Robotic Refueling Mission 3:
Cryogenic Demonstration Subsystem Operations

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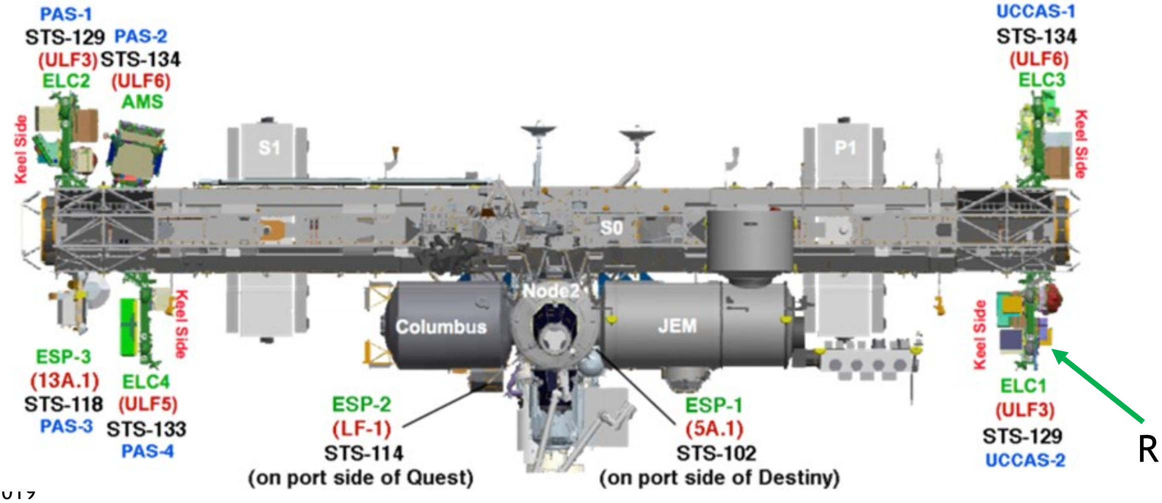
Overview

- RRM3 mission and CDS design
- CDS test program
- RRM3 launch campaign
- RRM3 installation and checkout
- CDS vent ops (burst disk)
  - ISS power glitches
- Open items

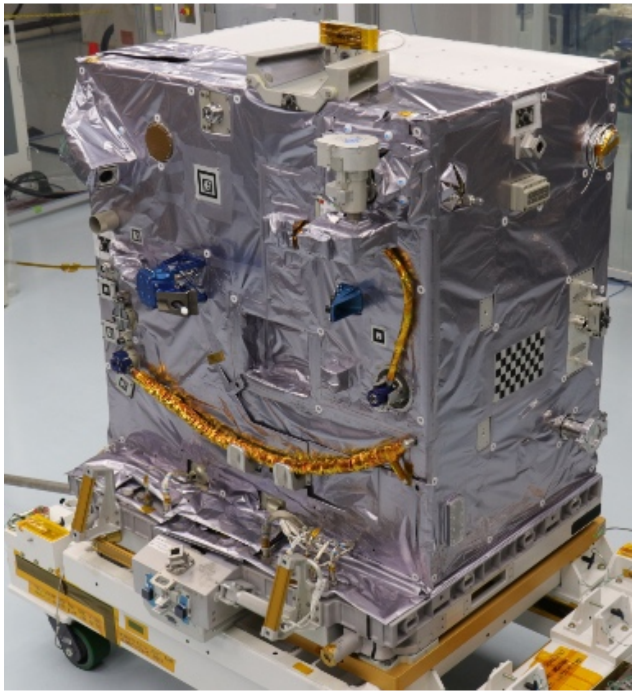


RRM3

RRM3 Objectives

RRM3 is an ISS external payload demonstrating technologies required to service satellites with both conventional and cooperative cryogenic and xenon interfaces

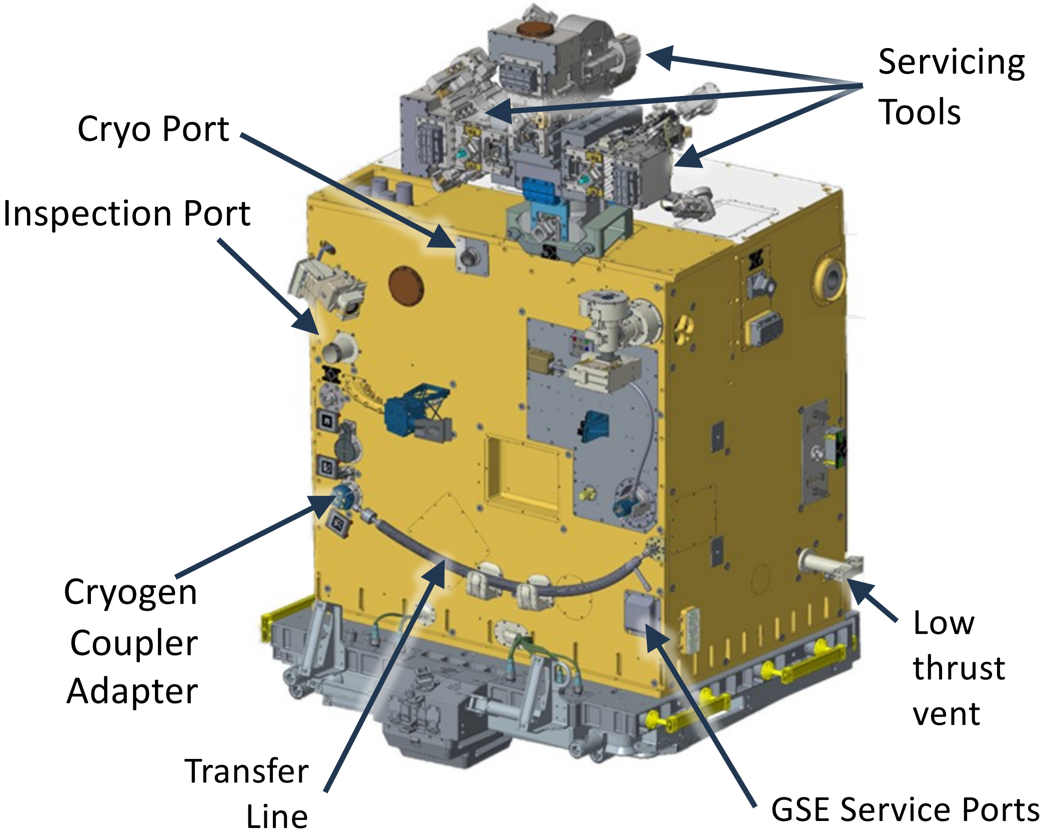
- RRM3 High Level Objectives:
  - Demonstrate methods to store, transfer and freeze standard cryogenic fluid in a zero-gravity environment through the use of innovative component designs and techniques for both conventional and cooperative interfaces.
  - Maintain fluid mass for six months via zero boil-off
  - Transfer fluid via “zero vent” technique without forming ice plugs
  - Demonstrate the transfer of xenon gas from a supply tank to a client tank via a robotically-enabled interface in a zero-g environment.
  - Verify robotic manipulation and actuation techniques necessary for cryogenic fluid and Xenon transfers



