NASA Extreme Environment Mission Operations: First Underwater Spectroscopic Scanning Electron Microscopy

Christopher S. Own[1], J. Martinez[2], T. DeRego[1], L. S. Own[1], G. Weppelman[1], K.T. Thomas-Keprta[2], Z. Rahman[2], D.R. Pettit[3], T. Graff[2], C. Ari D'Agostino[5], S. Pomponi[6], M. Reagan[7]

[1]1001 26th Ave E, Seattle, WA, csown@voxa.co. [2]Jacobs-JETS, NASA Johnson Space Center (JSC), Houston, TX; [3]FOD JSC, Houston, TX; [4]Univ. Southern Florida, Tampa, FL; [5]Florida Atlantic Univ., Boca Raton, FL; [6]EISC JSC, Houston, TX.

Mochii is the world's smallest production electron microscope, scheduled to travel to the International Space Station (ISS) where it will serve as an ISS National Laboratory (ISSNL) facility upon successful demonstration [1-3]. With high native resolution and chemical energy-dispersive X-ray spectrometer (EDS-enabled "S" model), this tiny coffee-maker sized instrument will provide *in-situ* engineering analysis and microgravity mission science on-orbit. Scientific inquiries include morphological, textural and chemical characterization of extraterrestrial samples and impact craters produced by exposure to the space environment, as well as samples from living creatures. Mochii will also enhance crew and vehicle safety by rapidly and accurately identifying microscopic mission threats to guide mission decisions, especially in time-critical situations where debris from damaged systems cannot be sent back. Examples of such critical situations are crewmember Luca Parmitano's waterlogged extra-vehicular activity (EVA) suit in 2013 and the ISS starboard solar alpha rotary joint failure in 2007 where chemical analysis of microscopic particles played a central role in identifying point of failure, source, and problem resolution.

A unique test program for space environment operations and equipment testing is the NASA Extreme Environment Mission Operations (NEEMO), an analog flight-like environment implemented 63 ft. underwater at the Aquarius Reef Base in the Florida Keys [4]. NEEMO missions bring together space mission operators, astronauts, scientists, technology developers, and vehicle specialists who conduct extravehicular activity, perform mission science and conservation on gathered samples, test new technology, and perform medical evaluations benefiting both space and terrestrial applications. Mochii was recently included as part of the 23rd NEEMO mission (June 11-21), where it received dedicated crew feedback on training, procedures, and end-to-end operability. Potential ISS-National Laboratory customers were able to operate Mochii on-vehicle from across the continent while in-mission, similar to planned utilization on ISS. At NEEMO, the Mochii team had full immersion in a NASA operational flight-like environment, and practiced engineering support to be provided to NASA and the public research community as an ISSNL facility in the coming years.

Figure 1. Mochii S installed underwater in Aquarius Reef Base in the Florida Keys.

Technology considerations for spectroscopic electron microscopy in this novel extreme environment, for which conditions exceeded 2.5 atm and 90% relative humidity, included modifications of Mochii's integrated metal coater observation window, and adjustment of automated vacuum processes to protect the spectrometer's X-ray detector window from elevated pressure gradients. Monitoring through remote telemetry indicated that high voltage spark gaps were enhanced by the increased pressure and improved the voltage stability despite increased humidity. Surprisingly, pumpdown cycles were not significantly impacted by the moisture, resulting in routine sample exchanges of 10-15 min. Elevated temperatures were seen at times due to the excess energy from repressurization events in the Aquarius habitat.

