ABSTRACT

In response to concerns raised during the mishap investigation of the Extravehicular Activity (EVA) 23 high visibility close call that occurred on July 16, 2013, the Johnson Space Center (JSC) commissioned a team of experts to investigate the existing deionized (DI) water system and production at the Center, and report any opportunities for improvement in processes and practices related to DI water production and use.

The results of this institutional system investigation identified opportunities for improvement that could be true anywhere there is a capability requiring the use of DI water that has experienced changes in mission, workforce turnover, and aging infrastructure.

1. BACKGROUND

NASA had an on-orbit close call during an Extra Vehicular Activity (EVA) conducted in July of 2013 on the International Space Station (ISS). That close call involved unexpected water collecting in one of the astronaut’s helmet during the EVA, forcing an early termination of the space walk and an emergency retreat by the EVA crewmember back to the ISS airlock. That event triggered a Mishap Investigation Board (MIB), and a summary of the results of the MIB was previously published in this journal (Vol.1 No.1 – June 2014). The JSC DI Water System Investigation Team was formed as a proactive measure by JSC leadership to provide Center management with the status of campus DI water systems and operations.

1.1 Team Charter

The team was asked to examine the existing DI water system and uses, and answer the following questions.

a. What does JSC currently have as a DI water production system?

b. Which JSC organization is responsible for which part of the production process?

c. What are the applications for DI water at JSC?

d. Which of the applications for DI water is critical to space flight hardware and processes?

e. What are there implications for past processing?

1.2 Team Membership

Tab. 1 illustrates the diverse organizations that supported the team. The team of 14 included representatives from eight different organizations at JSC, and members’ academic credentials included degrees in engineering disciplines, mathematics or science. All members were recognized experts in their technical fields.

Table 1 – Organizations Supporting the Team

<table>
<thead>
<tr>
<th>Mission Operations Directorate</th>
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<tbody>
<tr>
<td>• Space Flight Systems Division</td>
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<tr>
<td>Engineering Directorate</td>
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<tr>
<td>• Crew and Thermal Systems Division</td>
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<td>• Propulsion and Power Division</td>
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<td>• Structures and Mechanics Division</td>
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<td>Center Operations Directorate</td>
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<td>• Facilities Management and Operations Division</td>
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<td>Astromaterials Research and Exploration Science Directorate</td>
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<td>• Astromaterials Research Office</td>
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<td>Safety and Mission Assurance Directorate</td>
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<td>• Quality and Flight Equipment Division</td>
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<td>International Space Station Program (ISS)</td>
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<td>• Vehicle Operations Division</td>
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<tr>
<td>White Sands Test Facility</td>
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<tr>
<td>• Materials and Components Laboratories Office</td>
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<tr>
<td>Human Health and Performance Directorate</td>
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<td>• Biomedical Research and Environmental Sciences Division</td>
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2. JSC’S DI WATER PRODUCTION AND USES

2.1 Reverse Osmosis Water Production

Fig. 1 is a simplified schematic of JSC’s reverse osmosis (RO) water production and distribution system. Reverse osmosis is an efficient pretreatment step in the overall water purifying process. There is a centralized production and storage capability at a building illustrated in the top left, and a pipeline that supplies RO water to various buildings on campus illustrated in the lower right corner. The tank at the centralized production building holds
10,000 gallons of RO water. Pumps at the tank circulate the RO water through the pipeline that loops back to the tank. The message here is that there are multiple buildings on the RO water supply line, clearly with different applications. To gain insights into the expansive applications at the Center, the team developed a data collection questionnaire to collect information from each user of DI water.

2.2 DI Water Use at JSC

Fig. 2 illustrates DI water use locations at JSC, including those with critical applications. Circles are buildings with DI water uses. Red circles are buildings using DI water for critical applications. The circles with beige “halos” are buildings that are supplied by the campus RO production system. Small circles represent the reported points of use of DI water at the building. The figure reveals the complexity of the response to the questionnaire issued by the team to determine DI water applications.