RRM3 Payload Pre-launch

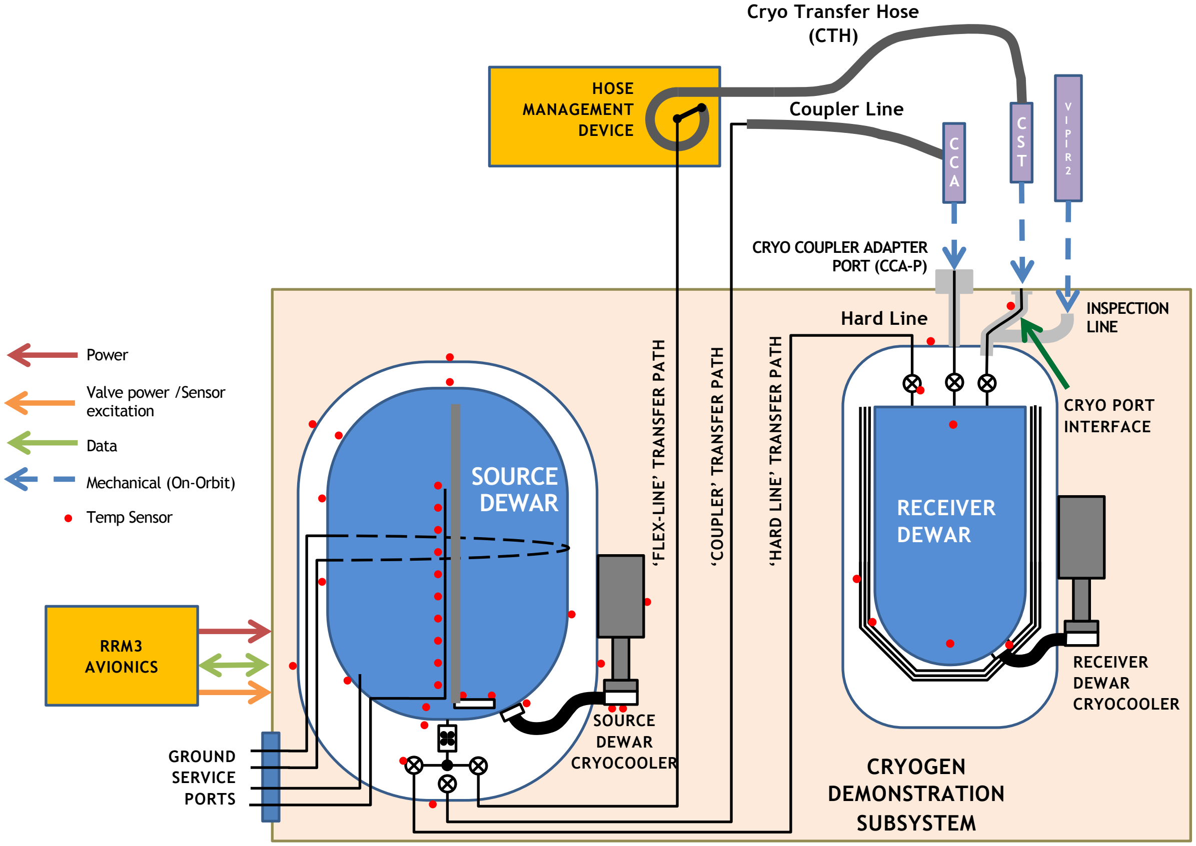
RRM3 Features

- Two dewars
  - 50 liter Source and 10 liter Receiver
  - Individual cryocoolers to maintain temperature and pressure
- ”Cryo Port” and “Inspection Port” simulating a non-cooperative payload
- Three transfer lines
  - Rigid line, Coupler line, “Flex line” on hose reel
  - Aerogel insulation system
- Radio Frequency Mass Gauge in Source Dewar



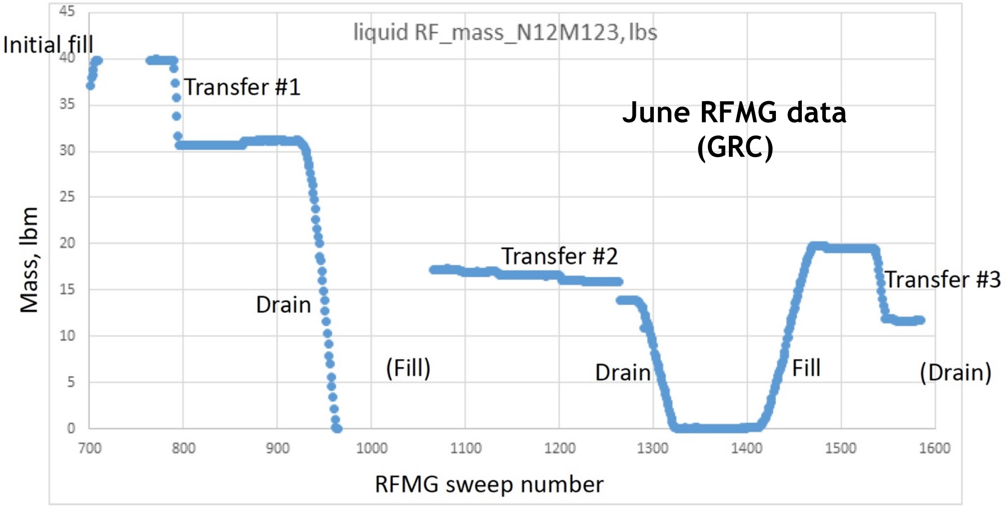
RRM3 Features (cont’d)

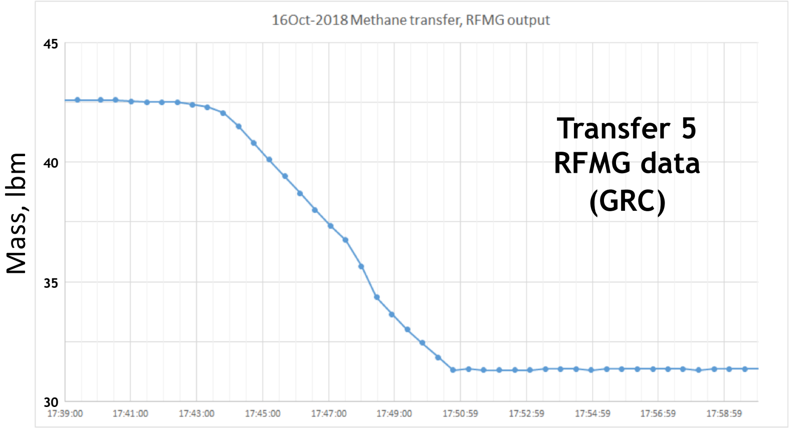
- Cryogenic solenoid valves
- 44 temp sensors
  - 10 in wet/dry mode
- 4 pressure transducers 0-700 kPa
- Liquid acquisition vane system
  - Nested geometry to accommodate wet/dry sensors
- Wick pressurization system
- Turbine flow meter
- Integrated MLI on Receiver tank



Methane Transfer Testing – pre-flight

- Five transfer tests
  1. May 27 9.5 liters
  2. May 30 1 liter (unsuccessful)
  3. June 3 8.5 liters
  4. Oct 15 0.8 liters (unsuccessful)
  5. Oct 16 >10 liters
     - Liquid lock, RD burst disc rupture
- Flow meter (electronics?) were not reliable
- With no-vent process, start box had to be carefully balanced
- Liquid lock on Transfer 5 almost resulted in loss of mission