Four crew members, (Drs. Ari, Pomponi, Watkins, and Cmdr. Cristoforetti) each conducted *in-situ* analyses on samples acquired from the marine environment on-board and during EVA, using model crew procedures under test for use on ISS. These analyses – of *cnidaria* skeleton, brine shrimp eggs, sediment, and marine sponge as well as pre-prepared samples – additionally model activities at the forefront of exploration on other worlds, for example for future crewed missions to the Moon and Mars. Over multiple visits by crew, plus simultaneous remote analyses by researchers at mission control and across the country, a picture of the diversity and chemistry of the local environment was ascertained. In the cnidarian skeleton, C, O, Na, Ca, and P compounds were identified, common to the reef environment where Ca-shelled organisms are abundant, while sediment consisted primarily of coral and reef crustacean shells and skeletons, plus silica. Marine sponges sampled during EVA had Ca shells and silicate spines. Sulfur and metals important to the ecosystem such as Ni, Fe, Mg, and Al were detected in trace amounts in organic structures. The marine samples imaged surprisingly well without need for the metal coating capability of Mochii, expediting results. An example analysis is that of brine shrimp (*Artemia Salina*) eggs provided by Ari and analyzed by Pomponi showing the diversity of compounds (Fig. 3). The ability to pinpoint at sub-micron scale where these compounds reside will have great significance for exploration activities beyond low earth orbit (LEO), where sample return will be highly selective, and instantaneous analyses can be crucial for time-sensitive decisions.

Figure 2. NEEMO XXIII crew members outside Aquarius Reef Base, located 63 ft. underwater off Conch Reef in the Florida Keys National Marine Sanctuary. https://aquarius.fiu.edu/

The Mochii team was fortunate to achieve all target mission objectives, ranging from end-to-end crew operations testing for ISS (including experience handling remote telemetry outages and planned loss-of-signal), to crew-driven *in-situ* exploration of the environment at the microscopic scale. NEEMO XXIII marks the first time electron microscopy and spectroscopy have been operated successfully in an underwater environment, opening up the benefits of SEM technology to exciting new areas such as ocean exploration, natural resources prospecting, and on-vehicle safety such as nuclear containment monitoring.

References:

[1] Own, et al, LPSC 2019 (https://www.hou.usra.edu/meetings/lpsc2019/pdf/3238.pdf).
[2] Own, et al, Microscopy & Microanalysis **23** S1 (2017), 1082-2083.
[3] Eds, Microscopy & Microanalysis **26** 5 (2018), 34-38.
[4] https://www.nasa.gov/mission_pages/NEEMO/index.html

[5] This work was supported by Voxa, NASA, and Jacobs.

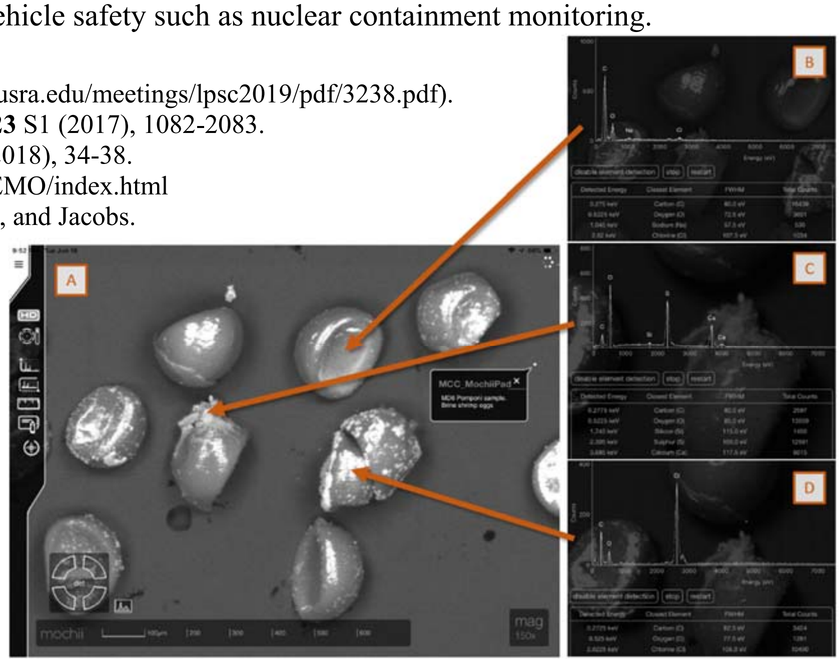

Figure 3. Spectroscopy of brine shrimp (*Artemia Salina*) egg surfaces during NEEMO XXIII mission. a) Quadrant backscatter electron image showing morphology of ~200 um particles. Spectra from b) organic egg body, c) stony inclusion adhered to surface, d) brine deposits on egg surface.