The Demonstration of a Robotic External Leak Locator on the International Space Station

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Nomenclature

BEAM = Bigelow Expandable Activity Module
CDRA = Carbon Dioxide Removal Assembly
COTS = Commercial Off The Shelf
DOUG = Dynamic Onboard Ubiquitous Graphics
ECLS = Environment Control and Life Support
ECLSS = Environment Control and Life Support System
EATCS = External Active Thermal Control System
EuTEF = European Technology Exposure Facility
EVA = Extravehicular Activity
GSFC = Goddard Space Flight Center
HD = High Definition
ISS = International Space Station
JEM = Japanese Experiment Module
JSC = Johnson Space Center
MBS = Mobile Base Station
MEDET = Materials Degradation and Exposure Experiment
MER = Mission Evaluation Room
MLI = Multilayer Insulation
PFCS = Pump and Flow Control Subassembly
QD = Quick Disconnect
RBVM = Radiator Beam Valve Module
RELL = Robotic External Leak Locator
RGA = Residual Gas Analyzer
RiTS = Robotic Tool Stowage
ROBO = Robotic Flight Control
SPDM = Special Purpose Dexterous Manipulator
SSRMS = Space Station Remote Manipulator System

I. Introduction

The International Space Station (ISS) and all currently conceivable future manned spacecraft are susceptible to mission impacts due to fluid/gas leaks to the exterior environment. For example, there is a well-known risk of ammonia leaks from the ISS External Active Thermal Control System (EATCS) loops and as of 2016 there was no method to locate them. It was, therefore, critical to develop a method for detecting and locating leaks to preserve vehicle health. The Robotic External Leak Locator (RELL) was developed and deployed to the ISS to provide this capability. An on-orbit validation and demonstration was successfully completed in December 2016 and leak locating operations occurred in February 2017. This paper discusses the results of these exercises including measurements of the environment around ISS, detection of a small ammonia leak and implementation of leak locating methodologies. RELL is a collaboration between NASA's Goddard Space Flight Center (GSFC) and Johnson Space Center (JSC) and was launched to the ISS as a Technology Demonstration Payload in December 2015 on Orbital-ATK Commercial Resupply Flight 4.

II. Technology Overview

RELL was developed as a technology demonstration unit to show that pressure detection technology in concert with robotics operations has the ability to detect and locate an external ISS leak. Using robotics reduces the amount of astronaut interaction but requires precise data of exactly where RELL is pointing. RELL consists of two pressure detection sensors to accomplish this task: a Residual Gas Analyzer (RGA) and a Cold Cathode Ion Gauge. The RGA, a small mass spectrometer, provides high sensitivity (1E-12 to 1E-5 Torr) and the ability to identify individual gases by ionizing gas molecules and atoms and sorting them using quadrupole technology. This functionality is critical in order to distinguish the target gas (in this case, ammonia) from gases found in the natural and induced environments. A large spacecraft such as the ISS has numerous intentional gas vents and materials outgassing which contribute to the induced environment that can mask the presence of the leaking gas without an RGA capable of differentiating these various gases. The ion gauge measures total pressure, has a higher operating pressure range than the RGA (1E-9 to 1 Torr), provides real-time pressure measurements and can be used during proximity operations even with larger magnitude leaks. An ion gauge works by generating electrons that collide with gas atoms present in the environment and generate positive ions. The positive ions are attracted to a suitably biased electrode known as the collector. The current in the collector is proportional to the rate of ionization, which is a function of the pressure in the system. Hence, measuring the collector current gives the gas pressure. Hot- and cold-cathode ion gauges are commonly used to measure pressure in vacuum chambers. Ion gauges have been used in space applications as well: for example the MIR program flew hot-cathode and cold-cathode ion gauges and a mass spectrometer while the European Space Agency flew a cold-cathode ion gauge for 18 months as an experiment on ISS. To manage costs, the RELL design incorporates a Commercial Off The Shelf (COTS) RGA and ion gauge that was adapted and ruggedized for application on ISS as shown in Figure 1.

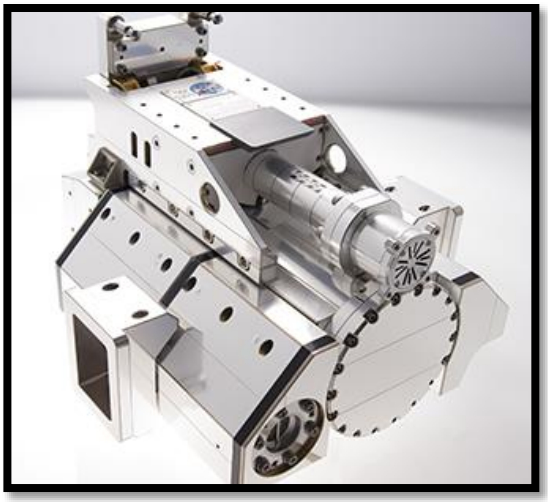


Figure 1: Flight-ready RELL.

RELL is currently stowed inside the ISS, though an external stowage bay is currently in development. The Japanese Experiment Module (JEM) Airlock is used to transfer RELL to the external environment where it is picked up by the Space Station Remote Manipulator System (SSRMS) and Special Purpose Dexterous Manipulator (SPDM), as shown in Figure 2. After the SPDM grapples RELL, operations are controlled entirely from the ground, minimizing impact to the ISS on-orbit crew. Ground operators maneuver the robotic assets around the ISS in predetermined trajectories based on potential leak locations.

Figure 2: RELL attached to the SSRMS/SPDM during the Technology Demonstration in December 2016.

RELL leak locating activities serve as an intermediate step between identification of a suspected leak and leak repair, which saves valuable crew Extravehicular Activity (EVA) time for actual repair tasks.

III. On-Orbit Demonstration

A. Purpose of Demonstration

RELL was developed as a technology demonstration payload. Being such, the culmination of the project would be a demonstration on-orbit to show that pressure detection and mass spectrometry technology in concert with robotics operations can perform the function of locating leaks in the ISS external (unpressurized) environment. To launch RELL and put it in stowage until a real leak locating scenario came up was ill-advised due to the many unknowns about the environment around the ISS and how it would affect the sensor package. Accomplishing the test objectives would provide confidence to the ISS Program that this technology was viable and give the operators real data about the environment and how it would affect an actual leak locating scenario.