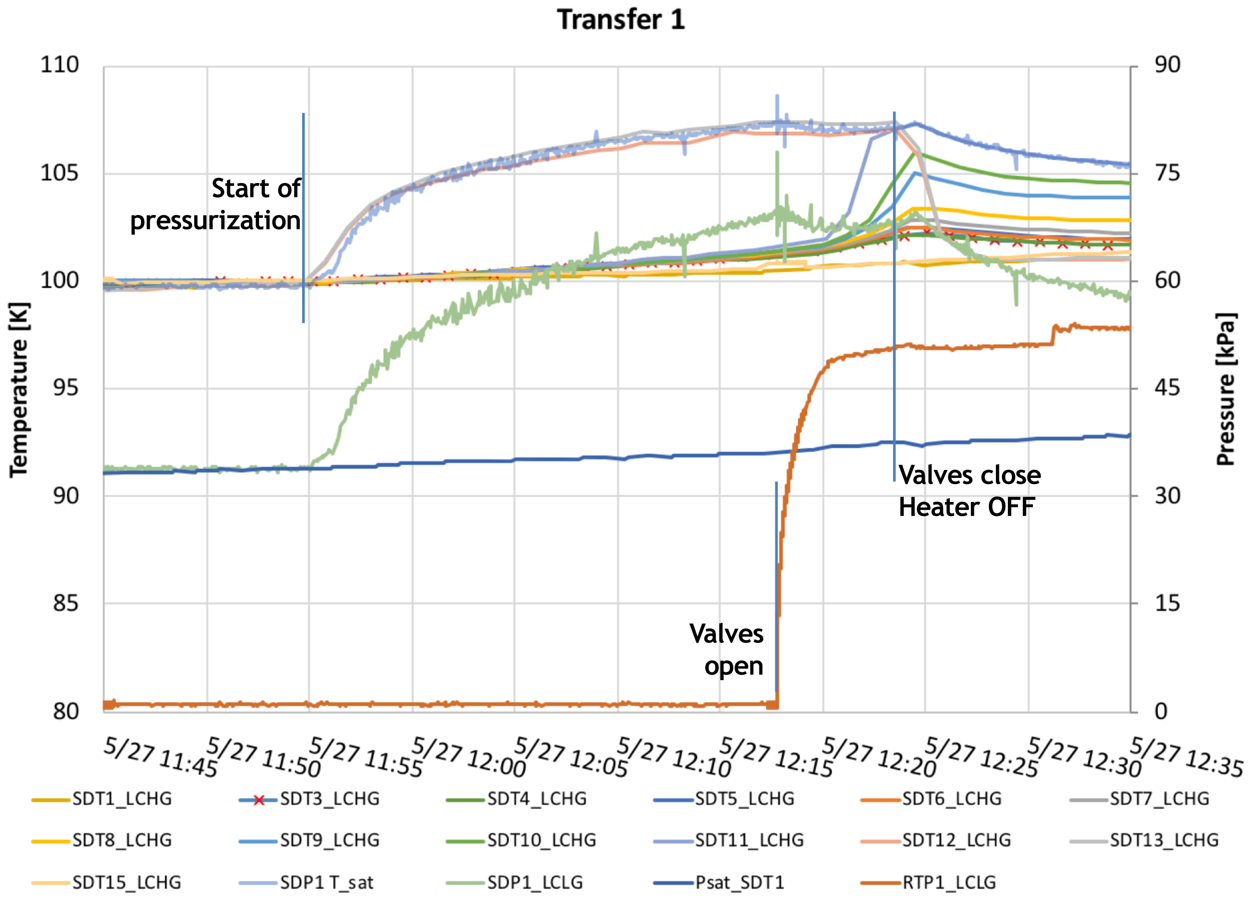




Transfer 1 - successful

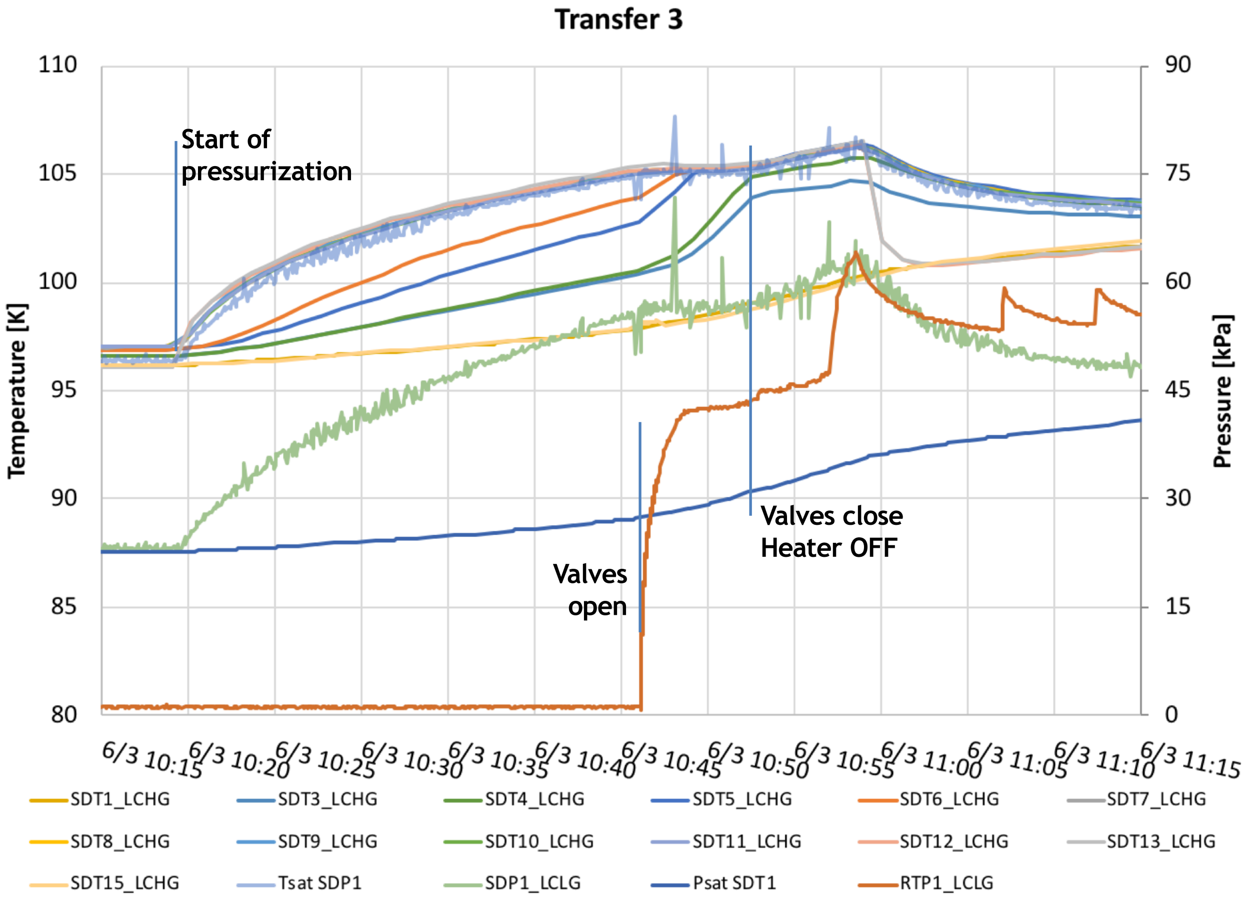
- SDP1: 70 kPa at start of transfer
- RTP1 came up to 50 kPa and stabilized

- Liquid from SD was cold enough to absorb transfer line heat, and arrive in RD with saturation pressure ~15 kPa below delivery pressure



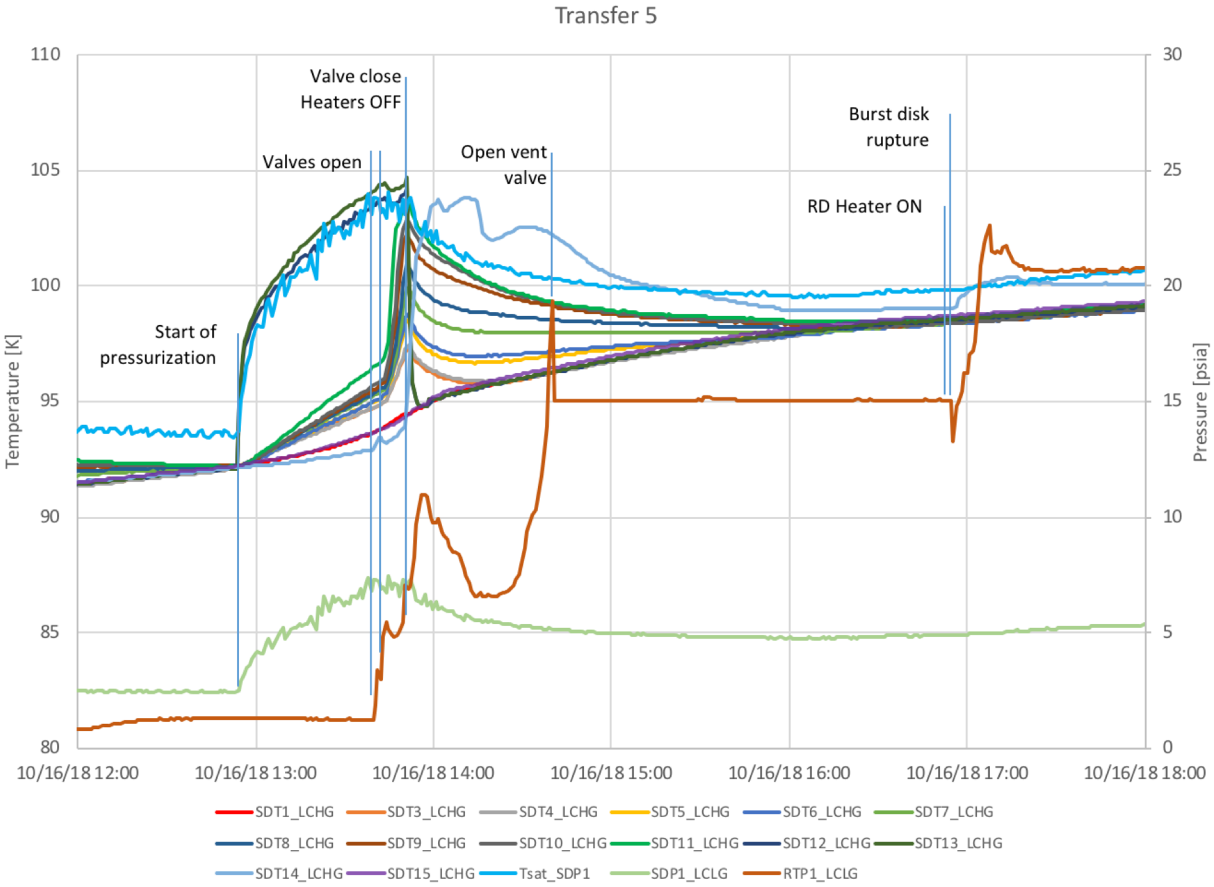
Transfer 3

- 55 kPa at beginning of transfer
- Solenoid valves dropped closed after 6 minutes
- Re-opened valves, but transfer stalled
- No flowmeter data



