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# Upgrades and initial weathering test results of the liquefied natural gas testbed at NASA Kennedy Space Center

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**Abstract.** Responding to commercial space launch vehicle providers developing rocket engines fueled by liquefied natural gas (LNG) in recent years, NASA began exploring "weathering" of the cryogenic mixture—the preferential evaporation of lower boiling point constituents over time, leading to a change in the bulk liquid composition. Due to relatively long delays between launches historically, cryogenic propellants sit idle in storage tanks, with the normal boiloff vented to atmosphere. In the case of LNG, boiloff gas would primarily be methane, the main constituent in the mixture, leading to a build-up of other species in the bulk liquid, which could affect engine performance. To better understand LNG weathering, in 2019 NASA performed boiloff testing using a custom 400 L dewar with five vertical sample ports within the fluid volume. Samples were routed to a gas analyzer to determine the compositional change over time. Although successful, numerous system improvements were identified following the 2019 campaign. In 2022, NASA funded an effort to perform these improvements and conduct additional testing, which culminated in two successful LNG tests in 2024. Upgrades to the LNG testbed will be presented, as well as the new weathering test results.

## 1. Introduction

Historically, two primary fuels have been employed for powering large space launch vehicles using liquid-fed rocket engines: liquid hydrogen ($LH_2$), or propellant grade kerosene (RP1). These are used in conjunction with liquid oxygen as an oxidizer for combustion. Until recently, virtually every vehicle put into active service since the dawn of space travel utilized one, or both, of these propellants. For example, platforms such as the Saturn V moon rocket employed RP1 for its first stage and $LH_2$ for the second and third stages; Atlas did the same; the Space Shuttle consumed $LH_2$ within its main engines, as does NASA's current Space Launch System (SLS) rocket; and the SpaceX Falcon 9 vehicle utilizes RP1 for both the first and second stages.

With the development of new vehicles such as SpaceX's Starship, New Glenn from Blue Origin, and Vulcan from ULA, came the utilization of liquefied natural gas (LNG), or sometimes referred to as liquid methane. Liquid methane has been studied/tested by NASA for a variety of applications over the years, such as the Morpheus lander [1] and Altair lunar lander [2], but never deployed operationally, and not for large space launch vehicles. LNG trades well versus the incumbent fuels as it provides better engine efficiency than RP1—that is, the specific impulse is higher—but is roughly 6 times denser than $LH_2$, which allows for smaller propellant tanks and less aerodynamic drag (for first stages). It is still cryogenic, but with a boiling point above 100 K, LNG is relatively simple to handle compared to liquid hydrogen at 20 K.

A downside to using LNG is that it is a mixture of gasses. Generally consisting of at least 90% methane by volume, other constituents may also be present, including ethane, butane, pentane, propane, carbon dioxide, nitrogen, and others. During normal storage, or transfer operations requiring chill down of warm equipment, the methane preferentially boils away, changing the bulk composition of the liquid product. This process is referred to as "weathering." RP1 is also a complex mixture of constituents, however it is not cryogenic, hence is compositionally stable. $LH_2$ constantly boils away, but at 20 K, only helium and neon could exist as a contaminant, and are generally not an issue. Therefore, with an incumbent fuel, engineers can be confident that the quality of the propellants loaded on-board the launch vehicle matches the design parameters of the engine. With LNG however, this becomes a question. And the situation is exacerbated by how cryogenic storage tanks are typically operated at launch facilities. Due to relatively long delays between launches historically, cryogenic propellants sit idle in storage tanks, with the normal boiloff vented to atmosphere. This will lead to weathering of the LNG, which could affect engine performance or lead to possible damage, or cause a violation of launch commit criteria.