B. Objectives

The test objectives were broken into two categories: Understanding the Natural Environment, and Performing Simulated Leak Locating. Each objective was designed to help the team characterize the variables involved in locating leaks.

1. Understanding the Natural Environment

To understand the natural environment around the ISS, the team measured the total pressure and constituent partial pressure in key areas around the station. Further measurements of how those signals changed with orientation were also critical. Locating leaks requires being able to pick the gas of interest out from the natural background and determine which direction it is coming from, so this objective was critical to accomplish. There have only been a couple experiments that have made measurements of this kind previously, though they were limited to total pressure from a single position and orientation. The Materials Degradation and Exposure Experiment (MEDET) ran from February 2008 to September 2009 as part of the Columbus module payload European Technology Exposure Facility (EuTEF) [1]. Russian scientists also made various pressure measurements during thruster firings and vents for the ASTRA-II experiment on the MIR Space Station [2]. However, this data set would need to be substantially increased in order for RELL to do its job. In addition to characterizing the total pressure in various regions around the ISS, the team was interested in measuring mass spectra to determine the makeup and quantity of gases in the environment. Indeed, there are constituents like atomic oxygen and water that have similar mass spectrum patterns to ammonia that could provide false positives if not well understood. Measuring the existence and amount of those constituents was important to estimating how small of a leak could be located by RELL on ISS. For this part of the technology demonstration the specific objectives were:

1. Characterize atmospheric makeup
2. Characterize diurnal variability
3. Characterize atomic oxygen reflectance
4. Measure material outgassing
5. Measure baseline ammonia levels around EATCS hardware

2. Performing Simulated Leak Locating

During ground performance testing, RELL was placed in a vacuum chamber with a simulated leak. A series of scans was performed to determine what a leak signature would look like with RELL. This test was successful and highlighted the directional sensitivity of RELL, which is critical to actually locating a leak. However, since this test was done on the ground there were certain limitations that prevented it from accurately simulating the ISS environment. The background in the chamber did not mimic the natural gas environment around the ISS. Also, there was no way to simulate the complex geometry of the ISS and molecular volatility around that structure. Thus, performing a leak locating test on orbit before looking for an actual leak was planned. Ideally, this activity would use a leak on-orbit with known constituents and leak rate. This would allow correlation between theorized values and actual measured values by RELL and provide a side-by-side evaluation of the two primary techniques for locating leaks: the grid technique and angular sweep technique. Flying a dedicated, calibrated leak source specifically for this test was cost prohibitive, so instead the plan was to use the Node 3 Carbon Dioxide Removal Assembly (CDRA) vent as a known leak source. This vent is used intermittently and a known quantity of gas, with known constituents, is dumped overboard. The idea was for the robotic assets to position RELL in front of the CDRA vent and move it through a series of different trajectories. Unfortunately, due to the loss of the first RELL flight unit on the Orbital-3 launch and subsequent delay in getting to the ISS, this vent became blocked by the installation of the Bigelow Expandable Activity Module (BEAM). After a thorough investigation it was determined no other ISS vent met the necessary criteria for this objective with the operational constraints that existed. This objective was instead replaced by scans of additional parts of the EATCS. At the time there was a known, low level leak in the system. The idea was to scan potential locations that could be leaking, executing a similar protocol as originally intended at the Node 3 CDRA vent. In addition to potentially finding the leak, the opportunity could be used to evaluate the scanning techniques and accomplish this objective. With the help of the Robotics Flight Control Team (ROBO), a list of locations of interest was generated and turned into a series of scanning maneuvers:

1. Radiator Beam Valve Modules (RBVM)
    a. RBVM P1-1-1
    b. RBVM P1-1-2
    c. RBVM P1-2-1
    d. RBVM P1-2-2
    e. RBVM P1-3-1
    f. RBVM P1-3-2
2. Pump Flow Control Subassembly (PFCS)
3. Z1 Truss

C. Operations Summary

A team of ground controllers was able to monitor and analyze the data through the 9 days of on-orbit operations. All of the objectives were successfully completed and the hardware performed nominally, with each sensor working as expected and instrument temperatures staying within range. This demonstration turned out to be fortuitous, as RELL also unexpectedly located a relatively large ammonia signature indicating a potential leak site.

D. Natural and Induced Environment Around ISS

Each of the scans related to understanding the natural environment around the ISS was successfully completed. Expected molecules like atomic oxygen, atomic nitrogen, molecular nitrogen and water were measured. Figure 3 shows an example of a mass spectrum plot as measured by the RGA.

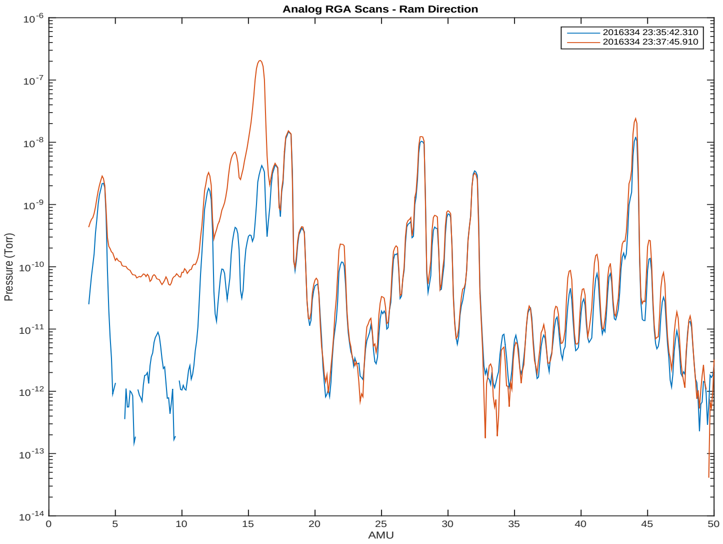


Figure 3: An example of a mass spectrum plot generated by the RGA. This plot goes from 1 – 50 amu, showing the partial pressure of each mass number. The red spectrum was taken near the ammonia leak. The blue spectrum is the background away from the ammonia leak.

