sources is essential for the calculation of crew-induced loads. To address these limitations, in previous work, we developed and validated a clothing model that considers heat and moisture transport within the fabric layers. The clothing model was integrated within the TAITherm Human Thermal Model (HTM), which uses an explicit geometric representation of the human body to predict thermo-physiological state by resolving the body in terms of its individual tissue thermal properties and simulating its thermoregulation mechanisms. In this paper, we describe validation of the model for simulating crew-induced loads during periods of vigorous exercise. The HTM's predicted total moisture output is within 23g of a linear fit through measured values from human subject tests performed at NASA. This study lays the groundwork for conjugate assessments between crew and spacecraft for evaluating an exploration vehicle's thermal control, environmental control, and life support systems.

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[269] *Microgravity Effect on Bacterial Growth: A Literature Review*

Wenyan Li (URS Federal Services), Angie Diaz (URS Federal Services Inc), Tesia Irwin (The Bionetics Corporation), Aubrie Orourke (NASA) and Luz Calle (NASA).

Gravity is a well-known, but little understood, physical force. It interacts with other physical environmental factors to impact the formation of today's Earth, and to contribute to biological variations between water and land species. It is also involved with cell differentiation process, and is responsible for setting the boundaries for life and keeping the cells small. With their simple structures and small sizes, microbes are expected to be less gravity sensitive than larger species. Nevertheless, various effects of space flight on bacterial growth have been reported, but the reports have been sometime inconsistent, and the underlying mechanism remains unclear to many. This paper summarize the systematic efforts to evaluate the effect of space flight on microbial growth, while highlighting the extracellular mass transfer mechanism: bacterial growth is a function of intracellular and environmental factors; the availability of the nutrients and the removal of metabolic by-products, through extracellular mass transfer, are the most important ones. Gravity results in cell settlement and induces density-driven convection within the fluid media, thus impacts the bacterial growth indirectly through the extracellular mass transfer process; where the immediate, direct influence of gravity might otherwise deem negligible.

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[272] *Management of Fecal Waste Utilizing a Hybrid Organic Processor Assembly Unit Designed for Resource Recovery*

Alexandra Smith (University of South Florida), Talon Bullard (University of South Florida), Daniella Saetta (University of South Florida), Ben Hoque (University of South Florida), Celia Devito (University of South Florida), Katrina Haarmann (University of South Florida), Daniel Yeh (University of South Florida), Robert Bair (University of South Florida), Paul Long (University of South Florida), Mark Fehrenbach (University of South Florida), Jason Fischer (NASA) and Luke Roberson (NASA).

Current environmental control and life support system (ECLSS) technologies aboard the International Space Station (ISS) only recycle low strength wastewater (e.g. condensate, hygiene, urine) but not the organic wastes generated by the crew (e.g. fecal and unutilized food), these are considered a solid waste and processed as solid waste. The high water content (fecal material being ~75% water), complexity, high organic strength, and the presence of pathogens make fecal waste

difficult to stabilize and process. An organic processor assembly (OPA) unit was developed through collaboration between the University of South Florida and NASA's Kennedy Space Center to address the need to improve on the current fecal collection process. OPA1 is comprised of a hybrid technology that couples an anaerobic bioreactor with a tubular ultrafiltration membrane (AnMBR) designed to treat and recover resources from the solid organic waste stream of a crew of four astronauts on an early planetary base. Organic wastes are a rich source of nutrients (e.g. N,P,C). These can be recovered to supplement a fertilizer and water demand for potential in situ food crop and algae production, boosting crew nutrition and overall mental well-being. Aspects of OPA1's initial run on a waste simulate was presented at ICES 2021. This conference paper will present OPA1's current operating parameters of running for over 200 days, treating actual canine feces as a surrogate for crew metabolic wastes, showing the removal of 93% chemical oxygen demand (COD) and the retention of 99% total suspended solids to the bioreactor while recovering soluble nitrogen in the form of ammonia within the permeate. Overall, preliminary data highlights OPA1 as a capable candidate to bridge the gap between waste management and resource recovery as a next-generation technology capable stabilizing a problematic solid waste while treating and recovering resources from all available waste streams.

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[273] *Experience of Water Supply Systems Working on the ISS Russian Segment and Development Prospects*

Petr Andreychuk (RSC Energia), Sergey Romanov (RSC Energia), Alexander Zeleznyakov (RSC Energia), Leonid Bobe (NIICHIMMASH), Alexey Kochetkov (NIICHIMMASH), Alexander Tsygankov (NIICHIMMASH) and Dmitry Arakcheev (NIICHIMMASH).

The SRV-K system for water regeneration from humidity condensate, the ASU-SPK-U system for receiving and preserving urine and the water reserve system SVO-ZV – Rodnik are working in the Russian segment of the ISS for 21 years. Since 2018 the urine water regeneration system SRV-U is undergoing flight tests. Until the end of 2008 water supply of the ISS was provided by the systems of the Russian SM service module. Since the end of 2008 the water supply systems SRV-K, ASU-SPK-U, SVO-ZV of the Russian segment and the urine processor UPA and the water processor WPA in the American segment are working in parallel on the ISS. In addition, the Russian-developed ASU-SPK-U toilet with interface units was installed in the American segment of the ISS. During the period under review, extensive experience was gained in operating systems and improving them directly in flight, data on the water balance at the station, the efficiency of regeneration processes, energy and mass consumption, and features of the operation of separation and heat and mass transfer equipment in microgravity were obtained. It was accumulated experience of interaction in managing the operation of systems in the RS and AS of the ISS. Based on the experience of operating water supply systems, it is concluded that after appropriate improvements, modern systems would be the basis for water supply for promising space missions. The report discusses the experience of water supply systems for the Russian segment from the ISS-1 to ISS-66 expeditions. Technical data on the SRV-K system for water regeneration from humidity condensate and the ASU-SPK-U system for receiving and preserving urine working in the ISS Russian orbital segment are presented. Data on flight tests of the urine water recovery system SRV-U are presented. The tasks of modernizing systems for future flights were discussed.

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[274] *The COSPAR Planetary Protection Knowledge Gaps Workshop Series – An Agency Perspective*

J Andy Spry (SETI Institute), Bette Siegel (National Aeronautics and Space Administration), Elaine Seasly (National Aeronautics and Space Administration) and J Nick Benardini (National Aeronautics and Space Administration).

The COSPAR (Committee on Space Research) workshop series on "Planetary protection requirements for human extraterrestrial missions" has, over several years identified, refined and proposed solutions to a set of planetary protection knowledge gaps for crewed Mars missions. If addressed, closure of these knowledge gaps would represent one path to a successful planetary protection implementation strategy for the first human mission to Mars. As the workshop series completes its work, it can be anticipated that the emphasis will now switch to the COSPAR Planetary Protection Panel, to revisit the Planetary Protection Policy on this topic, and to individual space agencies, to develop plans to integrate the findings and technical solutions into their own mission architectures. The studied knowledge gaps fall into three main topic areas: microbial and human health monitoring (in both habitat and in crew); microbial contamination control and mitigation in spacecraft systems, and; transport and survival of terrestrial life at Mars. A timeline developed from the 2018 workshop described for the first time a detailed path to a tractable end-to-end planetary protection solution for a crewed mission to Mars. This paper provides an update on the current status of NASA policies, approaches, activities and opportunities in this area. In particular, the application of the COSPAR workshop series findings into the Moon to Mars Program is included, covering intra-agency co-ordination of planetary protection-related activities, ISS analogs, lunar surface planning and Mars Architecture Team integration.

[275] ***Solid Oxide Electrolysis Based Lunar PSR Ice Processing System for Propellant Hydrogen and Oxygen Production***

Michele Hollist (OxEon Energy, LLC), Joseph Hartvigsen (OxEon Energy, LLC), Jessica Elwell (OxEon Energy, LLC), S Elangovan (OxEon Energy, LLC), Abel Gomez (OxEon Energy, LLC), Don Claus (OxEon Energy, LLC), Merrill Wilson (OxEon Energy, LLC), Gregory Jackson (Colorado School of Mines), Christopher Dreyer (Colorado School of Mines), George Sowers (Colorado School of Mines), David Dickson (Colorado School of Mines), John Schmit (Colorado School of Mines) and Nasim Emadi (Colorado School of Mines).

In-Situ Resource Utilization (ISRU) of ice from the permanently shadowed regions (PSRs) on the lunar surface presents an opportunity to produce liquid hydrogen (H2) and oxygen (O2) propellant fuels for cislunar transport and exploration of more remote areas of the solar system. OxEon Energy and the Colorado School of Mines (Mines) have teamed to integrate OxEon's high-temperature solid-oxide electrolysis (SOXE) stack technology with an effective and reliable balance-of-plant (BOP) that produces separated H2 and O2 streams from recovered lunar ice. OxEon's SOXE stack technology is used in the MOXIE (Mars Oxygen ISRU Experiment) system that demonstrated O2 production from atmospheric CO2 on Mars in 2021. In a Tipping Point partnership with NASA, OxEon and Mines modeled tradeoffs between efficiency, reliability, and system portability to design a thermally integrated SOXE BOP system. Extensive analysis of initial system models mapped the operating envelope and informed the design of a lab-scale demonstration unit. Fabrication and testing of a 2.5kWe SOXE stack and its associated BOP is approaching completion. Testing in a cryo-vacuum chamber at Mines to simulate the lunar environment will be completed in 2021. Results of system testing in a lunar-relevant environment will be presented. The integrated breadboard system is designed to produce 1.8kg/day of H2 with a system specific power target of 46kWh/kg H2. Initial SOXE stack tests have demonstrated electrochemical compression of the O2 product stream, which will reduce the work and size of the post-processing equipment required to liquify and store LOx . Results from operating the lab-scale system will be used to refine system models and inform a technoeconomic analysis of the system. The improved models and technoeconomic analysis will address the value of scaling up via modular systems versus a single full-scale system for actual lunar PSR application.

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[277] ***ASU SPK-U Toilet System Development and Operation Review and Its Upgrading Plans***

Petr Andreychuk (RSC Energia), Natalia Shamshina (RSC Energia), Leonid Bobe (NIICHIMMASH) and Alexander Pavlov (NIICHIMMASH).

Disposal and sanitary devices (ASU) provides capability to collect crew urine and fecal from earliest Russian human space stations "Salut" and space vehicles "Soyuz" for about forty years. Their design was improved step by step to provide the most convenient toilet for the crew, conditions for the safe storage and disposal of waste, and then the water recovery from urine as part of the regeneration life support complex of the orbital station. Starting from the Mir station, the toilet is based on the SPK-U urine feed, separation and pretreatment system, which provided the possibility of further obtaining water from the urine in the SRV-U regeneration system, as well as long-term safe storage of waste before it is processed or removed from the station. The use of the upgraded ASU SPK-UM system in the Russian segment of the ISS since November 2000 and the same system with the addition of interface liquid units as part of US WHC since November 2008 fully provided the needs of ISS crews for the collection of urine and faeces, as well as reclaiming of water from urine in the US urine processor (UPA) and in the RS experimental system SRV-U-RS. Experience in the operation of ASU SPK-UM systems revealed the advantages and disadvantages of design and circuit solutions and made it possible to begin the modernization of systems for use in orbital stations and manned space vehicles. This paper will provide an overview of the changes in the design of Russian space toilets starting from the Salyut stations, summarize the experience of the operation of ASU SPK-UM as part of the ISS RS, highlight the ongoing developments on the modernization of the toilet for the station and manned space vehicles and plans for the introduction of new developments on the ISS.

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[278] ***Model Development of Large-Scale Spacecraft Fires during the Saffire-IV Experiments***

John Brooker (NASA) and Justin Niehaus (NASA).

An accidental fire can pose dire consequences to crew safety and mission success. The Saffire Project aims to investigate large-scale fire behavior in microgravity in order to aid in the prediction of spacecraft fires. These series of experiments ignite solid materials within the Northrop Grumman Cygnus vehicle after it departs from a resupply mission to the International Space Station. A model of the Cygnus vehicle during the Saffire-IV experiment was developed using the commercial software PyroSim. The cargo arranged during the descent phase was used for the geometry of the model. In the model, cabin air flows into the Saffire payload while heat and combustion species flow out of the Saffire downstream through a standoff to a bed of sensors called the Far Field Diagnostic. The temperature sensors near the Saffire payload were used to determine the heat addition rate at the outlet of Saffire, while the details of the combustion and

stoichiometry are used to determine the species flow at the outlet. Gas measurements previously reported for the Saffire-IV experiments are compared against the simulation results and sources of error are discussed.

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[279] *Demonstration of a Full Size Integrated Greywater Recycling System Combining Biological Pretreatment with Reverse Osmosis*

Ghaem Hooshyari (Texas Tech University), William Jackson (Texas Tech University), Evan Gray (Texas Tech University), Lianfa Song (Texas Tech University), Arpita Bose (Texas Tech university) and Micheal Callahan (Texas Tech University).

Water is a critical limiting factor in long-term space habitation and water recovery systems are essential. Future habitation systems with partial gravity will likely have expanded hygiene activities (e.g. shower) and laundry. These wastewaters greatly increase the volume of wastewater to be treated. The combined hygiene, laundry and humidity condensate (greywater) has low organic carbon (151 mg/L), N (20 mg/L), and TDS (167 mg/L). Removal of the organic carbon allows subsequent use of membrane desalination systems. We demonstrate the operation of a full-size (4 crew/d) membrane aerated biofilm reactor (MABR) to pretreat habitation greywater prior to desalination using a commercially available RO system. Two commercially available membranes are being tested. To date over 8,000 L of greywater has been treated using this process. The bioreactor serves as a common collection tank for all wastewaters added as they are produced. In addition, the bioreactor did not require any start-up period. The bioreactor removed more than 90% of the DOC and total ammonia. The RO membrane (FilmTec) was able to operate for >3 months at moderate pressure (<50 PSI) at a 90% recovery rate. Permeate was near potable quality for DOC (3.5 mg/L), NH_3 (0.2 mg/L), and TDS (6.5 mg/L). The production of permeate decreased over the 3 month period from 106.6 L/d to 57.6 L/d. Testing of the second membrane (AQUAPORIN) is ongoing. Our results highlight the ability of combined biological and membrane-based desalination to produce potable water with minimal consumables.

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[280] *Solid Oxide Electrolysis Cathode for Increased Robustness for ISRU Application*

Tyler Hafen (OxEon Energy, LLC), Taylor Rane (OxEon Energy, LLC), Dennis Larsen (OxEon Energy, LLC), Jenna Pike (OxEon Energy, LLC), Joseph Hartvigsen (OxEon Energy, LLC), Jessica Elwell (OxEon Energy, LLC) and S Elango Elangovan (OxEon Energy, LLC).

The production of oxygen for life support and ascent vehicle propellant oxidant is essential for human expedition to Mars. OxEon's team led the development of SOXE stacks for the Mars 2020 mission in collaboration with the Jet Propulsion Laboratory (JPL) and Massachusetts Institute of Technology (MIT). A stack that was installed in the Perseverance Rover has been operated five times so far to demonstrate the production of high purity oxygen by electrolyzing Mars atmosphere CO_2.

Traditionally, SOXE stacks use nickel–zirconia or nickel–ceria composite cathode to reduce the oxidized species. Nickel based electrodes are susceptible to oxidation by the feed gas (CO_2 or steam) at the inlet conditions and are often irreversibly damaged unless reduced species (carbon monoxide or hydrogen) are also present. This necessitates a complex, recycle loop that introduces a fraction of the product gases to the inlet, as was used for the Mars rover mission. Under the SBIR program OxEon investigated a combination of materials and engineering solutions to improve redox tolerance of the nickel-based cathode so that 100% dry CO_2 could be fed directly into a stack without harming the electrode. OxEon has now successfully demonstrated this redox tolerance through the use of a modified nickel-based cathode composition, and a unique backbone and infiltrated cathode structure. Button cells and a stack have been shown to completely tolerate partial and full (i.e., complete oxidation of Ni to NiO before re-reduction) redox cycling, with performance recovery occurring in a matter of minutes using CO generated by the electrolysis reaction. The redox tolerant stack was also demonstrated to show improved coking tolerance over the traditional cathode material. This feature allows higher conversion of CO_2 enabling increased O_2 production.

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[281] *NASA Environmental Control and Life Support Technology Development for Exploration: 2021 to 2022 Overview*

James Broyan (NASA-HQ), Melissa McKinley (NASA-JSC), Imelda Stambaugh (NASA-JSC), Gary Ruff (NASA-GRC) and Andrew Owens (NASA-LaRC).