Examining Fig. 2, it is important to note that the investigation covered all of JSC including the central campus, Ellington, and the Sonny Carter Training Facility in Houston, plus the White Sands Test Facility (WSTF) in New Mexico. Since numerous responses to the questionnaire were received, the team had to develop some criteria for what was considered a critical use by the team members. The team decided critical meant the use of DI water could impact crew health, vehicle health, or vehicle utilization. The word vehicle in this context meant either the ISS or the space suit, also known as the Extra Vehicular Mobility Unit (EMU). As previously explained, on Fig. 2 the circles represent buildings with DI water use; the red circles are buildings with critical applications; a circle with a halo means the building is supplied by the campus RO production system; and the small circles represent reported DI water points of use. An interesting discovery illustrated on this chart is that not all buildings with critical applications of DI water are supplied by the campus RO system. To ensure questionnaire responses were understood, members of the team visited the work locations that were considered critical in order to interview the workforce, witness the installation and check the procedures.

2.3 Typical DI Water Production Systems and Considerations

Fig. 3 provides some insights into DI water production, with an illustration of a typical industry approach.
Tab. 2 illustrates considerations related to deionized water because DI water aggressively re-ionizes. These considerations include materials compatibility, propensity for stagnation and bio-loading, recommended flushing practices, and the need to verify water purity just before use.

<table>
<thead>
<tr>
<th>Materials compatibility</th>
<th>Production, storage, piping and transport (stainless steel, PVC)</th>
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<tbody>
<tr>
<td>Stagnation and Bio-load</td>
<td>Recognize aggressive nature of DI water</td>
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<td></td>
<td>DI water dilutes biocides, facilitating bacterial or algae growth</td>
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<tr>
<td>Flushing</td>
<td>To avoid using stagnant DI water, first flush, running at least three times the volume of the</td>
</tr>
<tr>
<td>Point of Use (POU)</td>
<td>Verification of purity just before use</td>
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*Table 2 – Typical industry considerations for working with DI water production, transport and storage*

Fig. 4 illustrates the effectiveness of various membrane types in removing particulates and contamination.

**Figure 4 – Typical Filter Sizes for Thin-Film Composite Membranes**

It is important to note that reverse osmosis is the most effective membrane type of particulate removal illustrated in Fig. 4, outperforming ultrafiltration and even nanofiltration techniques.

Fig. 5 is a notional illustration of the campus DI water production. Note first on the left side that production starts with tap or potable water from the local water district (see the dashed line). The illustration captures the pretreatment steps at the central RO production building, the RO water supply loop, and a typical water polishing station that creates the DI water for the user in the building. As shown in the middle of the figure, for polishing, there is a canister with activated charcoal, plus a sequence of ion-exchange canisters. Note there is an indicator light located on the connection between the last two canisters (red/green light) which is normally set at 5.0 micro Siemens/centimeter (µS/cm) by the vendor. That sensor indicates saturation of the ion-exchange beds, and the need to replace the ion-exchange canister. Sensitivity and location of that sensor is important to provide assurance of water purity. One unexpected discovery during the investigation was that the team found that at every building on the RO water supply loop, there was a selector valve to allow for potable water feed to the building supply polishing system if the RO supply side pressure dropped.

The right side of Fig. 5 illustrates some examples of points of use of DI water at JSC involved in processing space flight hardware or laboratory analysis. At the top of the right side of the illustration, there is an image of a miniature version of a water polishing system located in a lab with critical applications. Just below is an image of a countertop version of a polishing system, once again in use for critical laboratory applications. Both of these configurations at the points of use are capable of taking potable and making ultrapure water. For this reason, either approach is sufficient to allow the user to bypass the building RO water system if necessary. The difference between the top two configurations is simply due to volume demand for DI water.