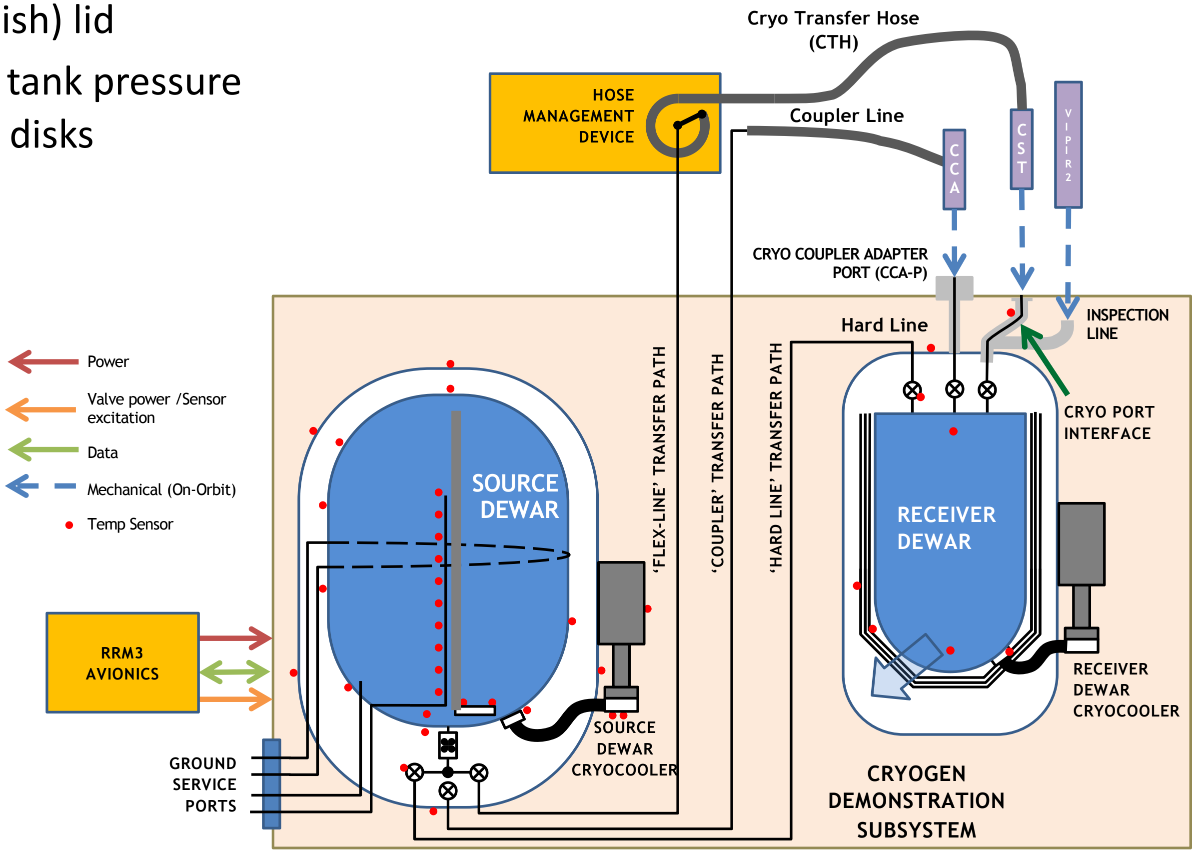
Transfer 5 – too successful

- Tank liquid locked at end of transfer, cryocooler successfully densified the fluid
- RD cryocooler controlled pressure, until it was turned off to evaporate RD contents
- RD tank liquid locked again, vent valve successfully alleviated pressure rise
- RD tank heater was turned on to evaporate RD contents, caused expansion faster than vent valve could accommodate
- At least one BD on tank ruptured into vacuum space, but outer BD's were left intact
- Cryo team did not recognize criticality of liquid lock, and did not recognize compromised vacuum space



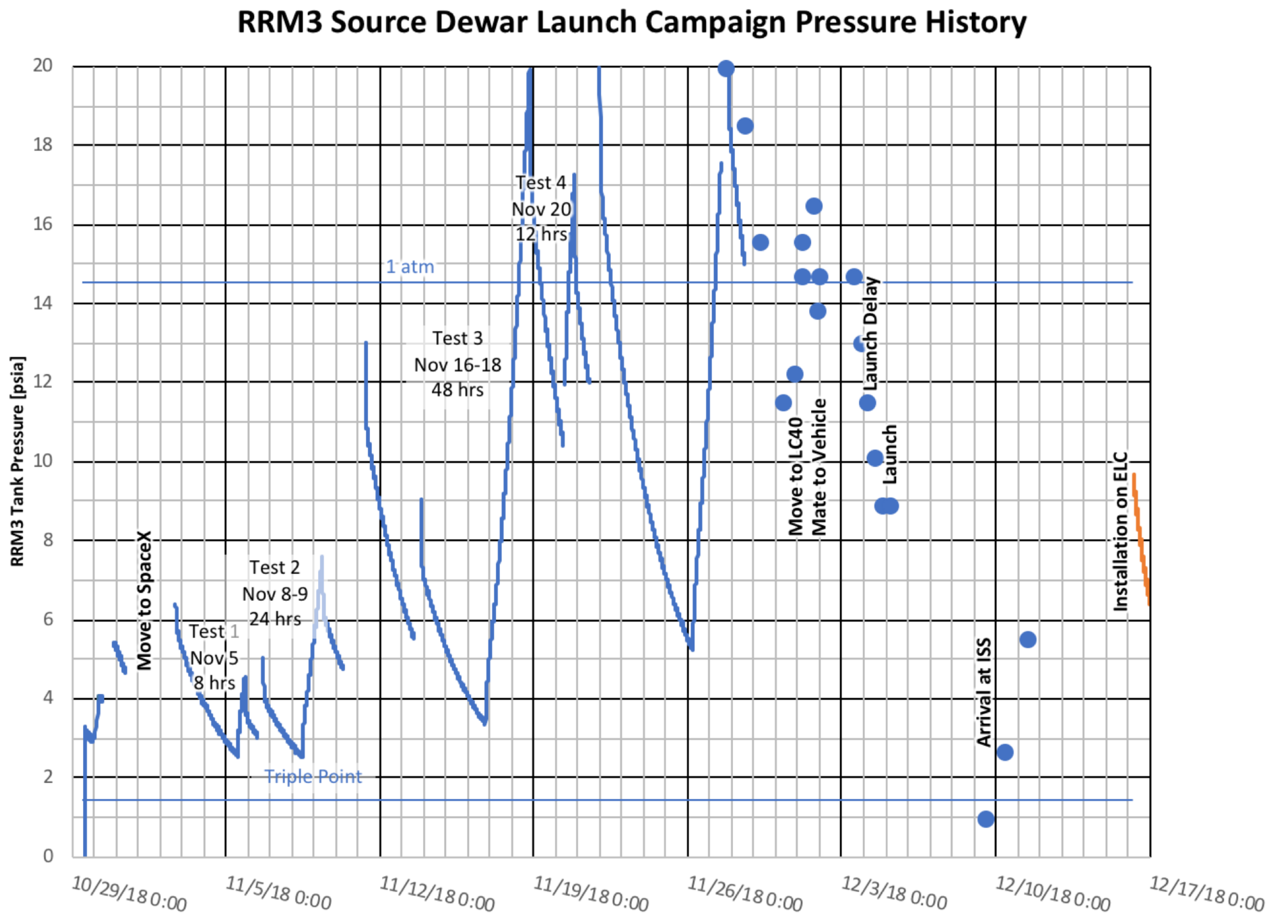
RD Burst Disk

- Expanding liquid contacted the (warmish) lid
  - High vent line impedance allowed tank pressure to exceed set point for inner burst disks
- Burst disk had released into vacuum jacket, but had not ruptured the outer burst disk
- Compromised vacuum jacket on RD allowed high heat load, but ops team did not recognize the symptoms
- Loss of vacuum jacket was only recognized two days later