Over the past year, significant progress has occurred in technology development, ground testing, and ISS technology demonstrations within the NASA Environmental Control and Life Support (ECLSS) community. This paper provides a technology development update in the following capability areas: life support, environmental monitoring, fire safety, and logistics. Technologies for exploration missions must be reliable in their operation which support crewed mission phases. However, they also need to be put into reduced use or dormant states to support uncrewed mission phases and then

successfully and reliably returned to a nominal state to support crew. Multi-year demonstration of systems operation across this range of conditions are essential to mission success. Project overviews will include how the current activity supports the goal of multi-year demonstrations, planned follow-on activities, and what type of exploration mission elements are targeted for infusion. Technologies must be demonstrated and validated early enough to inform early exploration element milestone reviews (mission concept reviews, systems requirement reviews and no later than preliminary design reviews) so that supporting vehicle systems can also be matured.

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[282] ***Modeling and Separation Performance of the Condensate Separator for Microgravity Conditions (COSMIC)***

Robert Jacobi (Paragon Space Development Corporation), Kelly Stukbauer (Paragon Space Development Corporation) and Connor Joyce (Paragon Space Development Corporation).

Paragon Space Development Corp. has developed a COndensate Separator for MIcrogravity Conditions (COSMIC) patent pending technology that harnesses centrifugal acceleration to continuously separate the liquid and gas phases from a high flowrate, high void fraction mixed-phase flow in a compact, low-power design and pump the removed liquid at pressure to a water collection or processing system (WPS). The initial target application is the separation of condensate from the airflow exiting a condensing heat exchanger (CHX) in the Common Cabin Air Assembly (CCAA) on the International Space Station (ISS) or commercial habitats, but its infusion potential extends to thermal and humidity control and water recovery and management for all crewed space missions. This includes Low Earth Orbit (LEO), lunar, and planetary surface habitats as well as deep space, cislunar, and gateway spacecraft. As a versatile liquid-gas separation technology that will operate equally well in micro, partial or full gravity, applications for COSMIC include climate control, water recovery for crew consumption and reuse in plant growth facilities, and separation of mixed-phase products for in-situ resource utilization (ISRU). This paper presents analysis and test results for the performance of the COSMIC engineering development unit (EDU) under flow conditions representative of operations in the ISS CCA. The experimental work utilizes a testbed supplying an airflow with condensate injection upstream of the separator and is performed in an adverse orientation to gravity. Testing has demonstrated the continuous capture and removal of 3.2–6.6 lbm/hr, or 25–50 mL/min, of liquid condensate and slugs up to 500 mL, with a pressure drop below 0.5 inH2O for airflow rates of 25–425 CFM. Test results show that COSMIC is capable of delivering the captured liquid at pressures consistent with delivery to the ISS WPS and excellent water quality with a gas fraction below 0.1%.

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[284] ***Generating Anomalous Regenerable CO2 Removal System Data for Environmental Control and Life Support System Self-Awareness***

Samuel Eshima (University of Colorado Boulder), James Nabity (University of Colorado Boulder), Monica Torralba (University of California Davis), Daniela Ivey (University of California Davis) and Stephen Robinson (University of California Davis).

Human spaceflight beyond Earth orbit will require autonomous deep space habitats that can keep the crew alive when present and keep the habitat “alive” when not. To achieve this goal, the autonomous agent must be both self-aware and self-sufficient. A self-aware Environmental Control and Life Support System (ECLSS) that can perform diagnostics and failure prognostics will be especially crucial towards enabling autonomy. A machine learning-based autonomous agent requires time-dependent data to train, test, and evolve the algorithm. Unfortunately, such data are not available during nominal or anomalous ECLSS operations. The Simulation Testbed for Exploration Vehicle ECLSS (STEVE), a 13X zeolite sorbent bed with CO2-laden simulated cabin atmosphere flow, was developed along with a Simulink and Aspen Adsorption-based computational model of STEVE to produce data of a regenerable CO2 removal system. Experiments and simulations can be conducted at nominal operating conditions and with faults to rapidly generate a diverse set of data. This paper describes the design and development of STEVE and the corresponding computational models. We recommend guidelines for generating data to develop machine learning algorithms for ECLSS self-awareness.

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[285] ***SERFE Water Quality Results***

David Westheimer (NASA), Colin Campbell (NASA), Alicia Contreras-Baker (NASA/Jacobs) and John Steele (MRI).

NASA has been developing a new spacesuit, for over a decade to support missions to the International Space Station (ISS) and also to the Moon. Improvements in the life and robustness of the Portable Life Support System (PLSS) has been a major objective of these efforts. Water quality, and how that impacts the performance of the life support system hardware, are areas where improvements could greatly help to achieve these goals. The Suit Water Membrane Evaporator (SWME) was chosen as the technology to provide cooling to the xEMU and has undergone several iterations of development over this period. An ISS flight experiment centered around the SWME and other thermal loop technologies was developed and has been under test in an ISS EXPRESS rack since November of 2020. In addition to the

SWME, The SWME EXPRESS Rack Flight Experiment (SERFE) contains several technology demonstrations from the xEMU project and has been demonstrating their performance in micro-gravity and over an extended duration. This paper will summarize the results of the water quality analysis performed to date throughout the SERFE testing program. Special care was taken to select materials, process hardware, and control the quality of the feedwater used in SERFE testing so that it would be representative of a thermal control system that could be used on a spacesuit for a lunar mission. In addition, the testing schedule, including periods of quiescence in between tests, was also selected to simulate a real mission profile in ways that would be critical to water quality. Results include data and analysis on microbial activity, biocidal iodine, metals, organic carbon, and several other customary indicators of water quality in an operational system. Testing spans over a year and a half of wetted life of the SERFE Flight Unit and the SERFE Ground Unit.

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[288] *Presence of Metal Aerosols on the International Space Station*

Amanda Rodell (Missouri S&T), Wenyan Li (URS Federal Services), Luz Calle (NASA) and Marit Meyer (NASA).

During 2016 and 2018 Passive Aerosol Samplers (PAS) were placed on vents and filters around the United States Orbital Segment (USOS) of the International Space Station (ISS). Once the samples were collected, they were sent back to earth for analysis using scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDS). This analysis provided size, morphology, and elemental compositions of the individual aerosol particles that were collected. Using filter area, vent flow rate, and the concentration of particles on the samples the airborne concentration was calculated and compared to the standards set by the Occupational Safety and Health Administration (OSHA). All the atmospheric elemental concentrations on the ISS were below 1% of their corresponding OSHA standards. While this analysis does provide us with the first estimate of aerosol levels on the ISS, there are several assumptions that were made throughout this process and further research will be required to validate these assumptions.

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[289] *Carbon Dioxide Removal by Ionic Liquid System (CDRILS): Impacts of Trace Contaminants and Ground Prototype Testing*

Rebecca Kamire (Honeywell International Inc.), Phoebe Henson (Honeywell International Inc.), Stephen F. Yates (Honeywell International Inc.), Emir Rahislic (Honeywell International Inc.), Mark Triezenberg (Honeywell International Inc.), Breydan Dotson (Honeywell International Inc.), Sean Skomurski (Honeywell International Inc.), Jack Ford (Honeywell International Inc.), Eric Pope (Honeywell International Inc.) and Kristen Pedersen (Honeywell International Inc.).

The Carbon Dioxide Removal by Ionic Liquid System (CDRILS) utilizes a continuously recirculated ionic liquid sorbent and hollow fiber membrane contactors for carbon dioxide removal from air. Endurance testing under realistic operating conditions and at realistic scale are critical for demonstration of the feasibility of the technology for revitalization of cabin air in human space missions. CDRILS has undergone challenge testing with trace contaminants and demonstration testing at full-scale on a ground prototype. Common contaminants present in the cabin air of ISS were divided into four groups based on chemical similarity and fed in simulant cabin air at varied concentration to the CDRILS scrubber or dissolved directly into the CDRILS liquid sorbent. The degree of capture and release of the contaminants, as well as the ability of CDRILS to withstand the chemical stressors, were evaluated. No decrease in carbon dioxide removal rate due to any of the contaminants was identified. In addition, the liquid sorbent was aged under simulated operating conditions for further evaluation of system durability. The full-scale CDRILS ground prototype was commissioned and operated as a demonstration of scale, validation of system modeling, and further evaluation of system durability.

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[290] *SERFE Thermal Performance Results*

David Westheimer (NASA), Colin Campbell (NASA), Alicia Contreras-Baker (NASA/Jacobs), Chane Sladek (NASA/JETS) and Glen Waguespack (NASA/JETS).

NASA has been developing a new spacesuit, called the Exploration Extravehicular Mobility Unit (xEMU) for over a decade. This spacesuit is underdevelopment to support missions to the International Space Station (ISS) and also to the Moon. Improvements in the life and robustness of the Portable Life Support System (PLSS) has been a major objective of these efforts. The Suit Water Membrance Evaporator (SWME) was chosen as the technology to provide cooling to the xEMU and has undergone several iterations of development over this period. An ISS flight experiment centered around the SWME and other thermal loop technologies was developed and has been under test in an ISS EXpedite PRocessing of Experiments to the Space Station (EXPRESS) rack since November of 2020. In addition to the SWME, The SWME EXPRESS Rack Flight Experiment (SERFE) contains several technology demonstrations from the xEMU project and has been demonstrating their performance in micro-gravity and over an extended duration. In addition to the SWME, these include two dissimilar water pumps, custom check valves, custom bypass relieve valves, a custom thermal control valve,

development pressure and temperature sensors, and the Thermal Loop Controller. This paper presents thermal and fluids testing results of the system as a whole and of key components.

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[291] *Shape Memory Alloys for Regulating TCS in Space (SMARTS): System Design and Thermal Vacuum Demonstration*

Daniel C. Miller (Paragon Space Development Corporation), Darren Hartl (Texas A&M University), Douglas E. Nicholson (Boeing Research and Technology), Othmane Benafan (NASA Glenn Research Center), Connor Joyce (Paragon Space Development Corporation), Sean Nevin (Boeing Research and Technology), Priscilla Nizio (Texas A&M University), Glen S. Bigelow (NASA Glenn Research Center) and Darrell J. Gaydosh (NASA Glenn Research Center).

NASA has identified variable-geometry radiators and thermal switches as a key technology in their 2020 Technology Taxonomy for enabling human exploration and operations. Variable-geometry radiators provide variable heat rejection capability, or turndown, to meet variable heat loads and environments, as might be experienced in a Lunar habitat or interplanetary vehicle carrying astronauts. Shape Memory Alloy (SMA) actuation offers lightweight, compact, and rugged methods for passive control of morphing radiators that vary geometry, providing turndown, in response to thermal stimuli. Additionally, SMA actuators used to passively activate thermal switches to control conduction paths produce more work output per unit mass than conventional actuators (exceeding an order of magnitude) and other active material actuators, including piezoelectric and paraffin wax actuators. SMAs for Regulating thermal control systems (TCS) in Space, or SMARTS, is an SMA enabled radiator system with thermal switch for adverse heating protection. SMA wires are conductively coupled to coolant passages, providing thermally responsive actuation to open and close the radiator at design temperatures to passively vary heat rejection, ensuring stable coolant outlet temperatures. SMA actuators, conductively coupled to the radiator, respond to adverse heating on the radiator panels by breaking thermal contact between the panel and the coolant passages at design temperatures. SMARTS has been built at a prototype system level and demonstrated in a relevant TVAC environment. Heat rejection comparable to flat panel radiators was demonstrated with the additional benefits of greater turndown than the NASA roadmap target of 6:1 and passive protection to adverse heating conditions. This work demonstrates design and analysis methods employed to tune SMA transition temperatures and predict response to thermal and mechanical loads. Upon project completion, the SMARTS technology is anticipated to be at a technology readiness level (TRL) 6, ready for implementation on upcoming Lunar missions.

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[292] *Preliminary Tests with Variable Conductance Radiator for CO2 Deposition in Deep Space Transit*

Balmore Giron-Olivares (University of North Texas), Huseyin Bostanci (University of North Texas), Cable Kurwitz (Texas A&M University), Grace Belancik (NASA Ames Research Center) and Darrell Jan (NASA Ames Research Center).

NASA's challenging deep space exploration missions demand innovative, reliable, and cost-effective technologies to achieve the required life support systems. An alternative technology under consideration, to replace current solid sorbent-based CO2 removal technology, is CO2 deposition that leverages the different phase change temperatures of air constituents to selectively remove CO2. NASA has recently demonstrated use of Stirling cryogenic coolers to create cold surfaces and deposit CO2 out of flowing air stream. Such cryocoolers are very reliable but require significant energy input to operate. As Mars missions provide a capability to view deep space at environmental temperature of ~4K, thermal radiators are emerging as an opportunity to complement or replace cryogenic coolers. This study investigates an innovative Variable Conductance Radiator (VCR) that could provide modulated and efficient heat rejection technology for CO2 deposition systems. The VCR operates in CO2 capture and CO2 recovery modes in alternating manner. During capture mode, a liquid is circulated through the radiator, transporting heat from the CO2 deposition surface to the heat rejection surface, and creating a low temperature gradient/thermal resistance across the radiator. In recovery mode, the circulating liquid is evacuated and replaced with a stagnant, non-condensable gas, enabling high temperature gradient/thermal resistance across the radiator. During recovery mode, a heater sublimates the deposited CO2 layer and prepares the surface for the next capture period. The prototype VCR system consists of two radiator panels separated by an enclosed space. It features electric heaters to represent heat input during CO2 deposition and dry ice/acetone bath to represent heat rejection to deep space. The prototype is used to evaluate the VCR performance at various operating conditions and obtain results for comparison with simulations. Initial data showed variable conductance, low and high temperature gradient/ thermal resistance across the radiator in CO2 capture and recovery modes, respectively.

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[293] *Microbial Characterization of Heat Melt Compaction for Treatment of Space Generated Solid Wastes*

Mary Hummerick (Amentum Services), Jason Fisher (Amentum Services), Raymond Wheeler (NASA), Tra-My Justine Richardson (NASA, ARC), Michael Ewert (NASA, ARC), Jeffrey Lee (NASA, ARC) and Lawrence Koss (Amentum Services).

One treatment process in development for solid waste management in space has been the Trash Compaction Processing System (TCPS). Heat Melt Compaction (HMC) technology, a TCPS liked hardware, which is operated to reduce trash volume and safen the trash by compaction and heat, while simultaneously removing water. Human space mission wastes typically contain large percentages contaminated wet solid waste. The HMC is being developed to be a multi-function means of water recovery, volume reduction, and the safening of contaminant-rich trash with the potential for waste stabilization and/or sterilization. To determine the efficacy of the HMC treatment to kill microorganisms in solid waste and remain biologically stable, testing was done on three tiles produced by HMC Gen 2 at Ames Research Center. Samples were shipped to Kennedy Space Center to test for microbial viability after compaction, determine the bio-stability of the HMC disks during storage (43 days), and assess potential airborne contaminate microbial growth on surfaces. In addition to the products of waste processing, there is a concern that the crew might come into contact with hardware surfaces that have been contaminated by microorganisms during waste processing. The extent of microbial surface contamination of waste processing hardware was determined by surface sample swabbing and analysis for total bacterial and yeast counts and cultivable counts of aerobic and anaerobic bacteria, spore-forming bacteria, and fungi. Results indicate that trash processing increased bacterial counts on the surfaces of the compacter. All but one biological indicator spore strip imbedded in the tiles were negative for growth after incubation for five days indicating effective sterilization through the heat melt compaction process. Analysis of core samples and surface growth of tiles inoculated with Aspergillus niger fungal spores incubated at three different humidities indicate that HMC created tiles do not support the proliferation of bacterial and fungal growth.

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[294] *Supercritical Water Oxidation: A Promising Wastewater Treatment Technology*

Adrialis Figueroa (University of Puerto Rico), Michael Flynn (NASA Ames research Center), Rosa Padilla (University Space Research Association (USRA)), Daniel Gotti (University Space Research Association (USRA)), Uday Hegde (Case Western Reserve University (CWRU)), Jun Kojima (Case Western Reserve University (CWRU)) and Michael Hicks (NASA Glenn Research Center).

Supercritical water oxidation (SCWO) is a water treatment technology that operates above the critical point of water. The main benefits of SCWO are its ability to completely oxidize organic compounds and mineralize/separate inorganic compounds from wastewater. This suggests SCWO technology can conceptually be applied as a single step water treatment system. Additionally, with proper design and operations it is capable of handling liquid waste streams with high solid loading, thus eliminating the need for extensive pretreatment of the waste stream. This paper provides a description of commercial, academic and NASA developed SCWO reactors. A trade study is presented that shows SCWO is competitive with the International Space Station (ISS) state-of-the-art water recovery systems in all categories except power. However, thermal and mechanical energy recovery approaches are discussed that could be used to reduce SCWO energy consumption to a level that is more competitive with the ISS state-of-the art.

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[295] *SERFE Project Overview*

David Westheimer (NASA), Colin Campbell (NASA), Alicia Contreras-Baker (NASA/Jacobs), Benjamin Greene (NASA), Adam Korona (NASA/JETS) and Shonn Everett (Booz Allen Hamilton).