Figure 4 shows a graph of partial pressures versus time for a number of different atomic masses. This is one method of analyzing data acquired using the RGA. Of note in this figure was an odd-shaped bump that occurred throughout operations in which RELL was facing in the ISS forward (+X) direction.

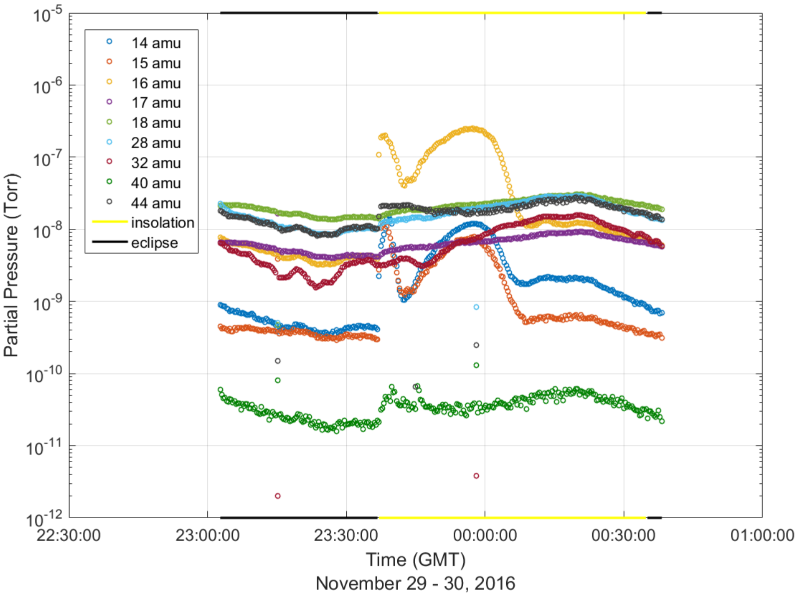


Figure 4: Series of partial pressure versus time plots, specifically highlighting unique shape noticed throughout forward (+X) direction RELL operations.

The Boeing Space Environments team has determined that this bump can be attributed to the ISS floating potential interacting with the RGA, and is not a real feature of the background environment. This is exactly why a demonstration like this was needed. This can now be noted as an expected bump in the RGA measurement data, and should not be confused with a leak signature.

Another major finding was that the water background signal measured by the RGA takes a significant amount of time to decrease to the overall background levels. As Figure 5 shows, the water molecules dominate the signal at the beginning of operations but slowly decay until flattening out 12-14 hours later. This was determined to be water outgassing from RELL, specifically from the RGA probe. Since RELL is currently stowed inside the ISS, water condenses on the hardware. As soon as RELL is taken to the vacuum environment, that water starts to bake out and is directly measured by the RGA. This is especially important to understand since ammonia and water have similar atomic mass signatures. Immediately trying to detect an ammonia leak upon taking RELL outside the spacecraft would be inadvisable due to this changing, induced environment. Any future RELL operations should allot at least 12 hours of time for water inside the RGA probe to bakeout prior to use. Stowage of RELL external to the spacecraft would eliminate the need for this delay. Detailed results about these topics can be found in the paper titled "Natural and Induced Environment Around the International Space Station as observed during on-orbit operations of the Robotic External Leak Locator" by Fox, Katie L. et. al. [3]

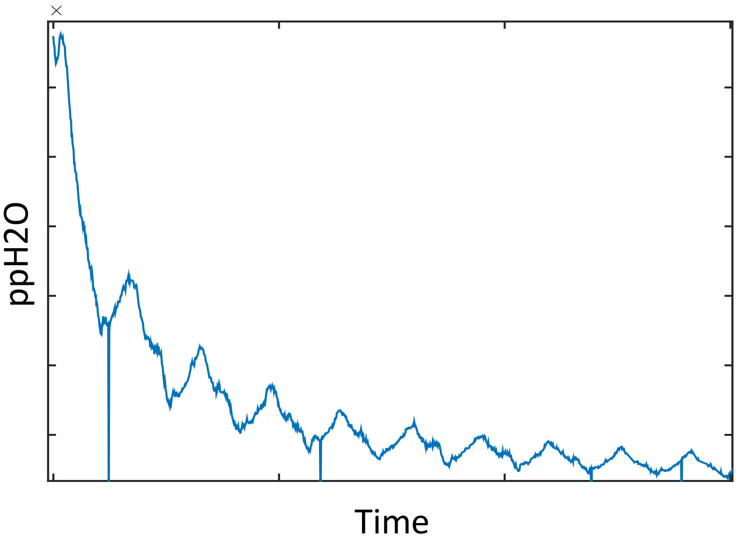


Figure 5: Partial pressure of water over a 14-hour period.

Analyzing the total pressure data from the ion gauge showed multiple pressure spikes throughout the duration of the operations, regardless of where RELL was pointing at the time. Initially this was thought to be an issue with the instrument, but upon further inspection each of these pressure spikes was correlated with a known venting event from ISS, specifically the Russian Environmental Control and Life Support (ECLS) vent and the CDRA vent. Figure 6 shows what these spikes look like, including the cyclic nature of the ECLS vent. Not only do the timing of the spikes in the RELL total pressure data correspond to the recorded times of the vents, the RGA was able to measure the makeup of these pressure spikes, which were compared to the known vent constituents. For example, the RELL RGA confirmed the total pressure spikes that occurred during the CDRA venting cycle were driven by carbon dioxide. It was unexpected that venting events like these would be measured even when RELL was pointing away from these vents. There appears to be a great deal of scattering and reflection off of the ISS structure by the molecules released in these events. This has implications for leak locating because these pressure spikes could interfere or mask real leaks. Now that this has been observed, the team understands what it is and knows to account for this when interpreting data. Detailed information about this topic can be found in the paper titled "International Space Station Environmental Control and Life Support Vent Flow Reflection and Detection by Robotic External Leak Locator" by Huang, Alvin Y. et. al. [4].