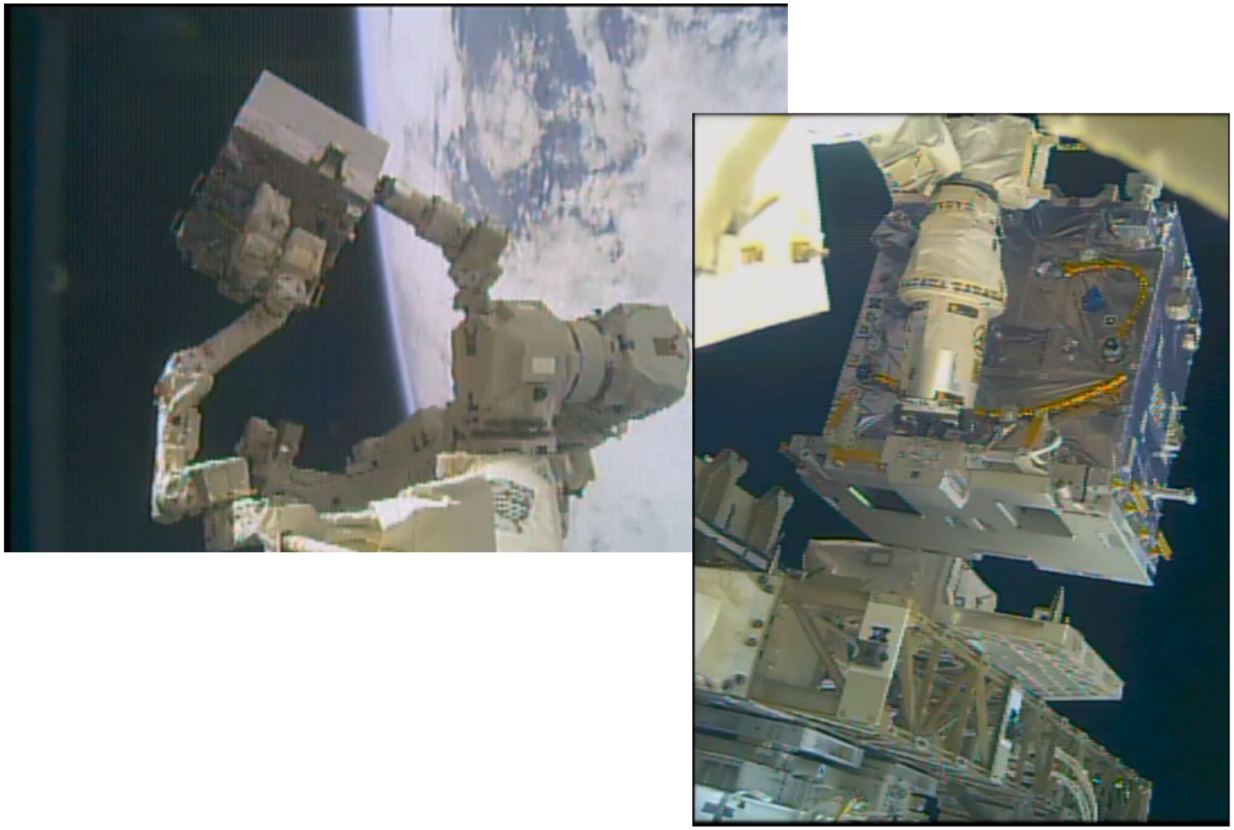
Launch campaign

- Move to SpaceX Oct 30
- SpaceX interface allowed monitoring of basic telemetry through launch campaign
- Power (GSE or vehicle) available with mandatory gaps ≤ 24 hours
- Operations at SpaceX facilities were closely controlled, but were negotiable
- Last touch T -60hrs
- Launch on CRS-16 Dec 5 13:16 EST



Installation on ELC

- Removed from Dragon trunk Dec 14 20:00 EST, installed on ELC1 Dec 15 23:40 EST
- Typical ISS command window 1300-2100 GMT, data windows subject to TDRS downlink
- All components checked out okay except power electronics
  - Compromised input filter prevented simultaneous operation of high-power components, such as cryocoolers



RRM3 Install on ELC1

Reboost – tank surface sensors

- Re-boost of the ISS with cryocooler running showed very little reaction, but with cryocooler off, the liquid de-stratified at ~200 µg

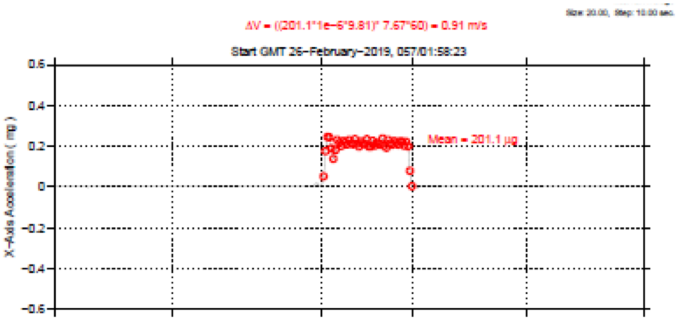


Fig. 3: Interval average of SAMS 121f03 sensor data shows Progress 71P reboost.

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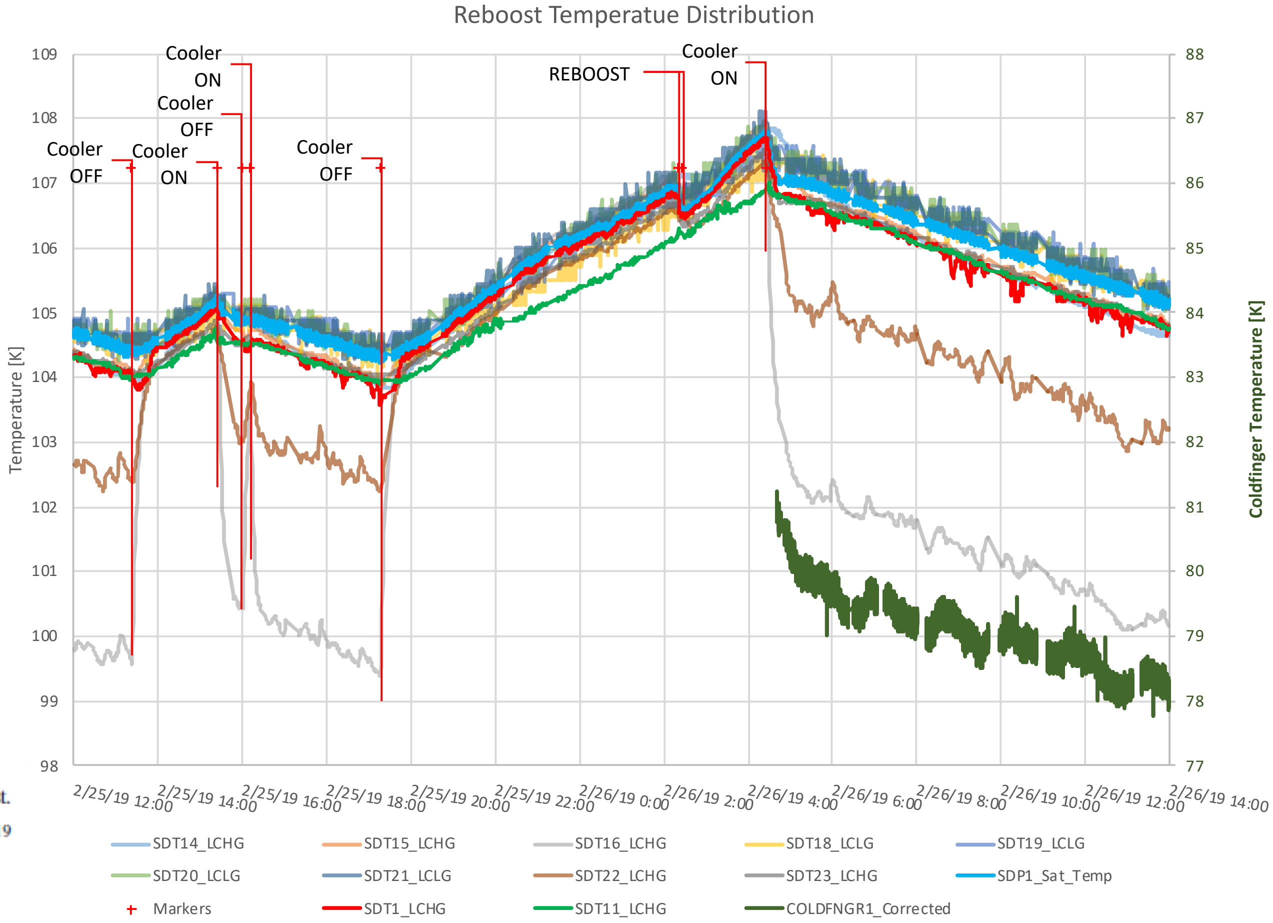
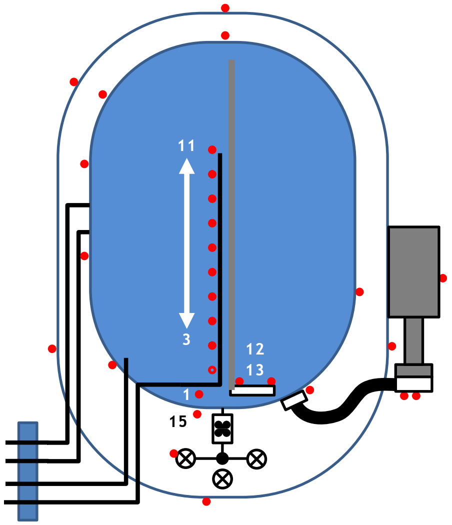
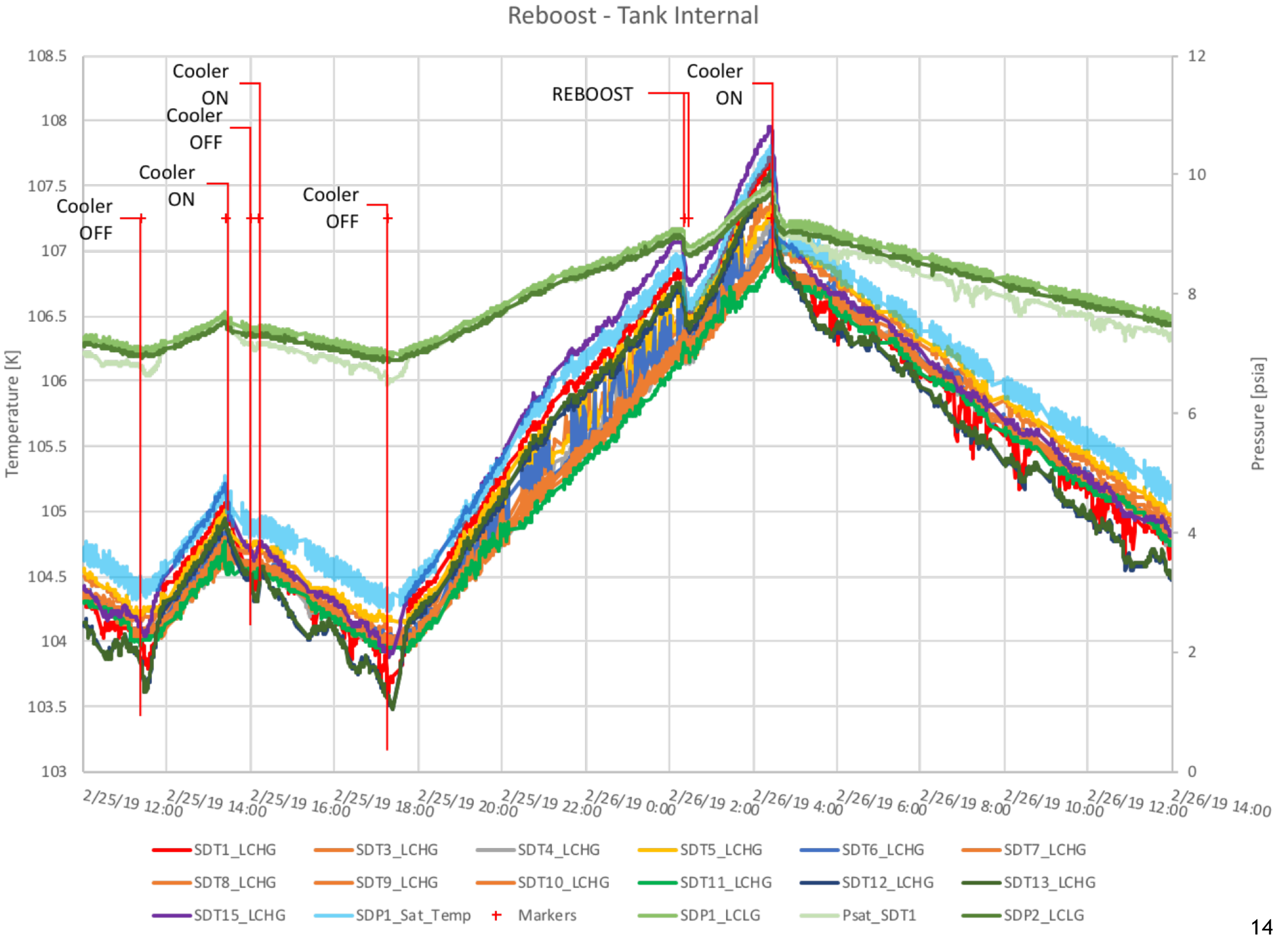