NASA has been developing a new spacesuit, called the Exploration Extravehicular Mobility Unit (xEMU) for over a decade. This spacesuit is underdevelopment to support missions to the International Space Station (ISS) and also to the Moon. Improvements in the life and robustness of the Portable Life Support System (PLSS) has been a major objective of these efforts. The Suit Water Membrane Evaporator (SWME) was chosen as the technology to provide cooling to the xEMU and has undergone several iterations of development over this period. An ISS flight experiment centered around the SWME and other thermal loop technologies was developed and has been under test in an ISS EXpedite PRocessing of Experiments to the Space Station (EXPRESS) rack since November of 2020. In addition to the SWME, The SWME EXPRESS Rack Flight Experiment (SERFE) contains several technology demonstrations from the xEMU project and has been demonstrating their performance in micro-gravity and over an extended duration. This paper summarizes the design and operation of the SERFE experiment and provides a basis for subsequent papers to focus on more specific aspects of performance of individual technologies.

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[297] *AMORE - Concept Study for a lunar research village*

Michail Magkos (KTH), Anne Stadtmüller (ABK Stuttgart), Yassin Amara (University of Stuttgart), Abhishek Anil (University of Stuttgart), Souktik Bhattacherjee (Jadavpur University), Sisinio Dargent de Vicente (ETH Zürich), Patrick Haffmans (Syddansk Universitet), Nicolas Heinz (University of Stuttgart), Maximilian Hengstmann (University of Stuttgart), Andrea Hinkel (University of Stuttgart), Apoorva Joshi (JSS Science and Technology University), Merve Karakas (University of Stuttgart), Aleksandr Kolchin (Bauman Moscow State Technical University), Christian Korn (Insitute of Space Systems at the University of Stuttgart), Vipul Mani (TU Berlin), Rafael Rivera (University of Puerto Rico Mayagüez Campus), Ilja Skrypnyk (Technische Universität Berlin) and Dominik Tokarz (Warsaw University of Technology).

Interest in creating a lunar base for further space exploration has intensified in recent years. Several companies are working on solving the different challenges in the implementation of such an ambitious project. The scale and intricacy of such a base lead to its need for self-sufficiency. This multinational project needs to: (a) have a technical life-cycle longer than 15 years, (b) be self-sustainable and financially viable, (c) allow for continuous expansion, and (d) maintain the users' well-being. To fulfil these criteria, a base needs to be scalable, modular and sustainable. The mission architecture needs to allow for In-Situ Resource Utilization (ISRU), recycling, crew physical and psychological health, and high performance. Astronauts are the most important resource of any crewed mission. Hence, human factors and architecture are identified as critical aspects. The concept-study Advanced Moon Operations Resource Extraction (AMORE) takes existing designs into consideration but integrates the users' psychosocial health needs. These change with the increasing duration of each crewed mission and the number of crews. Scalability and functional upgrading allow for long-term planning. The layout of the habitat elements supports its growth. The concept that was generated outlines a modular base. It consists of (a) an initial core, (b) a quiet module that accommodates sleeping, social, dining and working areas, and (c) a loud module for working, exercise, noisy subsystems, and common areas. Garden areas are incorporated into both modules and function as the main element of the Life Support System. These modules are large-diameter inflatable cylinders with ellipsoidal tops covered by a composite regolith superstructure. Eight modules serve the needs of a crew of sixteen. This concept allows for the expansion of the astronaut selection pool, elevates the performance of the crews, and nurtures their well-being.

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[298] *Lunar base design concept of DIANA - Dedicated Infrastructure and Architecture for Near-Earth Astronautics*

Alma Kugic (Vienna University of Technology), Madison Diamond (University of North Dakota), Elizabeth Gutierrez (University of Stuttgart), Denis Acker (University of Stuttgart), Adrian Pippert (University of Stuttgart), Nadine Barth (University of Stuttgart), Prishit Modi (University of Stuttgart), Javier Palacios Calatayud (University of Cadiz), Hubert Gross (Rzeszow University of Technology) and Vincent Krein (University of Stuttgart).

The Dedicated Infrastructure and Architecture for Near-Earth Astronautics (DIANA) is a concept for a permanently crewed base on the Lunar South pole with the objectives of furthering space exploration and achieving self-sustainability. The initial base will be autonomously deployed and robotically constructed near the De Gerlache crater ridge. DIANA's architecture and design address the challenges imposed by the Lunar environment alongside structural, technical and habitability requirements.

The construction of DIANA is divided into three phases. Upon reaching the Lunar surface, the modules are autonomously deployed from their compressed state, expanding to a habitable volume. This first phase of the station accommodates four astronauts and includes a multipurpose lab, a window module, a greenhouse, and a common module with cooking facilities and sleeping quarters. The second phase sees the expansion of the base to support eight astronauts. The stations design relies on in-situ resource utilization of regolith to provide radiation shielding and construction materials. The goal of the final expansion is to create a sustainable base that provides better living conditions capable of accommodating tourists and astronauts alike. This is achieved by using enhanced in-situ 3D printing with regolith.

DIANA's interior design has been directly informed by human factors needs promoting physical and mental well-being, optimal performance and safety. Its modules consist of multiple stories both above and below ground. The open layout and interior windows provide visual cues across both rooms and levels. Some unique features include the gym's placement within the greenhouse module, a dedicated window module with dining area and crew quarters which double as a safe haven below ground. Providing a sense of nature and a connection to Earth are mainstays to DIANA and are achieved through private areas for confidential communication with Earth, customizable and personalized furniture and the use of both real and virtual windows.

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[299] *NASA Crew Health & Performance Capability Development for Exploration: 2021 to 2022 Overview*

Andrew Abercromby (NASA), Grace Douglas (NASA), Kent Kalogera (NASA), Jeffrey Somers (NASA), Rahul Suresh (NASA), Moriah Thompson (NASA), Scott Wood (NASA), Emma Hwang (KBR Wyle Services), Kyle Parton (KBR Wyle Services) and James Broyan (NASA).

Radiation, reduced gravity, distance from earth, isolation and confinement, and habitation within artificially created and controlled life support environments are hazards that present risk to human space explorers. In many cases, research is required to characterize those risks and help identify risk mitigation strategies. Where new capabilities are necessary to maintain crew health and performance (CHP) during exploration missions, a multi-step process is followed: 1) a Capability Gap is defined; 2) a plan or "roadmap" to develop that capability is established based on agency priorities and anticipated mission development timelines; and 3) work defined on the roadmap is then initiated as resources allow, with the objective that the capability will be available in time to support the future mission. Over the past year, significant progress has occurred in CHP technology development, ground testbed development, ground-based testing, and in preparations for ISS technology demonstrations. This paper provides a development update in the following capability areas: crew health countermeasures, EVA physiology and performance, food and nutrition, exploration medical capabilities, and radiation. Project overviews will include descriptions of CHP development activities over the past year, the human system risks and capability gaps being targeted, as well as planned follow-on activities and anticipated program infusion points.

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[300] *Crew-Passenger Ratio Implications on Commercial Spaceflight Design & Survivability: A Discrete Event Simulation Framework*

Victor Kitmanyen (Florida Institute of Technology), Hisham Ghunaim (Florida Institute of Technology), Kazuhiko Momose (Florida Institute of Technology) and Luis Otero (Florida Institute of Technology).

As the commercial/private spaceflight industry begins to take off, it is unclear how many professionally trained staff members should be on-board these trips compared to the number of paying passengers. With airlines and cruise ships, for example, there are specific crew-to-passenger ratios that are followed for safety and customer-experience reasons. However, unlike airlines and cruise ships, the current cost of commercial spaceflight is not yet scalable due to the limited reusability of vehicles. Thus, the business factor is highlighted: each crewmember represents the lack of a paying passenger (i.e., expense rather than revenue). Paramount to the economic perspective, an appropriate balance in occupant composition is worth identifying considering the potential for an emergency and the anticipated response/recovery (i.e., survivability). For example, it can be expected that astronauts or professional crewmembers will have far more training and familiarity with responding to an emergency scenario – thereby being able to act faster and more appropriately – as compared to a paying passenger. The dynamics of this dilemma are further exacerbated by other factors (e.g., launch vehicle, crew vehicle capacity, flight duration, destination location, destination volume, destination layout, number of safe havens, time of emergency, type of emergency, etcetera). This paper presents a discrete event simulation approach to studying the relationship between varying crew-to-passenger ratios and evacuation times within the context of a generic, low-earth orbit, commercial spaceflight design reference mission. A conceptual modeling and simulation framework is provided for preliminary feasibility and safety studies in future commercial spaceflight design.

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[302] *Effects of E-Textile Circuit Components on Signal Quality for Wearable Sensing Applications*

Alireza Golgouneh (University of Minnesota-Twin Cities), Brad Holschuh (University of Minnesota-Twin Cities) and Lucy Dunne (University of Minnesota-Twin Cities).

Wearable sensors are an emerging area of interest for next-generation spacesuits. Wearable sensors can be used to measure things like physiological signals or forces experienced by the body to obtain information about crew members' wellness, mobility, and body position. Obtaining this information within rigid, constrained environments such as spacesuits can be challenging and labor-intensive. Requirements of comfort and conformability are often at odds with both functional and durability requirements involved with wearing a sensing layer underneath a stiff suit. Using E-textile components such as conductive threads and rubbers instead of typical electrical components can help manage the comfort/durability requirements of a sensing baselayer for space suit applications. However, flexible e-textile components may influence circuit integrity and sensor signal quality, and lead to inaccurate measurement. This study seeks to quantify the effects of various approaches to integrating soft textile-based electrical connections (such as threads and rubbers) on the responses of soft strain sensors. Changes in Signal to Noise Ratio (SNR) for textile-based piezoresistive and capacitive strain sensors were measured under wearability conditions including three e-textile lead configurations, a body curvature condition, and a skin proximity condition. Effects were most significant for the capacitive sensor. All lead types maintained strong SNR for the piezoresistive sensor, and body curvature did not induce significant changes. Skin proximity (and particularly motion artifacts) affected the capacitive sensor response, but effects were smallest when using conductive rubber leads.

[303] *A Diagnostics Model for Detecting Leak Severity in a Regenerable CO2 Removal System*

Samuel Eshima (University of Colorado Boulder), James Nabity (University of Colorado Boulder), Ayush Mohany (Georgia Institute of Technology), Heraldo Rozas (Georgia Institute of Technology) and Nagi Gebraeel (Georgia Institute of Technology).

Human spaceflight beyond Earth orbit will experience high latency in communication and data transmission requiring autonomous deep space habitats that can keep the crew alive when present and keep the habitat "alive" when not. To achieve this goal, the autonomous agent must be both self-aware and self-sufficient. A self-aware system able to perform advanced diagnostics and prognostics of possible failures will be crucial towards enabling autonomy. Keeping the crew alive will demand a robust Environmental Control and Life Support System (ECLSS), the health of which can be sensed in real-time (self-aware) and appropriate corrective action taken when something's wrong (self-sufficient). To investigate the feasibility for autonomous control of ECLSS, a case study utilized a machine learning-based diagnostics model for a leaky regenerable CO2 removal system. A zeolite 13X sorbent bed processed simulated cabin atmosphere flows laden with elevated levels of CO2. Experiments were conducted at nominal operating conditions as well as with faults to generate a diverse set of data for training the model. For this paper, a leak was introduced into the CO2 removal bed. We present the experimental data, describe model development for diagnostics, and then discuss its validation and performance. This paper will further pose a design framework for self-aware ECLSS that utilizes machine learning-based algorithms.

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[305] *The Spacecraft Water Impurity Monitor, a Framework for the Next Generation Complete Water Analysis System for Crewed Vehicles Beyond the ISS*

Richard Kidd (Jet Propulsion Laboratory), Margie Homer (Jet Propulsion Laboratory), Aaron Noell (Jet Propulsion Laboratory), Jurij Simcic (Jet Propulsion Laboratory), Byunghoon Bae (Jet Propulsion Laboratory), Marianne Gonzalez (NASA Jet Propulsion Laboratory), Valeria Lopez (Jet Propulsion Laboratory), Murray Darrach (Jet Propulsion Laboratory), Stuart Pensinger (NASA Johnson Space Center), Mike Callahan (NASA Johnson Space Center), Evan Neidholdt (KBRwyle) and Nikki Gilbert (KBRwyle).

On-orbit analysis of the total organic carbon (TOC) content of recycled water, as provided by the ISS TOCA, has been an indispensable tool for monitoring the performance of the WRS and for ensuring that water is fit for crew consumption. While TOC has been, and will continue to be an important metric for spacecraft water quality, it provides only limited insight into the total picture. As a measurement, TOC only provides a single "lump sum" quantity of all organic chemicals present in a water sample. Nor does the TOC measurement begin to address inorganic constituents, such as metals resulting from corrosion nor an intentionally-dosed biocide. For exploration missions beyond LEO, the return of water samples to Earth for analysis will be logistically challenging or impossible.

The Spacecraft Water Impurity Monitor (SWIM) is a joint collaboration to develop an instrument platform that will perform in-flight measurements and deliver a more complete picture of water quality to decision makers. Eventually, missions to the moon, Mars, and beyond will be equipped with analytical capabilities equaling those found in terrestrial labs. Based on what we know about current and future spacecraft environments, SWIM will seek to provide enhanced analytical capability that enables NASA to confidently send astronauts on distant missions without the possibility of returned water samples.

This paper discusses the challenges presented by exploration requirements and the research and development progress toward the goal of a total water analysis system. For organic analysis, one of the analysis technologies that the SWIM team have been developing is a liquid-injection gas chromatograph mass spectrometer system; these systems are the workhorses of analytical chemistry laboratories world-wide. For inorganic analysis, the team is exploring a number of technologies ranging from traditional liquid chromatography technologies (e.g. ion chromatography, capillary electrophoresis) to flight-heritage technology such as ion-specific electrodes.

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[307] *Proposed protocols for defining requirements and sizing of media-based filters for spacecraft and planetary lander applications*

Robert Green (NASA), Rajagopal Vijayakumar (AERFIL), Juan Agui (NASA), Gordon Berger (USRA) and Matthew Johnson (Jacobs Technology Inc.).

The air quality control equipment aboard future deep space exploration vehicles provide the vital function of maintaining a clean cabin environment for the crew and the hardware. This becomes a serious challenge in pressurized space compartments since no outside air ventilation is possible, and a larger particulate load is imposed on the filtration system due to lack of sedimentation in low gravity, and can experience short durations of peak dust loading from planetary surfaces for Lunar or Mars landers. The filter industry has established methods to properly size filters for a given

particulate load, but requirements for the space or planetary application introduce additional considerations. In this work, a methodology for evaluating and sizing particulate filters for a Lunar surface pressurized environment will be presented, including estimating the loading and particle size distributions of the loading based on mission requirements. In addition, a scaling analysis from single filter media sheet to full-scale filters for this application, based on recent testing, will also be presented. The results of this study may provide meaningful guidance in early design phase for air revitalization systems utilizing media-based particulate filters for deep space exploration missions.

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[310] *International Space Station as a Testbed for Exploration Environmental Control and Life Support Systems – 2022 Status*

Alesha Ridley (National Aeronautics and Space Administration), Laura Beachy (National Aeronautics and Space Administration), Christopher Brown (National Aeronautics and Space Administration), Paul Caradec (Leidos Innovations Corporation), John Garr (National Aeronautics and Space Administration), Lynda Gavin (National Aeronautics and Space Administration), David Hornyak (National Aeronautics and Space Administration), Christopher Matty (National Aeronautics and Space Administration), Laura Shaw (National Aeronautics and Space Administration) and Katherine Toon (National Aeronautics and Space Administration).

Human exploration missions beyond low earth orbit, such as NASA's Artemis Program, present significant challenges to spacecraft system design and supportability. A particularly challenging area is the Environmental Control and Life Support System (ECLSS) that maintains a habitable and life-sustaining environment for crewmembers. NASA is utilizing the experience gained from its current and prior spaceflight programs to mature life support technologies for exploration missions to deep space. The intent is to establish a portfolio of life support system capabilities with proven performance and reliability to enable human exploration missions and reduce risk to success of those missions. As a fully operational human-occupied platform in microgravity, the International Space Station (ISS) presents a unique opportunity to act as a testbed for exploration-class ECLSS, such that these systems may be tested, proven, and refined for eventual deployment on deep space human exploration missions. This paper will provide an updated status on the testbed development including hardware and ISS vehicle integration progress to date as well as future plans for efforts to design, select, build, test and fly Exploration ECLSS on the ISS.

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[311] *Lessons Learned from the Airborne Particulate Monitor ISS Payload*

Marit Meyer (NASA) and Bettylynn Ulrich (Jacobs Technology, Inc., Houston, Texas 77058).