In 2017, the Cryogenics Test Laboratory (CTL) at NASA Kennedy Space Center (KSC) began developing an LNG testbed to explore aspects such as weathering and controlled storage in the context of launch pad infrastructure and operations [3,4]. An existing 400 L, vacuum-insulated dewar was repurposed from a prior project, and became the core of the testbed. A new top plug assembly was fabricated for the vessel that accommodated a vertical probe with five 1.6 mm diameter sample tubes that terminated at different fill levels (0%, 25%, 50%, 75, and 100%), along with corresponding temperature sensors. During testing, LNG boiloff would be allowed to vent naturally, and liquid samples could be pulled from each of the ports periodically and routed to an gas analyzer (MKS Precisive® 5) to determine the compositional change over time. The plug assembly also housed a cryocooler coldhead that could be used to perform long-duration zero boiloff (ZBO), or other advanced storage operations such as in-situ liquefaction and densification. Figure 1 presents the retrofitted dewar configuration, with major components/details called out.

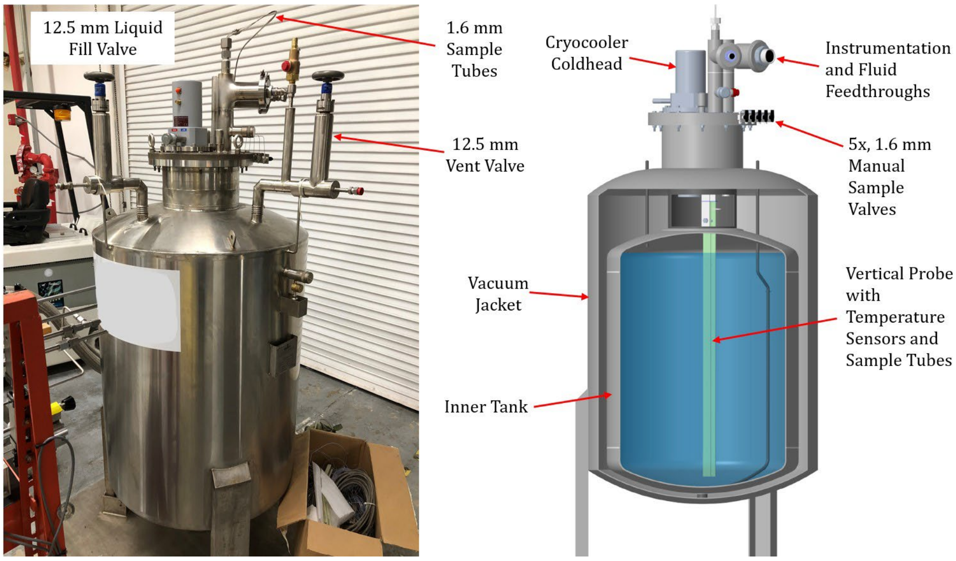


**Figure 1.** 400 L Dewar used for the LNG Testbed (left); Cut-Away Showing Internal Details (right)

This initial testbed configuration was successfully tested at the CTL in 2019 and yielded promising results [5]. However, the system was not very sophisticated: sampling was all manual, and taken once per day on average, so the data was coarse, with multiple-day gaps over weekends and holidays; backpressure on the dewar was handled via a manual regulator, which required constant adjustment leading to a varying tank pressure; no instrumentation was employed to quantify the boiloff rate (e.g. flow meters and/or load cells on the tank); and with only five vertical temperature sensors inside the tank, thermal stratification was not easy resolved. Therefore, coming out of the 2019 effort it was acknowledged that upgrades addressing these shortcomings could allow for much higher fidelity data and a more valuable testbed overall.

In 2022, the NASA Rocket Propulsion Test Program funded an effort to perform upgrades to the system and carry out additional LNG testing. Utilizing this enhanced capability, two separate LNG tests were performed between August 2024 and February 2025, with the system outperforming expectations, and producing a wealth of high-quality data. Improvements to the testbed will be presented, as well as the additional weathering test results.

## 2. LNG Testbed Upgrades

Upgrades to the system tested in 2019 revolved around obtaining higher quality weathering data, exercising better control of the tank pressure, and gathering additional data not available during the initial campaign due to limited resources.