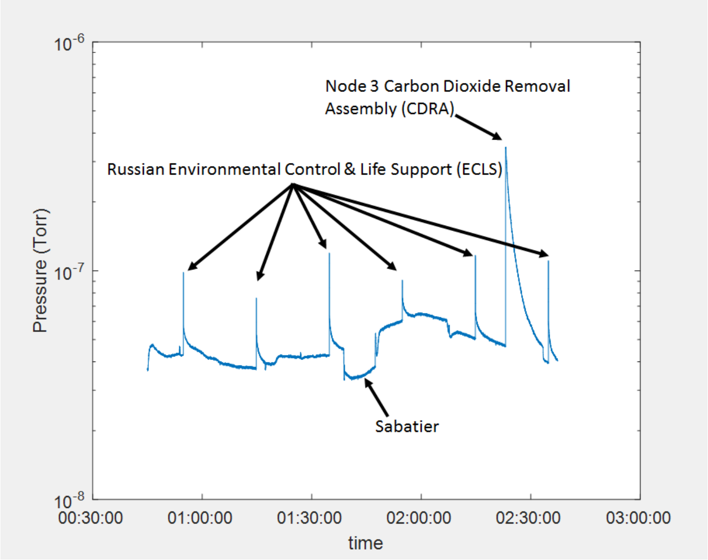


Figure 6: Total pressure versus time over a two hour period shows 6 different total pressure spikes.

Atomic oxygen was measured throughout the operations, with the biggest signal occurring when RELL was pointed directly into the ram direction (+X). However, there does not appear to be a notable impact of atomic oxygen reflectance off of the truss segments. Additionally, outgassing from materials outside the ISS does not impact RELL operations because the associated pressure is low and the atomic mass of those constituents is high enough that they can be separated out.

E. Leak Locating Scans

Upon completion of the natural environment scans, RELL proceeded to scan the RBVMs, PFCS and Z1 Truss. RELL proceeded through planned maneuvers at each RBVM, unsure of what to expect. RELL measured a large ammonia signal that seemed to be emanating from RBVM P1-3-2, which happened to be the first RBVM that was scanned (see Figure 7 below). The total pressure was two orders of magnitude larger than any other pressure observed, as can be seen in Figure 8. It appeared that RELL had in fact measured the known ammonia leak. The team thought it prudent to pause in this area for an entire orbit (~90 minutes) to determine how the signal changed throughout the orbit. The ammonia signal did in fact change in a sinusoidal nature as the ISS went around the Earth, as shown in Figure 9. This was expected, due the changing temperatures around the ISS as it goes around the Earth and is similar to the diurnal affect measured during the natural background scans. However, the rising and falling of the natural background pressure does not temporally match up exactly with the rising and falling of the ammonia signal. Also, the magnitude of the variation is far greater than would be explained by bulk temperature change assuming the ammonia behaves as an ideal gas. More work is needed to understand the exact cause of this phenomenon but for now, this diurnal variation is another factor that needs to be taken into account when searching for leaks.

Figure 7: A screenshot of RELL scanning RBVM P1-3-2 as taken from the mast camera of the SSRMS.

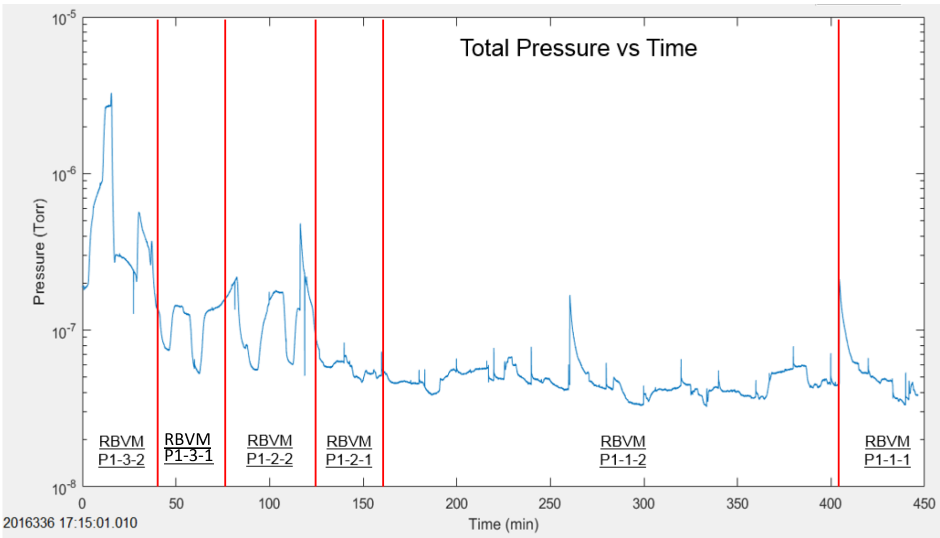


Figure 8: Total pressure versus time of all scans performed on the RBVMs on the port-side radiator.

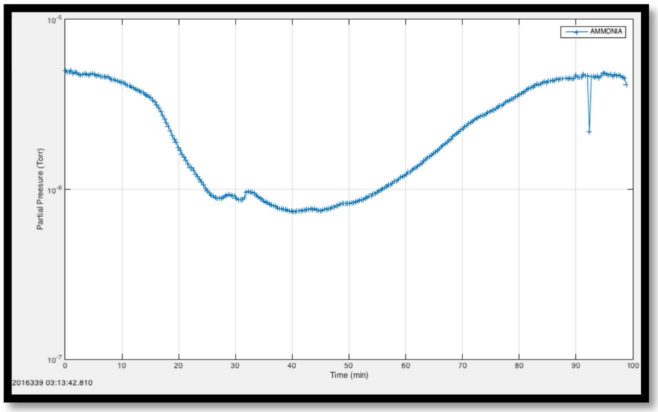


Figure 9: Partial pressure of ammonia over an entire orbit while RELL was stationary.

The operations proceeded through scanning the remaining RBVMs, the PFCS and the Z1 truss though nothing significant was found during those scans. Due to the detection of the large ammonia signal, the ISS Program thought it prudent to add additional scans since RELL was already configured for use and near the suspected leak location. The RELL and ROBO teams worked through the night to develop two additional scan patterns, in the hope of narrowing down the location of the leak. There was limited time to fit in these new scans due to upcoming robotic operations unrelated to RELL, so the planned scanning patterns were quick and simple. These additional scans did in fact help narrow down the leak source to an area under the RBVM.

IV. Leak Locating Success

As with any leak, the known leak in Loop A of the EATCS was being watched closely, dating back to early 2014. As the leak rate began to increase it was decided RELL would go back outside in February 2017 to perform additional scans. These scans provided critical data that eventually led to a series of events that would stop the leak.