Particulate monitoring on spacecraft has not been undertaken for air quality purposes until the recent payload on the International Space Station (ISS). The Airborne Particulate Monitor (APM) is a reference-quality instrument technology demonstration that characterized the airborne particles in the ISS cabin in real-time. Onboard aerosols have been measured with this higher fidelity instrument, so future miniaturized low-power aerosol instruments can be reliably compared in future ISS experiments. Several issues were encountered during the payload operations that are a result of the unique environment on ISS, which could not have been anticipated or eliminated by ground testing. First, the ISS had very small amounts of particulate matter in the particle measurement size range of the APM, which was unexpected. Second, despite the measured 'clean' environment, larger debris such as lint accumulated regularly on the cleanable inlet screen, which required regular inspection and crew time. The third issue is that particle emissions measured on ISS depend only on the activities in the immediate vicinity of the particle instrument and total particle concentrations cannot be generalized for the entire module. Finally, the sampling efficiency of APM on ISS is unknown because aisle-deployed instruments attached to wall panels of ISS are in the boundary layer of the large-scale ventilation flow of the modules. These issues are discussed and potential solutions for future particulate monitors are presented.

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[316] *Utilizing Finite Element Analysis (FEA) to Predict Fit and Performance of an EVA Lower Arm Assembly Pressure Garment*

Dillon Hall (Texas A&M University), Bonnie J. Dunbar (Texas A&M University) and Darren J. Hartl (Texas A&M University).

Digital human modeling (DHM) is a developing field of study that has proven useful in human systems engineering to analyze how the design of space systems are influenced by human factors and anthropometrics. The overarching benefit of this analysis is the ability to predict human performance of a design prior to fabrication, which also reduces prototype building and testing costs. Specific to space suit systems, DHM is currently being used to interface 3D scans of human subjects with CAD models of the new Exploration Extravehicular Mobility Unit (xEMU) to determine preliminary sizing of hard components that will accommodate the full anthropometric range of crewmembers. While extensive work has been done to model the influence of hard pressure garment components (i.e. hard upper torso and waist-brief-hip assemblies),

little research exists that analyzes the influence of the multi-layered fabric components of pressure garments on human fit and performance after pressurization. Since finite element analysis (FEA) tools have been utilized extensively to model inflatable fabric pressure vessels for space habitats and other applications, similar FEA tools were applied to a pressurized EVA suit arm (using the EMU as a model). The results of this paper evaluate the effects of the location, number, and size of convolutes on the location of the presumed suit elbow buckle, force and torque required for bending at the elbow, and contact pressures experienced on the arm. The goal of this FEA research is to provide a first step in the modeling framework required to predict and analyze fit and performance for the multilayered "soft" pressure garments. Additionally, the creation of these models will help to better understand which design factors of soft space suit components have the greatest influence on pressure garment fit and predicted performance.

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[317] *Closing the Water Loop for Exploration: 2022 Status of the Brine Processor Assembly*

Stephanie Boyce (Paragon Space Development Corporation), Sunday Molina (Paragon Space Development Corporation), Walter Harrington (Paragon Space Development Corporation), Connor Joyce (Paragon Space Development Corporation), Patrick Pasadilla (Paragon Space Development Corporation) and Philipp Tewes (Paragon Space Development Organization).

Paragon Space Development Corporation developed a Brine Processor Assembly (BPA) for demonstration on the International Space Station (ISS). BPA recovers water from urine brine produced by the ISS Urine Processor Assembly (UPA) via a patented process and ground testing has demonstrated water recovery rates greater than 90% from the previously concentrated urine brine. BPA utilizes the forced convection of spacecraft cabin air coupled with a membrane distillation process to recover purified water from 22.5 liters of brine within a 26 day cycle. By increasing overall water recovery on ISS to greater than 98%, BPA demonstrates a critical capability needed to close the brine processing technology gap identified in NASA's Water Recovery Technology Roadmap. This paper discusses operational progress since launch to the ISS in February 2021.

After installation, checkout, and activation on the ISS, BPA operations were successfully initiated in April 2021. Despite successful nominal operation, crew members expressed discomfort due to malodor from effluent BPA air. After the initial dewatering cycle was completed, it was determined that BPA would need to mitigate odor before on-orbit operations resumed. To address these concerns, an outlet filter system was developed, and an extensive characterization study was conducted to test the efficacy of the filter in reducing odor. This study included analysis of gas, odor, and condensate samples of filtered and unfiltered effluent air during a brine dewatering cycle with an identical BPA ground unit. The filter assembly demonstrated > 85% first pass reduction in odor without detrimental effects to BPA operations. As a result, a similar assembly was launched to the ISS, installed, and BPA operations were resumed in October 2021. This technology achieves an essential capability to enable human exploration of deeper space, and this experiment was an opportunity to identify the importance of human factors in life support spaceflight hardware.

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[319] *Thermal Architecture and Design of the Cruise Heat Rejection System of Mars Sample Retrieval Lander*

Razmig Kandilian (Jet Propulsion Laboratory - California Institute of Technology), Pradeep Bhandari (JPL), Kaustabh Singh (JPL), Keith Novak (JPL), Brian Carroll (JPL), Michael Cox (Jet Propulsion Lab) and Jacqueline Lyra (Jet Propulsion Lab).

NASA and the European Space Agency are planning a Mars Sample Return campaign that would bring Martian regolith and rock samples, collected and cached in tubes by the Perseverance rover, back to Earth for scientific investigation. The Mars Sample Retrieval Lander (SRL) would carry the Mars Ascent Vehicle (MAV) that launches samples tubes into Mars orbit to be collected by an Earth Return Orbiter (ERO) and placed into an Earth Entry Vehicle (EEV) for return and landing on Earth. The baseline design of the SRL spacecraft uses a mechanically pumped fluid loop as primary means of thermal control during cruise to Mars. The heat rejection system (HRS) would be similar to those on previous JPL missions such as Mars Pathfinder, Mars Exploration Rovers, Mars Science Laboratory, Mars 2020, and Europa Clipper. It uses a centrifugal pump to circulate CFC-11 working fluid through the system. The fluid picks up heat from the lander and the cruise avionics and rejects it to radiators located on the cruise stage. The HRS also uses a thermal control valve to modulate fluid flow to the radiator and control heat rejection rate by the system in response to variation in heat dissipation from the avionics as well as changes in the thermal environment. The loop services hardware with varying temperature limits making it challenging to accommodate hardware on the loop with different temperature limits. Heat exchanging would be achieved through the use of flanged tubing bonded to the lander avionics module plate that hosts all the avionics and the battery. This paper discusses the tradeoffs performed before choosing a mechanical pumped loop as the thermal control system. It also describes the analysis, design, and predicted performance of this system.

[322] *The Effect of Trace-Contaminant Sorbent Monolith Geometry on Sorbent Performance*

Marek A. Wójtowicz (Advanced Fuel Research, Inc.), Joseph E. Cosgrove (Advanced Fuel Research, Inc.), Michael A. Serio (Advanced Fuel Research, Inc.), Andrew E. Carlson (Advanced Fuel Research, Inc.) and Cinda Chullen (NASA).

The current trace-contaminant (TC) control technology in the Exploration Portable Life Support System (xPLSS) involves a packed bed of acid impregnated granular charcoal, which is difficult to regenerate and is considered a consumable. The preferred implementation of TC control is pressure-swing adsorption (PSA) using a regenerable sorbent, where TCs are adsorbed in adsorption steps followed by regeneration by exposure to space vacuum (desorption steps). The adsorption-desorption steps are repeated cyclically in parallel beds, which ensures continuous TC removal. The use of sorbent monoliths is advantageous due to the low pressure drop and low fan-power requirement. TC-sorption capacity is an important sorbent property, which, in conjunction with the gas residence time within the sorbent, strongly affects sorbent performance. Sorbent-monolith geometry plays an important role through the complex mass-transfer and sorption/desorption kinetic phenomena that occur within the sorbent structure. In this paper, results are presented on the development of vacuum-regenerable TC sorbents for use in the xPLSS, with the effects of sorbent-monolith geometry studied in sorption-desorption experiments. The sorbents were derived from 3D-printed polymer honeycomb monoliths that were carbonized and oxidized to develop porosity, and also to enhance the TC-sorption capacity by the creation of carbon-oxygen surface complexes. Results are presented on the following aspects of sorbent-monolith geometry: (1) monolith size (volume); and (2) channel cross-sectional shape and size. The use of predominantly microporous carbon monoliths is associated with the following benefits: high sorption capacity; low pressure drop; rapid vacuum desorption; high mechanical strength and resistance to attrition; good thermal management (high thermal conductivity and low thermal effects associated with physisorption/desorption); good resistance to dusty environments; low toxicity and flammability.

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[328] *Assessing Dust Migration Though Pressurized Habitable Volumes*

Elizabeth Marandola (Sierra Space) and William O'Hara (Sierra Space).

Lunar dust is a hazard to both crew and equipment during lunar surface missions. Understanding the properties of dust particles and their interactions with the human body and the damage they can cause to sensitive hardware is essential to mission success. Also crucial to mission success is understanding the movement of dust within a pressurized habitable volume after dust particles have been introduced to the system. Sierra Space, in support of the Dynetics led Human Landing System development program, developed a framework for modeling dust migration patterns and mitigation methods, and mitigation methods to predict dust loading in a pressurized, habitable volume over time. The basis of the migration model is a block diagram which captures the sources of dust intrusion into a pressurized volume and the methods of dust removal. The analytical portion of the migration model incorporates generation rate data, airflow data, and removal efficiencies. The rate data is easily modified by the user which allows for rapid iteration during the vehicle design phase. Requirements levied on crewed systems set limits on astronaut exposure to dust particles of specific sizes at certain concentrations. The resulting dust migration model aids in evaluation of compliance to the dust contamination requirements. This paper details the development of the dust migration model, the process for incorporating key inputs, and integration with additional dust analysis models.

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[331] *Supercritical Water Oxidation: Testing of Ersatz Wastewater*

Michael C. Hicks (NASA - Glenn Research Center), Uday G. Hegde (Case Western University), Rosa E. Padilla (University Space Research Associates), Daniel J. Gotti (University Space Research Associates), Jun J. Kojima (Case Western University) and Michael T. Flynn (NASA - Ames Research Center).

Supercritical Water Oxidation (SCWO) technology is under consideration by NASA for treatment of wastewater and other wet waste streams. The dramatic changes in water’s thermophysical properties near its critical point (374 °C and 218 atm) result in nearly complete solubility of organics and gases. The absence of interphase phase transport processes and phase separation results in dramatically reduced reaction timescales. Organic waste conversions in SCWO are complete and result in product streams that are microbially inert, benign and highly compatible with resource recovery schemes.

This paper first describes the design and construction of a tubular SCWO reactor built at NASA Glenn. The reactor consists of separate “fuel” (i.e., watewater) and oxidizer inlets, which are independently heated and pressurized to conditions near the critical point of water. These independent injection streams are then either (i) premixed or (ii) injected as separate co-axial reactant streams upon introduction into the main reactor chamber, having a volume of 50 cc. The reactor section is heated to desired operating temperatures within a range of 450 °C - 650 °C. A pressure regulator maintains operating pressures between 230 atm and 250 atm. The product stream is captured downstream of the pressure regulator during experiment runs and a separate vent line is used for collection of volatiles.

The results of the SCWO experiments, using proxy waste streams comprising ethanol/water solutions or ersatz wastewater simulants, provided by NASA Ames, are presented. Concentration measurements fomr a Raman diagnsotic system are presented as the metric for the conversion efficacy of the organic and inorganic constituents. Of particualr interest are ammonium compounds, typically found in wastewater streams. Supplementary chemical kinetics modeling results of ethanol oxidation with and without inclusion of nitrogeneous compounds (e..g., ammonia) is also be presented.

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[332] *ECLSS Architecture and Breakeven Analysis for Mission-Flexible LIFE™ Habitat*

Elizabeth Marandola (Sierra Space), Sam Moffatt (Sierra Space) and Laura Kelsey (Sierra Space).

Loop closure for Environmental Control and Life Support Systems (ECLSS) has long been a goal for extended duration crewed missions. Journeys to destinations beyond Low Earth Orbit can take days, months, or years. As the distance from the Earth increases so does the need for efficient life support systems and effective allocations for consumables. Different mission durations have different ideal ECLSS configurations. System mass, crew size, consumables mass, and technology readiness level all factor into designing a suitable ECLSS. Sierra Space's Large Integrated Flexible Environment (LIFE™) habitat is suited to a wide range of low Earth and deep space missions. The flexibility of LIFE necessitates an evolvable and adaptable ECLSS design. To encompass a wide range of potential LIFE missions, ECLSS selections were made for three mission durations: 30 days, 180 days, and 1100 days. A literature survey was completed for each major environmental control and life support subsystem to determine the current state of the art, up and coming technologies, expected operational lifetime, and support services needed. Armed with the information gathered, the team evaluated each subsystem technology against mission needs, logistical limitations, and crew size and made selection recommendations for each mission configuration. This paper summarizes the considered options, resulting integrated systems, and necessary consumables for each of the three mission durations.

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[334] *An Overview of Augmented Reality Solutions for the Enhancement of Space Exploration and Operations*

Kaitlyn Baker (University of Baltimore).

Augmented reality (AR) offers the potential to be a versatile instrument in the completion of complex tasks during space exploration missions. Among countless other applications, AR technology can be utilized to guide astronauts through routine yet vital tasks by providing procedural instructions in real time, assist exploration through GPS functionality, and improve astronaut safety on extravehicular activities (EVA) by means of interaction with the interface and communication between devices.

This paper discusses the distinct capabilities of AR technology as they relate to the facilitation of scientific operations in space, focusing on identifying the requisite characteristics of an AR system in this setting. These characteristics can enhance the informational richness of the astronaut's immediate environment while simultaneously minimizing distraction, hands-on use of the AR system, and attention disruption.

Noted are the shortcomings of such devices in their current standing, as well as potential solutions such as that may be implemented in future iterations to mitigate the problems caused by the current generation's limitations. The workload demanded from the AR Head-Mounted-Display's (HMD) processor can produce a high amount of heat and eyestrain can occur due to the nature of the HMD's lack to mimic a human's ability to focus on an object. Some of the solutions discussed in this paper note on coding techniques that may be implemented to reduce the workload on the HMD's processor, as well as implementing retinal blur to help reduce eye strain. These solutions will improve the functionality of an AR system and help create a device suitable for active fieldwork in a location as uniquely demanding as space.

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[335] *Design of the Portable Offloading for Walking, Exercise, and Running (POWER) Device*

Logan Kluis (Texas A&M University), Deanna Kennedy (Texas A&M University), James Hubbard (Texas A&M University) and Ana Diaz-Artiles (Texas A&M University).

The return to the Moon through the Artemis missions will bring the return of planetary extravehicular activity (EVA). Planetary EVAs will be more complex than the current microgravity EVAs on the International Space Station because of the required ambulation to and from the mission locations. Spacesuits are known to be cumbersome because of poor fit, high pressure, changes in soft material volume during movement, and additional mass. The combination of these factors can lead to suboptimal EVA performance and impact mission operations. Thus, robust modeling of walking factors, such as kinematics, kinetics, and metabolic cost in partial gravity environments would be invaluable to spacesuit design, astronaut training, and mission planning. In addition, these variables provide useful information for future planetary path planning tools. To accomplish the goals of modeling kinematics, kinetics, and metabolic rate in partial gravity, a body weight support system (BWSS) was created using a passive vertical force system attached to a mobile I-beam crane. In this paper, we discuss the design of the vertical body weight support system. One pilot subject was then connected to the

system via a full body harness and was offloaded to varying gravity levels (1g and 0.75g) and ambulated at a constant speed. Finally, minor changes and enhancements are proposed and discussed.

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[336] *Bringing it Home: Finding Synergies Between Earth and Space Construction and Design*

Christina Ciardullo (SEArch+ LLC), Rebeccah Pailes-Friedman (SEArch+ LLC), Michael Morris (SEArch+ LLC), Raymond Clinton (NASA Marshall Space Flight Center), Jennifer Edmunson (NASA Marshall Space Flight Center) and Michael Fiske (Jacobs Space Exploration Group).

The highly specific environmental and design constraints of occupied space habitats has often isolated the efforts of systems designers to aerospace applications, leaving traditional terrestrial architects also isolated from the technological developments available in the space industry. Yet recent efforts to consider surface habitation on the Moon and Mars, as well as efforts in the Earth construction community to push for smart, sustainable, and autonomous habitats have emphasized the natural overlaps between design and construction in all built environment applications regardless of location. The same sustainable development objectives of creating safer, healthier, and more circular economies in the built environment on Earth are shared with the development of safe, healthy, and closed loop habitation systems for space. However, while there is widespread belief in these potential values, and demonstration of spin-off technologies subsequent to space applications development, the ability for space and earth systems to be co-developed simultaneously in practice is examined. This paper describes the process of creating value across multiple stakeholders in the space and earth construction and design industries. By understanding the overlaps between the language and ontologies used by the earth sector to define project objectives with those used to describe space design requirements, a series of venn diagram exercises allowed stakeholders to reveal synergies in Construction Means and Methods, Material Innovation, Human Centered Design, and Sustainable Design Strategies. Many of these overlaps are at the surface intuitive, but the formal identification of these shared values and perhaps more critically, their limitations in practice, provides insight on the potential opportunities and challenges for co-development activities across previously isolated design sectors.