Just below the top two images of points of use, and located in the middle on the right side of Fig. 5 is an image of a water container. This is here on the illustration because the team discovered that some of users were collecting DI water from JSC’s laboratory production in bulk containers, then transporting that DI water for use in hardware processing remotely. That discovery raised
some questions about suitability of the DI water containers used for transport, what and how the DI water was used in the remote applications, as well as what user practices and shelf life constraints were enforced by remote users.

Continuing down the right side of Fig. 5, just below middle is an image of a precision clean room, and below that is an image of the test stand involved in the processing of water filtration cartridges used on ISS to ensure water purity.

Fig. 6 illustrates in the shaded area that JSC’s Center Operations Directorate is responsible for the infrastructure system that produces and distributes DI water to various locations in buildings on the central campus in Houston.

![Center Operations Directorate responsibilities for DI water production](image)

Fig. 6 also indicates on the right side of the illustration (unshaded) that the users of DI water have a responsibility to verify water purity at the point of use.

### 3. GOOD PRACTICES

The team had several favorable findings as a result of the investigation.

#### 3.1 Precision Analytical Labs

During the investigation, the team discovered that the precision analytical labs at JSC had disciplined lab hygiene practices that included the critical steps of flushing the lines and point of use verification of water purity just prior to use. Additionally, in several cases, the precision analytical labs maintained 3rd party certification, conducted quarterly independent validation of laboratory accuracy, and performed periodic proficiency testing of laboratory personnel. In one building with multiple analytical labs, users actively monitored critical parameters at their own dedicated, centralized building DI water production location.

#### 3.2 Hardware Processing Locations

JSC processes critical hardware in several locations. These locations include dedicated test stands as well as precision clean rooms at WSTF, NBL, and on the central campus. The team determined that JSC’s precision clean rooms all had good practices and the workforce was performing rigorous point-of-use verification of water purity just before use.

### 4. LESSONS LEARNED

This section lists some possible issues with the production and use of DI water that were discovered by the team.

#### 4.1 Evaluation of Quality Needs

It is not clear that all customers periodically reexamine their water quality needs to ensure that the proper system is in place. Users should verify requirements for the use of DI water per application and then should evaluate the adequacy of alarming, monitoring, flushing, and verification at point of use, the clarity of verification requirements, standard operating procedures (SOPs), and detailed process instructions (DPIs), as well as user awareness of DI water best practices.

#### 4.2 Long Runs of Piping

In many locations there is a long run of piping between the production location and the point of use allowing for stagnant water or water to become contaminated by corrosion or dissolving. Users should evaluate the proximity of deionizing system to the actual point of use to ensure the least possible distance thereby reducing the likelihood of DI water stagnation and degradation of purity.

#### 4.3 Unintended Contamination Sources

In some buildings there are heat exchangers on the DI water system, which could leak and contaminate the DI water. Users should minimize the number of possible sources of unintended contamination installed in a DI water system, and periodically verify system integrity.
4.4 Understanding System Sensors

It appears that in all buildings on the JSC central campus, all indicator lights for DI water production exhaustion are set at the conductivity of 5 μS/cm, which is not connected to any JSC requirements levels.

Fig. 7 illustrates the dilemma created when conductivity sensors are set at 5 μS/cm as mentioned above.

**DI Water Standards & Program Requirements**

The vertical (blue) scale indicates water purity, with the highest purity at the top of the scale. Fresh ion-exchange canisters can produce water purity at the top of the scale, and as you polish water, effectiveness erodes due to exhaustion of ion-exchange pellets in the canisters. Note the green line in Fig. 7 represents the green/red sensor which trips red at 5 μS/cm. Also note that the ISS Grade-A Deionized Water specification requires higher purity water than the sensor is indicating, so this could lead to a problem.

4.5 Monitoring of Sensor

The building DI water production conductivity sensors (indicator lights) are not observed continuously thereby allowing the possibility that if canisters are exhausted while performing a critical task, insufficiently deionized water is supplied downstream to the user at the application site or point of use.

4.6 Aging Infrastructure

In some buildings, piping lines and supporting structure may be compromised due to corrosion or fatigue, which could lead to leaks, breakages, and unpredictable loss of system pressure.