A. Decision for Additional RELL Scans

The EATCS System Management team at JSC was keeping a close eye on the known leak in Loop A. At the conclusion of the On-Orbit Demonstration in December 2016, the leak rate was low enough that it didn't require immediate action. However, there was a worry that the rate could increase rapidly as had happened previously with another piece of ammonia cooling hardware. In January 2017 the leak rate started to increase by a little, then by a lot. Figure 10 shows the trend of total ammonia in the system over time. The estimated leak rate in December 2016 was about 20-30 lbs per year. In late January 2017 that rate starting increasing, with some estimates as high as 100 lbs per year.

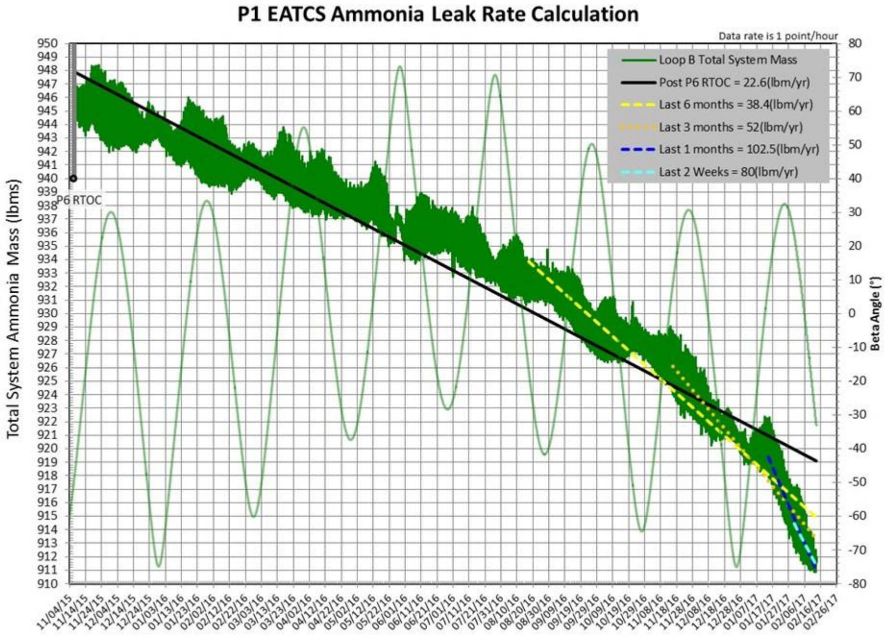
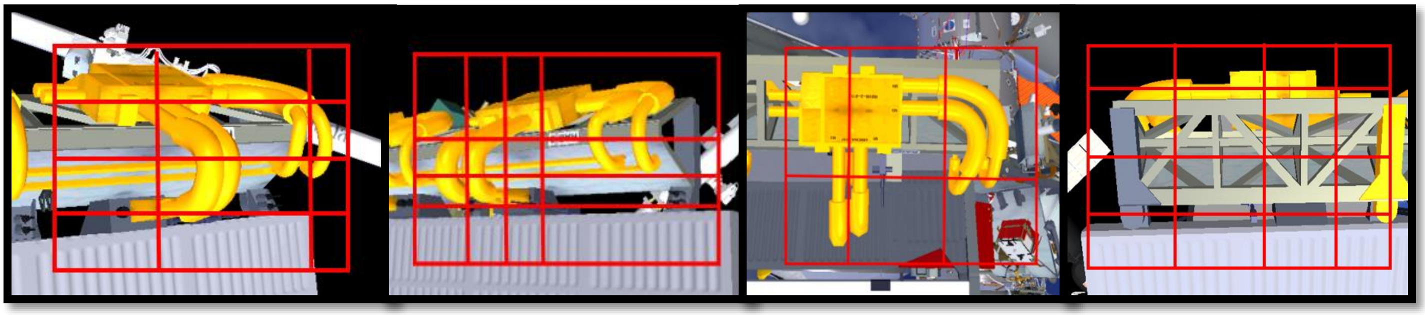


Figure 10: Leak trend data of the known ammonia leak through January 2017.

Even with the scan data from RELL captured from the On-Orbit Demonstration, there was not enough information to know exactly where the leak was coming from. Based upon the general location of the leak as determined by RELL, there were two different troubleshooting paths. If the leak was on the "Systems" side of the thermal loop, it would require one of set of actions, and if it was on the "Radiator" side of the thermal loop it would require a second set of actions. The "Systems" side of the loop has rigid tubing that transports ammonia to pull heat from all the different systems inside of the ISS. A leak on this loop would be hard to pinpoint because the tubing is buried and there is no ideal solution for plugging a leak in the tubing. The "Radiator" side of the loop consists of three radiators that radiate the heat collected on the "Systems" side to space. Troubleshooting in this scenario has much more flexibility as each radiator can be individually closed off from the system to isolate leaks. Thus, being able to narrow down the leak to the "Systems" side versus the "Radiator" side was essential for providing ISS Program management the information necessary to determine the proper action. Therefore the decision was made to employ RELL again for more focused scans. The operation came together rapidly with teams working through weekends prepping procedures and maneuvering the robotic assets into position.

B. Developing the Scan Plan

Once the decision to perform additional scans was made, the next step was to determine the scanning trajectories. The trajectory design was driven by one primary objective: determine if the leak was coming from the “Systems” side or the “Radiator” side of the EATCS. Therefore, each motion of the robotic arm was designed to provide data to answer that question. The team made an initial decision to utilize the grid scanning technique. This technique enables simplified data analysis by doing a series of passes along a plane, and was shown to be effective during the On-Orbit Demonstration. With the decision made to pursue the grid technique, the team then used a program known as Dynamic Onboard Ubiquitous Graphics (DOUG) to brainstorm where these scans should take place. DOUG provides a medium fidelity, virtual environment that enables users to maneuver around the ISS. DOUG enabled the team to go to the area of interest on the ISS, look at the hardware and determine the best planes in which to scan across. This process of brainstorming included stakeholders from the ISS Program, the EATCS System Management team, ROBO, Flight Directors, Mission Evaluation Room (MER) Managers, and the RELL technical team. The discussion was led by the system owners, with the diverse team providing unique inputs about their area of expertise. The team decided to pursue 4 different grids denoted by nomenclature related to the direction the scan plane was from the area of interest: Port Grid, Starboard Grid, Zenith Grid, and Forward Grid. A screenshot of the plane of interest was taken using DOUG. Then the team overlaid a red grid on top of the image with each red line highlighting a critical path for RELL to traverse. Figure 11 shows the four grids as initially imagined.