To address the first goal required taking sample measurements at a much higher frequency than once per day. A new target was set at twice per hour, which necessitated that the sampling system be completely automated, requiring the five manual sample valves be replaced with solenoid valves (ASCO Redhat 8262 series, explosionproof) and development of a more elaborate command and control (C&C) and data acquisition (DAQ) system built in NI LabVIEW.

Maintaining a constant tank pressure of 68.95 kpa (guage) throughout the test was desired, and important to establish and keep a consistent liquid saturation condition, as well as to provide the pressure difference necessary to transport fluid samples to the gas analyzer. During the 2019 campaign a manual back pressure regulator (Swagelok KBP Series) was utilized for pressure control, but required constant adjustment. This configuration was updated to a diaphragm style regulator (EQUILIBAR GS series) that was precision controlled via an electropneumatic motor actuator regulator (TESCOM ER5k kit), and achieved outstanding performance, controlling to the desired setpoint to ±1.45 kPa on average throughout the entire 40+ day test durations in 2024-2025, with an average standard deviation of 0.46. A potential future improvement will be to compensate for atmospheric pressure fluxuations to achieve absolute pressure control.

To supplement the gas analyzer data used to determine weathering, it was desired to also capture the LNG boiloff rate throughout a test, as well as more finely resolve thermal stratification within the tank. The former was achieved via two different methods: a mass flow meter positioned in the vent system, and load cells placed under the three tank support legs to measure the mass loss over time. A 12.5 mm diameter, 30 slpm mass flow meter (MKS 0558A series) was employed downstream of the back pressure regulator to record the continuous boiloff rate, and was placed within a 3-D printed enclosure and constantly purged with dry nitrogen gas to protect it from moisture intrusion while outdoors. Three, 300 kg load cells (ATO TJH-4A series) supported the entire dewar weight, and were summed together in the data acquisition software and tared following an LNG fill to record the total liquid mass loss. To capture better liquid temperature data, four additional platinum RTD sensors (Lake Shore Cryotronics model PT 103) were installed between the existing five, at increments of 12.5% between 0% and 100% fill levels.

## 3. Final Testbed Configuration

Figures 2 and 3 present the system mechanical schematic (SMS), as-tested configuration of the testbed hardware, and details of the vertical probe assembly. For safety reasons, the testbed was located outdoors in a covered location adjacent to the CTL. All venting of flammable gas, both from chill-down of equipment during an LNG fill, and normal boiloff, occurred above the roofline, through dedicated stacks. In compliance of the NFPA 497 code [6] most of the electrical equipment was located outside the Class I, Division II zone that, for LNG, encompassed an area 4.57 m around the dewar on every side. This included the DAQ/control box and electropneumatic regulator (EPC-1) shown in figure 2 (this equipment is not shown in figure 3 (left), but resided 4.6 m to the lower right of the picture). All electrical hardware inside this zone, including the six solenoid valves (SV-1 through 6), MKS gas analyzer (SYS-02), pressure transducer (PT-1), mass flow meter (MFM-1), and load cells, were either classified (i.e. explosionproof), or made safe through continuous purging using inert nitrogen gas ($GN_2$).