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[338] *Architectural Design of a Human-Centered Lunar Geology Lab*

Adam Oswald (University of Colorado Boulder).

This paper examines factors driving the design of a human-centered geology laboratory on the Moon. In-situ lunar geological research has not been done by humans since the Apollo era, but will be a cornerstone of future lunar research activities. While the International Space Station is the prevailing model for an operational space science laboratory, both the environment and nature of science investigations differ in significant ways on the lunar surface. The operational environment includes pervasive dust, partial gravity, frequent extravehicular activity field work, and challenging thermal, mass, volume, and power constraints. This study explores current best practices for laboratories in space, on Earth, and in analog environments, while taking into account several decades of experience with astromaterials curation from meteorite recovery and robotic sample return missions. Similarly, this study emphasizes the basic tasks of space architecture: typology investigation, structural and systems integration, and understanding crew comfort and performance as key design drivers. As space habitats become longer-duration, increasingly commercialized, and accommodating of a broader diversity of occupants and science objectives, there is a need for future design work to go beyond traditional human factors engineering and emphasize crew performance, comfort, and well-being. A review of space and space analog laboratory architectures and typologies complements heritage space habitat design for ergonomics and the application of best practices for contemporary labs on Earth to define an integrative approach to a human-centered lunar geology lab.

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[339] *Design and Build of HelmHoltz Coils to Generate Hypomagnetic Field for Low Cost Space Biology Experiments*

Terry Trevino (American Military University), Terry Rector (University of North Dakota), Nicholas Vasquez (Washington University), Kolemann Lutz (Magneto Space) and Herve Cadiou (Institut des Neurosciences Cellulaires et Intégratives).

Zero field and near null magnetic field (NNMF) studies demonstrate that a lack of electromagnetic fields beyond Earth’s 20-70uT (2-.7mG) geomagnetic field introduces biological challenges to the health of organisms, bacteria, plants, and humans. Electromagnetic Helmholtz (HH) coils cancel out the Earth's magnetic field and reproduce a highly uniform 3D magnetic field with an MF intensity approaching zero inside the coils.

In 2022, researchers designed and built two HH coils to test the effect of NNMF, PEMF, and Mars Crustal Field (MCF; 300 nT to 5 µT) on plants, microorganisms, and algae in vitro. The first HH coil prototype demonstrated the potential to cancel out Earth’s MF field. Due to the changes in coil radius, substrates, and materials, it is a challenge to create a truly uniform

field accommodating the right current and amplitude. A larger helmholtz coil apparatus (250mm x 240mm x 230mm) is under development with 6 aluminium coils, turns of copper, and 24 3D printed parts. 3D CAD designs of coils and Magpylib free Python Package were used to develop 3D analytical models of magnetic fields and interactions.

Research study discusses and presents softwares, mathematics, subsystem design, materials, images, and build of the first and second generation HH coil prototypes. The research study provides a guidebook to design, build, and test helmholtz coils with COTS parts at orders of magnitude lower cost to enable low cost space biology experiments to sustain biological function in hypomagnetic field (HMF) space environments on Moon, Mars, Venus, and beyond.

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[346] *Responses to Elevated CO2 on Food Production and Life Support Systems in a Mars Habitat*

Grant Hawkins (Over the Sun, LLC), Ezio Melotti (Over the Sun, LLC) and Kai Staats (Over the Sun, LLC).

Plants are highly complex systems with specific responses to the over-supply or deprivation of particular resources and combinations thereof. Elevated atmospheric carbon dioxide (eCO_2) in particular has been linked to responses in the amount of atmospheric CO_2 sequestered, N_2 absorbed from the soil, H_2O vapor produced, edible biomass yield, nutrient composition of edible biomass, and more. In closed-loop ecosystems such as a Mars habitat, the cascading and compounding impacts of these responses on the other biological and mechanical systems can be significant. This study leverages decades of experimental data and modelling of plant responses to eCO_2 (motivated primarily by climate change research) to explore its impact on food production and life support systems in a Mars habitat. A species-specific model of responses to ambient CO_2 on plant CO_2 absorption, transpiration and biomass production is integrated into SIMOC [ICES 2019, 2021], an agent-based model for high-fidelity ECLSS and bioregenerative simulations. Several scenarios are defined with varying combinations of humans, ECLSS components, and different amounts and combinations of crop species. A target CO_2 level is defined for each simulation and the relevant ECLSS components programmed to add or remove CO_2 as necessary to maintain this level. For each scenario, simulations are conducted with the ABM at different target CO_2 levels and system-level impacts are observed. Maintaining elevated levels of CO_2 is shown to not only increase crop yields, but also reduce the load on ECLSS and power production systems. Moreover, combined with the varying responses by different plant species to eCO_2, our results offer new insights into the relative fitness of different crops for cultivation in a Mars habitat.

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[347] *Electrochromic Visors for Advanced Spacesuit Helmets*

Avni Argun (Giner, Inc.), Andrew Weber (Giner, Inc.), David Markham (Giner, Inc.), Kristine Davis (NASA Johnson Space Center) and Tymon Kukla (NASA Johnson Space Center).

NASA's Extravehicular Mobility Unit (EMU) is a personal spacecraft that comprises the spacesuit assembly and life support systems. The current EMU has a manually operated extravehicular visor assembly (EVVA) that uses a reflective gold visor to reduce the intensity of incoming solar radiation. This binary method requires crew members to manually raise or lower the visor depending on ambient light conditions. There is a need for developing an advanced visor system with tunable tinting to provide improved visibility with hands free operation. Integration of a dynamically switching technology with NASA’s next generation spacesuit helmet would provide continuous shading, radiation protection, and optimized light modulation.

Taking advantage of solution processed electrochromic polymers (ECP), Giner is developing a functionally improved alternative to the existing EVVA. Giner’s automated polymer processing on doubly-curved surfaces and electrochromic device fabrication methods are readily adapted to a wide variety of substrates with unique geometries. By combining color-neutral ECPs with transparent electrode coatings, Giner has successfully demonstrated tunable optical switching on curved polycarbonate substrates and obtained high optical contrast (>55% ΔT at 550 nm) with rapid response times (<3 sec). The devices show excellent switching stability (<5% ΔT loss over 1,000 switches), long optical memory (<1% ΔT loss after removal of power at open circuit), and low energy consumption (0.150 watt-Hours per 1,000 cycles for 6” x 10” active area). Fully developed, Giner’s dynamic visor will be compatible for integration with NASA’s new generation spacesuit helmet to allow instant darkening when exposed to sunlight to protect the astronaut’s eyes from solar glare. In addition, the versatile and scalable device platform could provide variable shading on windows used in space stations and vehicles, or on deep space shelters.

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[348] *Effects of Ball Milling on Zeolite powders for use in Additively Manufactured Solid Sorbents*

Tiago Costa (Analytical Mechanics Associates, INC.), Tra-My Justine Richardson (NASA), Tane Boghozian (Analytical Mechanics Associates, Inc.) and Nichole Carder (Analytical Mechanics Associates, INC.).

Zeolite is used as an adsorbent in carbon dioxide (CO¬2) removal systems in spacecraft cabins. Reducing the size of zeolite powder particles may provide uniform particle size distribution and increase the materials manufacturability as a paste for additive manufacturing (AM) or slip casting. This paper will describe the zeolite powder ball milling process and the analysis methods used in characterizing the materials particle size, particle size distribution, surface area, and CO2 gas adsorption. Multi-variable dry ball milling in a planetary ball mill was used as the process for this experiment: the amount of time powder was milled, rotational speed of the milling machine, ball to powder ratio, and ball to jar volume ratio where considered. Virgin powder was compared to milled powder through laser diffraction and SEM imaging techniques.

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[350] *NUtritional Closed-Loop Eco-Unit System (NUCLEUS) for Food Production in Deep Space*

Barbara Belvisi (Interstellar Lab), Jim Rhoné (Interstellar Lab), Graham Gordon (Interstellar Lab), Jérémy Jauzion (Interstellar Lab) and Antoine Pineau (Interstellar Lab).

Interstellar Lab develops controlled-environment modules for sustainable farming on Earth and life support in space. NUCLEUS is a modular ecosystem that produces fresh microgreens, vegetables, mushrooms, and insects to provide key nutrients for long-term space missions. It combines modular autonomous phytotrons with a fluid and electrical distribution network to create a controlled biological system that minimizes water, air, and nutrient inputs. This modular plug-and-play approach minimizes complexity while providing autonomous crop watering and monitoring to reduce human intervention.

Biomimicry allows NUCLEUS to replicate several trophic levels of naturally occurring ecosystems. This closure of the nutrient loop is the next step in cutting-edge bioregenerative life support, supplementing air & water recycling to enable long-term space habitation. NUCLEUS is also designed to minimize critical resource inputs in terms of mass, water, power, and crew time. A 9-unit configuration has been designed for the constraints of the NASA Deep Space Food Challenge, fitting within a volume of only 2 cubic meters. This system weighs 116kg before the addition of water and substrate, needs only 23L of water per year, uses a maximum of 1380W of power, and requires just 4 hours of crew time per week. The result is 62kg per year of fresh microgreens, produce, mushrooms, and insects to eat.

Interstellar Lab's bioregenerative approach is at the core of NUCLEUS. The integration of various species in the interconnected ecosystem makes for an efficient and robust crop cultivation platform. This makes NUCLEUS widely applicable to all types of sustainable food production scenarios, whether in space exploration, emergency relief, humanitarian aid, off-grid homesteads, or even large-scale municipalities.

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[355] *Thermal Amine Scrubber – Operational Status, Optimization & Improvements*

Holden Ranz (Collins Aerospace), Steven Dionne (Collins Aerospace), William Papale (Collins Aerospace) and John Garr (NASA Johnson Space Center).

The carbon dioxide (CO2) removal flight experiment known as 'Thermal Amine Scrubber' (TAS), developed collaboratively by Collins Aerospace and Johnson Space Center, has been operating and scrubbing metabolically produced CO2 from the International Space Station (ISS) over the past 3 years. Since publication of the previous ICES paper, TAS has demonstrated CO2 removal performance close to exploration mission goals and there have been multiple lessons learned for more reliable and effective operation of TAS in the ISS flight environment. Efforts to optimize on-orbit CO2 scrubbing capabilities have included adjustments to system valve programming and CO2 bed thermal cycle characteristics, installation of new hardware for enhanced metrics on performance, and redesign of the system process air blower to yield additional flow-DP performance using the CST-100 fan controller. New hardware including (1) a spare Bulk Water Save valve assembly, (2) inlet and cabin CO2 sensors, and (3) a product CO2 sampling assembly were developed, built, tested, and delivered for launch on Northrop Grumman-14 (NG-14) (1 and 2) and SpaceX-21 (SpX-21) (3), respectively. These components were installed in the payload by crew on the ISS at the end of 2020. In 2021, additional spare hardware was launched on NG-16 and SpX-23, including a new Desiccant Wheel Assembly with an improved gearbox assembly which was installed and activated in September 2021. Anomaly investigations and lessons learned are also discussed including an undersized valve drive motor gear-set and ball valve leakage issue which suspended operation for periods of time. Lastly, further candidate enhancements will be identified along with plans for continued operation of TAS.

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[357] *Experiments on a Loop Heat Pipe with a 3D Printed Evaporator*

Rohit Gupta (Advanced Cooling Technologies, Inc.), Chien-Hua Chen (Advanced Cooling Technologies, Inc.) and William Anderson (Advanced Cooling Technologies, Inc.).

The construction and testing of a loop heat pipe with a 3D printed evaporator is described in this paper. The system was developed as part of a larger engineering demonstration unit for thermal management on NASA's Volatiles Investigating

Polar Exploration Rover. A state-of-the-art 3D printed evaporator, developed in a previous effort, was used in the current system. This evaporator had a cylindrical geometry with a length of 0.1 m and a diameter of 0.025 m and featured a primary wick with a bubble point pore radius of under 8 µm. The vapor, condenser, and liquid lines were constructed from 0.003 m diameter tubing and routed to conform to the geometry of the rover. A thermal control valve was also incorporated in the loop heat pipe to force the vapor to bypass the condenser at a lower-than-threshold temperature. The loop heat pipe was tested successfully under a range of thermal loads of up to 70 W against a mission-expected load of 50 W. Due to startup difficulties observed at the low condenser temperatures, a series of dedicated startup tests were conducted to identify the underlying causes and to study the effects of major variables, such as the heat location and charge quantity. Based on this analysis, a number of changes were identified to help improve the startup performance of the system.

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[358] *Development and Testing of the BioBot EVA Support System*

Charles Hanner (Space Systems Lab), Nicolas Bolatto (University of Maryland), Joshua Martin (University of Maryland), Daniil Gribok (University of Maryland) and David Akin (University of Maryland).

With the resumption of human lunar exploration and plans for eventual Mars landings, extravehicular activities (EVAs) in gravitational environments will again become a primary focus. Geological exploration in early missions will require daily EVAs, rather than the roughly monthly sorties on International Space Station. Even in the reduced gravity of the Moon, EVA system weight on the crew will be the predominant factor in crew performance, fatigue, and safety; the largest single item of which is the weight of the portable life support system. Under NASA NIAC sponsorship, the University of Maryland has been investigating the “BioBot” concept, using a highly capable rover to accompany each EVA crew, carrying their life support system and supplying necessary consumables via a robotically-tended umbilical. During the NIAC Phase 2 effort, a prototype BioBot system has been developed to explore the concept of remotely-tended life support. Field testing accomplished to date includes extended simulated geological traverses performed both with BioBot and with a simulated “conventional” EVA backpack-mounted PLSS. These tests examine the trade-off between decreased on-suit life support weight and increased untethered activity duration in geological and base-servicing scenarios, as early studies have shown the desirability of giving the crew the option to disconnect from the umbilical and perform short traverses untethered from BioBot. This paper presents an overview of the BioBot concept and results from field testing to date, including specifics of the component systems: the rover itself, capable of traversing any terrain suitable for walking in EVA; a robotic umbilical tending system; a spacesuit simulator capable of interfacing to the umbilical, but with some onboard life support to support independent operations as needed; and the sensors, algorithms, and software to provide robust and safe autonomous robotic operations in the vicinity of an EVA crew.

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[361] *Development of an Autonomous Umbilical Tending System for Rover-Supported Surface EVAs*

Nicolas Bolatto (University of Maryland), Robert Fink (University of Maryland), Joshua Martin (University of Maryland), Zachary Lachance (University of Maryland), Rahul Vishnoi (University of Maryland) and David Akin (University of Maryland).

For surface extravehicular activities, no parameter is more impactful on the design of spacesuits than the “weight on the back,” or the weight of the suit system that must be supported by the astronaut under gravity. The portable life support system (PLSS) alone has nearly doubled the weight on the astronaut historically, significantly increasing the exertion required to conduct manned surface activities and drastically curtailing the range of motion of the astronaut due to the movement of the center of mass rearwards and upwards. Both of these negatively affect EVA performance of astronauts; as a result, the capability to offload an astronaut's PLSS would be of great benefit to future EVA operations. The University of Maryland Space Systems Laboratory has been investigating one potential solution to this via its “BioBot” concept, supported by the NASA NIAC program. The overall concept is of a rover carrying the life support system for the EVA crew and supplying consumables via umbilicals. This paper will focus on the critical technology to make this approach viable: the umbilical-handling robot and its associated rover-mounted life support hardware. The robotic manipulator must support both its own weight and that of the umbilical, while keeping close enough to the EVA crew to eliminate the need for additional slack which could snag the umbilical on surface features. This paper details the design of the umbilical-handling robot, which must function as an Earth analog system for human factors testing, and the designs of the umbilical, suit disconnect, and Earth analog life support system. Additionally, this paper describes the sensors and algorithms for smoothly blended motion between the manipulator and the rover, as well as the design implications for the astronaut-following rover itself. Test results to date are also presented and future design modifications discussed.

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[365] *Model and Full-Scale Testing of Outfitting Approaches for Inflatable Habitats*

Nicolas Bolatto (University of Maryland), Colby Merrill (University of Maryland), Ronak Chawla (University of Maryland), Olivia Naylor (University of Maryland), Elizabeth Myers (University of Maryland) and David Akin (University of Maryland).

Inflatable habitats feature prominently in many future space program concepts, but generally there is little focus on how the system transitions from its newly inflated configuration to a fully operational system. The nearest flight analog was the Skylab “wet workshop” concept in the early 1970’s, which was rejected due to the length of time required to outfit an empty volume into a functional habitat. Under support from the NASA Moon to Mars X-Hab program, the University of Maryland has initiated an experimental study of outfitting inflatable habitats to an operational configuration. To keep the study manageable, the team adopted the basic Transhab configuration developed at NASA JSC. The pressure envelope would launch packaged around a central 3m diameter core, which takes all launch loads and contains all necessary systems and components. The envelope would inflate to an 8m diameter, and then be outfitted by moving selected components into the newly inflated volume. Potential agents include both human crew and robotic systems. While the systems were modeled in CAD, it was decided that the large number of potential operations and movement trajectories would be prohibitively difficult to evaluate using only computer graphics. For that reason, an approach was developed which used CAD, a 1/12 scale physical model, and full-scale segments of the habitat for evaluation purposes. The CAD model was used to derive the basic configuration of the central core, and to define major components such as crew compartments, movable and fixed equipment, and utilities including air handling, power, and data. Initial testing was done at 1/12 scale, including human and robotic figures, to consider strategies and test cases. Final testing was done with both humans and robots in the laboratory, and in neutral buoyancy to provide a microgravity environment. Results to date are presented, along with future plans.