Port Grid Starboard Grid Zenith Grid Forward Grid

Figure 11: The four grids outlined the requirements for a detailed inspection around RBVM P1-3-2.

The ROBO team then went into their software and determined what could actually be done based on what was initially imagined. The RELL team was invited to see the actual trajectories that would be robotically flown to ensure they were satisfactory. This collaborative effort was critical in ensuring the flown trajectories of the robotic arm with RELL attached would complete the objective.

C. Operations Summary

The operations were successfully completed without any issues with all grids flown on target. There was, however, some additional scans completed beyond the original plan. The idea with each grid was to begin scanning far enough away from the leak location, so that as the robotic arm and RELL were moved toward the middle of the grid, where the hardware of interest was located, the ammonia level would increase and then decrease as it reached the other side of the grid However, on one edge of the Starboard Grid, the pressure signature continued to grow instead of decay. This meant that the leak location was likely beyond the scope of the planned grid. Normally, robotic operations like this cannot be changed real-time. Robotic maneuvers on the ISS are planned in advance and reviewed by multiple parties to ensure they can be flown without any singularities or running into ISS structure. The robotic arms are not flown with a joystick on the ground. That being said, the robotic team had planned for minor adjustments in advance and were able to modify the grid. The same grid pattern was flown, however, the starting place of the grid was shifted over to capture the edge of the leak plume which was being missed in the earlier grid pattern. This new Starboard Grid was reflown and provided the data needed.

D. Results

The team analyzed the data real-time during operations and did additional in depth analysis in the days following. A couple key data visualizations were produced by the team that were supportive in data analysis and conveying this data to ISS Program management. One visualization was a video file that showed a recording of what RELL was pointing at within the DOUG environment coupled with the total pressure data being measured from RELL at that time. This is a great way to correlate pressure spikes with location. Figure 12 shows a screenshot of one of these videos.

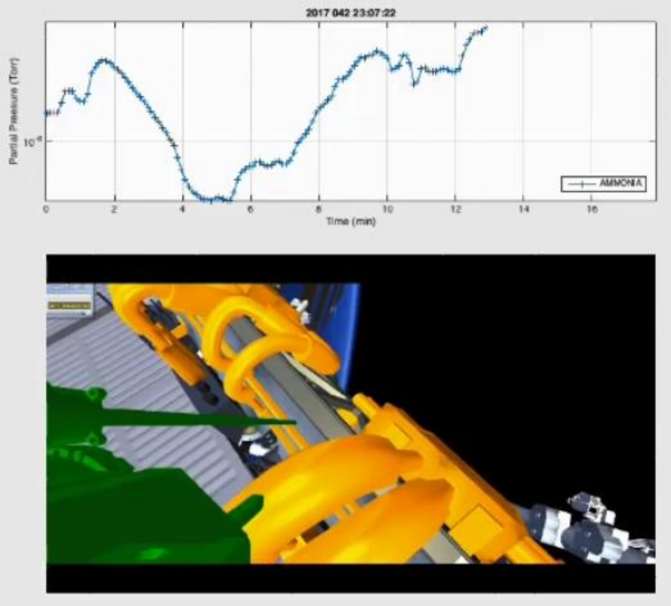


Figure 12: A screenshot of a video showing ammonia partial pressure versus time along with a view from DOUG along the RELL pointing vector.

Another data visualization was the pressure contour map. This graphic took advantage of the two dimensional nature of the grid technique and plotted the total pressure measured at each point in a grid. The graph was colored on a range from blue to yellow depending on the total pressure, with yellow corresponding to high pressure and blue corresponding to low pressure. Taking this plot and overlaying it with the plane as viewed in DOUG enables a quick look of where the highest pressure was detected. Figure 13 shows the pressure contour maps and DOUG screenshots for each of the four grids.