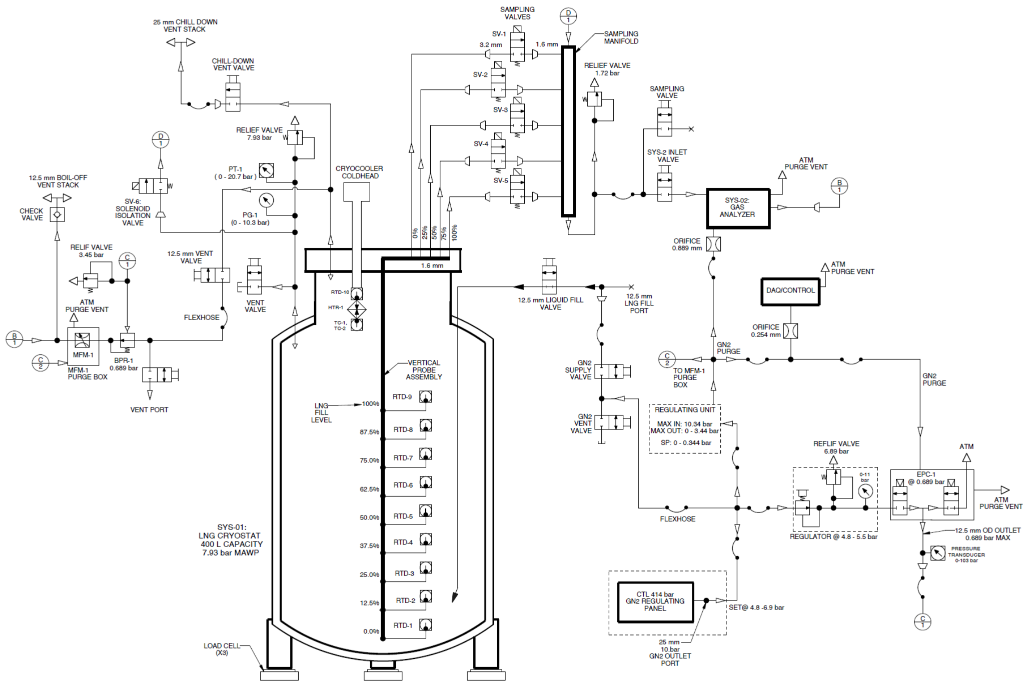


**Figure 2.** System Mechanical Schematic of the Upgraded LNG Testbed

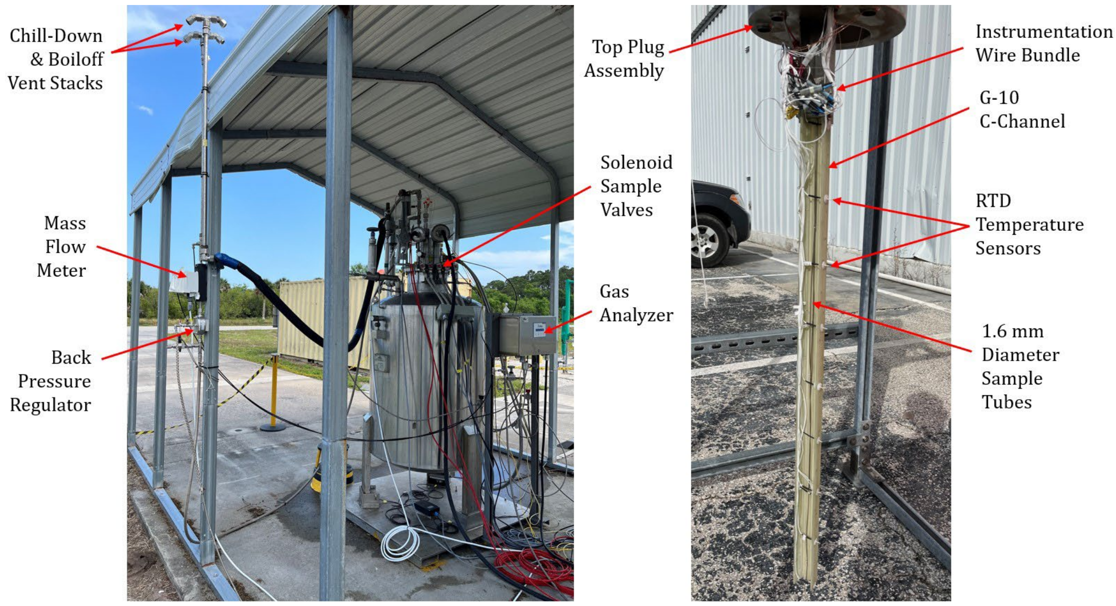


**Figure 3.** Upgraded LNG Testbed in the As-Tested Configuration (left); and Top Plug Assembly Removed with Vertical Probe Details Called-Out (right)