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[367] *Experimental Investigation of Minimum Cabin Sizes at Varying Gravity Levels*

Zachary Lachance (University of Maryland), David Akin (University of Maryland), Charles Hanner (Space Systems Lab) and Nicolas Bolatto (University of Maryland).

The return to the development of near-term human exploration missions beyond low Earth orbit has necessitated renewed investigation of low size, low mass, and cost-effective human spacecraft. However, very little experimental data on the effects of smaller cabin sizes on crew performance exists, and that which does is mainly focused on micro-gravity habitation in low Earth orbit and thus not directly extensible to the Moon or Mars. The focus of this research is to experimentally analyze the impact of reducing habitat size on crew performance to determine the minimum effective habitat volume for future manned spacecraft. This paper summarizes ongoing research being conducted by the University of Maryland Space Systems Laboratory with support from the NASA X-Hab program to investigate minimum effective habitat and spacecraft sizing, as well as results and conclusions to date for crew effectiveness within restricted cabin volumes under short-term, high-workload testing conditions. Utilizing modular resizable habitat mockups, tests in habitats ranging from 5 to 25 m3 were conducted in simulated micro, Lunar, and Martian gravities through underwater testing with body-segmented ballasting, as well as a surface Earth-gravity control. The impact of size and configuration on crew effectiveness was measured by timed habitat translations, which are compared along with qualitative data to arrive at spacecraft sizing conclusions. While the underwater environment prevents long-duration studies, thus not allowing for analysis of the psychological impacts of smaller habitat sizes, the short-term, high-workload human effectiveness in varying gravity environments provides new insights into the sizing of future manned spacecraft designs.

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[370] *Additively-Manufactured, Net-Shape Adsorbent Beds for Carbon Dioxide Removal*

Jim Steppan (HiFunda LLC), Keng Hsu (PADT Inc.), Byron Millet (HiFunda LLC), Kai Morikawa (PADT Inc.) and Tom Meaders (HiFunda LLC).

Current and future human space exploration missions require an optimized air revitalization system (ARS) that can reduce the system mass, volume, and power, and also increase reliability. The ARS systems contain a carbon dioxide reduction assembly (CDRA) that is adsorbent-based and is limited in performance because commercially-available packed bed sorbent materials are used. Hierarchical (meso, macro, micro porosity) zeolite-based, monolithic adsorbent beds (MAB) for CO_2 removal were designed and modeled using computational fluid dynamics (CFD). Over 13 different adsorbent test lattice designs were evaluated for pressure drop (□P) and surface area to volume ratio (A/V). CFD modeling results show two designs that offer a significant improvement in both A/V ratio and □P over a packed bed. The MAB were 3D-printed using an aluminosilicate (geopolymer) to bind commercially-available zeolite X13 particles together (3DZeoGeo). The aluminosilicate binder was cured via chemical reaction at low-temperatures, ranging from room temperature (RT) to 400 °C. Proof-of-concept (POC) 3DZeoGeo paste formulations, mixing methods, and 3D-printing on modified commercially-available systems and curing processes were developed and demonstrated for producing MAB. 3D-printed monoliths with zeolite loadings as high as 94 wt % were fabricated and characterized for robustness, mechanical properties, pressure drop, and CO_2 removal efficiency. 3D-printed monolithic zeolite adsorbent beds have the potential to be drop-in replacements for existing packed adsorbent beds with improved mass transfer, heat transfer, and mechanical robustness properties. The new 3DZeoGeo process demonstrated improved 3D-printing processes and paste formulations which have the potential to increase the technology readiness level (TRL) of 3D-printing processes for producing net-shape, monolithic sorbent beds as drop-in replacements for packed sorbent beds such as those in the CDRA.

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[371] *Biologically Reliable Integration and Design for Growth Environments in Space (BRIDGES)*

Davi Souza (Federal University of Rio Grande do Norte), Eran Shileikis (Independent) and Sai Tarun Prabhu Bandemegala (University of North Dakota).

Establishing sustainable architectures beyond existing environmental control and life support systems (ECLSS) into closed ecological environments is of utmost importance for long duration human spaceflight. BRIDGES facilitates the progress from regenerative physicochemical processes to a modular hybrid framework that incorporates a new system; biological life. Modular systems will support scalability and enable increased system closure in both ground-based analogs and reduced gravity environments. This approach seeks to characterize the dominant gas and water dynamics in the microclimate surrounding microgreens by monitoring them in small controlled volumes in test environments. Microgreens are quick and practical sources of edible biomass with high nutritional value, ease of handling, short seed-to-feed period, and minimal resource requirements. Envisioning sensor specifications, locations, and frequency of data acquisition will be the immediate focus to determine the degree of time sensitivity required for autonomous or human response to adverse conditions. Understanding the impact on the ECLSS control algorithm and cultivation feedback loops will be critical for future design considerations that can accommodate the needs of all life. In turn this increases the safety of the crew by detecting and overcoming faults, failures or other issues that will reinforce overall system reliability. In summation, BRIDGES aims to standardize the evolution of life support systems using smart agriculture to establish a ground control setup with capabilities such as data acquisition, controls and automation, systemic impact, and risk mitigation. This will lead to a better understanding of synergies between the built environment and the natural environment before introducing ecological habitats on the Moon and Mars.

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[375] *Development of an Inertial and Cold Trap Filter For Carbon Fines Management*

Juan Agui (NASA), Robert D. Green (NASA) and Gordon Berger (USRA).

The Plasma Pyrolysis Assembly (PPA) is a methane processing technology that integrates with the Sabatier Reactor Assembly (SRA) to further advance oxygen loop closure for spaceflight. A problematic reaction byproduct of the PPA is very fine carbon dust which accumulates on the walls of the reactor and migrates to downstream Environmental Control and Life Support System (ECLSS) components with the effluent flow. The reactor is regenerated periodically by generating a CO2 plasma within the reactor to clean the internal walls and microwave stub. To address the flow of carbon dust to downstream components, the PPA will require an effective carbon capture management system. While various methods have been attempted through prototype testing, the effective filtering and regenerative performance of these devices remains a challenge. A new approach is being explored which will provide large carbon dust holding capacity by flow inertial impaction and recirculation and low temperature particle quenching techniques. The technique involves a custom-designed housing to produce a strong and large recirculating pattern to remove the dust through inertial forces and confine it to a large collection cup. The collection cup is enshrouded in a cold trap to quench the PPA effluent and precipitate the remaining carbon from the reaction. The flow then passes through a single stage baffle and tube filters before exiting through the outlet at the top of the housing. A prototype of this concept was built and is being tested with simulant dust. This report will highlight the design and operation of the prototype and provide preliminary test results.

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[381] *Robocast Zeolitic Lattices For Reversible CO2 Sorbent Monoliths*

Joe Cesarano (Robocasting Enterprises LLC), Michael Niehaus (Robocasting Enterprises LLC), Tra-My Justine Richardson (NASA Ames Research Center) and Eric Coker (Sandia National Laboratories).

There is room for improvement for NASA's current systems used to control CO2 levels in a cabin's atmosphere. Currently, packed beds of granules of zeolite are used as sorbents for CO2 in NASA CO2-removal assemblies. Problems and inefficiency associated with packed beds are related to random packing of granules and resulting poor thermal management and poor mechanical stability. An improved system is envisioned with the creation of a sorbent bed in the form of a 3D-printed monolithic lattice.

This presentation will show the potential of the extrusion–based additive manufacturing (AM) technique known as robocasting for fabricating prototype lattices of zeolite 13X that are robust and efficient for reversibly adsorbing and desorbing CO2. 13X by itself is difficult to sinter without inducing a tremendous loss of surface area. Therefore, the use of effective sintering aids (inorganic binders) was explored and assessed for the ability to suitably partially sinter zeolite particles together at temperatures of 725C.

Down-selected binder systems were successfully incorporated into zeolite paste feedstocks suitable for the robocasting process and were shown to have the ability to partially sinter into robust structures while simultaneously retaining relatively high surface area and microporosity. Strength data and adsorption data will be presented.

A further objective was to demonstrate the incorporation of heating elements into a robocast zeolite assembly and show the potential for in-situ desorption of CO2. A stack of 50mm lattice monoliths of zeolite 13X with adequate strength, adsorption capacity, and the ability to be heated to 250C will be demonstrated and the potential for up-scaling to systems capable of controlling CO2 levels in a cabin's atmosphere will be discussed.

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[382] *Designing a hybrid approach for space analog missions in Brazil*

Davi Souza (Habitat Marte), Julio Rezende (Habitat Marte) and Luisa Santos (Habitat Marte).

The COVID-19 pandemic induced a challengefull moment to carry out face-to-face space analog missions in Brazil, given that there could be a spread of the disease if one of the participants was infected, transmitting it to another. In view of this scenario, a proposed innovative methodology for the continuity of Habitat Marte Space Analog Station's operations was virtual missions. Aiming at providing a professional space experience, the participants become involved in activities such as mission planning, including routines scheduling process, and training on topics related to management of habitats, food production, sanitation (water supply, sewage and waste), energy and education. After virtual missions success, participants were invited to collaborate in both in-person and remote activities related to the Habitat Marte protocols and research themes that associate space and sustainability. Habitat Marte operates in the state of Rio Grande do Norte, in the Brazilian semiarid region, and is one of the most innovative projects in stimulating the development of skills in the Brazilian aerospace sector. During the Hybrid Space Analog (HSA) mission type, a trained and experienced team was established for virtual support in the main involved activities and tasks presented during the in-person mission occurrence. On the hybrid moments, the participants at the station meet with the remote crew to meet demands that were presented as tasks and challenges during the mission. Some of the protocols for collecting local data in hybrid missions are: initial survey; psychological protocol; greenhouse monitoring; and final survey. These activities have generated a large volume of data, which has allowed us to provide a variety of studies and publications. With that, face-to-face routines at Habitat Marte are carried out to provide knowledge on operational and research activities while collaborating on technological and operational processes that will support future missions on Moon and Mars.

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[385] *Summary of Research and Outreach Activities during the 2021 Season of the EDEN ISS Antarctic Greenhouse*

Vincent Vrakking (German Aerospace Center), Paul Zabel (German Aerospace Center (DLR)), Markus Dorn (German Aerospace Center (DLR)), Daniel Schubert (DLR) and Jess Bunchek (SURA/LASSO).

The EDEN ISS greenhouse is a space-analogue test facility near the German Neumayer Station III in Antarctica. The greenhouse design, construction, and test phase began in 2015, and the facility was deployed in January 2018. From 2018 until early 2022, the greenhouse was in continuous operation during every winter-over period, with the 2021 season being the latest to be completed. The purpose of the facility is to enable multidisciplinary research on topics related to plant cultivation on future human space exploration missions. Research on food quality and safety, plant health monitoring, microbiology, system validation, human factors, horticultural sciences, and resource demand was conducted. During the 2021 season, research and operation of the EDEN ISS greenhouse was done as part of a DLR-NASA collaboration with an American on-site operator. Part of this collaboration was testing new crops like chili pepper, broccoli, cauliflower, and beans, which had never been grown inside EDEN ISS. These crops were complemented by a variety of lettuces, mustard greens, herbs, tomatoes, cucumbers, radishes, and kohlrabi. In total, approximately 300 kg of fresh produce was harvested during the 2021 season. Frozen and dried plant subsamples were collected and transferred back to Europe and the United States for further investigation. Additional samples were taken from the nutrient delivery subsystem and from surfaces inside the EDEN ISS facility in order to continue the microbiological research activities from previous years. Another research focus was capturing crew time for all activities inside the MTF and select support activities inside NM-III to increase the understanding of work time demand for future food production systems in space. DLR and NASA also continued the numerous outreach activities of the past years. This paper summarizes both the research and the outreach activities during the latest operational season of the EDEN ISS Antarctic greenhouse in 2021.

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[386] *Analysis on the Effect of Flow Interruption in the Oxygen Ventilation Loop on Inspired Carbon Dioxide*

Noah Andersen (HX5, LLC).

The Oxygen Ventilation Loop (OVL) of the Exploration Portable Life Support Subsystem (xPLSS) provides oxygen gas (O2) and removes water (H¬2O) and carbon dioxide (CO2) from the Exploration Extravehicular Mobility Unit (xEMU). The

Rapid Cycle Amine (RCA) uses two cycling beds to remove CO2 and H2O from the OVL. Flow through the OVL is interrupted when the RCA switches between the two beds. This paper discusses an analysis conducted to determine the impact of the OVL flow interruption on the inspired partial pressure of CO2 (ppCO2). The analysis uses a computational fluid dynamics (CFD) model of the upper portion of the Exploration Pressure Garment Subsystem (xPGS) to determine the ppCO2 inspired by the crewmember during the flow interruption. The impact of various parameters on the inspiration of elevated ppCO2 by the crewmember is analyzed. This analysis shows that flow interruption in the OVL causes the first inhale after the interruption to have elevated ppCO2. However, the inspired ppCO2 returns to near nominal values by the second inhale, so the impact of flow interruption on the average ppCO2 is small. The effect of the flow interruption is most significant with high metabolic rates and long flow interruption times.

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[387] *Electrochemically-driven CO2 Removal using Anion Exchange Membranes for Spacecraft Cabin Air Revitalization*

Stephanie Matz (University of Delaware), Brian Setzler (University of Delaware) and Yushan Yan (University of Delaware).

Cabin CO2 removal remains a crucial obstacle to overcome for extended, manned deep space missions. Incumbent state-of-the-art CO2 removal technologies require frequent and costly maintenance. Numerous substitutes are being evaluated for possible replacement including solid and liquid sorbents as well as cryogenics. This work proposes an alternative CO2 removal technology harnessing the alkaline environment surrounding an anion exchange membrane to separate CO2 from air. The electrochemically-driven CO2 separator (EDCS) is a low-cost, compact, continuous device able to effectively separate CO2 at environmental levels and moderate temperatures using only a small hydrogen stream to drive separation. The only products from the EDCS are a CO2-depleted air stream and a CO2-concentrated stream contaminated with unreacted hydrogen and pure water. This paper reports on the development of the EDCS at relevant conditions for cabin air CO2 removal, demonstrating the feasibility of the EDCS in life support applications. At cabin air levels of CO2 (in the thousands of ppm), the EDCS can remove > 85% of CO2 at a ratio of ~2 H2 per CO2 molecule removed at 60 °C. Additionally, the EDCS operation is evaluated to minimize the size of the scaled EDCS stack for a 6-person crew while balancing the CO2 removal and air throughput and minimizing hydrogen consumption. Based on the proposed stack design, a 3.4 L EDCS weighing 12.9 kg could continuously remove CO2 for a six person crew (6.24 kg/day). This is less than 6% the volume and less than 16% of the mass of the existing desicant/adsorbent beds of the Carbon Dioxide Removal Assembly (CDRA) on the International Space Station.

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[388] *A Review of Baseline Assumptions and Ersatz Waste Streams for Partial Gravity Habitats and Orbiting Microgravity Habitats*

Dean Muirhead (Barrios Technology, Jacobs JETS Contract), Stacey Moller (Aerodyne Industries, Jacobs JETS Contract), Niklas Adam (NASA) and Michael Callahan (NASA).

Highly efficient water management and recovery systems will be required to support human missions beyond the low Earth orbit of the International Space Station (ISS). A review of baseline assumptions for the human activities and associated water cycle in surface, partial gravity habitats and orbiting, microgravity habitats is conducted. The paper reviews and updates ersatz formulations and water flow rates for the main liquid water waste streams of urine, humidity condensate, hygiene, and laundry. A framework is provided to coordinate development of water recovery systems for 30-day crew occupancies under partial gravity with longer term, continuous occupancy in orbiting microgravity habitats and the Mars transit habitat.

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[389] *Ionic Silver and Iodine Biocide Losses from Potable Water in ISS-Material Tubes under Stagnant Conditions*

Dean Muirhead (Barrios Technology), Niklas Adam (NASA) and Michael Callahan (NASA).