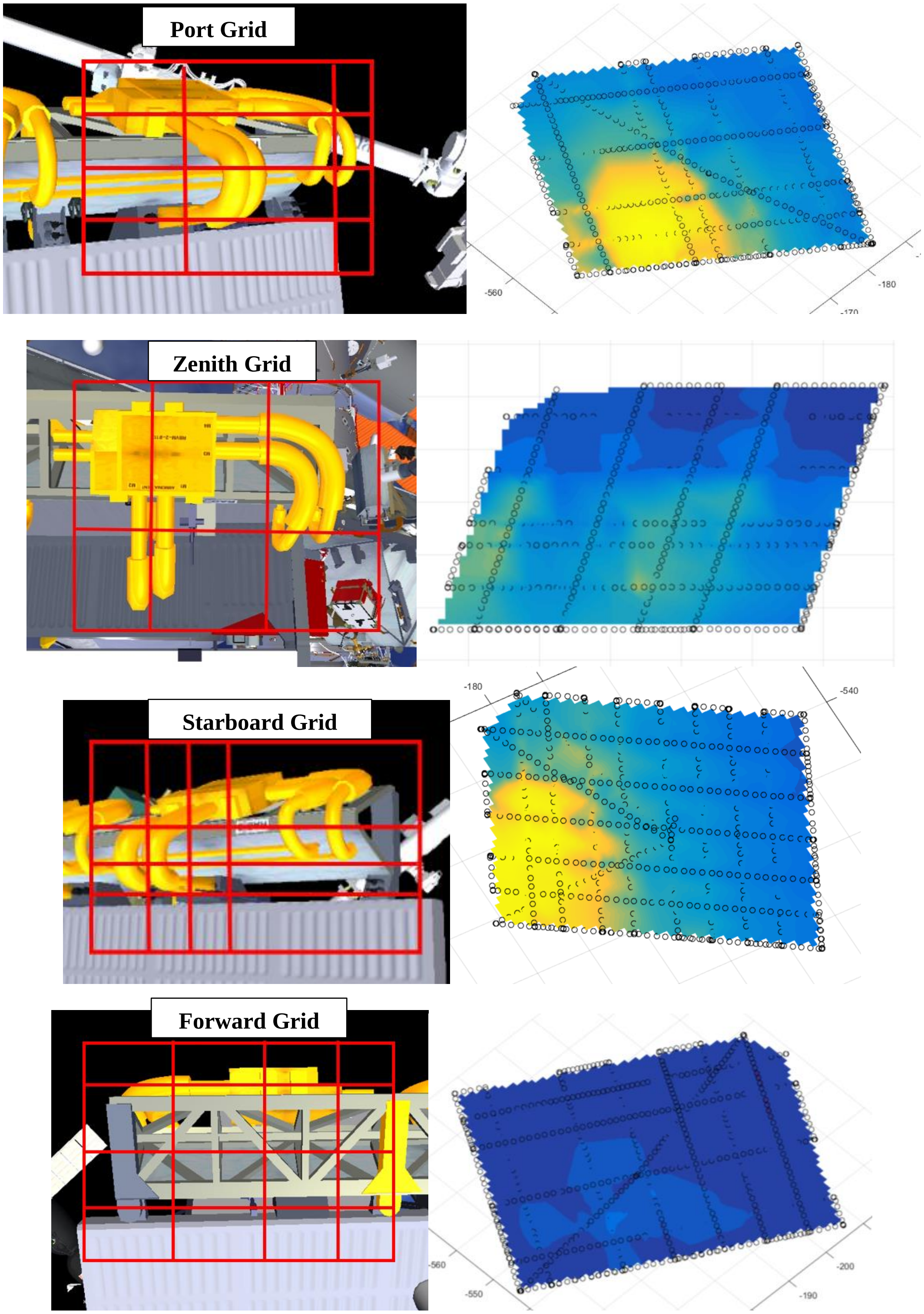


Figure 13: Pressure contour maps for each of the grid scans performed in February 2017.

The Port and Starboard Grids showed the highest pressure in the area of the two flex hoses that connect the RBVM with the radiator. However, directly behind these flex hoses is a hard lined tube from the “Systems” side of the loop. This situation highlights a difficulty of leak locating around the ISS and potentially with future pressurized vehicles: overlapping hardware and pluming. This scenario presented a pluming leak in which the gas expands from the leak site in a diffuse, spherical nature as opposed to a jet style leak which is emitted linearly from the leak site. The leaking gas in pluming leaks will bounce around and cause RELL to sense an increased pressure in multiple locations, eliminating the ability to truly pinpoint the location of the leak. Having hardware that is in close proximity or overlapping provides an additional layer of complexity. One can imagine designing a future EATCS to minimize overlapping hardware and consider what it would look like to search for a leak at any given point throughout the system.

The data from these operations along with an understanding of the likelihood of which side could be leaking, provided strong evidence that the flex lines on the “Radiator” side was the leak site. Detailed information regarding this topic can be found in the paper titled “Robotic External Leak Locator Leak Plume Field Detection on the International Space Station” by Deal, Alexandra M. et. al. [5].

E. EVA Tasks

With the completion of the additional scans, the confidence level that the leak was on the “Radiator” side increased. However, there was still some residual uncertainty. In this instance, definitively pinpointing the location of the leak was nearly impossible due to deviation of the plume due to blanketing and reflections from nearby structure, and this should always be kept in mind in leak locating scenarios. Therefore, the ISS program directed that the crew perform a close-up inspection of the suspected area during an upcoming EVA (US EVA 40) to provide additional information. The EVA crew member had the following objectives:

- Take High Definition (HD) pictures using EVA camera at various angles
- Visually inspect and provide observations to the ground and note any white flakes
- Obtain HD video of the area using EVA GoPro camera
- Pat down the radiator flex hoses from Quick Disconnect (QD) to QD attempting to liberate flakes and determine origin
- Inspect and manipulate QDs to determine if they are set correctly
- Open silver Multilayer Insulation (MLI) on “System” side lines and visually inspect.

During the EVA no white flakes were reported by the crew member, nor were there any other signs that implicated one side versus the other. However, upon completion of the EVA, the team reviewed the imagery and video in detail. Figure 14 shows a screenshot of footage taken during the EVA.

Figure 14: A screenshot from the EVA GoPro during inspection of RBVM P1-3-2.

It was in watching the EVA GoPro footage that the team noticed multiple white flakes emanating directly from one of the flex lines. White flakes are an explicit sign that ammonia gas is being released into space and condensing. This experience highlighted that high resolution images, coupled with the proper lighting conditions are required to be able to see flakes like this. Standard definition video from the crew member’s helmet camera was not sufficient. This was the final piece of evidence the team needed to have high confidence that the leak was indeed on the “Radiator” side.

F. Venting of Loop

Shortly after the EVA, the decision was made to proceed with the troubleshooting steps associated with a leak on the “Radiator” side, which consisted of isolating and venting that radiator path via ground commanding. This action would cut that radiator flow path off from the rest of the system and then vent the remaining ammonia in the now-isolated flow path (~40 lbs) overboard into space. The operation occurred successfully on May 3, 2017. Figure 15 shows a screenshot of the video recorded from this venting.