The nine RTD temperature sensors along the vertical probe shown in figure 3 (right) penetrate the G-10 fiberglass epoxy C-channel at the predetermined fill locations, and are held in place using buttons of thin PTFE sheet material. The five 1.6 mm diameter sample tubes run down the middle of the C-channel, terminating at the 0%, 25%, 50%, 75%, and 100% fill levels. It is important to note that these fill levels are approximate. At the exact elevation of the 100% sample tube, the liquid volume is 422 L, or 5.5% higher than the nominal max capacity of the tank. At 75%, 50%, and 25 % the true volumes are 328.5 L, 219 L, and 113 L respectively. At the 0% fill level, the true volume is not exactly zero, but leaves a pool of liquid about 66 mm deep, or roughly 10 L worth. This was a consequence of a discrepancy between the design intent communicated to the cryostat manufacturer versus the as-built configuration, and was only discovered once the hardware was received by NASA. It was decided to leave the sample tubes at the slightly higher elevations, but retain the original fill level designations for DAQ and reporting purposes.

## 4. 2024-2015 LNG Testing

The first test of the upgraded system began on August 13th, 2024, with a delivery from Pivotal LNG out of Jacksonville, Florida. To reduce methane losses due to chill-down the dewar had been prechilled with a full load of liquid nitrogen ($LN_2$) the prior day, and was drained as the LNG tanker was being positioned for offload. Once the $LN_2$ was drained the tanker immediately interfaced to the dewar and began the fill operation. This procedure worked well, and the team was able to load roughly 175 kg of LNG, or about 408 L, into the tank in a little over an hour, with minimal losses. Following the LNG offload the system was configured to begin the weathering test, with boiloff flow first detected by the mass flow meter roughly four hours later, once the tank pressure rose to the setpoint of the backpressure regulator. For the next 46 days the system ran flawlessly, autonomously gathering compositional and boiloff data every 30 minutes, and at an almost constant 68.33 kPa tank pressure. Testing was terminated on September 29th, 2024.

While examining the data during the initial run it was realized that the methane composition in the vent gas, which was known to be ~100% from the 2019 testing, was trending lower than expected by roughly 4.5%. This behavior was consistent over the entire test duration, however, the trend in the liquid composition closely matched that of the 2019 data. Therefore it was believed that the lower values were a result of settings in the analyzer, and/or its calibration. Following the first test run the team consulted MKS engineers and were directed to perform a re-zeroing procedure on the instrument, which restored proper functionality for the following test.

LNG offloading for the second test occurred on December 10th, 2024, and followed a similar procedure to the first offload, except that the dewar was only partially filled with $LN_2$ for prechilling. Beginning with a full tank of $LN_2$ for the first test resulted in subcooling of the initial LNG load, which did not reach saturation for roughly 6 days. Therefore, only a small amount of $LN_2$ was used the second time, just to chill the bottom of the inner tank. Beginning phases of the test procedure were modified slightly as well. Where the first test immediately began gathering boiloff weathering data, the cryocooler was activated during the initial phase of the second test to perform ZBO operations—it was decided to focus on only the weathering results for this paper, and commit a future report to ZBO. The ZBO testing ran for roughly nine days before transitioning into a standard weathering test, with the liquid showing some slight thermal stratification in roughly the upper third of the column—which disappeared after approximately 2.5 days of boiling off—and a uniform composition at the outset. Like the first round, the second weathering test also ran for ran for about 46 days before the effort was terminated on February 4th, 2025.

Table 1 presents the LNG analysis provided by the vendor for both tanker loads. Samples were taken at the storage tank when loading the tanker and processed using a Ramen gas analyzer. Results show that the LNG composition for each test was >96% methane, with the next most abundant species being ethane.