Reboost – array sensors

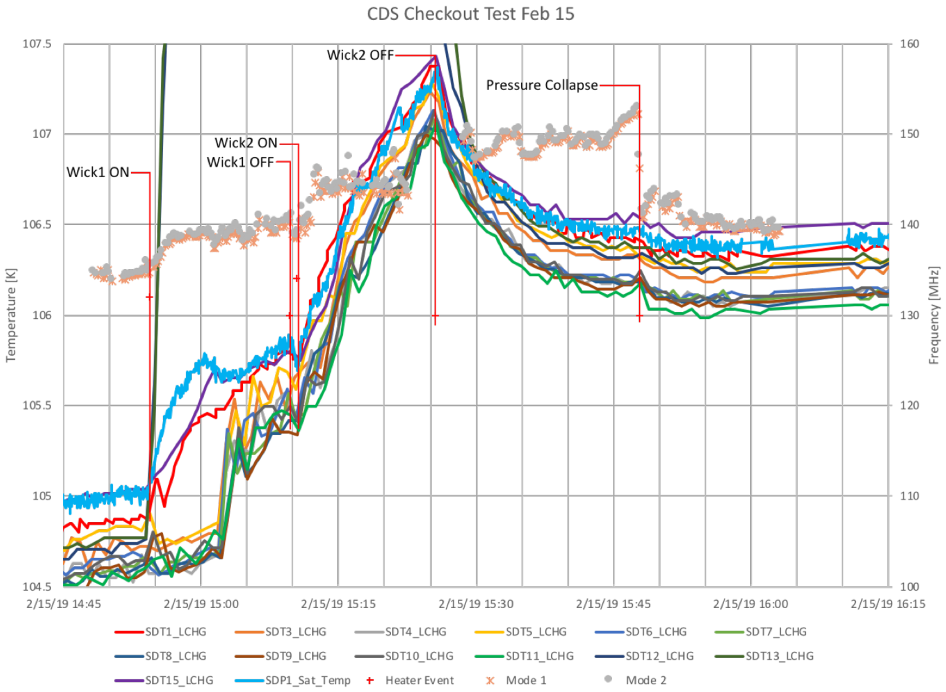
- Sensors in the middle of the sensor array showed high variability during pressurization (cooler OFF) prior to reboost event
- SDT1 at the bottom of the sensor array showed high variability during cooldown (cooler ON) before and after reboost

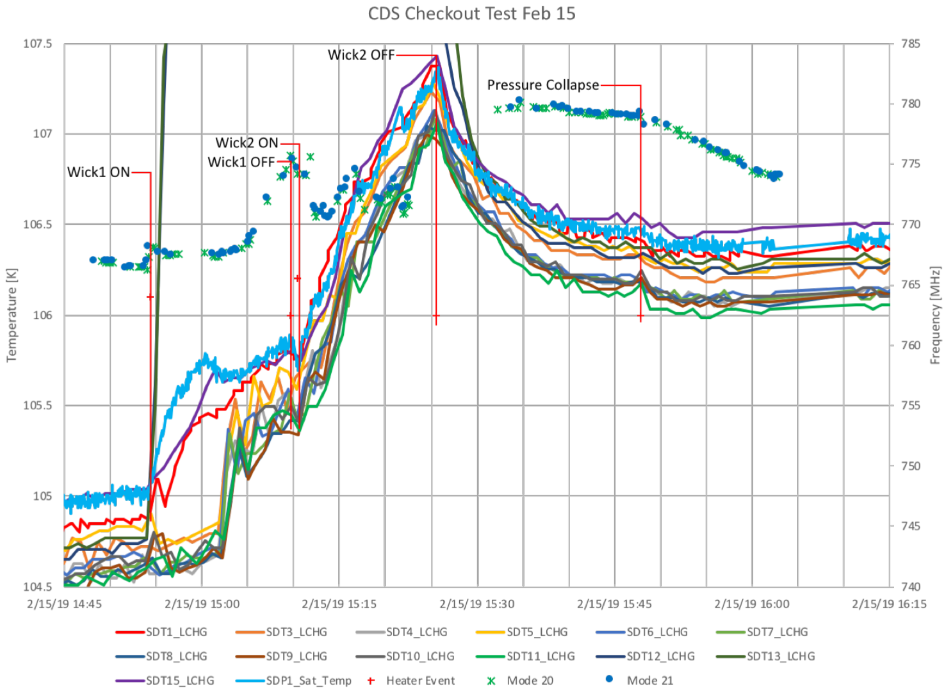




Wick pressurization – CDS checkout

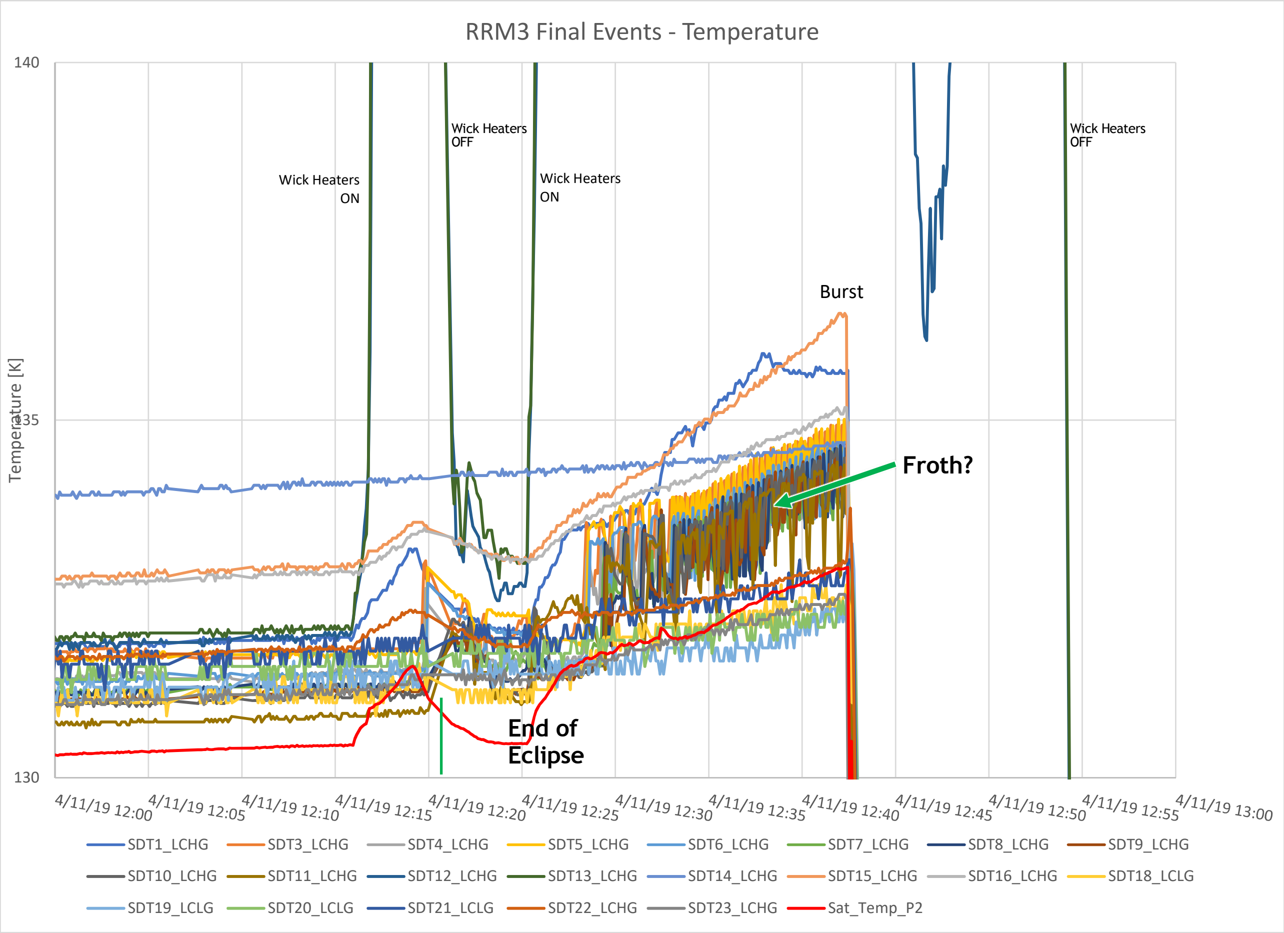
- In CDS checkout test Feb 15, RFMG seems to show redistribution of fluid inside tank





