Robotic Refueling Mission-3—an overview

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Abstract. Robotic Refueling Mission-3 (RRM3) is an external payload on the International Space Station (ISS) to demonstrate the techniques for storing and transferring a cryogenic fuel on orbit. RRM3 was designed and built at the National Aeronautics and Space Administration/Goddard Space Flight Center (NASA/GSFC). Initial testing was performed at GSFC using liquid nitrogen and liquid argon. Final testing and flight fill of methane was performed at the NASA Kennedy Space Center (KSC) to take advantage of KSC’s facilities and expertise for handling a combustible cryogen. This paper gives an overview of the process and challenges of developing the payload and the results of its on-orbit performance.

1. Introduction
RRM3 is a technology demonstration mission sponsored by the NASA’s Science and Technology Mission Directorate. Its goal is to develop technologies and processes for storage and transfer of liquid methane in a microgravity environment [1, 2]. It also will demonstrate robotic manipulation of cryogenic transfer lines on-orbit building on techniques demonstrated by the precursor payloads RRM1 and RRM2 [3]. This capability would allow on-orbit fueling of rockets for lunar exploration as well as deep-space missions such as human habitation on Mars. RRM3 was launched from Cape Canaveral Air Station aboard SpaceX Commercial Resupply Service (CRS) 16 on December 5, 2018 and berthed on the ISS Express Logistics Carrier on December 15 as shown in figure 1.
2. **RRM3 Cryogenic Demonstration System (CDS)**

The RRM3 Cryogenic Demonstration System (CDS) is housed inside the Fluid Transfer Module (FTM), shown in figure 2. It comprises a 50-liter Source Dewar, a 10-liter Receiver Dewar, and associated plumbing, sensors and electronics. The CDS is shown schematically in figure 3.

![Figure 1. RRM3 Fuel Transfer Module (FTM) on the International Space Station (ISS).](image1)

![Figure 2. The RRM3 FTM plumbing interfaces are routed from the CDS dewars to the FTM panels for on-orbit robotic and venting operations. The Receiver Dewar nominal vent port is obscured by the Source Dewar emergency vent port.](image2)
2.1. Transfer lines
Three transfer lines are provided for on-orbit operations as shown in figure 3. The hard transfer line is permanently attached to both dewars and was used during ground test to demonstrate cryogen transfer between the Source and Receiver dewars using liquid argon and liquid methane. The hard transfer line is wrapped with MLI/aerogel to provide thermal insulation during ground testing. The other two transfer lines, known as the Cryo Coupler Adapter (CCA) Hose and the Cryogenic Transfer Hose (CTH), will demonstrate robotic servicing techniques. The CCA is a moderately flexible transfer line with a specially designed robotic-friendly adapter. The CCA was launched in a disconnected, stowed configuration. The CCA will be mated and demated robotically on-orbit. The CCA technology will be used on future payloads that are designed to accommodate robotic fluid servicing, known as cooperative payloads. In contrast, the CTH simulates fluid transfer to a noncooperative payload—one that was not designed for robotic servicing. The CTH is a flexible transfer line that was launched in a disconnected configuration and coiled onto a Hose Management Device (HMD). On-orbit the HMD will deploy the transfer line and a Cryogenic Servicing Tool (CST) will position the line at the inlet to an open tube. The transfer line will be snaked through a tortuous path to the inlet of the Receiver Dewar. The CST will provide a seal against the tube to prevent leakage of the cryogen during the transfer.

![Diagram](image)

**Figure 3.** RRM3 Cryogen Demonstration System block diagram.

2.2. On-orbit operations
At launch the Source Dewar contained approximately 19 kg of liquid methane. The Receiver Dewar was launched with a residual amount of dry nitrogen gas at a pressure <0.1 psia. The Source Dewar was filled at KSC on October 28, 2018. After the dewar was filled, a Sunpower cryocooler was operated in a thermostatic mode, turning the compressor on and off as needed to keep the methane above 92 K to avoid the triple point at 90.7 K and below ~110 K. The upper temperature range was dependent on a variety of factors including the need to remain well below the burst disk set point of 65 psia during times when RRM3 was powered down during ground processing at SpaceX and launch pad operations for up to 36 hours. At one atmosphere of pressure, methane liquefies at 111.7 K, so most of the testing was performed at sub-atmospheric
conditions. On April 8, 2019, the cryocooler electronics failed and on April 11 the methane was vented through the burst disk. Without the cryocooler, the methane pressurized passively without venting for over 72 hours and then the pressure was purposely raised to the burst disk pressure to allow a predictable venting of the methane. The cryocooler had been successful in maintaining the methane in the Source Dewar in a zero boiloff condition for nearly 6 months through ground processing, launch, installation on ISS, and 4 months of on-orbit operation.