**Table 1.** Vendor Supplied LNG Analysis of Each Tanker Load; Units in Percent by Volume

| Tanker | Methane | Ethane | Propane | Isobutane | Nitrogen | Total |
|---|---|---|---|---|---|---|
| #1 | 96.058% | 3.772% | 0.170% | 0% | 0% | 100% |
| #2 | 96.874% | 2.723% | 0.176% | 0.030% | 0.197% | 100% |

## 5. Weathering Test Results

Figure 4 presents the temperature and pressure data for the first LNG run; the second run was very similar, hence is not included here. Aside from the initial six days, when the LNG was warming from a subcooled to saturated state, it is clear from the data that thermal stratification within the bulk saturated liquid was minimal. All nine RTDs trended very close to each other and to the boiling point (dotted line; obtained using RefProp version 10 and based on the changing liquid composition), only deviating when the liquid level dropped below the sensor location. Clear as well is the stability in the tank pressure provided by the upgraded back pressure regulator.

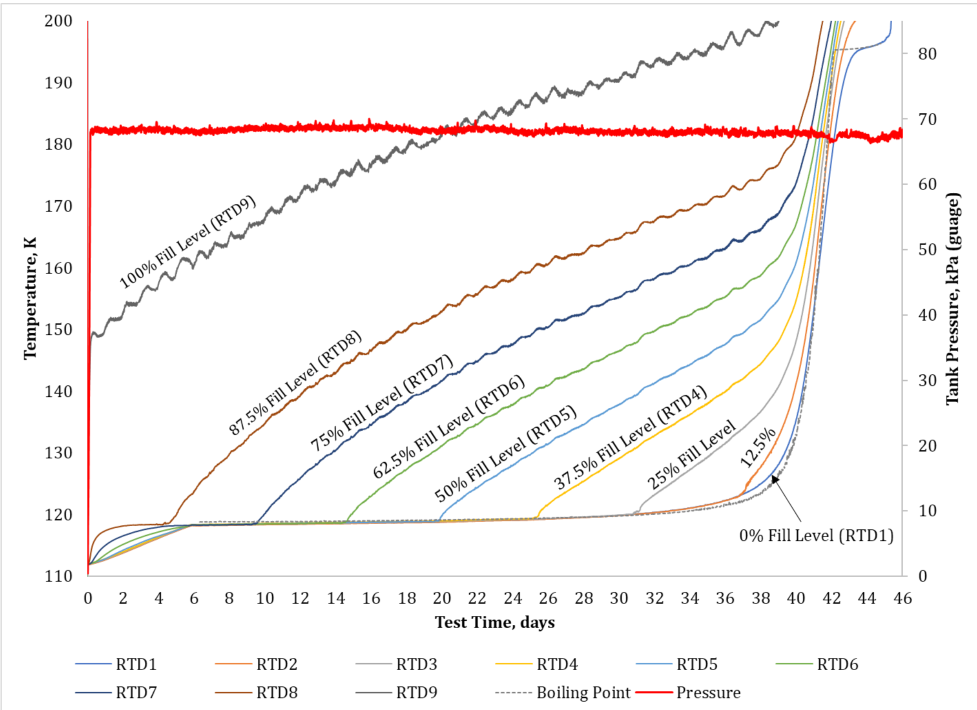


**Figure 4.** Temperature and Pressure Profiles for the First LNG Run

Figure 5 presents the weathering curves for methane and ethane, the two primary constituents in the LNG tested, for both test runs. Data is displayed for each species, at each sample port, over the entire test durations. The instantaneous jumps in the data correspond to when the liquid level dropped below the indicated sample port location, and the analyzer began to measure ullage gas instead of liquid—the 100% fill levels are not shown in the figure because the liquid levels were just below that port at time=0 on the chart. Both data sets are time-aligned to the jump at the 75% fill level marks for better comparison of their individual behaviors over time. Also, the methane percentage for run #1, both in the liquid and gas phases, is seen to be consistently below that of run #2. This was the result of the aforementioned MKS gas analyzer re-zeroing operation following run #1. Therefore, it is reasonable to assume that the methane values in run #1 were artificially low, and in reality, were much closer to what was witnessed for run #2.