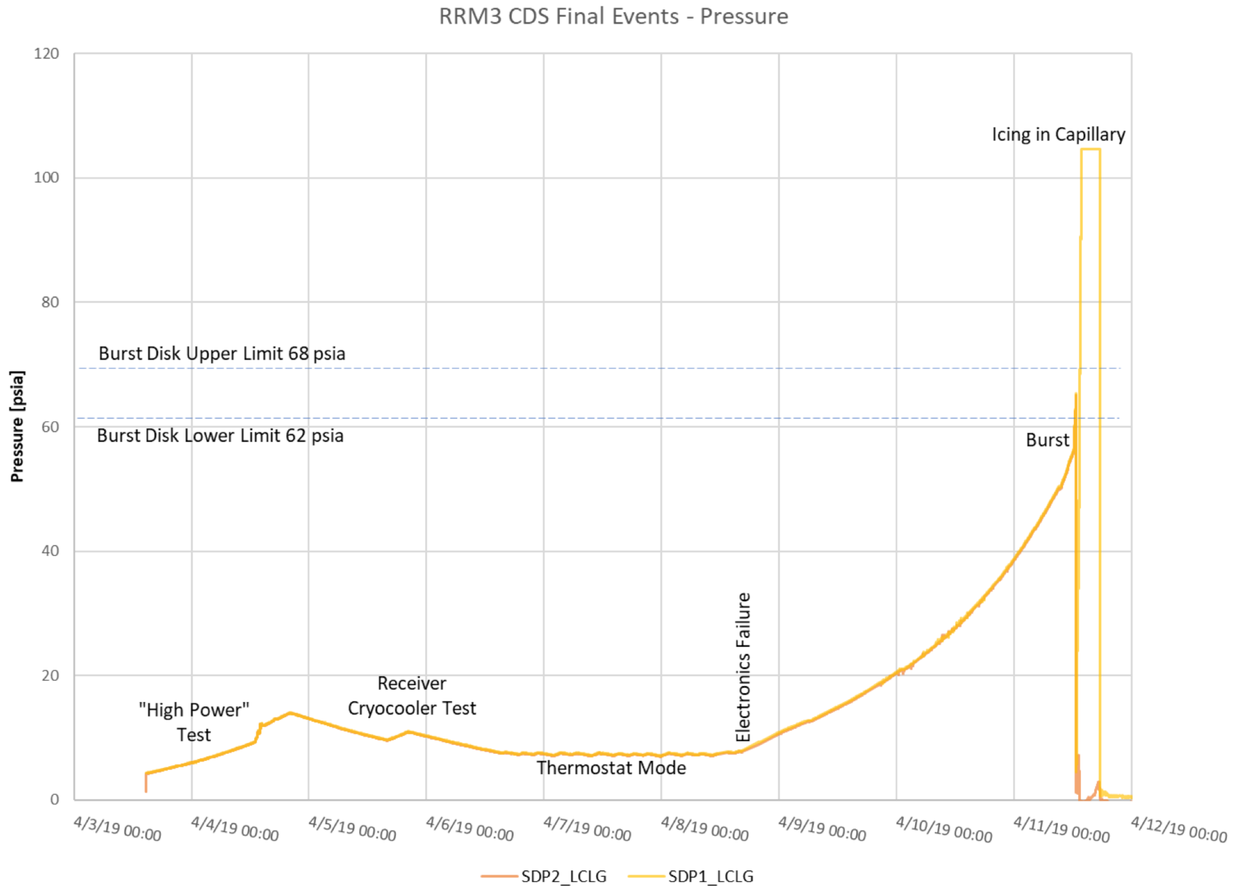
Wick pressurization – final ops

- Wick heaters ran as high as 265 K
    - Previous events operated at saturation temp
- Initial pressurization was very rapid (local heating), then slowed down (more like global heating)
- Frothing in the central cone?



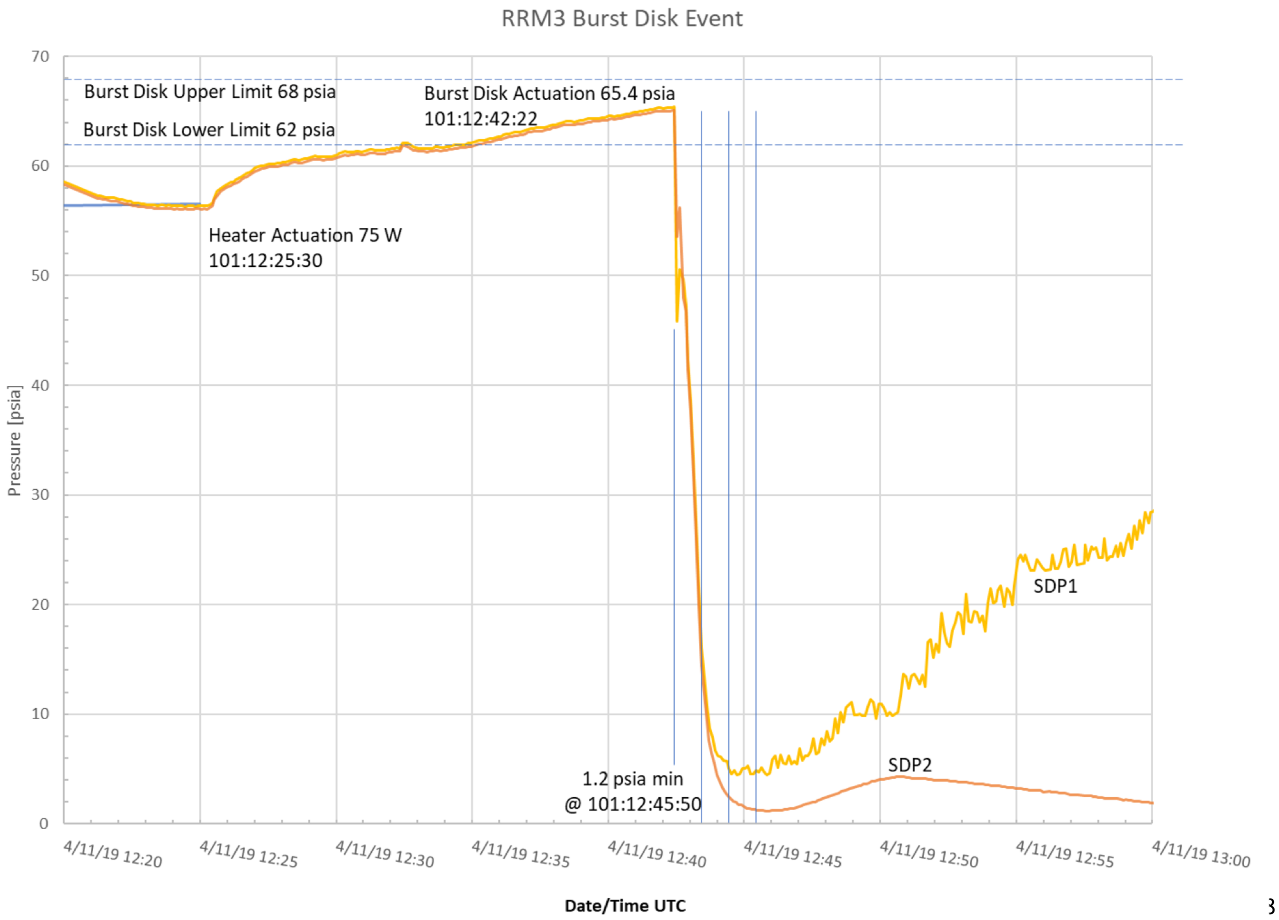
Loss of Cryocooler Function

- Payload power glitch April 8 at 1200 GMT
- Cryocooler power restored at 1742, circuit breaker trip at 1749
  - Circuit breaker could be reset if cryocooler was held OFF
- Electrical fault isolated to cryocooler output circuits
  - Not recoverable
- Burst disk projected to activate 4/11 – 4/12
- ISS requested coordinated operation to mitigate disruption of ISS activities
  - Use wick heaters to instigate burst disk rupture