Combinations of multiple different biocide-treated potable water solutions in multiple tube materials that are used in the International Space Station water distribution system were evaluated to determine the fate of the biocides during storage of water within the tubes. This phase of testing utilized the geometries, surface materials, passivations, and cleaning procedures used for tubes launched with ISS (“legacy tubes”). Results cover the first phase of testing, which used the weekly draining and refilling of tubes with fresh potable water solutions to simulate how the potable water’s biocide interacts with tube walls and how those interactions change with repeated stagnant exposures. Key findings from the test are presented. A comparison of silver loss rates to iodine loss rates indicates that on a molar basis, the loss of iodine concentrations in the 1000 to 4000 ppb range were almost an order of magnitude more than the silver loss rates from the target biocidal range of 200 to 400 ppb. Forward work to maintain ionic silver concentrations at target biocidal

concentrations for potable water is discussed, focusing on optimizing the potable water formulation and the procuring, passivation, cleaning, and conditioning of tube materials.

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[390] *Chemical Vapor Deposition Methane Pyrolysis Enables Closed-loop Oxygen Recovery: Path to Flight*

Amanda Childers (Honeywell International Inc.), Stephen Yates (Honeywell International Inc.), Abigail Parsons (Honeywell International Inc.), Jeff Spencer (Honeywell International Inc.), Jason Smoke (Honeywell International Inc.) and Mehrad Mehr (Honeywell International Inc.).

Deep-space long-duration human exploration missions to Mars will require advanced oxygen recovery technologies. Honeywell Aerospace is developing a methane pyrolysis technology in partnership with NASA that would recover hydrogen from the methane generated by the existing Sabatier unit during recovered carbon dioxide reduction. Complete pyrolysis of this methane to carbon increases the overall system oxygen recovery to almost 100%, while leveraging proven Sabatier technology. Due to the high-temperature, low-pressure pyrolysis reaction, flight-ready reactor hardware must limit heat loss, employ robust materials of construction, and optimize performance. Honeywell is designing a flight-like methane pyrolysis reactor that will utilize advanced materials of construction and state-of-the-art thermal optimization. Computational fluid dynamics (CFD) simulations of the complex hydrogen generation and carbon deposition reactions of methane pyrolysis both in the gas phase and within the internal substrates will be used to optimize maintenance interval and limit consumables. Honeywell will present the technical approach to integrating this technology on the International Space Station for demonstration of a fully closed-loop oxygen recovery system.

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[391] *Clothes Cleaning Research for Space Exploration*

Michael Ewert (Johnson Space Center), Evelyne Orndoff (NASA JSC), Mark Sivik (Procter & Gamble Company, Inc.), Kristi Niehaus (Procter & Gamble), William Shearouse (Procter & Gamble), Jessica Zinna (Procter & Gamble Company, Inc.), Steven Patterson (Procter & Gamble), Dean Muirhead (Barrios Technology) and W. Andrew Jackson (Texas Tech University).

As the National Aeronautics and Space Administration (NASA) plans to establish a sustainable presence on the Moon to prepare for missions to Mars, there is an increased need to find effective and sustainable laundry solutions that are compatible with space travel and reduce the need for clothing resupply. Research and development to overcome resource constraints in space can lead to new products and practices on Earth. This paper describes a collaboration between NASA and Procter & Gamble (P&G) to advance their individual goals as well as provide additional benefits to humanity through more sustainable use of resources. In particular, the two organizations have been working together since August 2020 to advance state-of-the-art, environmentally friendly laundry solutions. Both traditional and novel approaches are being considered and held up against strict resource constraints that may exist in space missions or on Earth in the future. The results of this work are expected to contribute to NASA’s strategic goal of extending human presence deeper into space and to the Moon for sustainable long-term exploration and utilization. Likewise, the collaboration will advance one of P&G’s 2030 corporate sustainability goals by promoting water savings among its 5 billion consumers.

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[393] *Providing Experimental Data for Dust Transport Models Using Novel Technology Aboard a Suborbital Lunar-g Test Flight*

Benjamin Sumlin (Universities Space Research Association) and Marit Meyer (National Aeronautics and Space Administration).

Human activity on extraterrestrial bodies such as the Moon or Mars will necessarily comprise extra-vehicular activity (EVA). Using the Apollo missions as historical evidence, dust will be a significant obstacle in the success of these activities, both during the EVA and upon returning to a pressurized, habitable area. To understand the effects of the artificial atmosphere and reduced gravity on dust transport, modifications to terrestrial equations of motion for dust can be applied to geometries relevant to habitable areas such as airlocks and landers. However, the initial conditions of these models must be assumed, for example, the amount and initial velocities of dust liberated from spacesuit fabric during doffing. To provide such data, an experiment will be flown aboard Blue Origin’s New Shepard platform in 2023, with the goal of measuring the transport behavior of lunar dust simulant as it is released from a small patch of spacesuit fabric which is agitated in a way to mimic doffing. Active and passive dust samplers will analyze time-resolved and time-integrated size distributions at several points throughout the volume of the experiment enclosure. These data will be used as entry points to refine models of lunar dust transport for the upcoming Artemis missions. Future flights may mimic

the gravitational acceleration on other bodies such as Mars. Presented is a description of the dust liberation apparatus, nicknamed ClothBot, along with a description of the flight platform and discussion of stated goals of the experiment.

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[396] *Development of Improved Thermal Analysis Capabilities at the NASA Goddard Space Flight Center*

Hume Peabody (NASA-GSFC) and Eric Yee (NASA-GSFC).

Goddard Space Flight Center (GSFC) has been developing a framework of additional analysis capabilities to aid in the verification, development, and execution of thermal models using the OpenTD Application Programming Interface (API). This paper provides a brief overview of the data structures, properties, methods, and relationships between the objects accessible through the current API and describes some of the algorithms necessary to implement the desired functions at GSFC. Some example code snippets are also provided to aid potential users in the development of their own utilities. Following the overview are descriptions and algorithm methodologies of the new capabilities added to the GSFC framework, including: a new PI heater/controller approach for improved steady state predictions, selective copying of symbol over-rides from one source CaseSet to destination CaseSet(s), comparison of submodel object counts between a source and destination model to verify model integration, comparison of thermo-optical and thermo-physical properties between models, and improved display of extracted thermo-optical and thermo-physical properties for documentation.

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[398] *Inflatable Habitat Structural Health Monitoring via Embedded Fiber Optic Sensors*

Osgar John Ohanian III (Luna Innovations Incorporated), Susan M. Pope (Luna Innovations Incorporated), Bret Heaslet (Sierra Space Corporation), Grant Woods (Sierra Space Corporation), Matthew Morgan (ILC Dover), James Kirwan (ILC Dover), Joseph Welch (ILC Dover), Thomas Carno Jones (NASA Langley Research Center) and Douglas A. Litteken (NASA Johnson Space Center).

Inflatable structures present a novel solution to high volume-to-weight habitation for future space missions. Structural health monitoring (SHM) of flexible softgoods materials cannot be achieved with many traditional techniques. Fiber optic sensors that measure strain every 0.65 mm along the fiber have been embedded in Vectran webbing to measure strain profiles, gradients, and anomalies within these flexible load-bearing structures. The sensors directly address the two leading failure modes of inflatables: creep and micro meteoroid impact. Fiber optic data were collected during creep tests of an individual strap and during a 1.5-month creep test of a 1/3-scale inflatable at NASA Johnson Space Center culminating in a burst. Distributed strain datasets from the embedded fiber optics were compared with photogrammetry/digital image correlation (DIC) results. System integration studies detailing how the sensing system could be included in future space deployments of inflatable habitats for increased reliability is also presented.

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[400] *Testing and Evaluation of Ultra-Thin Loop Heat Pipe as Lightweight Flexible Thermal Strap for Spacecraft*

Hosei Nagano (Nagoya University), Takuji Mizutani (Nagoya University), Satoshi Kajiyama (Nagoya University), Yuki Akizuki (Japan Aerospace and Exploration Agency) and Yoshihiro Machida (Shinko Electric Industries Co., LTD).

Thermal strap with high thermal conductance are required. Usually, thermal strap is made of high thermal conductive materials such as copper, aluminum, and graphite sheet. In order to obtain high thermal conductance, the thickness of the materials is increasing, and, as a result, the weight of the strap is increasing. To avoid this problem, this work proposes to apply an ultrathin loop heat pipe (UTLHP) as a thermal strap because the LHP has characteristics of high effective thermal conductivity more than several thousand W/mK even the thickness of the LHP is below 1mm. The thickness of the UTLHP in this work is only 0.6mm, and can operate even bending condition. The UTLHP is made of six layers of pure copper foils. The wick of the UTLHP is made by etching process. Pure water with the freezing point of 0 ℃ is used as a working fluid. In order to apply the UTLHP to the spacecraft, following factors should be guaranteed. -The UTLHP can operate with no degradation even after the working fluid has melted. -The UTLHP can operate with no degradation even in a vibrating environment. -The UTLHP can operate without leakage under a vacuum condition. In this paper, following evaluations were conducted for the UTLHP to evaluate a potential of this UTLHP as a thermal strap for spacecraft; -Thermal performance of the UTLHP before and after freezing. -Thermal performance of the UTLHP begore and after vibration testing. -Thermal performance of the UTLHP under the vacuum condition. The details of the experimental results will be presented in the full paper.

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[401] *A Two-Stage Regenerable Filter for Collection and Disposal of Carbon Fines*

Gordon Berger (USRA), Juan Agui (NASA), Cara Black (NASA), Jeff Mehan (Jacobs), John Holtsnider (Umpqua Research Company) and Bryan McCurry (Umpqua Research Company).

NASA is investigating the use of the Plasma Pyrolysis Assembly (PPA), which is a methane post-processing technology with the goal to recover hydrogen from the Carbon dioxide Reduction Assembly (CRA) currently onboard the International Space Station (ISS). The PPA can theoretically recover 75% of hydrogen from methane produced by the CRA. During methane processing the PPA creates roughly 40 mg/hr of carbon dust when operating at 4 crew member levels. The unwanted fines need to be removed from the stream to prevent any clogging of downstream components. The Regenerable Carbon Filter (RCF) was designed by Umpqua Research Company to address the carbon particulate created in the PPA. The RCF includes two stages. The first is an electrostatic precipitator designed to collect ultrafine particles. The second is a low pressure drop physical filter. Both filters are made of heat tolerant materials to allow regeneration of the filtration capacity by O2 oxidation of captured carbon. This paper will discuss the RCF hardware and test plans.

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[402] *Dragonfly Lander: Terrestrial Thermal Control Techniques on Titan, Saturn's Largest Moon*

Gary Holtzman (The Johns Hopkins University Applied Physics Laboratory LLC), Carl Ercol (The Johns Hopkins University Applied Physics Laboratory LLC), Robert Coker (JHU/APL), James Parkus (JHU/APL) and Elisabeth Abel (JHUAPL).

Dragonfly is a NASA New Frontiers mission that will send a rotorcraft lander to Titan, Saturn's largest moon. Titan has low gravity and a dense atmosphere, making flight an ideal way to traverse its surface, but its atmosphere also provides a way to manage temperatures of Lander components. The atmosphere of Titan is mostly nitrogen, like Earth, and the pressure at the surface is similar, about 1.5 times Earth pressure. The Lander thermal control system (TCS) will use the atmosphere that Titan generously provides to distribute heat from its Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) using a fan, which is one method used to manage previous missions' MMRTGs on Earth. The temperature of Titan at its surface is nearly constant but extremely cold at 94 K, nearly as cold as liquid nitrogen, so the TCS will retain the excess heat from the MMRTG by enclosing the MMRTG and Lander with a layer of insulation. Lander internal components will survive and operate in Earth-similar atmospheric temperature and pressure, and thus mass-efficient terrestrial thermal control techniques will be utilized to keep component temperatures within allowable limits. Lander external components will experience Earth-similar pressure but at an extremely cold temperature, so terrestrial thermal control techniques will be used, albeit attenuated to account for the extreme temperature. This paper will provide an overview of these still-evolving thermal design details with a discussion of the thermal testing campaign.

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[403] *Status and Results of the Spacecraft Atmosphere Monitor Technology Demonstration Instrument*

Murray Darrach (Jet Propulsion Laboratory / California Institute of Technology), Stojan Madzunkov (Jet Propulsion Laboratory / California Institute of Technology), Byunghoon Bae (Jet Propulsion Laboratory / California Institute of Technology), Richard Kidd (Jet Propulsion Laboratory / California Institute of Technology), Frank Maiwald (Jet Propulsion Laboratory / California Institute of Technology), Charles Malone (Jet Propulsion Laboratory / California Institute of Technology), Dragan Nikolic (Jet Propulsion Laboratory / California Institute of Technology), Anton Belousov (Jet Propulsion Laboratory / California Institute of Technology), Fang Zhong (Jet Propulsion Laboratory / California Institute of Technology), Jurij Simcic (Jet Propulsion Laboratory / California Institute of Technology), Margie Homer (Jet Propulsion Laboratory / California Institute of Technology), Marianne Gonzales (Jet Propulsion Laboratory / California Institute of Technology), Vachik Garkanian (Jet Propulsion Laboratory / California Institute of Technology), Valeria Lopez (Jet Propulsion Laboratory / California Institute of Technology), Cecile Jung-Kubiak (Jet Propulsion Laboratory / California Institute of Technology), Mina Rais-Zadeh (Jet Propulsion Laboratory / California Institute of Technology), Hannes Krause (Jet Propulsion Laboratory / California Institute of Technology) and Tina Tillmans (Jet Propulsion Laboratory / California Institute of Technology).

The Spacecraft Atmosphere Monitor (S.A.M.) is a miniaturized gas chromatograph mass spectrometer (GC/MS) instrument that is being developed for monitoring the cabin atmosphere for human spaceflight missions. The first Technology Demonstration Unit (TDU1) operated successfully aboard the International Space Station (ISS) from August 2019 to July 2021, exceeding its 1 year planned operational lifetime. The TDU1 continuously monitored the ISS cabin atmosphere for the major constituents. In June 2020 the TDU1 was also reconfigured at the request of the ISS vehicle office and successfully determined that there was no benzene leaking into the ISS atmosphere. The technology demonstration unit #2 (TDU2) is scheduled to be deployed on the ISS in 2022. While on-station, TDU2 will continuously monitor the major atmospheric constituents as well as trace organic volatiles. The S.A.M. TDU2 uses the same quadrupole ion trap mass spectrometer (QITMS) sensor as in TDU1, but includes a MEMS preconcentrator, gas chromatograph, and microvalve system. Its miniature, ruggedized form factor allows the S.A.M. to be aisle-deployed to

monitor the cabin in different locations and during activities such as exercise and sleep. The operational performance of TDU1 and the current status of TDU2 will be discussed.

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[404] *Temperature Oscillations in Loop Heat Pipe Operations – a Revisit*

Triem Hoang (TTH Research Inc.).

The oscillatory behaviors sometimes observed in Loop Heat Pipe (LHP) operations can be shown as the byproduct of the system (like all other dynamical systems) operating in certain unstable regimes. A LHP operational stability theory based on an linearized approximation was first introduced in 2014 focusing on the criteria for the appearance of High Frequency Low Amplitude (HFLA) and Low Frequency High Amplitude (LFHA) temperature oscillations for "unforced" external conditions (i.e. the power input, sink & ambient temperatures remain constant). In the current paper, the nonlinear effects shall be taken into consideration to reveal the transient behaviors of the LHP temperatures after the oscillations appear. In addition, test data from several LHPs are used to verify the updated theory.

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[409] *Working Fluid and Material Selection for Heat Pipes and Vapor Chambers for use in Air-Cooled Temperature Swing Adsorption Compression Systems*

Quinton Dzurny (Georgia Institute of Technology), Tra-My Justine Richardson (NASA Ames) and G.P. Peterson (Georgia Institute of Technology).

An air-cooled Temperature Swing Adsorption Compressor (AC-TSAC) has been identified as the preferred Temperature Swing Adsorption Compressor for use in long duration and space exploration missions. The AC-TSAC compresses Carbon Dioxide (CO_2) by thermally cycling an adsorbent material from 20°C to 200°C. Heat pipes and vapors have low mass and a high effective thermal conductivity, and it is desirable to use heat pipes and vapor chambers (HP/VC) in a new AC-TSAC design. For this to be possible, the HP/VC must be properly designed for the 20°C to 200°C temperature range. An important first step of this design process is identifying working fluids and envelope materials that can be used for the HP/VC across this temperature range. In this paper, a detailed selection process is followed to identify said working fluids and envelope materials. Comparison criteria are established, and identified solutions are then compared. This paper details the efforts to find working fluid and envelope material for HP/VC.

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[410] *Propylene Loop Heat Pipe Design and Thermal Performance*

John Thayer (AAVID Thermal Division of Boyd Corp.), Jianbo Jiang (AAVID Thermal Division of Boyd Corp.), Nelson Gernert (AAVID Thermal Division of Boyd Corp.), Sergey Semenov (NASA/GSFC), Deepak Patel (NASA/GSFC), Christopher Stull (Lentech, Inc), Triem Hoang (ATA Aerospace) and Wes Ousley (Lentech, Inc).