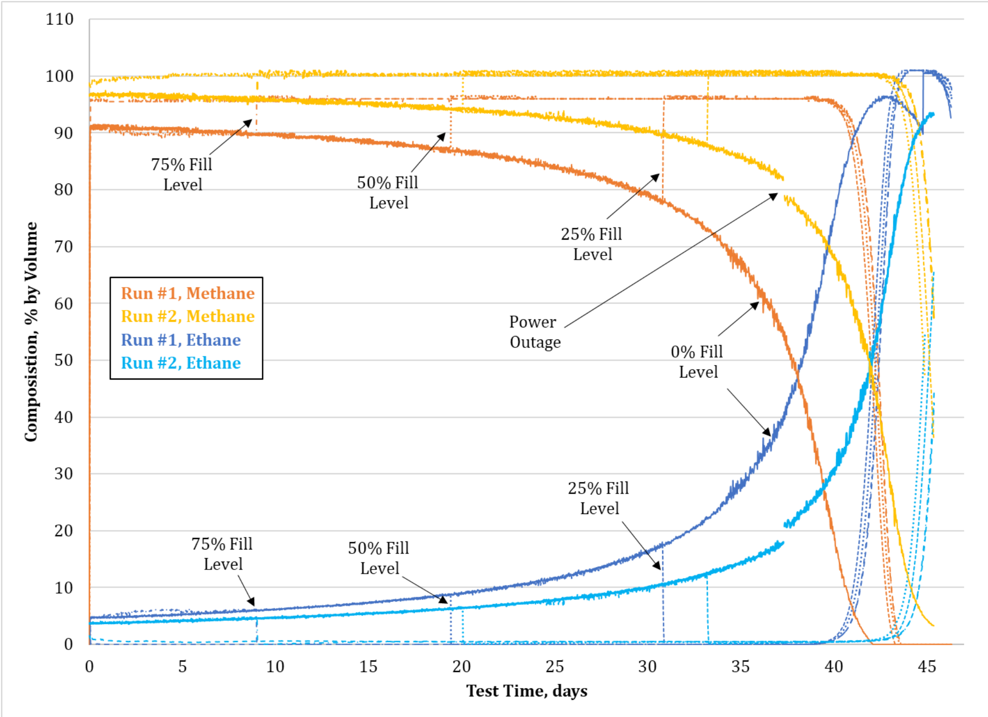


**Figure 5.** Methane and Ethane Weathering Curves for Both Test Runs

Perhaps the most obvious feature in figure 5 is the nonlinearity of the weathering process. Early on the compositional change in the liquid was relatively constant, with the methane decreasing and ethane increasing, but began to accelerate after about 50% full. Also, as was witnessed in the 2019 testing, the boiloff gas was ~100% methane throughout most of the process. This is obvious upon examination of the transitions to ullage gas at the 75%, 50%, and 25% sample ports called out. Prior to these jumps the liquid compositions all trended together for both species; afterward, the ullage gas jumped to ~100% methane and remined flat until the later stages when an abrupt transition from methane to ethane boiloff took place, followed by a rapid loss of the remaining methane, and enrichment of ethane in the liquid. Run #1 was allowed to progress long enough, and the 0% sample port was low enough in the tank to briefly capture the weathering process once the methane was completed depleted. This can be seen in the 0% fill level data as the ethane concentration peaked soon after the methane went to zero, followed by the ethane in the ullage gas going to ~100%. It then began to decrease until an instantaneous jump occurred indicating that the remaining liquid level dropped below the lowest sample port.