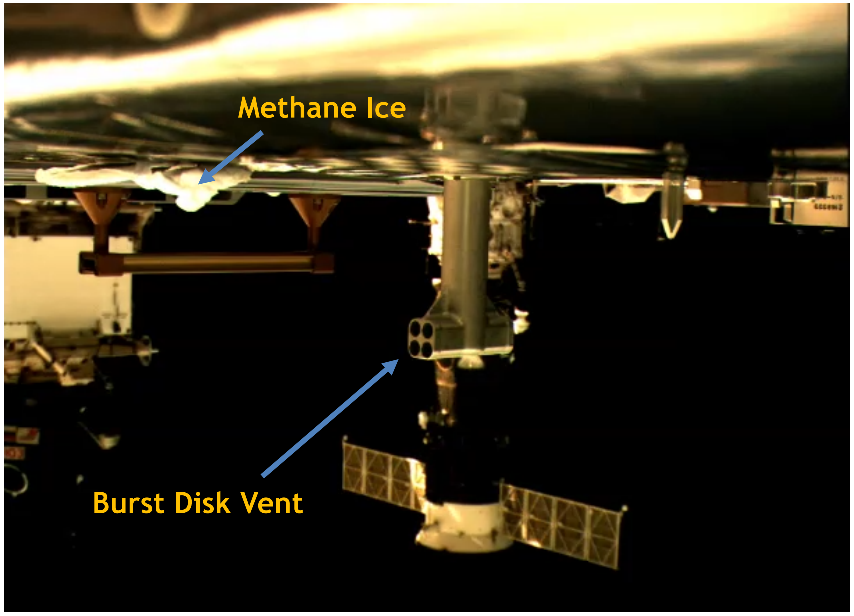
Burst disk rupture

- Heater operation was coordinated with ISS operations
- Blowdown to 5 psi took approx 90 seconds
- SDP1 re-pressurized to > 100 psia
    - Capillary to pressure sensor had plugged with methane ice

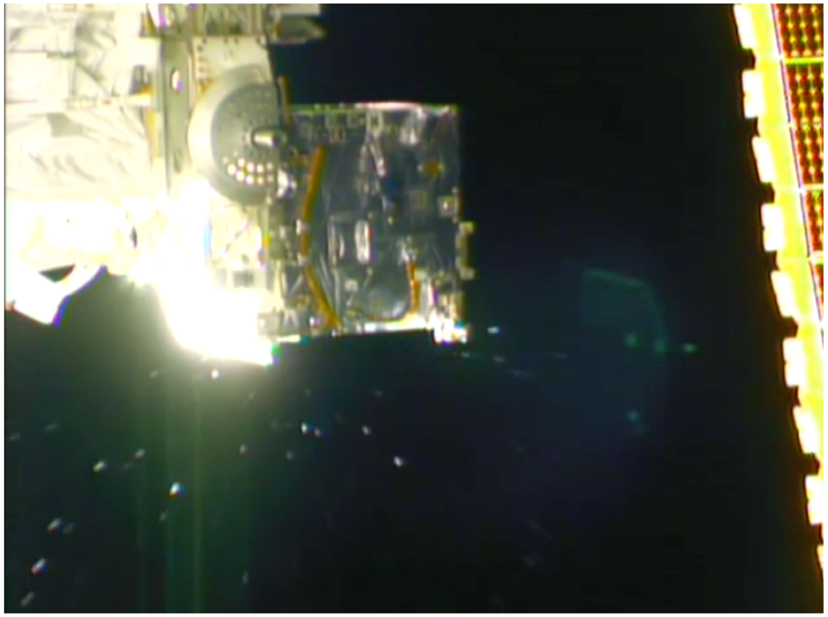


Views of methane venting

- All cameras were turned away at 1100 GMT, venting occurred at 1242 GMT
- RRM3 camera captured low-rate images from 1300 GMT
- ISS cameras captured video from 1400 GMT
  - Examples https://io.jsc.nasa.gov/app/info.cfm?pid=29301924
    https://io.jsc.nasa.gov/app/info.cfm?pid=29301888



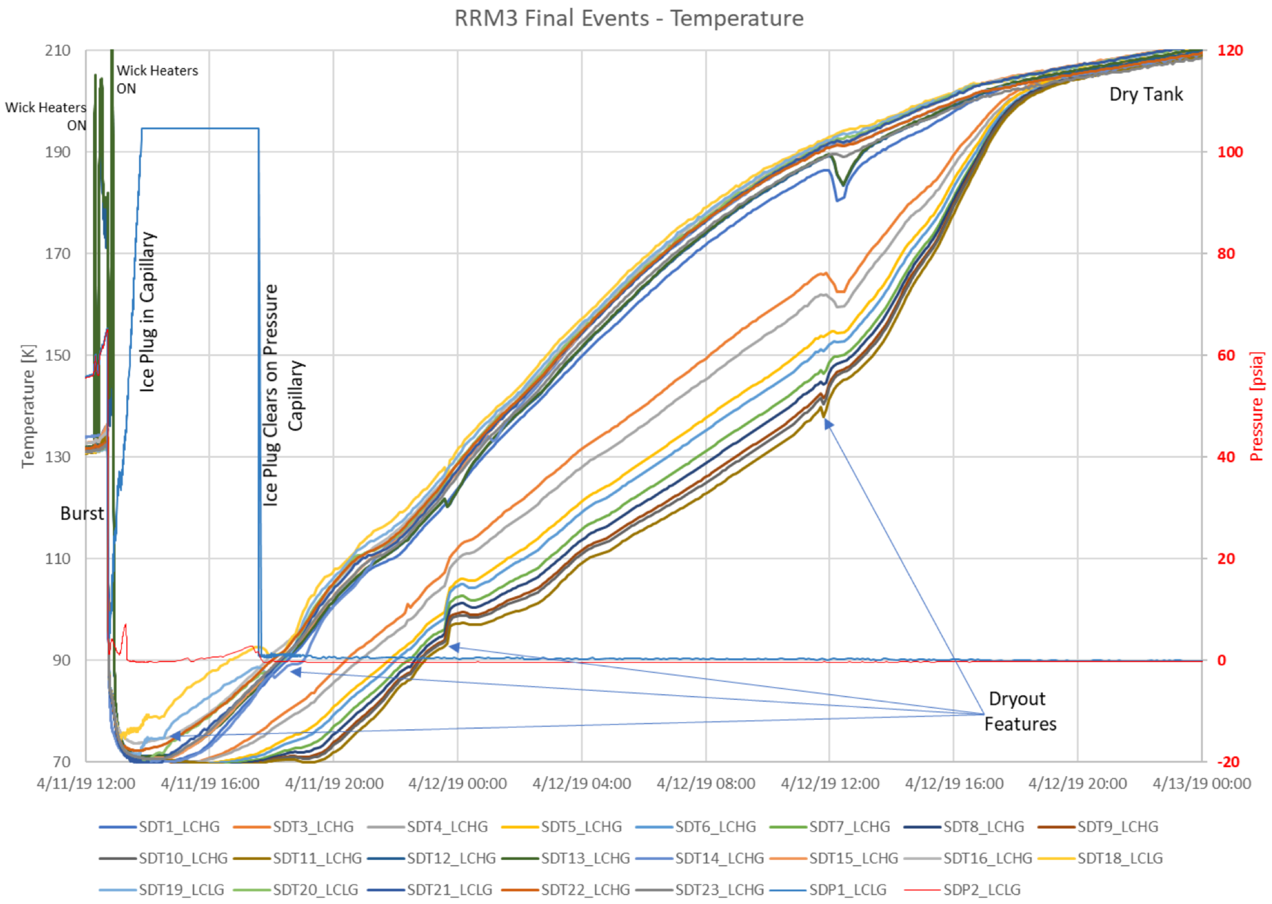
View of RRM3 side face and Burst Disk Vent



Ice Particles venting

Dryout

- Features in dryout are probably associated with impurities in cryogen



Conclusions

- No-vent fill was accomplished in ground test conditions
  - Autogenous pressurization with wick/heater system
- Cryocooler successfully held temperature and pressure until encountering electrical issues
  - No-vent for 165 days
- Tank stratification was sensitive to thrust disturbances
- RFMG was successfully calibrated by GRC for one-g and zero-g conditions
- Wet/dry sensors worked successfully in ground test conditions
- Transfer process
  - Successful process model was developed by GRC
- iMLI was used successfully on Receiver
- Aerogel was used successfully on transfer lines