A pair of propylene Loop Heat Pipes has been designed, built, tested and delivered for use in cooling the two main Ocean Color Instruments for the Plankton, Aerosol, Cloud, ocean Ecosystem satellite, due to be launched by NASA in 2023. The target operating condition was to convey 15W-25W in the -40C to -20C temperature range. All wetted materials were stainless steel, while aluminum saddles and radiator panels were used to enhance heat spreading. The evaporator wick was 100mm long and used micron scale sintered powder. The radiator, at 660mm x 326mm, was machined from a block rather than being assembled as a composite. Maximum heat transport was measured at 180W. A special round of testing to assess the capacity of the secondary wick qualified the design. The units were delivered in a flat configuration to enable thorough ground testing, and then bent into the final configuration for installation into the instrument.

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[411] *Thermal Vaccuum Testing of a Miniature Propylene Loop Heat Pipe*

John Thayer (AAVID Thermal Division of Boyd Corp.), Jianbo Jiang (AAVID Thermal Division of Boyd Corp.), Nelson Gernert (AAVID Thermal Division of Boyd Corp.), David Bugby (NASA/JPL), Jose Rodriguez (NASA/JPL) and Wes Ousley (Lentech, Inc).

This paper presents the design and thermal vacuum testing of a Miniature Loop Heat Pipe (MLHP) with propylene as working fluid. It is for cooling a prototype lunar power device and so needs to work against lunar gravity. The target operating condition was to convey 20W in the +20C to -30C temperature range. All wetted materials were stainless steel, while an aluminum saddle and radiator panel were used to enhance heat spreading. The outer diameter of the LHP primary wick is 5mm and the length is 55mm. The Bubble test showed a pore radius of 1.2 micrometer. The radiator is 265mm x 270mm. The MLHP was tested at different heat loads, different orientations in the gravity field and two sink temperatures of +20C and -30C. The MLHP thermal performance test included startup and steady state operation. Maximum heat transport limit was found to be 25W and peak conductance 6.6 W/C.

[412] *Thermal Ground Testing of Loop Heat Pipes for PACE OCI*

Sergey Semenov (NASA/GSFC), Deepak Patel (NASA/GSFC), Triem Hoang (TTH Research) and Christopher Stull (Lentech, Inc).

A pair of propylene Loop Heat Pipes (LHP) designed for the Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) Ocean Color Instrument (OCI) was tested in two configurations: flat (minimize the influence of gravity) and flight (bent/final configuration). The testing was conducted in the thermal vacuum chamber at NASA Goddard Space Flight Center facility. The test results are presented along with the lessons learned.

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[416] *James Webb Space Telescope Initial On-Orbit Thermal Performance*

Wes Ousley (Lentech, Inc), Keith Parrish (NASA/GSFC), Shaun Thomson (NASA/GSFC) and Kan Yang (NASA/GSFC).

The James Webb Space Telescope (JWST) is expected to be the premier space based astronomical observatory when it reaches its intended operational temperatures in the Spring of 2022. The cryogenic telescope portion features a deployed 6.5 meter primary mirror, backplane structure, and instrument complement passively cooled below 50Kelvin. Cooling to these temperatures is enabled by an L2 orbit, a 22x10 meter deployed sunshield, and numerous thermal isolation schemes. Proper observatory thermal performance will allow the scientific instruments to observe exoplanet formation, evolution of galaxies, and characteristics of the early universe. Prior to launch, extensive thermal testing was performed on a thermal simulator and the flight telescope to characterize on-orbit thermal performance including the ~120 day post-launch cooldown. This paper focuses on early JWST flight thermal performance, expected cryo-stable temperatures, and comparisons to test results and analytical predictions.

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[417] *Trade Study Analysis of a Cryogenic Oxygen Architecture for Lunar Outpost Life Support*

Thomas Chen (ERC, inc) and Jeffrey Sweterlitsch (NASA).

A trade study was performed to compare the use of cryogenic liquid oxygen (LOX) with high pressure gaseous oxygen (GOX) and electrolysis approaches for Lunar outpost life support, which consists of a surface habitat and pressurized rover. This analysis presents the relevant mission details pertaining to a Lunar outpost architecture, discusses the viable concept of operations (ConOps) for each architecture, and compares the equivalent system mass (ESM) of the cryogenic LOX, high pressure GOX, and electrolysis approaches across different parameter trades, e.g. mission duration or extravehicular activity (EVA) frequency, for the single and 10-year mission architectures. For a single nominal mission, high pressure GOX is favored for short missions (< 50 days); cryogenic LOX is favored for a wide-range of mission durations (50 – 270 days); and the electrolysis approach is favored for long missions (> 270 days). However, when considering a 10-year mission architecture, each additional resupply negatively impacts cryogenic LOX due to the additional replacement tankage. Thus, over a 10-year mission, an electrolysis approach, which can provide all life support O_2 needs utilizing solely recovered H_2O, appears to be favored over cryogenic LOX. However, a real electrolysis system may need resupplied H_2O due to incomplete closure of the air revitalization loop. Thus, the cryogenic LOX approach was compared with the electrolysis approaches utilizing 100% resupplied or 100% recovered H_2O to approximate the resupplied to recovered H_2O ratio, i.e. the degree of loop closure, where one approach trades over the other. Additionally, gaps were identified, which are expected to affect the viability and trade of LOX. These include the development of cryogenic pumps and vaporizers to generate high pressure GOX from LOX as well as understanding payload limitations which can affect O_2 resupply. This analysis highlights the possible viability and favorable trade of cryogenic LOX depending on mission parameters.

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[420] *in-Situ Individual Particle Sizer (iSIPS) apparatus*

Daniel Cantin (INO), Ovidiu Pancrati (INO), Denis Panneton (INO), Jean-Francois Cormier (INO), Sebastien Roy (INO), Simon Turbide (INO), Nafiseh Sang-Nourpour (University Alberta/INO) and Jason Olfert (Aerosol Science and Technology, Department of Mechanical Engineering, University of Alberta).

Aerosols are well known to have significant negative impacts on human health. For space instrumentation, they can also be detrimental to the proper operation and integrity of mechanical device dynamics. Therefore, the continuous monitoring of aerosols and particulate materials in suspension is important for space missions, both inside spacecraft and lander habitation areas and airlocks, and outside for Lunar or Martian missions. To address this important problem, an innovative in-situ particle in suspension monitoring approach is presented. This approach allows for characterization of particle size distribution and concentration based on the Mie theory through forward scattering of light by particulates. It does not require air to be sampled through pumping or ventilators and thus provides a very convenient way to address characterization of particles in suspension in vacuum or low-pressure environments like the Lunar or Martian surface.

Supplemental characterization modalities of particle shape and indicators on composition can be implemented. The latter provides clues on the presence of carbonaceous particles that can be a trigger to assess early detection of fire or slow combustion. First results from a bench top prototype show a size detection limit of 0.3 µm and sizing accuracy of better than 20% on actual size for sebacate oil spherical particles. These also show the relative independence of the particle sizing accuracy with respect to its composition for carbonaceous material particles, while information can be extracted to discriminate sebacate oil particulates from carbonaceous ones. Possibilities to implement fluorescence and polarisation measurements for enhanced information to monitor specific particulate composition and shapes, using easy to integrate supplemental components, is also presented.

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[421] *Development and Testing of a Lightweight Thermal Louver with Single Crystal Shape Memory Alloy*

Yuki Akizuki (Japan Aerospace Exploration Agency), Kenichiro Sawada (Japan Aerospace Exploration Agency), Hirobumi Tobe (Japan Aerospace Exploration Agency) and Hiroyuki Ogawa (Japan Aerospace Exploration Agency).

Space probes need to respond to short-term changes in the thermal environment caused by sunshine and shade during orbit, as well as long-term changes in the thermal environment during interplanetary navigation, where the sun's distance changes significantly. Until now, it has been supported by thermal louvers that control the amount of heat radiation by opening/closing blades with low emissivity, and SRDs whose surface emissivity changes depending on the temperature of the material itself. However, it is difficult to mount it on a small space probe from the viewpoint of mass and heat dissipation performance. In this research, we proposed a Shape memory alloy Thermal Louver (STL). Since the conventional thermal louver uses a spring-shaped bimetal as the drive source, it has a large mass and it is necessary to control the bimetal temperature by the heater. On the other hand, STL is compact, lightweight, and has a high effective emissivity On/Off ratio by using a shape memory alloy. This device uses a reversible actuator as the drive source that combines a single crystal shape memory alloy (SCSMA) and a bias spring, which enables autonomous thermal control according to the temperature of the equipment. In addition, it is lightweight and simple because it consists only of an aluminum frame, blades, and reversible actuators. In this study, a 50W-class STL was design, fabricated and tested. The following tests and evaluation results will be described in the full paper. ・Operation test results of a reversible actuator that combines a SCSMA and bias springs ・Thermal vacuum test results of 50W-calss STL prototype ・Evaluation of STL thermal performance using a thermal analysis model and TVT results

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[422] *Development of an Engineering Model of the Re-Deployable Radiator for Deep Space Explorer*

Kenichiro Sawada (Japan Aerospace Exploration Agency), Yuki Akizuki (Japan Aerospace Exploration Agency), Tomihiro Kinjo (Japan Aerospace Exploration Agency), Hiroyuki Ogawa (Japan Aerospace Exploration Agency), Takeshi Miyabara (Japan Aerospace Exploration Agency), Takakazu Okahashi (Japan Aerospace Exploration Agency), Hiroyuki Toyota (Japan Aerospace Exploration Agency), Kazutaka Nishiyama (Japan Aerospace Exploration Agency), Hiroshi Imamura (Japan Aerospace Exploration Agency), Takeshi Takashima (Japan Aerospace Exploration Agency), Keiji Miyamoto (WEL Research), Kan Matsumoto (WEL Research), Kazuki Watanabe (WEL Research), Hosei Nagano (Nagoya University) and Toshiaki Okudaira (Japan Aerospace Exploration Agency).

Future deep space explorers need a technology that can drastically reduce the power consumption of heaters to enter the outer planets with small spacecraft. We are developing the re-deployable radiator named a Reversible Thermal Panel (RTP), which is a device that autonomously deploys and stows the radiator in response to changes in the temperature of the heat source, stowing the radiator at low temperatures to achieve an insulated state, and deploying the radiator at high temperatures to maximize the amount of heat dissipation. In order to achieve this autonomous thermal control, shape memory alloys are used as actuators, and also use highly thermally conductive graphite sheets as fins to improve heat dissipation efficiency. Japan is developing a deep space demonstrator called DESTINY+ to demonstrate future exploration technologies. For the on-orbit demonstration using DESTINY+, we have been developing an RTP Engineering Model (EM) with a mass of about 1.2 kg and a heat dissipation capability of more than 100 W. In this presentation, we report on the design, fabrication, and testing of an RTP-EM.

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[423] *Planetary and Lunar Environment Thermal Toolbox Elements (PALETTE) Project Year Two Results*

David Bugby (Jet Propulsion Laboratory, California Institute of Technology), Jose Rivera (Jet Propulsion Laboratory, California Institute of Technology) and Shawn Britton (NASA Langley Research Center).

This paper summarizes the technology development progress made through year two of the three year JPL PALETTE project, which is funded by the NASA Game Changing Development (GCD) Program. The overarching goal is to ensure that a full palette of flight-ready (high TRL) thermal "toolbox" elements is available so that engineers can create passive, ultra-isolative thermal designs for science instruments on a variety of carriers in lunar/planetary extreme environments. The PALETTE technical focus areas include enclosures, radiators, MLI, thermal isolators, gimbals, thermal switches, thermal transport devices, thermal storage devices, deployables, and low heat loss feed-throughs. NASA has a renewed focus on lunar/planetary exploration that has resulted in science instruments being developed that are smaller, distributed, and eventually networked. If radioisotopes are to be avoided, existing capabilities will not meet future needs. Science instruments include magnetometers, seismometers, IR/mass spectrometers and several others. PALETTE is structured to meet the need by increasing thermal toolbox element TRL via four design/build/test tasks and four analysis/study tasks. Task 1 involves the development of nested thermally-switched enclosures featuring a new thermal switch that links a reverse-operation DTE thermal switch (ROD-TSW) to a propylene miniaturized loop heat pipe (mini-LHP). Task 2 involves the development of an affordable parabolic reflector radiator (PRR) for low-to-mid latitude lunar instruments. Task 3 involves the development of an ultra-low effective emissivity (e*) multilayer insulation (MLI) known as "spacerless" MLI. Task 4 involves the development of ultra-low conductance (G) thermal isolators. Prototype test results for Tasks 1-4 will be summarized in the paper as will the progress made on Tasks 5-8, the four analysis/study tasks. Task 5 focuses on optimizing gimbaled optical instruments, Task 6 on optimally combining thermal transport/storage/switching to achieve new instrument capabilities, Task 7 on instrument feed-through heat loss minimization, and Task 8 on instrument scalability, extensibility, and planetary use.

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[425] *Advanced Technology Infusion into a Spacesuit Portable Life Support System*

Cinda Chullen (NASA).

Advancement in technology drives our future. Moreover, the successful implementation of a technology drives its possibilities. The National Aeronautics and Space Administration (NASA) has invested in numerous technologies over the decades. A quote from NASA's Space Technology Mission Directorates indicates the importance of technology: "Historically, technology has driven humanity's progress and will continue to define our future. Our nation chooses to invest in new technology not only to maintain our edge in the global economy but also because technology helps us: Redefine the possible; Create a technologically advanced future; and Drive economic growth." It is difficult for a technology to satisfy these goals unless it can be successfully infused into a system. For a technology to continue to evolve, become a reality, and infuse into NASA's missions, there must exist a compilation of success-oriented factors for the technology to reach fruition. Understanding these factors could help decrease the complexity of technology infusion and bridge the gap between technology developers and system integrators. Ultimately, the knowledge gained could facilitate the design, development, and infusion of a technology to be more effective and efficient. Successful technology infusion is complex and can be even more daunting when advanced technologies infuse into complex systems such as a spacesuit portable life support system (PLSS). Overall, there is a need to understand and measure the success of infusing an advanced technology into a complex system. Industry and academia desire understand the infusion process. This paper focuses on advanced technology infusion into a spacesuit PLSS. A discussion of how the infusion began with a schematic study performed and documented in 2007 which influenced and shaped the design of the Exploration PLSS protype for the last 15 years. This research could help NASA and industry's project managers and system mangers integrate advanced technologies more effectively and efficiently.

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[429] *NASA Advanced Space Suit xEMU Development Report – Wired Heart Rate Monitor*

Ian Meginnis (NASA), Christopher Woodbury (NASA/Jacobs Technology, Inc), Jorge Rivera (NASA/Jacobs Technology, Inc), Michael Jennings (NASA/Jacobs Technology, Inc) and Sree Sreedhar (NASA/Jacobs Technology, Inc).

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.

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[431] *NASA Advanced Space Suit xEMU Development Report – Shoulder Assembly*

Ian Meginnis (NASA), Shane McFarland (NASA/Aegis Aerospace), Richard Rhodes (NASA), Jeff Watters (NASA) and David Cox (NASA/Aegis Aerospace).

For the past several years, the Exploration Extravehicular Mobility Unit (xEMU) team at NASA's Johnson Space Center (JSC) has focused on the development and detailed design 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 baseline detailed design of the xEMU Shoulder Assembly. This paper will outline 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 the shoulder will also be provided, along with a forward strategy for final maturation into a flight-ready design.

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[435] *In situ Manufacturing derived from Bioregenerative Life Support Systems*

Robert Morrow (Sierra Space), John Wetzel (Sierra Space) and Sam Moffatt (Sierra Space).

In situ resources from planetary sources can be used in conjunction with a bioregenerative life support system to produce excess biomass which along with miscellaneous waste streams can be used as a feedstock for manufacturing numerous items necessary to support and expand a planetary habitation. Materials that can be fabricated include: structural materials like beams, joists, wall studs, structural cables, and wall and floor panels, doors; furniture items such as tables, chairs, cabinets, beds, and shelves; geotextiles, fabrics for clothing, cushions and bedding; numerous specialty items like filters, plastics, thermal and sound insulation; and useful biochemicals like lubricants, detergents, alcohol, protective coatings, and adhesives. These feedstock materials can also be used in several manufacturing technologies such as compression forming, extrusion, and 3D additive manufacturing. One example is straw fiberboard, which is formed by fiberization and compression, with or without binding agents, and is used commercially as a renewable construction resource. More exotic materials that are produced through synthetic biology techniques, using genetically modified plants to produce materials that could not otherwise be produced in a remote setting, can be processed through biorefining (extraction, separation and purification) techniques before being processed by standard manufacturing techniques. Required processes for using biomass feedstocks can be evolved from information derived from similar processes now or previously used commercially, or that have been developed in the laboratory. A biomanufacturing system could provide a tool to reduce costs of maintaining and expanding a planetary outpost by eliminating the need to transport from Earth either finished items or the raw materials needed to fabricate those items on site. It also provides the means and flexibility to respond to sudden, unanticipated needs including repair or replacement of damaged items, and supports NASA's philosophy for long duration planetary bases to "make what you need where you need it.".