Other notable features in figure 5 are the data dropouts in run #2 caused by a brief power outage at the CTL—an unfortunate blemish in an otherwise flawless test run. Also, even though both datasets were time-aligned to when the liquid level dropped below the 75% fill level, run #2 took significantly longer to boiloff than run #1, by approximately 6 days. This is believed to be due to the lower environmental heat load on the system during the cooler winter months in Florida during run #2. And is evidenced by the data presented in figure 6 that show a slightly lower boiloff flow rate on average for run #2, as well as a smaller negative slope in the load cell data. Estimates for the heat loads yield and average of 22.1 ± 2 W across all tests.

Figure 6 also reveals a precipitous dip and rebound in the boiloff flow rate in run #1 that corresponded to the methane-to-ethane transition. The boiloff flow began to drop at roughly the same time the methane in the ullage dropped and ethane rose in figure 5. Flow hit a minimum just before the methane concentration in the liquid went to zero, and then rose again and peaked around when the ethane in the ullage maxed out.

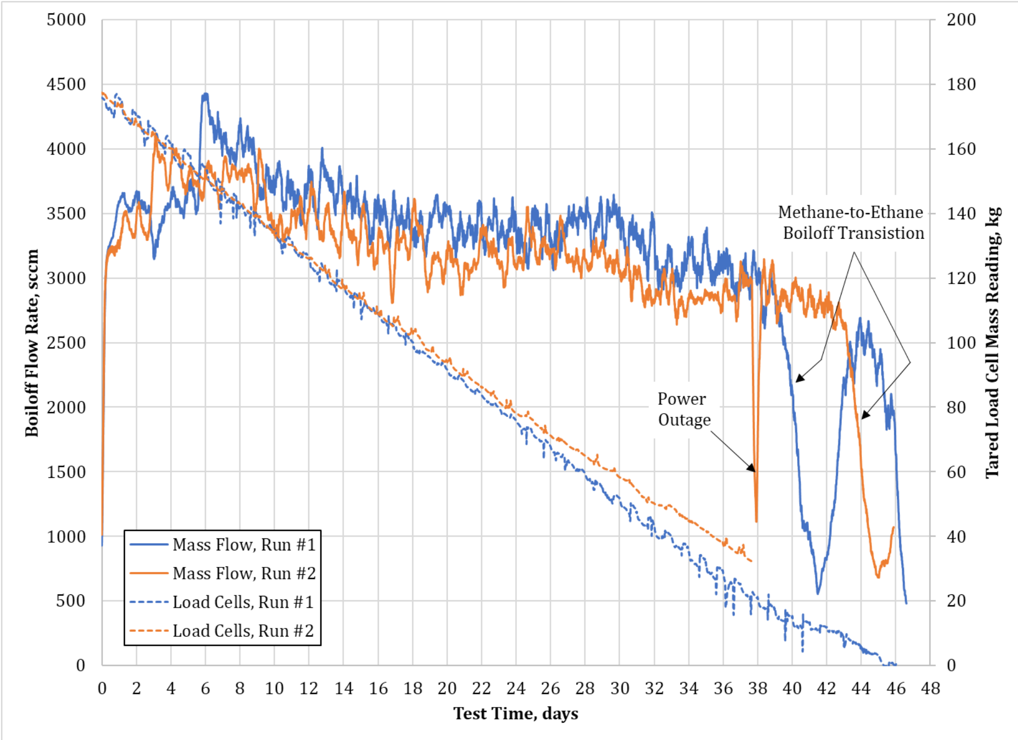


**Figure 6.** Boiloff Mass Flow Rate and Load Cell Data from Both Test Runs

## 6. Forward Work

Plans are being prepared for additional testing, with a focus on three primary goals: 1. More extensive ZBO testing across multiple fill levels; 2. Weathering with LNG refills at partial fill levels; and 3. Weathering with refills following LNG flows out of the tank. Goal 1 extends the ZBO testing conducted at the beginning of run #2 by running over longer durations and at multiple fill levels. Goals 2 and 3 represent more realistic operations at launch pads, where the LNG tanks would not be filled and completely drained, but have partial refills in conjunction with transfer events.

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