3. Technology demonstration
RRM3 was designed to demonstrate the following cryogenic technologies and microgravity cryogen management techniques:

- Zero boil-off storage of a cryogen
- Mass gauging in a microgravity environment through use of a Radio Frequency Mass Gauge (RFMG)
- Flow measurement with a turbine flowmeter
- Liquid/vapor detection with a cryogen other than superfluid helium
- Fluid management to orient liquid at the inlet to the transfer line
- Autogenous pressurization
- Integrated Multi-Layer Insulation (IMLI)
- Freezing of a cryogen in microgravity
- Use of multiple robotic tools to accomplish cryogen transfer for both cooperative and uncooperative cryogenic systems
- No-vent transfer

Although the cryogenic part of the mission ended prematurely, almost all of the technologies were at least partially demonstrated.

3.1. Zero boil-off storage of a cryogen
RRM3 demonstrated storage of liquid methane for nearly 6 months with zero boil-off, including 4 months on-orbit—meeting a major project goal and establishing a precedent for long-term storage of a cryogenic fuel in a low-gravity environment. While the cryocooler proved to be capable of controlling temperature and pressure both on the ground and on-orbit, the performance on the ground was a poor predictor of performance on-orbit with regard to time constants and correlation between cold-finger temperature and bulk methane temperature. During ground testing, whether with liquid nitrogen, argon, or methane, the cryocooler could be operated at constant amplitude to obtain a stable temperature. With nitrogen and argon, the cryocooler was at the lower end of its temperature range with relatively low cooling power. With methane, even though the methane is saturated liquid from 90.7 to 135 K, a higher temperature range than nitrogen or argon, the tests were performed under relatively warm ambient conditions, requiring that the cooling power be limited to avoid overheating the cryocooler heat sink. The heat sink consisted of a K-core thermal spreader plate on the back panel of RRM3. However, when RRM3 moved to SpaceX, the heat reject temperature was considerably lower and the cryocooler was powered off and on periodically to avoid both freezing the methane and over-pressurizing it. The methane warmed and cooled slowly over the course of days, so cycling of the cryocooler was determined primarily by the need to accommodate the launch preparation process.

On-orbit the cryocooler was commanded on start-up into a thermostatic mode with a preset temperature range at the cryocooler cold finger. The temperature range could be adjusted through commands. The temperature drop across the cold strap from the cold finger to the methane, which had been characterized during methane testing at KSC and SpaceX, did not match what was observed on-orbit. The time constants for cooldown and warmup were much shorter than had been observed on the ground as shown in figure 4, perhaps indicating poor
thermal contact of the thermal strap to the bulk liquid in microgravity resulting in less thermal mass contributing to the time constant. ISS slew maneuvers affected the thermal performance of the radiator and may have re-oriented the liquid, so adjustments in the setpoints were required on multiple occasions.

Figure 4. Temperature variation of the cryocooler cold-finger (top) and bulk methane temperature in the Source Dewar (bottom) over a 24-hour period on-orbit in thermostatic control mode. The bulk methane temperature is measured by an array of sensors located axially along a central post. On-orbit the bulk methane temperature was less strongly coupled to the cold-finger temperature than on the ground.

3.2. Mass gauging in a microgravity environment through use of RFMG
The RFMG [4] provided a measurement of the mass of liquid in the Source Dewar both on the ground and on-orbit. During testing at KSC the RFMG was compared to weight measurements of the FTM on a calibrated scale as methane was introduced during fills or removed following transfers. On-orbit, the RFMG’s ability to estimate not only the mass but the position of liquid and vapor was being assessed. Additional information on the RRM3 RFMG testing is presented at the 2019 Space Cryogenics Workshop by Zimmerli et al [5].

3.3. Flow measurement with a turbine flowmeter
The turbine flowmeter demonstrated mixed performance during ground testing. It was able to measure flow accurately at times, but at other times it failed to indicate any flow. Due to the limited number of transfers performed and the erratic behavior of the flowmeter, it was not determined if the turbine failed to turn or if the electronics failed to register the turbine rotation. The flowmeter was not tested on-orbit.

3.4. Liquid/vapor detection with a cryogen other than superfluid helium
The Superfluid Helium On-Orbit Transfer (SHOOT) experiment [6] demonstrated the use of thermometers operated at higher currents as liquid/vapor detectors to determine whether or not the thermometer was immersed in superfluid helium. Methane has both lower thermal conductivity and higher latent heat than superfluid helium, which makes liquid/vapor detection more challenging. During ground storage, the liquid/vapor detectors were able to distinguish between the two states in methane. During ground transfers, the results were more ambiguous
and the liquid/vapor detectors were not useful in determining flow rates. The ambiguous readings were attributed to the high saturation conditions in the Source Dewar during the transfer causing false liquid readings. On-orbit, the fill level and dewar geometry resulted in the liquid/vapor detectors always being submerged so they always registered as wet. However, once all the methane had been vented through the burst disk and the thermometers warmed above the triple point, they registered as dry.