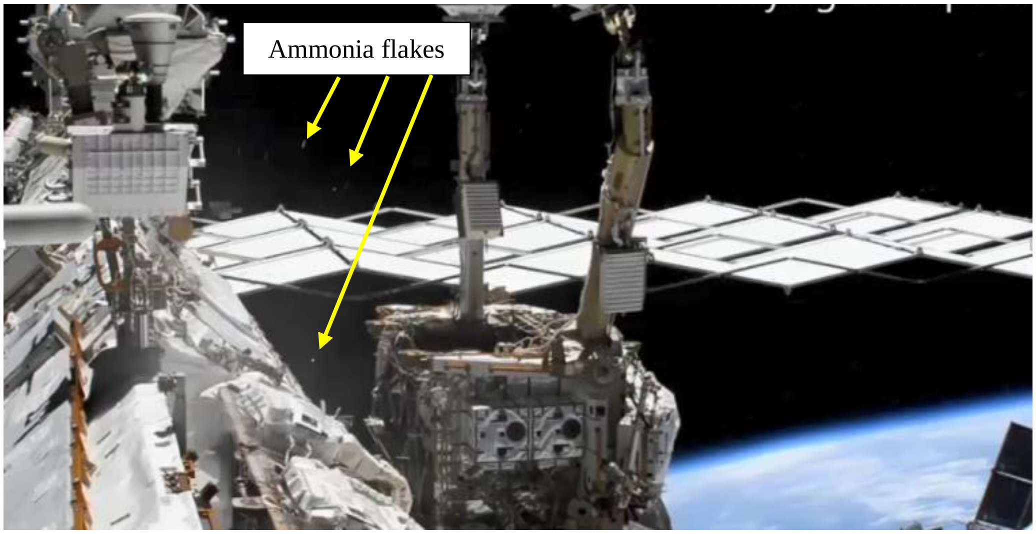


Figure 15: Ammonia flakes can be seen during the venting of the radiator.

G. Outcome

Upon completion of the ammonia loop venting, the team had to wait several weeks to determine if this action was successful. This has to do with the way the leak rate is calculated, which is estimated from a calculation made of the total system mass of ammonia. The total system mass is not a directly measured value and has some uncertainty in the day to day numbers. The teams look at long term trends to provide a more accurate story of leak rates. Consequently, the team wanted to wait at least a month before making any conclusions about the leak rate.

After the month had past, it became clear that the ammonia levels were holding steady, indicating the leak had been stopped (see Figure 16).

In the proceeding months, the ISS Program also decided to remove the suspected leaking flex lines from the EATCS during an EVA and bring them down to the ground for study. During ground testing leakage of one of the fluid connectors was confirmed to a similar level as was seen on-orbit. This information confirms that flex line as the leak site for the leak described in this paper and proves the usefulness and value of RELL and the scanning techniques employed.

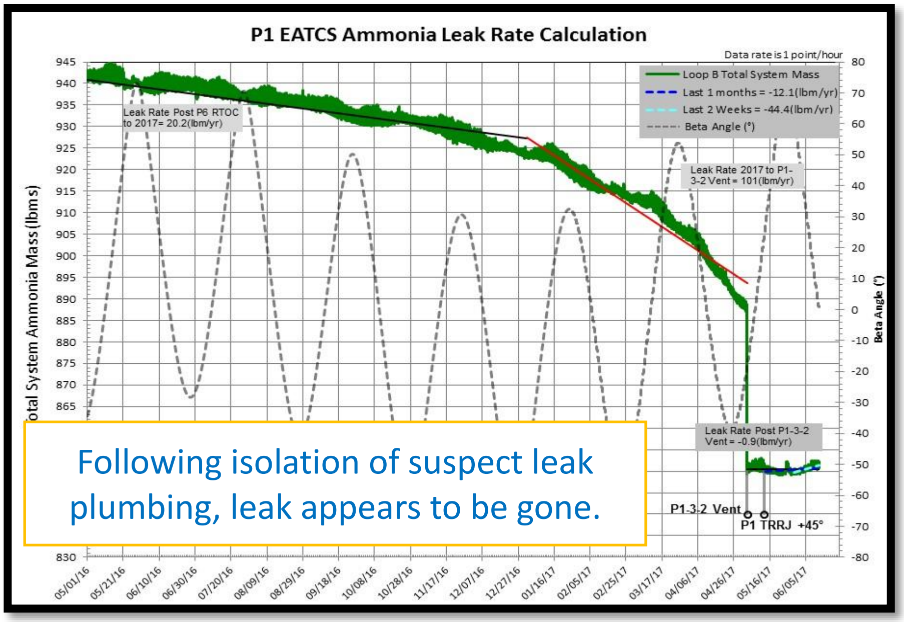


Figure 16: Graph of the ammonia mass within the EATCS loop, showing that the system mass had stabilized and the leak had stopped.

V. Conclusion

During two operations on the ISS, RELL proved its viability and value as a tool in leak detection and location, particularly in concert with robotics. Important data was gained about the natural and induced environments around ISS and leak locating techniques were evaluated. RELL brought to light previously unforeseen factors that could complicate future leak locating like the "bump" caused by the ISS floating potential, water bakeout from the RGA, induced vents that are measured by RELL regardless of pointing vector, and a changing ammonia pressure that doesn't match up with the normal diurnal changes. Furthermore, these operations proved the value of having both a total pressure gauge and mass spectrometer and these sensors should continue to be paired in future leak locating devices.

Locating leaks in manned spacecraft is a critical capability needed in the exploration of space. The ISS, Deep Space Gateway, lunar and Martian habitats and rovers, and other conceivable vehicles will always be susceptible to pressure leaks. Therefore, having a method for locating and repairing these leaks will be necessary in keeping those vehicles healthy in the long term. RELL or similar hardware should be considered as part of the tool kit of any future spacecraft. Additionally, external plumbing systems should be designed in a way to make locating leaks in them easier. This could be done by minimizing the overlapping of hardware and maximizing robotic accessibility to their systems.

It should be noted that while originally developed to locate leaks in the EATCS, RELL could support locating leaks in other ISS systems like the Environmental Control and Life Support System (ECLSS). In addition to evaluating reach and access of the robotics it is important to note that mass spectrometer detection of the molecules from the ECLSS can conflict with those that occur naturally in the background (e.g. O, N_2), so any leak would have to be above the background levels for RELL to find it.

It is also important to remember that leak location is a complicated undertaking with many variables playing a role in the event. While the leak locating operations described in this paper went really well with the leak being found quickly and the signal being obvious, future operations may not be so lucky. The teams will likely have to deal with the uncertainty present in any type of complex operation like this. But the uncertainty can be overcome with well thought out scanning patterns along with the use of other contextual information.

The flight unit used for the operations described in this paper will remain on-orbit. An additional flight unit is being assembled as a backup and will launch in early 2019. The Robotic Tool Stowage (RiTS) is being developed by GSFC as a location to store the two RELL units external to the ISS. RiTS will be placed on the Mobile Base Station (MBS) allowing easy access by the robotic assets. This new configuration substantially reduces the overhead required to utilize RELL and will enable a relatively quick turnaround for use whenever needed by the ISS Program management.

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