4.7 Well-meaning Ingenuity and Initiative

In some locations, the workforce has taken initiative to modify installations without consulting with designers and experts or coordinating with configuration management. This has led to RO / DI water system segments with incorrect back flow preventers, incompatible materials such as brass fittings or rubber hoses, incorrect labeling and use of incompatible storage containers.

4.8 Workforce Understanding of DI Water Properties

The NASA investigation team interviewed key technicians and made significant discoveries that led to findings in the final report. Of note was the responses obtained from some personnel involved in hardware processing (exclusive of precision analytical labs and not in the precision clean rooms). In these cases, the workforce did not appreciate the properties of DI water or the aforementioned considerations. These persons assumed all DI water from the internally plumbed lines met necessary quality standards. Many persons were not aware that DI water stagnates, “in the same way the beer or another carbonated drink goes flat if left uncovered,” and when informed, were clearly surprised to learn. When asked whether they flushed the DI plumbing lines prior to using the output, some replied negatively, appearing surprised that flushing, or sampling might be expected when using DI water. It should be noted that several of those interviewed expressed considerable pride to be working in the aerospace industry. The interviewing team felt that these technicians were earnestly committed to following written procedures drafted by NASA experts. However, it is clear that there was a deficiency of training which led to a lack of knowledge and appreciation of DI water properties by these workforce members. Without in depth appreciation of DI water, their work was ritualistically compliant to procedures, apparently trusting that NASA’s procedure-writers had “gotten it right.” The vulnerability was that, in some cases, the written procedures for hardware processing did not capture the best practices as seen in the precision analytical laboratories previously mentioned. Given the above examples, there is clearly a need for workforce training and improved awareness of the properties of DI water and considerations for proper use.

5. SUMMATION

Without doubt, use of DI water in ground processing of space flight hardware is an area where there is risk of introducing contamination into critical hardware systems. The results of the JSC DI Water Investigation Team pro-
vided some reassurances but also identified several opportunities. The results remind the aerospace community that clearly stated requirements are essential to determining appropriate water purity use. In addition, clearly stated processes and procedures assist the workforce in achieving the results intended. Additional lessons are that aging infrastructure, well-meaning ingenuity and initiative, combined with workforce unfamiliarity with the characteristics of DI water can compromise DI water system integrity, output, and possibly, the intended results. These last lessons accentuate the value of having a workforce trained in the characteristics and proper handling practices of DI water.

The above observations by the JSC DI Water System Investigation Team could be true anywhere there is a capability requiring the use of DI water that has experienced changes in mission, workforce turnover, or aging infrastructure.

6. ACKNOWLEDGEMENTS

The authors would like to acknowledge JSC leadership for commissioning this team to investigate and identify opportunities for improvement in processes and practices related to DI water production and use. In addition, the authors would like to acknowledge the members of the investigation team for their invaluable contributions to this investigation and report.

7. REFERENCES

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Progress in space safety lies in the acceptance of safety design and engineering as an integral part of the design and implementation process for new space systems. Safety must be seen as the principle design driver of utmost importance from the outset of the design process, which is only achieved through a culture change that moves all stakeholders toward front-end loaded safety concepts. Superb quality information for engineers, programme managers, suppliers and aerospace technologists.

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Progress in space safety lies in the acceptance of safety design and engineering as an integral part of the design and implementation process for new space systems. Safety must be seen as the principle design driver of utmost importance from the outset of the design process, which is only achieved through a culture change that moves all stakeholders toward front-end loaded safety concepts. Superb quality information for engineers, programme managers, suppliers and aerospace technologists.

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Space Safety Regulations and Standards is the definitive book on regulatory initiatives involving space safety, new space safety standards, and safety related to new space technologies under development. More than 30 world experts come together in this book to share their detailed knowledge of regulatory and standard making processes in the area, combining otherwise disparate information into one essential reference and providing case studies to illustrate applications throughout space programs internationally.

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