3.5. Fluid management to orient liquid at the inlet to the transfer line
Without the opportunity to transfer methane on-orbit, this question remains unanswered. The RFMG data suggests that some vapor may have collected near the bottom of the tank at various times throughout the mission. If vapor also collected under the baseplate near the transfer line inlets, that small volume of vapor would likely have been swept away upon opening the transfer valves. The ability to orient the bulk liquid would have become more apparent once multiple transfers had been completed.

3.6. Autogenous pressurization
Autogenous pressurization using a wick and heater technique developed at GSFC was accomplished both on the ground and on-orbit. The ability to pressurize the vapor in the Source Dewar while maintaining the bulk liquid temperature below the saturation point was key to being able to transfer into the Receiver Dewar. Autogenous pressurization was used during the final operation to vent the methane through the burst disk. The consistency of the wick heater pressurization allowed the team to accurately predict and control when the burst pressure would be reached, which allowed the team to coordinate with the International Space Station so that the timing of the event was known and any necessary precautions could be arranged.

3.7. Integrated Multi-Layer Insulation (IMLI)
The Receiver Dewar was insulated with an Integrated MLI, an advanced MLI developed and installed by Quest Thermal Group [7]. The effectiveness of the Quest MLI would have been determined by measuring the Receiver Dewar thermal performance after transfer on-orbit. On-orbit the Receiver Dewar cryocooler was used to cool the methane tank to temperatures between 70 and 82 K depending on the thermometer locations, indicating that the IMLI was performing as expected and was effective at insulating the Receiver Dewar methane tank.

3.8. Freezing of a cryogen in microgravity
Venting from the Receiver Dewar was to be accomplished by first freezing the methane and then letting it sublimate. The team demonstrated the ability to use a cryocooler to freeze both argon and methane in the Receiver Dewar during ground tests. On orbit, the Receiver Dewar methane tank was cooled more than 10 K below the methane triple point of 90.7 K, which suggests that the methane would have been likely to freeze during a transfer. Solid methane did form on the FTM panel near the Source Dewar vent during the process of venting from the Source Dewar, as shown in figure 5.

3.9. Use of multiple robotic tools to accomplish cryogen transfer for both cooperative and uncooperative cryogenic systems
The RRM3 will perform the robotic manipulations that would have been required for methane transfer on-orbit. The results of those activities will be presented at the International Astronautical Congress in October 2019.
3.10. No-vent transfer
The team performed five no-vent liquid methane transfers during ground testing at KSC. Figure 6 shows a typical set of temperatures and pressures as seen during a transfer. Initial conditions for the transfer were determined from a detailed model developed by Hauser et al. [8] The Receiver Dewar was precooled to near the triple point prior to the transfers. When working with liquid argon, the team performed partially vented transfers where the initial stage of the transfer required that the Receiver Dewar be vented but the vent valve could be closed part-way through the transfer. It is estimated that less than 3% of the transferred mass was lost during the partial argon transfers. The pressure required for argon transfers was very close to the Receiver Dewar burst disk pressure: otherwise it may have been possible to perform no-vent transfers with liquid argon as well. No transfers were attempted on-orbit before the loss of the methane.

4. Conclusion.
RRM3 presented numerous challenges over the course of its development, ground testing, and on-orbit operation. Many of the technical challenges are discussed by Boyle et al. at the 2019 Space Cryogenics Workshop. Facility limitations led to the use of alternate cryogens for the majority of ground testing and system characterization. With each change of cryogen, the team had to adjust procedures and thought processes for a different range of acceptable temperatures and pressures. The Receiver Dewar burst disk set-point was selected for methane, but was barely adequate for transfer testing with liquid argon. As a result of these limitations, the team had limited experience working with liquid methane at the time of launch. Once on-orbit, the ability to control temperature and pressure in the Source Dewar was different from what had been experienced on the ground and required more vigilance from the team at a time when circumstances limited the team’s access to data. The January 2019 government furlough of many team members during the first month on-orbit severely limited the team’s ability to consult amongst themselves or with outside parties to develop a clearer understanding of the performance. Given that the team was within a month’s time of attempting the first transfer when the methane was vented, the time lost at the beginning of the mission was most unfortunate. The team did demonstrate what it takes to build and launch a hazardous cryogenic payload and operate it safely on the ground and on-orbit. New technologies such as autogenous pressurization, RFMG, and IMLI were successfully demonstrated on-orbit. Finally, RRM3 was able to demonstrate a key milestone of long-term cryogen storage in microgravity.
Figure 6. Example of a no-vent transfer during ground testing. Transfer line temperature drops indicating flow of liquid methane into the Receiver Dewar. Source Dewar pressure has been rising steadily for approximately 20 minutes using autogenous pressurization. The Receiver Dewar pressure remains below the Source Dewar pressure throughout the transfer, equilibrating at the completion of the transfer as the fluid reaches saturation conditions.

5. References

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